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Title:	Lean Manufacturing effects of modularization on the outfitting process in shipbuilding: A case study of Royal IHC
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Title (in Dutch)	Lean manufacturing effecten van modularisatie op het afbouwproces in de scheepsbouw: een gevalsstudie voor Royal IHC

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Initiator (university):	Dr. W.W.A. Beelaerts van Blokland
Initiator (company):	TU Delft
Supervisor:	Dr. W.W.A. Beelaerts van Blokland
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Subject: Lean Manufacturing effects of modularization on the outfitting process in shipbuilding: A case study of Royal IHC

Next to the innovation of products, the innovation of production processes is an area that requires attention in order to enhance the competitiveness in shipbuilding. As modular outfitting is considered as an optimization of the outfitting process, increasing the portion of modular outfitting can be used to increase efficiency (Fafandjel, Rubesa, & Mrakovcic, 2008).

Prior studies focus mainly on cost saving by reduced labour hours using modularization. Fafandjel et al. study the shipbuilding duration and the related cost by shifting labour hours. Rubesa et al. come up with general cost saving equations by outfitting completion rates at various stages (Rubesa, Fafandjel, & Kolic, 2011). However, they did not emphasize the Lean Manufacturing improvements of their studies.

This assignment is to give an insight on the impact of modularization on the outfitting process with a Lean Manufacturing perspective by doing a case study for Royal IHC, a Dutch shipbuilding company. Therefore amongst others the following questions have to be answered:

- What are the constraints of the outfitting process?
- How can modularization contribute to the efficiency increase of the outfitting process?
- What implications can be encountered when implementing modularization and how can it be dealt with?
- How can relevant literature contribute to institutionalize modularization in shipbuilding?

Present the found literature and data in a report. It is expected that you conclude with a recommendation for further research based on the result of this study.

The report should comply with the guidelines of the section. Details can be found on the website.

The professor,

Prof.dr.Ir. G. Lodewijks

Summary

Next to the innovation of products, the innovation of production processes requires attention in order to enhance the competitiveness in shipbuilding. Production improvements are currently of great importance for increasing the efficiency of shipbuilding, which can result in lower cost and reduced lead times. Wei (2012) suggests that the outfitting work can be done more efficiently by completing outfitting earlier and that strict milestones of the production are constraints for pre-outfitting. Several studies that tried to calculate cost factors at different outfitting stages suggest that outfitting at later stage involves more cost (e.g. Fafandjel, Rubesa, & Mrakovcic, 2008). As modular outfitting is considered as an optimization of the outfitting process, increasing the portion of modular outfitting can be used to increase efficiency and reduce overall cost according to Fafandjel et al. Modularization decreases the number of items on a Bill of Materials (BOM) by making pre-assembled items. Less items on a BOM can result in fewer suppliers, which lowers the transaction risk and costs while increases responsiveness (Meysen et al, 2009). There are prior studies about modularization in shipbuilding but there is no emphasis on the Lean Manufacturing aspect of modularization. Lean Manufacturing is a method to reduce waste in manufacturing with a systematic approach. Furthermore, there is no general guideline for the shipbuilding industry to estimate the possible labour savings by making modules for outfitting. A possible guideline can provide a strategic approach when choosing a system to outsource as a module for outfitting. This case study analyses several Lean Manufacturing effects of reducing the items on the BOM for outfitting using data of Royal IHC, a Dutch shipbuilding company. These effects give an insight on the benefits of modularization with a Lean Manufacturing perspective. The goal is to increase the pre-outfitting percentage by identifying (possible) wastes and to facilitate modularization in shipbuilding using relevant literature.

The Theory of Constraints (TOC) is used to generate possible modules effectively. The movement time, movement distance, storage area, storage time and the transactions for the generated seven cases are analysed. The current situation and the modularized situation are compared to show the result in three parts of the outfitting BOM: foundation, equipment and piping. The seven cases save around 130 hours of labour and 13 km. of movement distance of the items on the BOM. This is a reduction of 0.24% labour hours at the pre-outfitting and 0.64% at the outfitting on board. This is a minor improvement, because small systems are analysed to have sufficient amount of cases taking the validity of the generated guideline into account. No significant change in storage area on the shipyard is found, but modularization increases ground storage and decreases shelve storage. Floor space of 26 m^2 is saved inside the ship. Assuming a safety margin of three days for the modules, the average storage time reduction is 40 days. To express the concern of the storage time, the value of the items are also taken into account. Two cases have relatively long storage time and/or high value compared to the assumed three day storage situation. The amount of items on the outfitting BOM is reduced on average 78%. The supplier transactions are reduced from six to one for two cases and four to one for the other five cases, assuming that the piping subcontractor is the module supplier. A correlation between the saved times for foundation, equipment and piping is determined. It is found that early finish of section erections do not have the same impact on an early start of the following section erection. The effect of modularization with respect to transaction cost, supply risk, supplier responsiveness and supplier innovation are discussed to show the implementation and implications.

It can be concluded that the reduction of movements leads to less confrontation and interruption of employees working on the shipyard and increases the overall pre-outfitting percentage compared to all outfitting activities. Accessibility inside the ship is increased by making modules. The necessity of applying Just in Time principle to reduce waste in form of Work In Progress inventory becomes more perceptible when taking the storage time and the value of the items into account. Less items on the outfitting BOM reduces the complexity in dependencies and resources and can decrease the probability of waste especially towards the end of outfitting where delays are found. A guideline for a strategic approach to generate modules in the future is generated by finding a correlation between the saved labour times. However, more case analyses can increase the reliability and make different correlations for various classifications. More aggressive estimations using lower bounds rather than averages of task durations at the start of outfitting can compensate the increasing delays to the end. Better work distribution and agreements with the customer can be made at the design phase by identifying possible additional delays. These delays can also be mitigated by lowering the utilization of resources to create a bigger capacity buffer to handle variation and unplanned usage. Not only the

external suppliers, but also the internal suppliers on the shipyard is reduced allowing a better manageable Just in Time principle. Defect possibility is mitigated by testing before supply if possible. These effects of modularization in this case study show the waste reduction that directly or indirectly facilitates a higher pre-outfitting percentage. Implications and implementation aspects due to supplier reduction are presented using relevant literatures.

So, reducing supply base by modularization can lead to significant advantages unless the complexity and the behaviour of the current situation for Royal IHC is understood well. The design-manufacturing integration and the information technology-concurrent engineering interaction are the key factors for an efficient implementation of modularization. Royal IHC is already implementing modularization, but these aspects can make the current situation more effective. Even though there are significant improvements in this case study, modularization in shipbuilding is not yet institutionalized (Doerry N. H., 2014). Efforts and more research to modularization possibilities in the shipbuilding like this case study will contribute to the institutionalizing. This research contributes theoretical and practical to the valuing of modularity with a Lean Manufacturing perspective by conducting a case study at one of the leading shipbuilding companies. The cost impact of the analysed cases is worth a further research to contribute to the valuing.

Summary (in Dutch)

Om het concurrentievermogen te verbeteren in de scheepsbouw eist productie innovatie de nodige aandacht naast productinnovatie. Tegenwoordig zijn productieverbeteringen essentieel om de efficiëntie in de scheepsbouw the verhogen, wat kan leiden tot lagere kosten en kortere doorlooptijden. Wei (2012) suggereert dat de afbouwwerkzaamheden efficiënter uitgevoerd kunnen worden door het eerder af te krijgen en dat de mijlpalen in de planning een beperking zijn voor de vroege afbouw (pre-afbouw). Verschillende studies, die een poging hebben gewaagd om de kostfactoren in verschillende stadia van de afbouw te bepalen, suggereren dat latere stadia meer kosten met zich meebrengt (e.g. Fafandjel c.s., 2008). Aangezien modularisatie in de afbouw wordt beschouwd als een optimalisatie, kan het vermeerderen van modules de efficiëntie verhogen en de kosten verminderen volgens Fafandjel c.s. Modularisatie vermindert het aantal items op een stuklijst (BOM) door het maken van voorgemonteerde items. Minder items op een BOM kan resulteren in minder leveranciers die de transactierisico's en kosten reduceert, terwijl de responsiviteit toeneemt (Meysen c.s., 2009). Er zijn eerdere studies gedaan over modularisatie in de scheepsbouw, maar er is beperkt aandacht gegeven aan de Lean Manufacturing aspecten. Lean Manufacturing is een methode om verspilling in de productie te verminderen met een systematische aanpak. Verder is er geen algemene richtlijn voor deze sector om de mogelijke arbeidsbesparing in te schatten door modularisatie in de afbouw. Een mogelijke richtlijn kan een strategische aanpak bieden bij het bepalen van een systeem dat gemodulariseerd en uitbesteed kan worden. Deze gevalsstudie analyseert verschillende Lean Manufacturing effecten van het verminderen van het aantal items in de BOM voor de afbouw door gebruik te maken van gegevens van Royal IHC, een Nederlands scheepsbouwbedrijf. Deze effecten zullen een inzicht geven op de voordelen van modularisatie met een Lean Manufacturing perspectief. Het doel is om hiermee de pre-afbouw percentage the verhogen door (mogelijke) verspillingen te identificeren en om de modularisatie te vergemakkelijken door gebruik te maken van relevante literatuur.

De Theory of Constraints (TOC) wordt gebruikt om effectief mogelijke modules te genereren. De bewegingstijd, bewegingsafstand, opslagruimte, opslagtijd en de transacties voor de gegenereerde zeven gevallen zijn geanalyseerd. De huidige situaties en de gemodulariseerde situaties zijn vergeleken om het resultaat in de drie delen van de afbouw BOM te zien: fundatie, apparatuur en leidingen. De zeven gevallen besparen ongeveer 130 arbeidsuren en 13 km. bewegingsafstand van de items op de BOM. Dit is een daling van 0,24% arbeidsuur bij de pre-afbouw en 0,64% bij de afbouw aan boord. Dit is een geringe verbetering, omdat er gekozen is voor meerdere en daardoor kleinere gevallen om de validatie van de richtlijn enigszins te verhogen. Er is geen significante verandering in de opslagruimte op de werf gevonden, maar modularisatie vermeerdert grondopslag en reduceert plankopslag. Vloeroppervlakte van 26 m^2 wordt vrijgemaakt in het schip. Uitgaande van een veiligheidsmarge van drie dagen, reduceert de gemiddelde opslagtijd met 40 dagen. Om het belang van de huidige opslagtijd te drukken worden de waarden van de items meegenomen. Twee gevallen hebben relatief een opmerkelijke lange opslagtijd en/of hoge waarden in vergelijking met de veronderstelde driedaagse opslagsituatie voor de modules. De hoeveelheid items op de afbouw BOM wordt verlaagd met gemiddeld 78%. De leverancierstransacties worden teruggebracht van zes naar één voor twee gevallen en van vier naar één voor de andere vijf gevallen, ervan uitgaande dat een huidige onderaannemer de moduleleverancier wordt. Een correlatie tussen de bespaarde tijden voor de fundatie, apparatuur en leidingen is gevonden. Het blijkt dat een vroege voltooiing van een sectie erectie niet resulteert in een vroege start van de volgende sectie erectie. Het effect van de modularisering met betrekking tot de transactiekosten, leveringsrisico, leveranciersresponsiviteit en leveranciersinnovatie zijn besproken om de uitvoering en de implicaties weer te geven.

Er kan geconcludeerd worden dat minder bewegingen op de scheepswerf tot minder confrontaties en onderbrekingen van en door de medewerkers leidt. Daarmee draagt het bij aan de verhoging van de totale pre-afbouw percentage. Toegankelijkheid in het schip is verhoogd door modules te gebruiken. De noodzaak van Just in Time principe om de verspilling te verminderen in de vorm van Work In Progress inventaris wordt meer waarneembaar als er naast opslagtijd ook rekening gehouden wordt met de waarde van de items. Minder items op de afbouw BOM vermindert de complexiteit in afhankelijkheden en middelen. Dit kan de kans op verspilling verminderen, voornamelijk aan het einde van de afbouw waar vertragingen zijn geconstateerd. Een richtlijn voor een strategische aanpak van modularisatie in de toekomst is gegenereerd. Echter, meerdere geval-analyses kunnen de

betrouwbaarheid verhogen en verschillende classificaties vormen. Agressievere schattingen, die dichter bij de ondergrenzen liggen in plaats van gemiddelden, van taakduren aan het begin van de afbouw kunnen de toenemende vertragingen aan het einde compenseren. Hiermee kan een betere werkverdeling en afspraken met de klant kan in de ontwerpfase worden gemaakt door het identificeren van mogelijke extra vertragingen. Deze vertragingen kunnen ook verminderd worden door het bezettingsgraad van middelen te verlagen. Een grotere buffercapaciteit kan hierdoor efficiënter omgaan met ongepland gebruik. Niet alleen de externe leveranciers, maar ook de interne leveranciers op de werf wordt gereduceerd waardoor de Just in Time principe beter beheerst kan worden. De kans op defect kan indien mogelijk worden verminderd door het testen vóór levering. Belangrijke implicaties en uitvoeringsaspecten veroorzaakt door leveranciersreductie zijn gepresenteerd door gebruik te maken van relevante literatuur.

Leveranciersvermindering door modularisatie kan leiden tot aanzienlijke voordelen, tenzij de complexiteit en de houding van de huidige situatie voor Royal IHC goed begrepen is. De ontwerp-fabricage integratie en de informatietechnologie-concurrent engineering interactie zijn de belangrijkste factoren voor een efficiënte uitvoering van modularisatie. Royal IHC voert reeds modularisatie, maar deze aspecten kunnen het huidige proces mogelijk effectiever maken. Ook al zijn er aanzienlijke verbeteringen in deze gevalsstudie, modularisatie in de scheepsbouw is nog niet geïnstitutionaliseerd (Doerry NH, 2014). Inspanningen en meer onderzoek naar modularisatiemogelijkheden in de scheepsbouw zoals deze studie zullen bijdragen aan de institutionalisering. Dit onderzoek draagt theoretisch en praktisch bij aan het waarderen van modularisatie met een Lean Manufacturing perspectief door het uitvoeren van een gevalsstudie bij een toonaangevend scheepsbouwbedrijf. De kosten van de geanalyseerde gevallen zijn zeker een toekomstig onderzoek waard om een bijdrage te leveren aan het waarderen van modularisatie.

Contents

1. Introduction

Becoming competitive in the market and enhancing that position has been more challenging for European shipyards than their "low cost labour" competitors in the last decades (Wei, 2012). Next to the innovation of product, the innovation of production processes is an area that requires attention in order to enhance the competitiveness. Therefore, competing with production processes has become important as it is not easy for competitors to copy. These production improvements contribute to efficiency increase in shipbuilding, which can result in lower cost and reduced lead times. The production of ships can be separated into two areas: the steel production of the hull and the outfitting of the ship. During the building of a ship, the dependency of a ships' steel sections on outfitting often exists and this dependency has an important impact on construction times and production hours. Separating the construction area on the yard and shipbuilding facilitates parallel activities (concurrent engineering) and thus efficiency (Baade, Klinge, Lynaugh, Woronkowicz, & Seidler, 1998).

Wei suggests that the outfitting work can be done more efficiently by completing outfitting earlier. This ensures that the required work can be performed in better conditions and that results in better quality in less time. The labour becomes more efficient with fewer men on board, where the space is often limited. Wei also emphasizes the fact that strict milestones of the production (such as section erection) are constraints for pre-outfitting. Every outfitting task that can be done in the assembly area, must be done on-board because of the constraint. Several studies that tried to calculate cost factors at different outfitting stages suggest that this involves more cost. For example, Fafandjel et al. show with long term statistics in observed shipyards that the cost of work performed in the workshop compared with the same work on section, on-board or in final outfitting is related respectively as 1:3:5:7 (Fafandjel, Rubesa, & Mrakovcic, 2008). Although different factors are found in literature, all of them are respectively increasing.

As modular outfitting is considered as an optimization of the outfitting process, increasing the portion of modular outfitting can be used to increase efficiency (Fafandjel, Rubesa, & Mrakovcic, 2008). Modularization decreases the number of items on a Bill of Materials (BOM) by making pre-assembled items. Less items on a BOM can result in fewer suppliers for a certain area in the production flow which can lower the transaction risk and cost while increasing responsiveness (Meysen, Beelaerts van Blokland, & Santema, 2009). Fewer products that are (half) finished remains in stock on the shipyard and that can lead to easier manageable parts in the flow and space savings. The resulting reduction in the supply chain means also a more accurate forecast demand. As a result, the labour is moved from on-board towards outside the ship or even outside the yard and the time necessary to do an outfitting task on-board is reduced.

Prior studies focus mainly on cost saving by reduced labour hours using modularization. Fafandjel et al. study the shipbuilding duration and related cost by shifting labour. Rubesa et al. come up with general cost saving equations by outfitting completion rates at various stages (Rubesa, Fafandjel, & Kolic, 2011). However, they did not emphasize the Lean Manufacturing improvements of their studies. Creative solutions can be overlooked by simply comparing costs in term of labour hours. For example, if the occupancy of the lifting crane is a big issue, a modularization solution without significant reduced time but with significant occupancy reduction can still be a solution. Furthermore, there are no general guidelines for the shipbuilding industry to estimate the possible labour savings by making modules for outfitting. The type of items on the BOM which are going to be modularized can have different influence on the savings. This relation can provide a strategic approach when choosing a system to outsource as a module for outfitting. As this needs a detailed analysis of a current example to verify, a case study is considered as a suitable research method. The rationalization of this is explained in Chapter 3: Case study rationalization.

This case study shows the Lean Manufacturing effects of reducing the items on the BOM for outfitting using data of a leading shipbuilding company Royal IHC. Several Lean Manufacturing variables are considered and reducing the items on the BOM is realized by making modules. So, the following research question is answered in this research:

"What are the Lean Manufacturing effects of reducing the items on the Bill of Materials using modularization on the outfitting process for Royal IHC?"

These effects will give an insight on the benefits of modularization with a Lean Manufacturing perspective. The goal is to increase the pre-outfitting percentage by identifying (possible) wastes and to facilitate modularization in shipbuilding using relevant literature.

Chapter 2 presents background information and Chapter 3 describes the rationalization of this study. In Chapter 4 the method of approach is introduced and Chapter 5 explains the selection of the module cases. These cases are analysed in Chapter 6 individually with the focus on the determined Lean Manufacturing variables. Then, the results of these cases are analysed further in Chapter 7. Chapter 8 discusses the planning and scheduling model for outfitting. The implementation of the findings are discussed in Chapter 9. Finally, conclusions are drawn in Chapter 10.

2. Theoretical background

Before starting with the in-depth analysis of the case study, more background information about the company, the relevance of the study and the Lean Manufacturing principles used in this research is introduced in this chapter.

2.1 Company description

Royal IHC is a Dutch shipbuilding company that designs and constructs complex vessels for the maritime and offshore sector at multiple international locations. With over 3.000 employees based at various locations it is the global market leader for efficient vessels and equipment. It has a focus on continuous development and technological innovation with vast experience. The underlying strength of continuous investment in research and development provides the opportunity to conduct a research like this case study. This study uses data of a pipe-laying ship built in Krimpen aan den Ijssel. Figure 1 shows an unfinished ship at the same location in front of one of the biggest indoor production halls in Europe.

Figure 1: Royal IHC, Krimpen aan den IJssel

Royal IHC is already using modularization in ships with success, so increasing the portion of modularization will be discussed in this report by generating new module possibilities.

2.2 Relevance

This study can be considered as a deliverable of prior studies about successful implementation of modularization in different industries like automotive and shipbuilding industries. One of the main differences between the automotive and shipbuilding industry is the relatively longer lead time and high customization of ships (Osterholt, 2014). There are even design changes during the building of the ship and that can lead to costly rework. In spite of the fact that shifting labour outside the ship has noteworthy improvements, the possible rework that needs to be performed at a later and less appropriate outfitting stage must be avoided. The production cost can possibly increase to eight times of the current production cost (Rubesa, Fafandjel, & Kolic, 2011). Therefore, Rubesa et al. emphasize the importance of higher effort in better engineering, better quality assurance and a higher level of design standards to avoid rework. These factors influences the trade-off for choosing modularization of specific parts for outfitting. However, modularization is an exquisite way to deal with these design changes because it provides flexibility lowering the impact on the total product (Gershenson & Prasad, 1997). Product agility can be created by controlling the impact of changes and responding to these changes. The challenge is to deal with the complexity of dependencies at shipbuilding (subcontractors, design changes, huge amount of items on the BOM etc.) and requires a thorough study to find out which possibilities are feasible.

The paper of Meysen, Beelaerts van Blokland & Santema (2009) presents cost saving for a helicopter company by outsourcing parts strategically. Analysing the make-buy decision by comparing cost savings and logistic improvements is out of the scope of this case study, but that paper gives a clear definition of the approach that can be used by Royal IHC. One of the findings in that paper is the reduction of the supply base realized by modularization. The key suppliers are more integrated. How the supply chain network will be determined is dependent on the suppliers of Royal IHC, but there are successful examples especially in the automotive industry. Mercedes Benz and Swatch built a new plant to accommodate modularization of the Smart car (Doran, Hill, Hwang, & Jacob, 2006). This purpose built plant reduced the supply base to 25 module suppliers whilst typical car manufacturers are dealing with around 200-300 suppliers. Other benefits were summarized as the increased ability to accommodate new product variations in a shortened life cycle environment and at lower cost, representing changes in both market structure and market demands. Another successful example is the company Lear based in Mexico. This company evolved from seat producer to entire interior systems by diversifying its productive process. This impressively expanded company currently produces and assembles different components and distributes to the automotive industry. This is achieved by three basic levels according to the company: intra-company coordination, strategy of capability expansion and by modular design (Lara, Trujano, & Garcia-Garnica, 2005). This technological upgrading of key suppliers can also be applied in the shipbuilding industry. These suppliers are determined and assisted if necessary to expand so they can facilitate the modularization of your company in return. Taking this successful example into account, the piping subcontractor of IHC is assumed as the supplier of the generated modules in this research, but obviously it needs a thorough study to decide whether a current supplier or an external company should be responsible of module supply.

Lastly, there are especially two processes that needs priority to mature the modularization process (Doerry N. H., 2014). The emphasis should be especially given to cost estimation and valuing modularity and flexibility as these are essential for the justification of modularization. This research contributes to these two processes as it analyses the Lean Manufacturing effects of modularization. These effects show the value of modularization and are necessary in order to do a cost/benefit analysis.

2.3 Lean Manufacturing

Lean Manufacturing is a method to reduce waste in manufacturing with a systematic approach. As it is a very wide area of study, only relevant methods for this research are described in this chapter. Considering the goal of the research, the Theory of Constraints (TOC) and the Just in Time (JIT) are found appropriate to realize the desired efficiency increase. The results are also translated into possible production and scheduling improvements in Chapter 8: Planning and scheduling model for outfitting.

Theory of constraints

The TOC of Goldratt focusses on the process that slows the speed of production and is essentially about change (Dettmer, 1997). There are three questions that have to be answered before applying this method:

1. Where is the constraint?
2. What should we do with the constraint?
3. How do we implement the change?

These questions can be answered as below taking the research question into account.

1. The constraint is at the pre-outfitting process.
2. The total pre-outfitting percentage compared to the total outfitting should increase.
3. By lowering the supply base using outsourced modules.

Dettmer mentions five steps in order to produce the most positive impact using TOC:

1. Identify the constraint
2. Exploit the constraint
3. Subordinate other processes to the constraint
4. Elevate the constraint
5. Repeat the cycle

These steps are considered in Chapter 5: Module selection. It must be noted that all module cases are contributing to one constraint and that the result shows the extent of improvement.

Just in Time

The Just in Time principle is described as the process of producing the necessary parts at the necessary time and have on hand only the minimum stock necessary to hold the processes together (Sugimori, Kusunoki, Cho, & Uchikawa, 1977). The importance of JIT can be seen in the factor loadings at agile manufacturing strategies, which modularization is a part of (Shah & Ward, 2003). The biggest loading factor is at the JIT principle as shown in Table 1.

Table 1: Loading factors

Lean principles	Loading factors of Agile manufacturing strategies
Just in Time	0.552
Total Productive Maintenance	0.327
Total Quality Management	0.075
Human Resource Management	0.146

By reducing the amount of items using modularization, it becomes more essential that the module arrives in time. This reduces the stock and the need for available employees and equipment particularly at the warehouse. For these reasons, JIT is an essential improvement aspect of modularization.

3. Case Study rationalization

Outfitting in shipbuilding is a complex field as many departments, subcontractors and suppliers are involved. Complexity can easily lead to disorganization which is highly undesirable for Lean Manufacturing. Kumar explains that a case study is a research that excels at bringing us to an understanding of a complex issue or object and can extend experience or add strength to what is already known through prior research (Kumar, 2008). Case studies emphasize detailed contextual analysis of a limited number of events or conditions and their relationships. This matches with the goal of the research to understand several Lean Manufacturing effects in a complex field like outfitting. Prior studies analyse modularization and this case study can add strength and experience to these studies. However, validation and verification must be taken into account to question the quality of the study.

3.1 Validation

Validation in case studies is complex because there are both a wide range of types of validity and different types of approaches to case studies (Yue, 2010). Before discussing these types, it is useful to give attention to the validity of validity described by Yue. There is an ongoing discussion about validation especially for case studies, because the researcher's perspective shapes dramatically how the question and application of validity is approached. Several types of validity for case studies defined by Yue is discussed in this chapter.

Convergent validity

Convergent validity concerns the theoretical defensibility of the relationship between the present research and logically and empirically similar constructed researches. Prior studies like Fafandjel et al. (2008) show their results by observing and using data of an existing anonymous shipyard. The result shows the relation between modularization outside the board of the ship and shipbuilding duration and cost. This case study uses the same type of data and observations of an existing shipyard, but outsources the labour from the shipyard to outside the shipyard. Next to the labour savings, the extent of Lean Manufacturing effects of the result is studied using the same method.

Internal validity

The internal validity concerns to the concluded causal relationship between variables. How do we know that the variables are not influenced by other excluded factors? Factors influencing the variables like time, space and distance are less important for this research if the data and result are reliable. For example, analysing the reasons why an outfitting task has lasted 10 days is out of the scope of this research and research method. Regardless of the reason why it is lasting 10 days, outsourcing is reducing it. Therefore, reliable data by long-term observations and multiple measurements are of great importance. However, when trying to find a trend line using these variables the causal relationship becomes important.

Predictive and external validity

Predictive validity concerns how well the future can be predicted consistently and accurately on the basis of the present. Generalizability and the ability to extrapolate the findings to future actions and outcomes are essential for external validity.

To be able to determine the generalizability, the result of this study can be tested at other shipyards as a further research. The variables like movement distances and labour time, which will be different at other shipyards, can be adapted to the result of Royal IHC. This research analyses the Lean Manufacturing effects of the modularization cases, so only the magnitude of these effects will vary at other shipyards. However, the necessity to know the magnitude of the effects to answer the research question remains the same. The extrapolation of the effects depends on the context and the relation of the variables. Each new case needs an individual analysis to show the Lean Manufacturing effects, but the correlation between saved times and the type of items in the BOM can be extrapolated. The deviations of the general guideline reflects the quality of it. The items on the BOM that are modularized are a system or a part that is similar or even the same for different type of ships. The result can be tested with more modules to increase the validity. That can be considered as an interesting further research.

3.2 Verification

Verification is an internal process which determines whether the specifications and requirements of the research are met. O'Leary (1993) describes several aspects of verification. These aspects are discussed in this chapter.

Consistency

The data exists of averages taken of multiple measurement, observations and interviews from skilled employees and that is used for all analysed cases. The structure of the cases are the same for consistency. These methods mitigates the errors in consistency.

Redundancy

This can occur if the researcher is able to develop the same case multiple times and can lead to confusions and possibly errors if the unrevised case is used. Establishing the necessary data only after establishing the list of specific cases mitigates redundancy. This approach matches to the method of approach of this study.

Completeness

As explained at redundancy, the method of first defining the cases and afterwards establishing the list of data needed decreases the possibility of incomplete case studies. Only complete cases must be handled with the same variables like time, distance and space. The case specifications are given in the method of approach.

Correctness

Primarily data of the same company is used in this case study and that makes it sensitive to circularity in the structure, which must be avoided for correctness.

Wei (2012) finished her PhD research also at Royal IHC. A long-term field study is done to gather valuable data by observations and interviews with foremen and workers about the outfitting process. This is an advantage for this research by providing data in the same context and same method of approach. This case study uses these data and data of the currently being built ships for both current situation and future situation (module). Use of triangulation with multiple sources, when possible and necessary, enhances verification and the representation of the phenomenon in the real world.

4. Method of approach

Taking the current situation and the Theory of Constraints into account, modules for outfitting are generated inside a pipe-laying ship that is built at Royal IHC. Obviously, one of the most important factors at this decision is the amount and type of items of the system or part that is going to be modularized. To test the relation between the amount and type of items on the BOM, the variety of the amount and type of items is crucial. The generated BOM for the outfitting is mentioned as the outfitting BOM. The more items on this outfitting BOM, the higher probability for combining items as a module. However, it is known and experienced that data/information gathering can be slow in big companies. Also not all necessary data are available or exists thus some of them must be generated. Therefore and due to limited time for this research, the complexity in terms of number of items are balanced to get satisfying results. Also taking the validity of the generated guideline into account, there must be a more than a few amount of cases. The CAD drawing, the outfitting BOM and the production flow are analysed in order to describe the current situation. The following variables are determined therefore:

- Movement time
- Movement distance
- Storage area
    - On board
    - Shipyard
- Storage time
- Transaction
    - Number of suppliers
    - Number of items on the outfitting BOM

By making a VBA movement model of the map of the shipyard the movements are translated into amount of meters covered. Multiplying the distance with the movement speed gives the time engaged at the movements and this is added to the movement time. Two sources are used for gathering storage time data. There are input and output dates for all equipment, except for the valves. The closest theoretical date when the valves can be used, which is the start of pre-outfitting for the section, is used to complete the data. The installation time is extracted from the data gathered by Wei or from expert opinion.

The map of the shipyard is analysed and the used definition of the locations are determined in Appendix B. The created VBA movement model is explained in Appendix C. The list of assumptions and used data for the estimations can be seen in Appendix D

Rationalisation

The feasibility of the proposed modules are briefly discussed with Chris Rose, a naval engineer. There are more dependencies like engineering and process interdependencies managed by engineering change control. Reasons like no skilled labour, lack of current budget and no space in the planning are not considered as sufficient to dismiss a case as they can be solved when there are sufficient resources like skills, budget and time.

Result

The modularized concepts are determined with the same methodology using the same variables as done for the current situation. The effects of modularization on the determined Lean Manufacturing variables are analysed. An outfitting BOM is generated for each case including foundation, equipment and piping. These three parts are separated activities of outfitting and describe the process comprehensively. Another part of the result is the attempt to find a correlation between the saved times for different types of items.

5. Module selection

The five steps of TOC is used to determine the areas of improvement by modularization. The engine room accounts for 40% of the production hours and ship costs (Bertram, 2005). Using the TOC and taking the possible Lean Manufacturing effects of the modularization described before into account, the engine room is considered as one of the most crucial rooms. According to Bertram, this offers a significant potential for savings using standardisation and modularization in the engine room design. There is a huge number of items in the engine room which leads to tremendous labour on board. Testing the engines is a crucial task and has to wait until all related items to the test are mounted and installed. Reducing the outfitting task of the engine room is therefore a strategic approach. There are also many parties involved like piping, cables, Heating Ventilation and Air Conditioning (HVAC) etc. and reducing labour decreases the possibility of interfering each other. However, there might be interesting module possibilities in other rooms and these are considered as "low hanging fruits". The study of Bertram (2005) showed that sea-water cooling module, lubricating and fuel oil module, standard fire pump module and control/starting air modules are experienced as appropriate modules in and around the engine room.

Mainly the engine room, but also other rooms of the ship are analysed and the following seven cases are chosen for this case study. So, the cycle is repeated to find new modules that elevates the constraint as mentioned before as the fifth step of TOC.

Auxiliary Sea Water Cooling System (Thruster)

The auxiliary sea water cooling system (SWCS) is located at a fairly open area in the winch room and has low interaction with other items. This is facilitating modularization as it has to take less space constraints into account. The pipes are coming from the piping subcontractor and the heat exchanger, pumps, strainer and the valves are purchased from different suppliers. Another advantage of modularization is the ability to test the system before arriving at the shipyard instead of testing on the shipyard (Bertram, 2005). This system can be tested by only providing access to water and electricity. This saves not only mounting time, but also testing time. The testing itself can be seen as the warranty for the product decreasing the defect possibility on the yard.

Auxiliary Sea Water Cooling System (Engines)

This is a system with same purpose as for the first case but it is on a bigger scale and includes way more items. It is a crucial system because it is necessary in order to test the engine and it is located in the very dense engine room.

Air compressor A

Compressed air is needed for several purposes inside a ship. The air compressor provides working air and control air. For example, the working air is needed for air compressor at workbenches and the control air is needed in case the pressure of a pneumatic equipment must be controlled. An air dryer is used optionally when humidity in the air is not desired. All these items are adjacent to each other, but are not yet a module. This is not directly related to the engine, but it is located in the engine room which makes it still interesting to reduce labour inside a crucial room. This module is mentioned as A, because the following module is also an air compressor unit.

Air compressor B

As mentioned in the previous case, this system is for the same purpose but there is a working air compressor in addition. These equipment are not located in the engine room, but making module of this similar but slightly bigger case can show the influence of the scale in modularization.

Lubrication valve system

Before running the engines in order to test the main engine, lubrication oil system must work properly. There is a quite complex system with a lot of valves, two pumps and a flow meter before the lubrication oil is routed to the engines. This is a promising system to make a module because it reduces engine related labour and the items are very close to each other.

Oil reclaim tank

Water collects in the bilge and is pumped overboard using the bilge water system. Oily water separators treat oily bilge water to make oily waste (stored in tank) and water to be pumped overboard. It is forbidden to pump oil into the water so the oil is reclaimed by a system called oil reclaim tank in this research. This system exists of a small pump, three assembled tanks and several valves. This case could be considered as a "low hanging fruit".

Fire extinguish system

Three pumps are only used for the fire extinguish systems. All three pumps have the same amount and type of equipment but with a different layout because they are located in different rooms. As discussed by Bertram (2005), this is also a promising system to modularise.

To summarize, the following cases are analysed in this case study:

1. Auxiliary Sea Water Cooling System (Thruster)
2. Auxiliary Sea Water Cooling System (Engines)
3. Air compressor A
4. Air compressor B
5. Lubrication valve system
6. Oil reclaim tank
7. Fire extinguish system

Two systems are analysed in two scales: the Auxiliary Sea Water Cooling System and the Air compressor. The bigger case of the SWCS and the smaller case of the Air compressor are located in the engine room, while the others are indirectly related. The lubrication valve system is small, but essential for testing the main engines. The oil reclaim tank and the fire extinguish systems are the "low hanging fruits". It can be concluded that these seven cases are suitable, especially when trying to find a correlation between the saved times.

6. Case analyses

All seven cases are analysed in this chapter. An outfitting BOM is generated for each case including foundation, equipment and piping. These are analysed in respectively order for the current and modularized situation. Lastly, the effect of the modularization is presented taking the determined Lean Manufacturing variables into account. Only the storage of items is analysed in Chapter 7.3 for all cases together instead of individually for each case. The first case is described more extensively compared to the others to help the reader being introduced to the method of approach. The improvements in term of these variables show the elevation of the constraint, thus the extent of success for the fourth step of the TOC.

6.1 Auxiliary Sea Water Cooling System (Thruster)

The pieces of this SWCS consist of 43 items: 2 foundations, 25 pipe spools and 16 equipment. The total weight of all items together is 2541 kg. The outfitting BOM is shown in Figure 2.

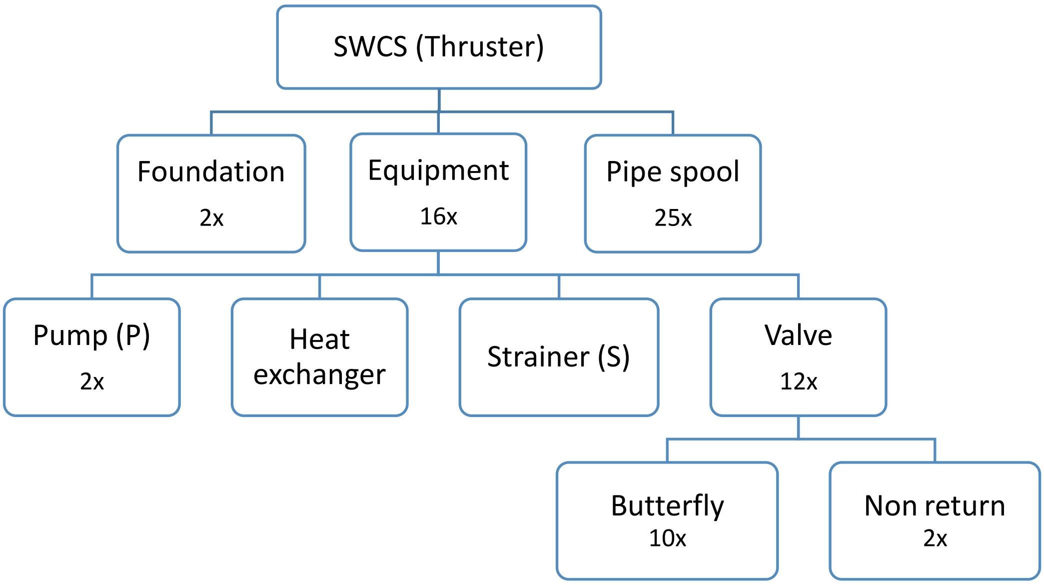

Figure 2: Outfitting BOM SWCS (T)

6.1.1 Current situation model analysis

The current situation is divided into three parts as it is done on the outfitting BOM.

Foundation

Equipment like the heat exchanger and the pump are not welded on the floor, but are bolted on steel foundations which are welded on the floor. The foundations are produced on the yard and transported to the assembly area. When the steel structure of the section is ready at the assembly area, the foundations are welded. There are currently two relevant foundations that carries the SWCS except the supports for the pipes. The first foundation is of the heat exchanger and the second foundation is of the pumps. The heat exchanger foundation is illustrated in Figure 3. The three grey small rectangles on the right side are the places where the heat exchanger is attached to. However, the foundation itself is attached to the wall.

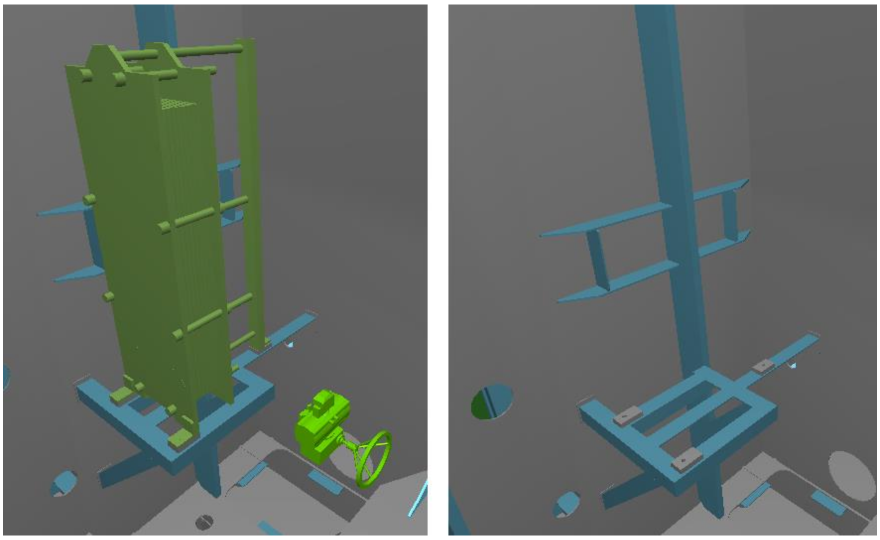

Figure 3: Foundation of heat exchanger

The VBA model in Appendix C calculates that the transportation of the foundations from the workshop to the assembly area takes 104 meters and 0.38 minutes into account. There is also an assumption of 0.25 minutes time for picking up and dropping off for the transported items by vehicles. Using the *foundation calculation* in Appendix D, 109 minutes of labour is calculated.

Equipment

All suppliers deliver through the supply entrance to the warehouse. The equipment are stored in the warehouse and brought to the assembly area when they are ready to be installed. Only small items like valves are installed before pre-erection, other equipment are only attached on their places in the assembly area and are installed after the pre-erection.

The route for equipment transport inside the yard starts from the supply entrance to the warehouse and from there to the assembly area next to the pre-erection area. Five suppliers arrive independently to store inside the warehouse, but assuming that the two valve types are transported together to the assembly area there are four rides to the assembly section from the warehouse. The VBA model calculates 4.5 minutes and 1308 meters for the transportation of all equipment to the assembly area. There is again a picking up and dropping off time of 0.25 minutes. Using the *equipment time calculation* in Appendix D, 703 minutes of labour is calculated for the equipment.

Piping

IHC has a subcontractor which provides the piping. The cradles of pipe spools are first transported by truck to the piping area of the subcontractor. The cradle of pipe spools are transported from the piping area to the assembly area when ready. The amount and shape of the supports are determined at the assembly area and are produced at the piping area. Afterwards the supports are welded and the pipe spools are positioned. The pipes are assembled at the assembly area, except the ones that are directly linked to equipment. Otherwise the equipment obviously does not fit between the fully assembled pipes.

The distance from the supply entrance to the pipe storage area and from there to the assembly area is 613 meters and the time needed is 1.84 minutes. From the dimension of the pipe spools assumed in Appendix D, it can be derived that there is only 0.32 cradle of pipes needed for this system. So the route is taken once. There is no guarantee that the spools are on the same cradle, but this expression shows the amount of occupancy of the cradles. Again there is a picking up and dropping off time of 0.25 minutes. Considering the length of the pipes, there are 7 supports necessary as explained in Appendix D. The result is 520 minutes of labour for the whole SWCS using the *piping time calculation* in Appendix D. Actions 1, 9 and 10 are done twice because the pipes are divided over two sections built at different times.

6.1.2 Modularized situation analysis

First, the module must be designed. Concentrating the SWCS in the corner by moving the other items towards the heat exchanger is one way to make a module. Analysing the surrounding taking the entrances into account, the items on the outfitting BOM is concentrated towards the corner of the room where the heat exchanger is located. However, the distance between the sea chest and the pump is now bigger and these pipes are heavy pipes around 32.5 kg per meter. It is wise to keep the length of the heavy pipes smaller. For that reason the sea chest (SC) can be moved towards the heat exchanger.

However, moving a sea chest is considered as a major engineering change. For this reason there are two versions of this module: one with moving the sea chest (major) and the other without moving the sea chest (minor). The major change situation is used for further result analysis, but the result of the minor change is calculated as well to provide Royal IHC another option. By observing and looking at the drawings of the room, the modules in Figure 4 are proposed. Note that these are top view, the red lines are illustrating the pipes and that the module sizes remain the same for both minor and major module. Both options needs only a short pipe to link the pipes of the module to the already assembled pipes.

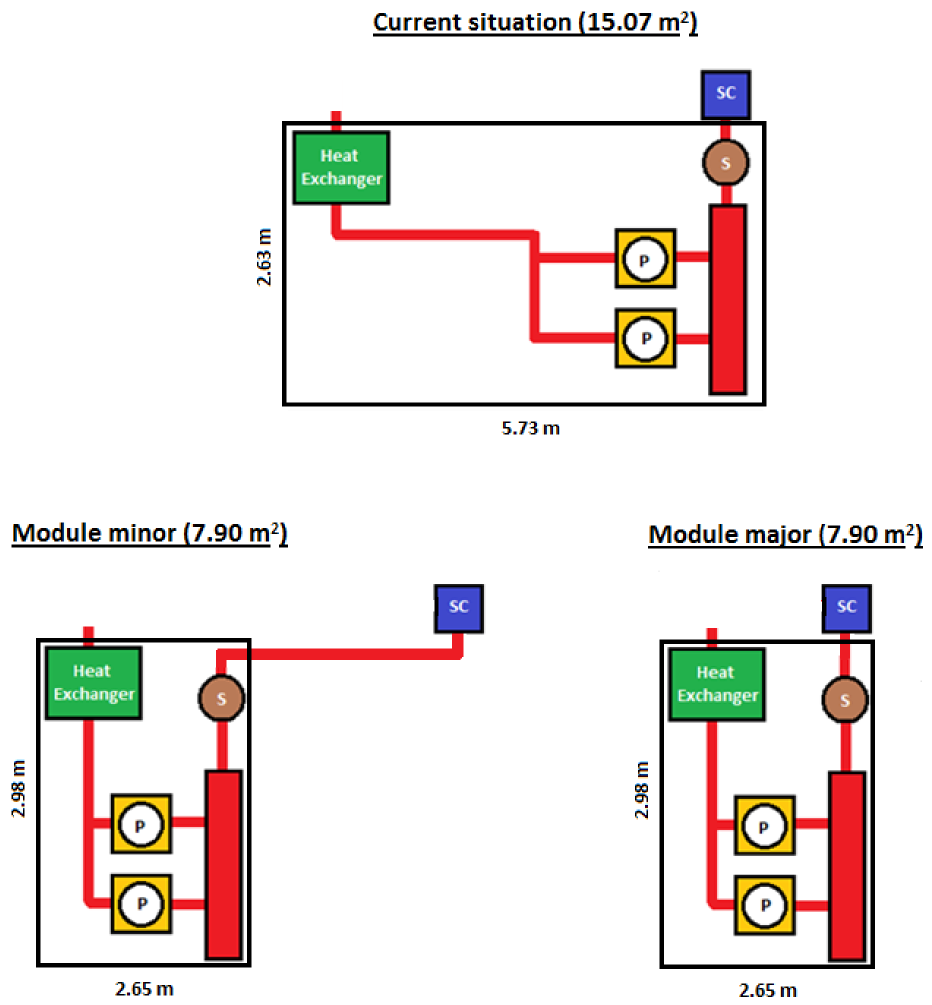

Figure 4: Current vs. module SWCS (T)

The production difference of the SWCS is divided into the same three parts as done for the current situation before.

Foundation

The transport distance and time of 104 meters and 0.38 minutes remains the same. The foundation of the heat exchanger, previously attached to the wall of another section, is no longer a part of that section. Of course it is still possible to attach the heat exchanger to the wall after the pre-erection like before if necessary. The foundation for the four pumps is halved and of the heat exchanger is gone. Now there is a foundation for the whole module which has a dimension of 2.65 x 2.98 meters. Using the *foundation calculation* in Appendix D, the labour for this foundation is 577 minutes.

Equipment

All equipment are mounted already, but that can be seen as one equipment. The only labour needed is welding the module on the foundation and attaching the necessary pipe spools to the equipment.

The total mass is at least 2077 kg so it is transported with a low speed of 10 km/h as explained in Appendix D. The VBA model gives 312 meters and 1.84 minutes of movement. The mounting time of this module is 240 minutes as explained in *equipment time calculation* in Appendix D.

Piping

The pipe cradle occupancy is reduced with 0.52 m^3 of pipe spools, which results in 0.10 cradle occupancy reduction. The short three pipe spools, that are mounted after the module is positioned on the slipway, can be included in the module package but not yet attached. These spools, less than 50 kg, can be attached without the need of a crane which means that it can be realized on board. Both module situations need still 30 minutes of labour for attaching the linked pipes using the *piping time calculation* in Appendix D. No transport from the piping area is needed for this module in this case.

6.1.3 Result

The results considering the previously mentioned variables of Lean Manufacturing are presented in this chapter.

Movement time and distance

A total of 492 minutes and 1607 meters of movement is reduced using modularization for this case as shown in Table 2.

Table 2: Movements of SWCS (T)

	Time [min]	Distance [m]
Foundation	-468	0
Equipment	468	995
Piping	492	612
Total	**492**	**1607**

Storage area

The dimensions of the equipment and the pipe cradles are used to estimate the storage area of the items on the outfitting BOM of the current situation. Loose items in the warehouse and the pipe area are covering 3.99 m^2, while the module is covering 7.90 m^2. There is an increase of 3.91 m^2 in the modularized situation. It can be concluded that the storage area is increased in this case. The on board saving inside the ship is 7.17 m^2.

Transaction

There were six suppliers as shown before and this is reduced to one assuming that the piping subcontractor becomes the module supplier. However, whether the items are pre-assembled at one of the suppliers or at another location is dependent on the supply chain and interests of Royal IHC.

The outfitting BOM of the modularized situation can be seen in Figure 5. It is reduced from 43 items to 5 items. The three short pipe spools are included to the module instead of getting the pipe at the piping area on the yard. There are now 5 items left of which 3 items are a part of the module until the last task on the production of the SWCS: attach the linking pipe spools. So it can also be considered as a reduction to two items: the foundation produced by Royal IHC and the module (including the short spools) supplied by the piping subcontractor.

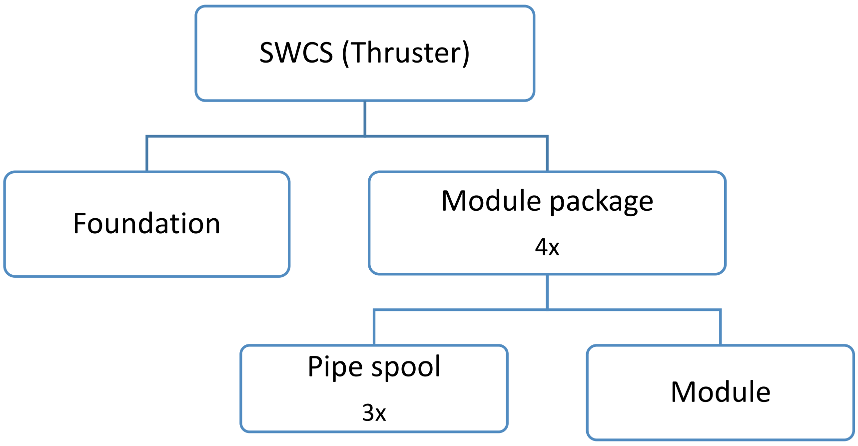

Figure 5: Module outfitting BOM SWCS (T)

6.2 Auxiliary Sea Water Cooling System (Engines)

The pieces of the SWCS for the engine consist of 86 items: 3 foundations, 40 pipe spools and 43 equipment. The total weight of all the items together is 37941 kg. The items on the outfitting BOM are shown in Figure 6.

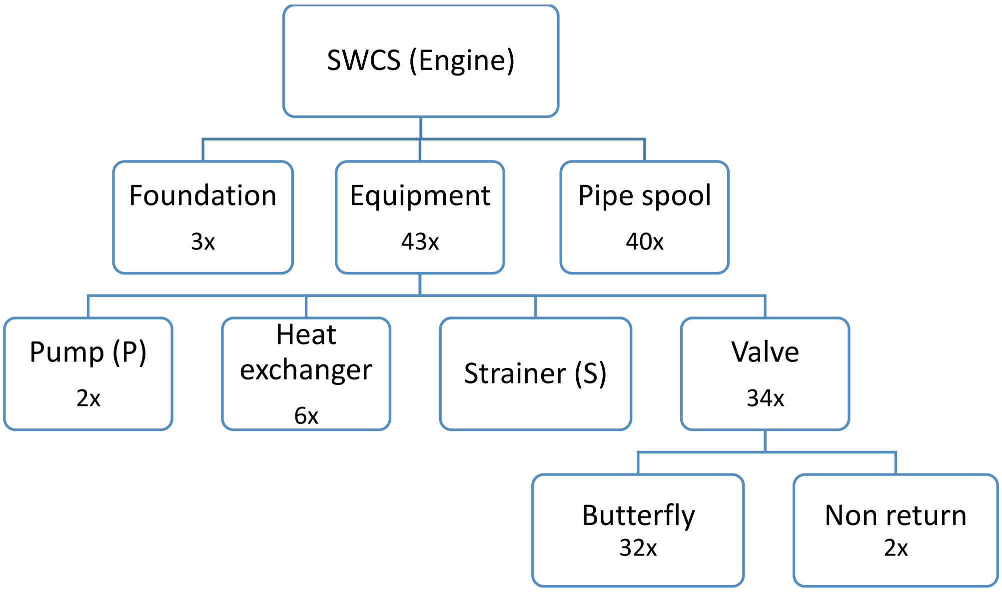

Figure 6: Outfitting BOM SWCS (E)

6.2.1 Current situation model analysis

The current situation is divided into three parts as it is done on the outfitting BOM.

Foundation

There are three foundations: one for the pumps and two for the heat exchangers. The VBA model calculates that each transportation of the foundations from the workshop to the assembly area takes 104 meters and 0.31 minutes into account. These are multiplied by 3 because there are three foundations to be delivered at the assembly area. Using the *foundation calculation* in Appendix D, the labour is 522 minutes.

Equipment

The equipment are distributed over three sections. Again five suppliers arrive independently to store inside the warehouse, but assuming that the two valve types are transported together to the assembly area there are four rides to the assembly section from the warehouse. The VBA model calculates 4.5 minutes and 1308 meters for the transportation of all equipment to the assembly area. Using the *equipment time calculation* in Appendix D, 2670 minutes of labour is calculated for the equipment.

Piping

The pipes are distributed over three sections. The distance from the supply entrance to the pipe storage and from there to the assembly area is 612 meters and the time needed is 1.84 minutes. The pipe spools for this system occupy 3 cradles, which means 3 rides from the piping area to the assembly area. Considering the length of the pipes, there are 24 supports necessary. The result of 1685 minutes for the whole SWCS using the *piping time calculation* in Appendix D. Actions 1, 9 and 10 are done three times because the pipes are divided over three section that are built at different times.

6.2.2 Modularized situation analysis

The SWCS for the engines is already positioned so that a module can easily made. No major layout changes are needed. The only change that facilitates modularization is moving the pumps towards the heat exchanger level or moving the heat exchangers and the big pipes from the wall to get the module layout shown in Figure 7. A smaller foundation can be made by doing this. The erection of both sections must be realized before the module can be erected and positioned. There is exactly one month before the top section is erected according to the planning and that is considered sufficient to install the module.

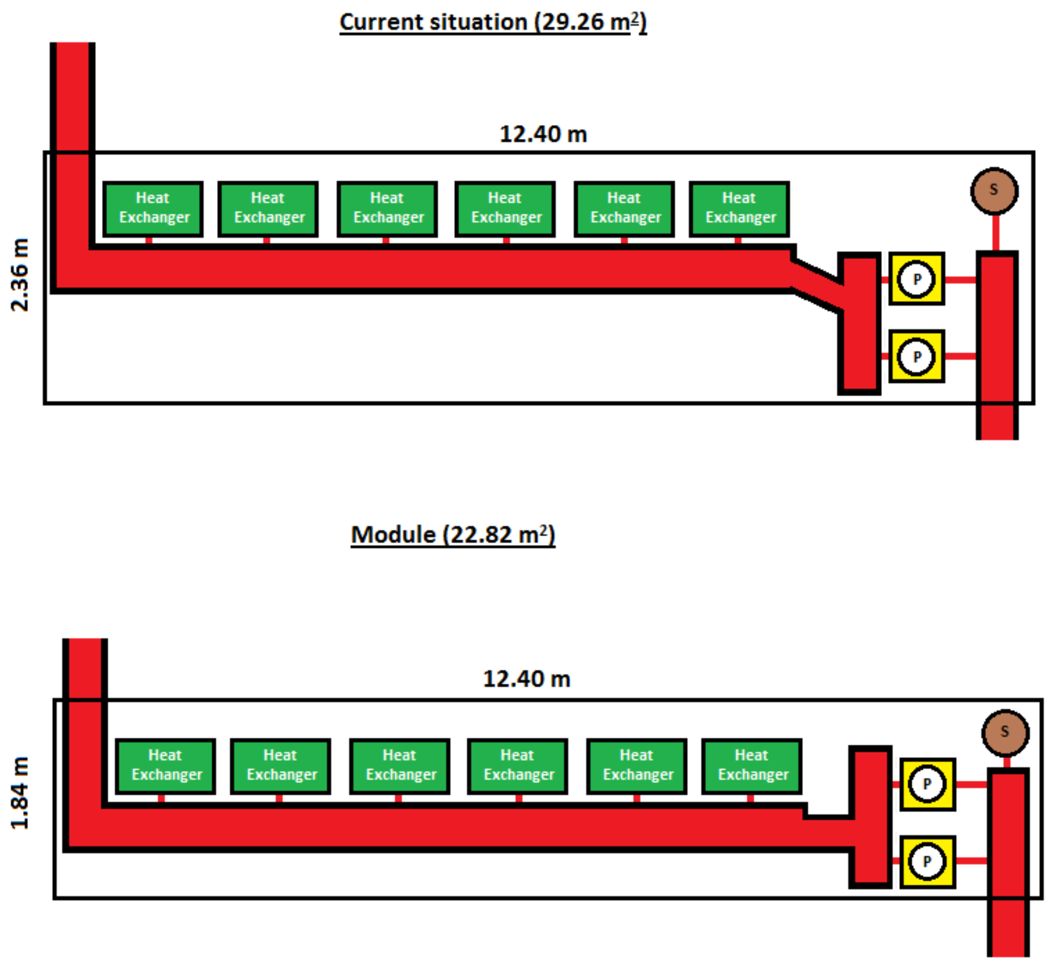

Figure 7: Current vs. module SWCS (E)

The differences in the production of the SWCS are divided into the same three parts as done for the current situation before.

Foundation

The labour for this foundation is calculated as 1664 minutes using the *foundation calculation* in Appendix D. The distance of 104 meters and the time of 0.31 minutes remains the same, but is covered once instead of three times.

Equipment

The total mass is over 1000 kg so it is transported with a low speed of 10 km/h. The VBA model gives 312 meters and 1.87 minutes of movement. The mounting time of this module is 240 minutes using the *equipment time calculation* in Appendix D.

Piping

The pipes included in the module reduce the cradle occupancy with 9.27 m^3. This is a reduction of 2.90 cradles. There are four pipe spools that have to be linked to other already assembled pipes on the section. So, the module situation needs 40 minutes of labour using the *piping time calculation* in Appendix D.

6.2.3 Result

The results considering the previously mentioned variables of Lean Manufacturing are presented in this chapter.

Movement time and distance

The effect of modularization for movement time and distance is shown in Table 3. A total of 2953 minutes and 5341 meters of movement is reduced using modularization for this case.

Table 3: Movements of SWCS (E)

	Time [min]	Distance [m]
Foundation	-1139	417
Equipment	2435	995
Piping	1657	3929
Total	**2953**	**5341**

Storage area

The foundation area of 22.82 m^2 is 1.1 m^2 less than the area covered by loose items. There is an on board saving of 6.44 m^2.

Transaction

The suppliers are reduced also from six to one like for the SWCS case for the thruster. The amount of items on the outfitting BOM is reduced from 86 to 6 and the outfitting BOM of the modularized situation is shown in Figure 8.

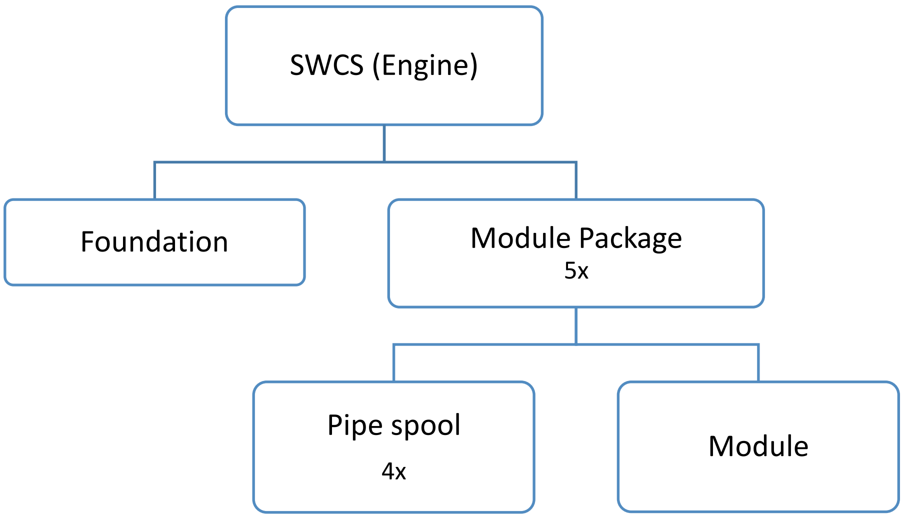

Figure 8: Module outfitting BOM SWCS (E)

6.3 Air compressor A

The pieces of the air compressor A unit consist of 43 items: 3 foundations, 26 pipe spools and 14 equipment. The total weight of all the items together is 2024 kg. The items on the outfitting BOM are shown in Figure 9.

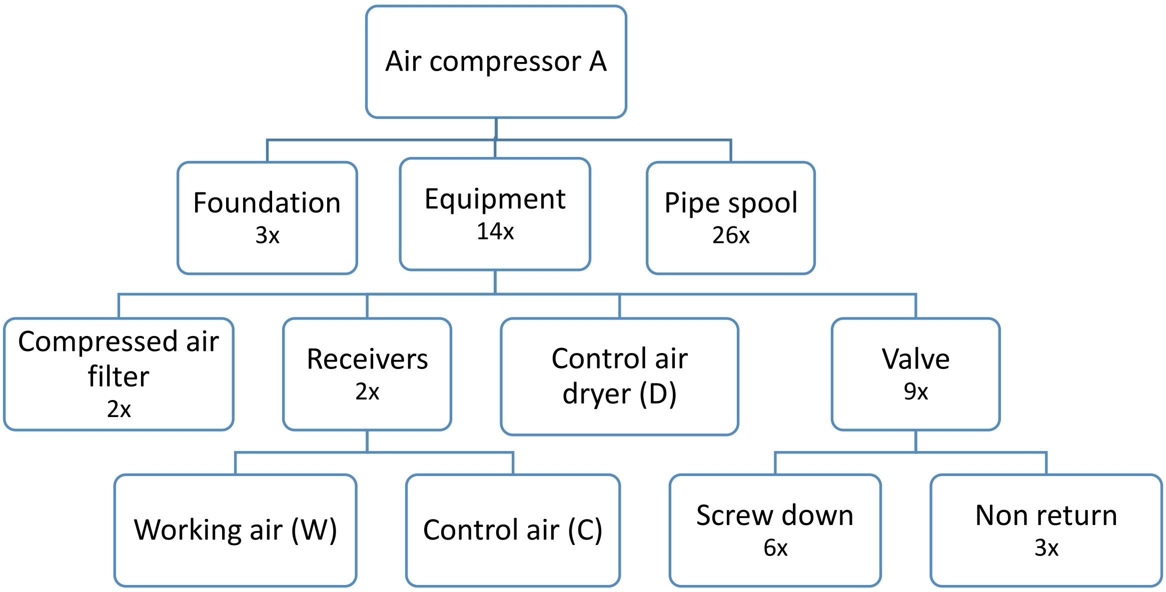

Figure 9: Outfitting BOM Air compressor A

6.3.1 Current situation model analysis

The current situation is divided into three parts as it is done on the outfitting BOM.

Foundation

The VBA model calculates that the transportation of the foundations from the workshop to the assembly area takes 104 meters and 0.31 minutes into account. Considering the dimension of the foundations, two rides with a forklift is estimated. Using the *foundation calculation* in Appendix D, the labour is 206 minutes.

Equipment

The VBA model calculates 2.82 minutes and 937 meters for the transportation of all equipment to the assembly area. Using the *equipment time calculation* in Appendix D, 632 minutes of labour is calculated for the equipment.

Piping

The distance from the supply entrance to the pipe storage and from there to the assembly area is 612 meters and the time needed is 1.84 minutes. The pipe spools of this module fits in one cradle, so one ride is taken into account. Considering the length of the pipes, there are 10 supports necessary. The result of 1040 minutes for the whole system is calculated using the *piping time calculation* in Appendix D.

6.3.2 Modularized situation analysis

Three biggest equipment are already in a row, but considering the CAD drawing, it is assumed that they can be positioned little closer to each other. The current and the module situation can be seen in Figure 10.

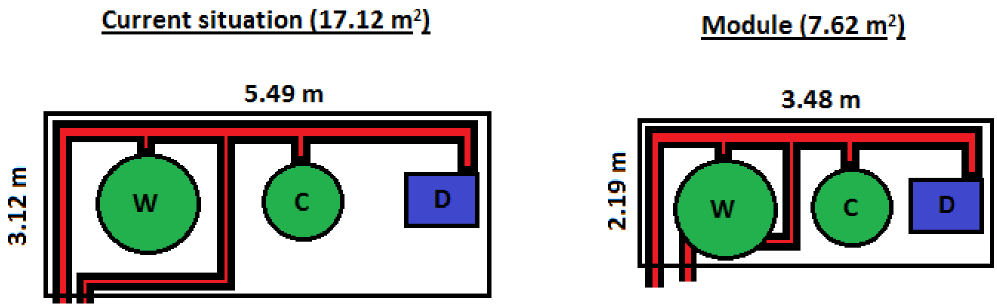

Figure 10: Current vs. module Air compressor A

The production differences are divided into the same three parts as done for the current situation before.

Foundation

The distance of 104 meters and the time of 0.31 minutes remains the same, but is taken once instead of three times before. The *foundation calculation* in Appendix D gives 556 minutes of labour.

Equipment

The total mass is over 1000 kg. so it is transported with a low speed of 10 km/h. The VBA model gives 312 meters and 1.87 minutes of movement. The mounting time of this module is 240 minutes using the *equipment time calculation* in Appendix D.

Piping

The pipes that belong to the module occupy 0.15 m^3 space and therefore save 0.05 cradle occupancy. There are five small pipe spools that have to be attached after the module is erected. The labour for these are 50 minutes using the *piping time calculation* in Appendix D.

6.3.3 Result

The results considering the previously mentioned variables of Lean Manufacturing are presented in this chapter.

Movement time and distance

The effect of modularization for time and distance is shown in Table 4. A total of 1036 minutes and 1446 meters of movement is reduced using modularization for this case.

Table 4: Movements of Air compressor A

	Time [min]	Distance [m]
Foundation	-349	209
Equipment	393	625
Piping	992	612
Total	**1036**	**1446**

Storage area

The foundation area of 7.62 m^2 is 2.14 m^2 more than the area covered by loose items. There is an on board saving of 9.5 m^2.

Transaction

The reduction of suppliers is three: from four suppliers to one supplier. The amount of items on the outfitting BOM is reduced from 43 to 7 and the outfitting BOM of the modularized situation is shown in Figure 11.

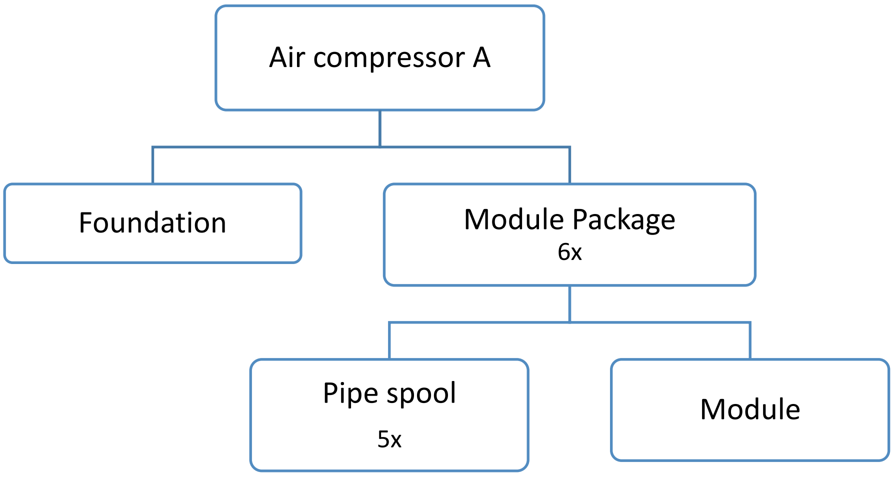

Figure 11: Module outfitting BOM Air compressor A

6.4 Air compressor B

The whole system consist of 45 items: 4 foundations, 23 pipe spools and 18 equipment. The total weight of all the items together is 4175 kg. The items on the outfitting BOM are shown in Figure 12.

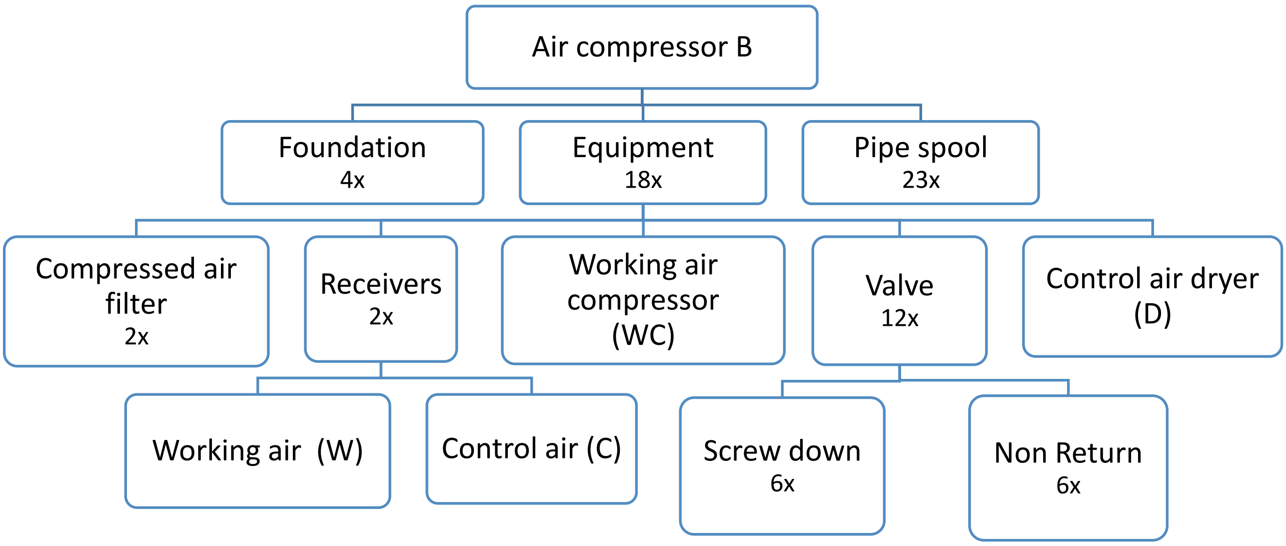

Figure 12: Outfitting BOM Air compressor B

6.4.1 Current situation model analysis

The current situation is divided into three parts as it is done on the outfitting BOM.

Foundation

The VBA model calculates that the transportation of the foundations from the workshop to the assembly area takes 104 meters and 0.31 minutes into account. Considering the dimension of the foundations, two rides are estimated. Using the *foundation calculation* in Appendix D, the labour is 246 minutes.

Equipment

Three suppliers arrive independently to store inside the warehouse. The VBA model calculates 2.82 minutes and 937 meters for the transportation of all equipment to the assembly area. Using the *equipment time calculation* in Appendix D, 855 hours of labour is calculated for the equipment.

Piping

The distance from the supply entrance to the pipe storage and from there to the assembly area is 612 meters and the time needed is 1.84 minutes. The pipe spool fits into one cradle, so one ride is assumed. Considering the length of the pipes, there are 12 supports necessary. The result of 1035 minutes is calculated using the *piping time calculation* in Appendix D.

6.4.2 Modularized situation analysis

All equipment are already in a row, but they can be positioned closer to each other like the previous case. The current and the module situation can be seen in Figure 13.

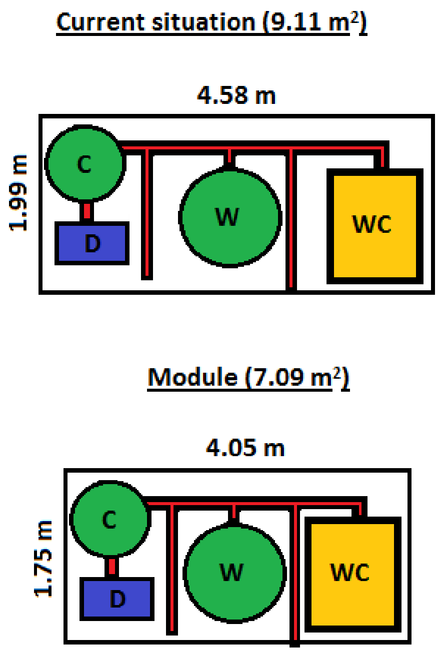

Figure 13: Current vs. Module Air compressor B

The differences in the production are divided into the same three parts as done for the current situation before.

Foundation

The distance of 104 meters and the time of 0.31 minutes remains the same, but is taken once instead of twice. The *foundation calculation* in Appendix D gives 517 minutes of labour.

Equipment

The total mass is over 1000 kg. so it is transported with a low speed of 10 km/h. The VBA model gives 312 meters and 1.87 minutes of movement. The mounting time of this module is 240 minutes using the *equipment time calculation* in Appendix D.

Piping

The pipes that belong to the module occupy 0.20 m^3 space and therefore save 0.06 cradle occupancy. There are 9 small pipe spools that are attached after the module is erected. The labour for these are 90 minutes using the *piping time calculation* in Appendix D.

6.4.3 Result

The results considering the previously mentioned variables of Lean Manufacturing are presented in this chapter.

Movement time and distance

The result of the current situation and the modularized situation is shown in Table 5. A total of 1292 minutes and 1341 meters of movement is reduced using modularization for this case.

Table 5: Movements of Air compressor B

	Time [min]	Distance [m]
Foundation	-271	104
Equipment	616	625
Piping	947	612
Total	**1292**	**1341**

Storage area

The foundation area of 7.09 m^2 is 0.97 m^2 more than the area covered by loose items. There is an on board saving of 2.02 m^2.

Transaction

The reduction of suppliers is three: from four suppliers to one supplier. The amount of items on the outfitting BOM is reduced from 45 to 11 and the outfitting BOM of the modularized situation is shown in Figure 14.

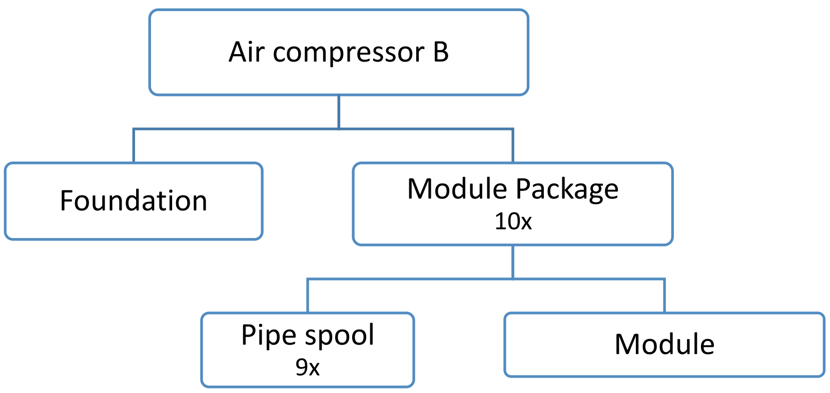

Figure 14: Module outfitting BOM Air Compressor B

6.5 Lubrication valve system

The pieces of lubrication valve system consists of 39 items: 2 foundations, 18 pipe spools and 19 equipment. The total weight of all the items together is 701 kg. The items on the outfitting BOM are shown in Figure 15.

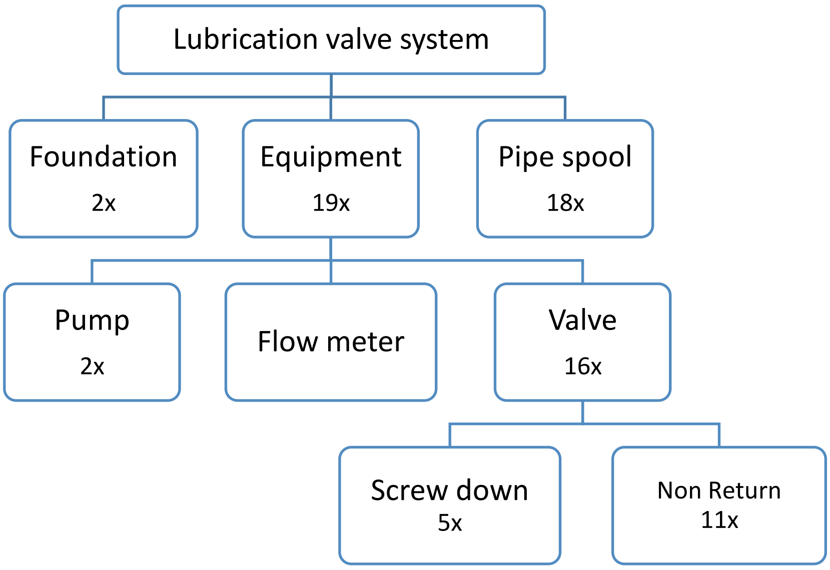

Figure 15: Outfitting BOM Lubrication valve system

6.5.1 Current situation model analysis

The current situation is divided into three parts as it is done on the outfitting BOM.

Foundation

There are two small foundations, each one for the pumps. Considering the dimension of the foundation, these are transported without the need of a transport vehicle. The model calculates that each transportation of the foundations from the workshop to the assembly area takes 104 meters and 1.25 minutes into account. Using the *foundation calculation* in Appendix D, the labour is 3 minutes.

Equipment

There are three rides from the supply entrance to the warehouse and one ride from the warehouse to the assembly area. The VBA model calculates 1.27 minutes and 429 meters for the transportation of all equipment to the assembly area. Using the *equipment time calculation* in Appendix D, 483 minutes of labour is calculated for the equipment.

Piping

The distance from the supply entrance to the pipe storage and from there to the assembly area is 612 meters and the time needed is 1.84 minutes. The pipe spools for this module occupy one cradle, so one ride is estimated. Considering the length of the pipes, there are 5 supports necessary. The result of 710 minutes is calculated using the *piping time calculation* in Appendix D.

6.5.2 Modularized situation analysis

The valve system is already a densely packed system, so there are no changes in the layout to facilitate modularization. The differences in the production are divided into the same three parts as done for the current situation before.

Foundation

The foundation movements and times remain the same, because there is no reason to change the current foundation.

Equipment

The total mass is below 1000 kg. so it is transported with a low speed of 20 km/h. The VBA model gives 312 meters and 0.94 minutes of movement. The mounting time of this module is 171 minutes using the *equipment time calculation* in Appendix D.

Piping

The pipes included in the module reduce the cradle occupancy with 1.15 m^3. This is a reduction of 0.36 cradles. There are 12 pipe spools that have to be linked to other already assembled pipes. So, the module situation needs 120 minutes of labour using the *piping time calculation* in Appendix D.

6.5.3 Result

The results considering the previously mentioned variables of Lean Manufacturing are presented in this chapter.

Movement time and distance

The effect of the modularization for time and distance is shown in Table 6. A total of 906 minutes and 729 meters of movement is reduced using modularization for this case.

Table 6: Movements of Lubrication valve system

	Time [min]	Distance [m]
Foundation	0	0
Equipment	314	116
Piping	592	613
Total	**906**	**729**

Storage area

The module area of 3.1 m^2 is 0.55 m^2 less than the area covered by loose items. There is no on board saving.

Transaction

The reduction of suppliers is three, from four suppliers to one supplier. The amount of items on the outfitting BOM is reduced from 39 to 15 and the outfitting BOM of the modularized situation is shown in Figure 16. This seems a slight improvement but the fact that the 12 pipe spools can be considered as a part of the module package, there are 3 items left to deal with until the module is positioned on board.

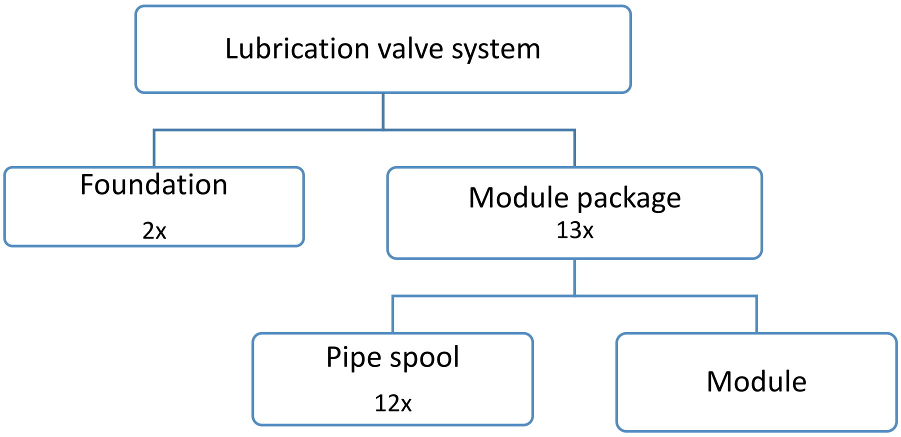

Figure 16: Module outfitting BOM Lubrication valve system

6.6 Oil reclaim tank

The pieces of the oil reclaim tank consist of 24 items: 2 foundation, 13 pipe spools and 9 equipment. The total weight of all the items together is 566 kg. The items on the outfitting BOM are shown in Figure 17.

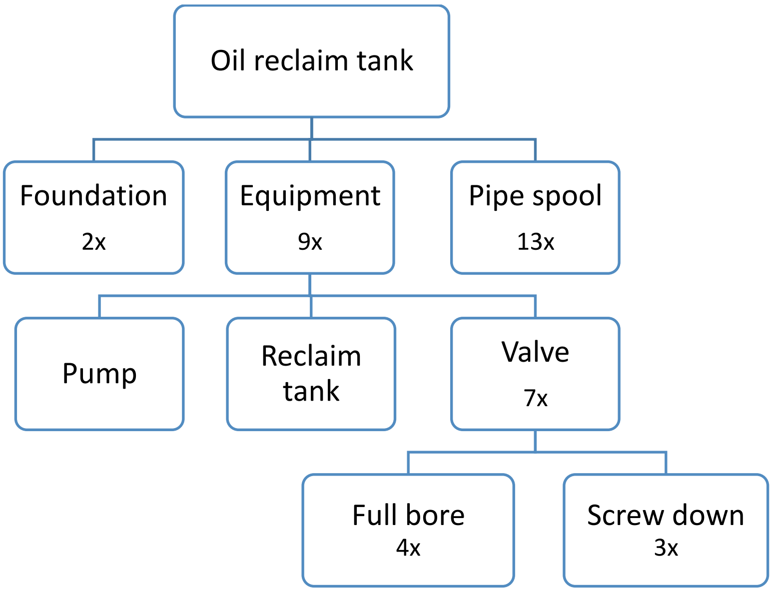

Figure 17: Outfitting BOM Oil reclaim tank

6.6.1 Current situation model analysis

The current situation is divided into three parts as it is done on the outfitting BOM.

Foundation

There are two foundations: one for the pump and one for the reclaim tank. The VBA model calculates that each transportation of the foundations from the workshop to the assembly area takes 104 meters and 0.31 minutes into account. Considering the dimension of the foundations, one ride is sufficient to transport. Using the *foundation calculation* in Appendix D, the labour is 9.48 minutes.

Equipment

The VBA model calculates 1.27 minutes and 429 meters for the transportation of all equipment to the assembly area. Using the *equipment time calculation* in Appendix D, 324 minutes of labour is calculated for the equipment.

Piping

The distance from the supply entrance to the pipe storage and from there to the assembly area is 612.48 meters and the time needed is 1.84 minutes. One cradle is sufficient to transport the relevant pipe spools in this case, so one ride is taken into account. Considering the length of the pipes, there are 2 supports necessary. The result of 505 minutes is calculated using the *piping time calculation* in Appendix D.

6.6.2 Modularized situation analysis

The oil reclaim tank system is already a very dense system, so there is again no change in layout to facilitate modularization. The differences in the production are divided into the same three parts as done for the current situation before

Foundation

The labour for this foundation is calculated as 150 minutes using the *foundation calculation* in Appendix D. The distance of 104 meters and 0.31 minutes remains the same.

Equipment

The total mass is below 1000 kg. so it is transported with a low speed of 20 km/h. The VBA model gives 312 meters and 1.87 minutes of movement. The mounting time of this module is 165 minutes using the *equipment time calculation* in Appendix D.

Piping

The pipes included in the module reduce the cradle occupancy with 0.03 m^3. This is a reduction of 0.01 cradle occupancy. There are two other pipe spools that have to be linked to other already assembled pipes. So, the module situation needs 20 minutes of labour using the *piping time calculation* in Appendix D.

6.6.3 Result

The results considering the previously mentioned variables of Lean Manufacturing are presented in this chapter.

Movement time and distance

The effect of the modularization for time and distance is shown in Table 7. A total of 505 minutes and 729 meters of movement is reduced using modularization for this case.

Table 7: Movements of Oil reclaim tank

	Time [min]	Distance [m]
Foundation	-141	0
Equipment	159	116
Piping	487	613
Total	**505**	**729**

Storage area

The foundation area of 2.06 m^2 is 0.4 m^2 less than the area covered by loose items. There is no on board saving, because the foundation remains the same.

Transaction

The reduction of suppliers is three: from four suppliers to one supplier. The amount of items on the outfitting BOM is reduced from 24 to 4 and the outfitting BOM of the modularized situation is shown in Figure 18.

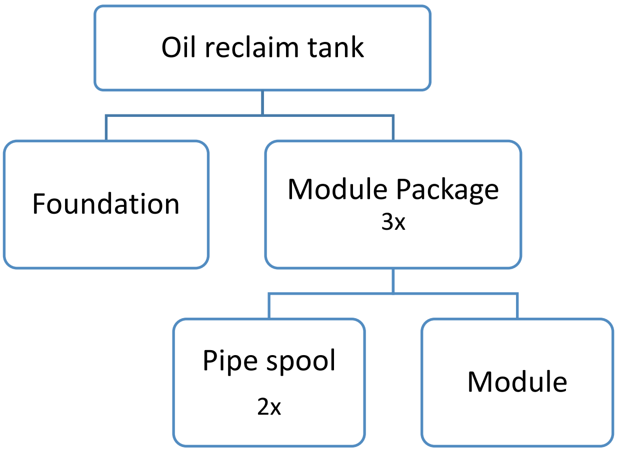

Figure 18: Module outfitting BOM Oil reclaim tank

6.7 Fire extinguish system

The pieces of the fire extinguish system for the engine consists of 10 items: 1 foundations, 4 pipe spools and 5 equipment. The total weight of all the items together is 1065 kg. There are three fire extinguish systems on the ship, so the total saved time in this case is tripled. The items on the outfitting BOM are shown in Figure 19.

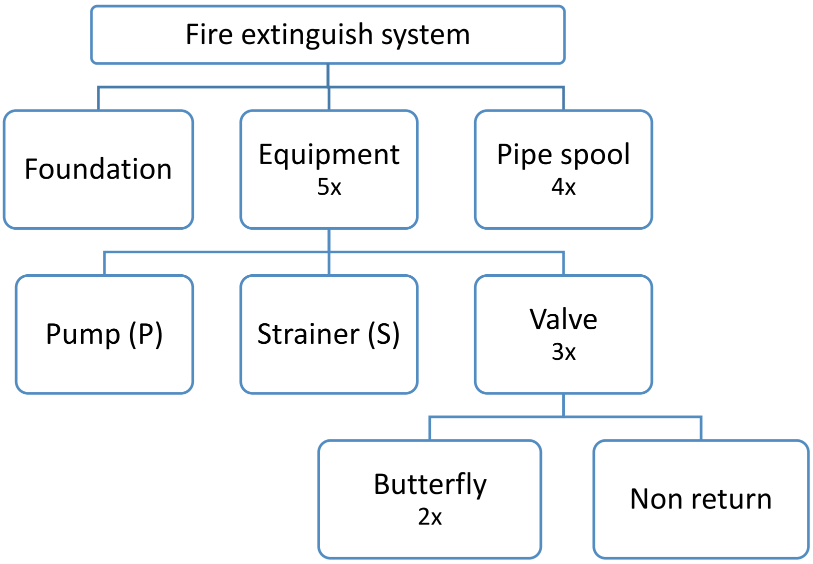

Figure 19: Outfitting BOM Fire extinguish system

6.7.1 Current situation model analysis

The current situation is divided into three parts as it is done on the outfitting BOM.

Foundation

There is only foundation for the pump. The VBA model calculates that each transportation of the foundations from the workshop to the assembly area takes 104 meters and 0.31 minutes into account. Using the *foundation calculation* in Appendix D, the labour is 31 minutes.

Equipment

The VBA model calculates 1.27 minutes and 429 meters for the transportation of all equipment to the assembly area. Using the *equipment time calculation* in Appendix D, 306 minutes of labour is calculated for the equipment.

Piping

The distance from the supply entrance to the pipe storage and from there to the assembly area is 612 meters and the time needed is 1.84 minutes. One ride is needed for this transport. Considering the length of the pipes, there are no supports necessary for the relevant part of the system. The result of 150 minutes is calculated using the *piping time calculation* in Appendix D.

6.7.2 Modularized situation analysis

There are three fire extinguish systems in the whole ship and the layout of these are adjusted to the room they belong to. A module that would fit in all situations is shown in Figure 20 with a top view. The green item is the non-return valve, which is also part of the module.

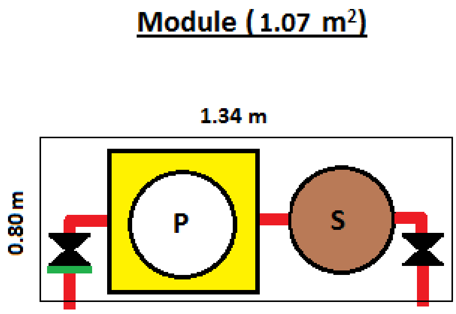

Figure 20: Module Fire extinguish system

The production differences are divided into the same three parts as done for the current situation before.

Foundation

The labour for this foundation is calculated as 78 minutes using the *foundation calculation* in Appendix D. The distance of 104 meters and the time of 0.31 minutes remain the same.

Equipment

The total mass is over 1000 kg. so it is transported with a low speed of 10 km/h. The VBA model gives 312 meters and 1.87 minutes of movement. The mounting time of this module is 177 minutes using the *equipment time calculation* in Appendix D.

Piping

The pipes included in the module reduce the cradle occupancy with 0.06 m^3. This is a reduction of 0.02 cradle occupancy. There are two other pipe spools that have to be linked to other already assembled pipes. So, the module situation needs 20 minutes of labour using the *piping time calculation* in Appendix D.

6.7.3 Result

The results considering the previously mentioned variables of Lean Manufacturing are presented in this chapter.

Movement time and distance

The effect of the modularization for time and distance is shown in Table 8. A total of 214 minutes and 728 meters of movement is reduced using modularization for this case for only one fire extinguish system. The total savings is tripled and that is used when calculating the total savings for the whole outfitting.

Table 8: Movements of Fire extinguish system

	Time [min]	Distance [m]
Foundation	-47	0
Equipment	129	116
Piping	132	612
Total	**214**	**728**
3x Total	**642**	**2184**

Storage area

The foundation area of a single fire extinguish system of 1.07 m^2 is 0.31 m^2 more than the area covered by loose items. When looking at the on board saving, the average of all three fire extinguish systems is taken into account. The result is a saving of 0.92 m^2 on board.

Transaction

The amount of suppliers is reduced from four to one. The amount of items on the outfitting BOM is reduced from 10 to 4 and the outfitting BOM of the modularized situation is shown in Figure 21.

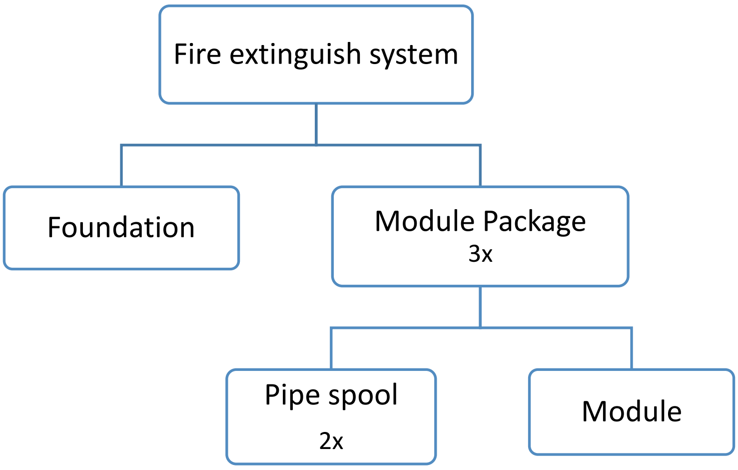

Figure 21: Module outfitting BOM Fire extinguish system

7. Result analysis

The Lean Manufacturing variables of the case results and the correlation of saved labour are discussed in this chapter in order to determine the effects of modularization.

7.1 Movement time and distance

The total theoretical time saving of the seven modules is 7827 minutes, which is equal to 130 hours, as shown in Table 9.

Table 9: Movement savings

	SWCS (Thruster)	SWCS (Engine)	Air compr. A	Air compr. B	Lubrication valve system	Oil reclaim tank	Fire extinguisher system	Total
Time [min.]	492	2953	1036	1292	906	506	642	**7827**
Distance [m.]	1608	5342	1446	1342	729	729	2187	**13381**

These numbers are very likely higher in practice because there are also movements not taken into account like employees who need to walk to forklifts, get tools from workshops or other employees, looking for welding machines, missing items, rework etc. The distance savings due to modularization is 13381 meters for foundation, equipment and piping movements. These are apart from the movements inside the ship, to and from the working area, travels during breaks etc. Employees who are working on the shipyard are less confronted and interrupted by other employees when they are working in the same area.

For expressing the savings in percentage of the whole outfitting, the *OF/POF calculation* in Appendix D is used. By doing only these seven cases, the theoretical reduction of the total outfitting time is 0.42%. However, at the beginning of this report, the goal to finish more outfitting before erection (pre-outfitting) is emphasized. The foundation and the piping labour savings are summed for pre-outfitting and equipment labour savings are used for outfitting on the slipway. This results in a 0.24% labour hour reduction in the pre-outfitting and 0.64% labour hour reduction in the outfitting on board. The reduction on board is bigger than the labour on board. This means that next to the slight reduction in the pre-outfitting, the bigger reduction on board facilitates the shift of labour towards the pre-outfitting stage. Less relatively expensive on board outfitting reduces the cost and that results in more profit without increasing the price as illustrated in Figure 22.

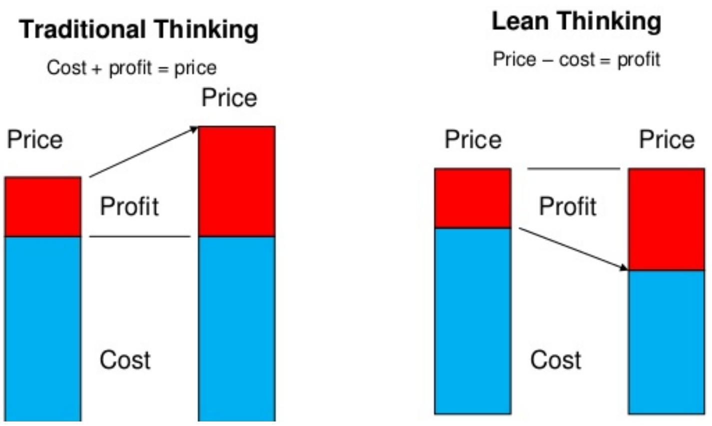

Figure 22: Traditional vs. Lean

The engine room is a crucial room as explained before, so analysing the delays at the engine room outfitting and expressing the profit of the analysed modules can show the effectiveness. Unfortunately, the delays of the outfitting process cannot be traced from the logged data. There are too many uncertainties to draw a reliable conclusion on amount of savings per section related to the engine room. However, modularization contributes exactly to that aspect of outfitting by lowering the variation and uncertainties for a possible delay. More about the uncertainty and variable reduction aspect of modularization is explained in Chapter 7.4: Transaction.

7.2 Storage area

The average change in storage area on the shipyard is a slight increase of 0.73 m^2. The average area that the modules are covering is 7.22 m^2. However, as mentioned before the foundations of the modules are not designed with engineering knowledge but with layout movements avoiding positioning items too close to each other that installation/maintenance might become risky. There is a probability that the items can be concentrated in even smaller area when looking at already modularized systems. This can probably reduce the storage area, but not drastically.

The main difference between storing the loose items and the modules is the location where the items are stored. There is a shift from the piping area towards the warehouse because the relevant pipe spools are included in the module. Loose items that are currently stored on the shelves make room for other items, because they will be a part of the module which has to be placed on the ground in the warehouse. The occupancy of the shelve area and the ground area in the warehouse tells whether the effect of this change is significant. If necessary, more space can be created by removing part of the shelves to create area for ground storage. Also the occupancy of the pipe area can be analysed to please the piping subcontractor, with whom Royal IHC can improve collaboration as it is a possible module supplier.

The densification of the system by modularization for the five cases where it applies results in a reduction of 26 m^2 floor space inside the ship. This can facilitate to build smaller ships theoretically, but this not expected to be applied instantly as the ship has to be redesigned and has major interdependencies. When designing new ships or when modularization is institutionalized in the future, this could be an interesting attempt. Institutionalizing of modularization is explained in Chapter 9: Implementation and recommendations. Other purposes like improved accessibility or cargo/storage capacity can be created.

7.3 Storage time

There are a lot of equipment stored longer than a week in the warehouse and some of them are relatively valuable. An overview of these equipment for the studied seven cases are shown in Table 10. The blue numbers are the amount of the items that are stored that many days in the warehouse.

Table 10: Storage times

Item	**Stored days in warehouse**																		
	9	**11**	**13**	**14**	**18**	**20**	**25**	**28**	**31**	**32**	**35**	**55**	**56**	**62**	**67**	**70**	**95**	**97**	**142**
Heat exchanger																			1
Pump 215-628 kg		3																	
Pump 30-38 kg				1													2		
Air receiver					2	2													
Compressed air filter												2		2					
Flow meter																		1	
Valve 7-29 kg			1				1	2	2	1	1				2				
Valve 108-158 kg	1												1			1			

The storage time of 142 days for a big and relatively expensive equipment like heat exchanger is a remarkable outlier. Using modules, the storage in the warehouse is reduced to several days dependent on factors like supply risk and reliability. The average of the items that are stored more than three days is 43 days. Assuming a safety margin of three days storage for the module, there is a reduction of 40 days. The storage is a Work In Progress inventory and together with unnecessary delays in flow time, it is one of the two major forms of waste (Shah & Ward, 2003). A JIT inventory management analysis can show the optimal day storage for the modules and reduce the waste.

Valuable items must be stored as short as possible in the warehouses, because Royal IHC is responsible for damages after supply. The higher the value, the greater the consequences of damage. For confidentiality reasons the values of the items cannot be presented. A *value-day calculation*, as explained in Appendix D, is made to express the concern of the storage of the items. The higher the value and/or the stored days of the items compared to the three day storage of the module, the higher the factor F. The calculated value-day factors can be seen in Table 11.

Table 11: Value-day factor

Cases	Value-day factor
SWCS (Thruster)	19.8
SWCS (Engine)	1.9
Air compressor A	3.7
Air compressor B	3.7
Lubrication valve system	31.8
Oil reclaim tank	4.7
Fire extinguisher system	3.7

The lubrication valve system and the SWCS (Thruster) cases have relatively high factors. As expected, storing a relatively expensive item as a heat exchanger for 142 days has its consequences for the SWCS (Thruster) case.

7.4 Transaction

The first two SWCS cases have a reduction of 5 suppliers and the other five cases have a reduction of 3 suppliers. All cases end up to one external module supplier, under the assumption that the piping subcontractor is the module supplier. It is also easier to coordinate activities as both sides are aware of the culture and work norms of each other by current collaboration. The management of the supply base for Royal IHC becomes more manageable when the number of suppliers, the level of interaction and the variation of the products are reduced. This reduction of the transactions can be considered as one of the main changes of modularization having effect on the transaction cost, supply risk, supplier responsiveness and supplier innovation (Choi & Krause, 2005). The description and implementation of these factors are discussed in Chapter 9.1 Impacts of supply base reduction.

The outfitting BOM of the modularized situation always contains one foundation (except lubrication valve system, because there is no change in foundation), one module and the short pipe spools that have to be linked on board to the previously assembled pipe spools. The reduction of the items on the outfitting BOM is on average 78%. This significant reduction reduces also the transaction on the shipyard. To show the difference between the current model versus the future model, the production model for the SWCS Engine case is illustrated in Appendix E. The current model has three internal supplies during the assembly at the assembly area and three internal supplies right before the pre-erection. The amount of suppliers to the section assembly area is reduced from six to two with one supply during the assembly and one supply right before the erection. The amount of supplies for the whole outfitting process is reduced from 13 to 4 supplies inside the shipyard for this case. This is a remarkable improvement, because JIT is not only important for external supply, but also for internal supply which facilitates On-Time Performance (OTP). OTP shows the level of success of the service, which is the shipbuilding in this case. Delays in supply can have serious consequences for the overall performance as it has a chain reaction. A late supply of an item can result in more outfitting labour on-board, late installation of the SWCS, late testing and probably late delivery of the ship. JIT for 4 supplies is more reliable and manageable than JIT for 13 supplies. The outfitting tasks have fewer dependencies and can more easily avoid costly penalties due to delay resulting in less waste. Reducing the variables, the uncertainty and the impact of them can be achieved by modularization in this way. It limits the offer to the customer and reduces the probability of a design change. Reducing the probability of not finishing the project on time can be achieved with a proper planning and scheduling. More theory about this is explained in Chapter 8: Planning and scheduling model for outfitting.

Lastly, looking at the on board installation in Appendix E, the current model has three equipment that have to be installed on board and 18 pipes to be attached to link the equipment to already assembled pipes. The future model has only four pipes to be attached. The installation process becomes considerably less complex and the possibility of a defect is lower because of testing before supply. This is another factor that reduces waste by reducing the probability of defect.

7.5 Correlation of saved labour

A possible correlation between the saved times for foundation, equipment and piping, which are including all items on the outfitting BOM, facilitates a strategic approach to generate modules. If there is a specific section that has a low pre-outfitting rate, making modules of systems/parts on that section can facilitate faster outfitting and increase the portion of desirable pre-outfitting. So, first determine the desired total time to save (S_{total}). Afterwards, the correlation shows the necessary time of the foundation (S_f), the equipment (S_e) and the piping (S_p) to save in order to achieve the desired time saving. Furthermore, a required amount of equipment that the module must include to reach the saved equipment time can be derived from the mounting estimation of Wei (2012). This is a strategic approach to generate modules that will be outsourced in the future.

Equation 1 is used therefore.

$$S_{total} = S_f + S_e + S_p \qquad (1)$$

S_{total} = saved total minutes
S_f = saved foundation minutes
S_e = saved equipment minutes
S_p = saved piping minutes

The movement time savings of all the cases, as can be seen in Table 12, are used to generate the equation.

Table 12: Overview of time savings

Case	Total [min.]	Foundation [min.]	Equipment [min.]	Piping [min.]
SWCS (Thruster)	**492**	-468	468	492
SWCS (Engine)	**2953**	-1139	2435	1657
Air compressor A	**1036**	-349	394	992
Air compressor B	**1292**	-271	616	947
Lubrication valve system	**906**	0	314	592
Oil reclaim tank	**506**	-141	159	487
Fire extinguisher system	**214**	-47	129	132

There are two methods used to generate an equation: average and linear regression model. The average method uses the average savings of all cases and generates an equation out of that. The linear regression model is used after verifying the linearity with the Pearson correlation factor. The Pearson correlation measures the linear correlation between two variables giving a *r* ratio between -1 and 1, where 1 is total positive correlation, 0 is no correlation and −1 is total negative correlation. The details and the calculation of these two methods can be seen in Appendix D below *correlation calculations*.

After analysis, the second strategy of the linear regression method, which has the overall lowest standard deviation shown in Table 13, is used in this research. This means that the generated module must have a foundation similar to the cases except the lubrication valve system and it must desire a total saving above 492 minutes as used in the sample. In other words, it is more suitable for system modules instead of small parts of bigger system as the lubrication valve system.

Table 13: Mean and standard deviation

	Foundation [%]	Equipment [%]	Piping [%]
Mean	17	3	3
Standard dev.	52.4	49.0	13.9

Using the trend line equations of this strategy as shown in Figure 35 in Appendix D, the module equation becomes:

$$Stotal = Sf + Se + Sp = (-0{,}3443 \cdot Stotal) + (0{,}8813 \cdot Stotal) + (0{,}463 \cdot Stotal) \qquad (2)$$

However, it must be noted that this method can not give the exact desired total saved time as it is not perfectly linear and must be corrected with the mean and standard deviation. To show this, an example is used. If the desired total saved time is 2000 minutes, it must be corrected with the mean percentages. The foundation is increased with 17% of its saved time, while equipment and piping increases with 3% of their saved times. These numbers are shown in Table 14.

Table 14: Example of guideline

	Total [min.]	Foundation [min.]	Equipment [min.]	Piping [min.]
Using trend line	**2000**	-730	1470	1260
After mean correction	**2207**	-605	1514	1298
Minimum Standard dev.	**1602**	-288	772	1118
Maximum standard dev.	**2812**	-922	2256	1478

The minimum and the maximum of the standard deviation show the boundaries of the saved times with 95% confidence level. So, the desired 2000 minutes results in 95% of the case between 1602 and 2812 minutes. Considering the little amount of cases, it can be used as an appropriate guideline to achieve the desired total savings. More case analyses can increase the reliability and can make more classifications of total savings or in weight and amount of item on the outfitting BOM.

8. Planning and scheduling model for outfitting

Changes in production method like modularization influences the outfitting sequence and a model for the modularized situation needs to be designed. Items like pipes and valves that are assembled at the assembly area are now a part of the module. This sequence change applies to all module cases because all of them are positioned at the slipway after the erection. Next to this sequence change, the two SWCS modules are currently part of multiple sections. The SWCS for thruster becomes a part of one section and the SWCS for the engine becomes a part of two sections as illustrated in Figure 23. Note that this rectangular box illustrates the boundaries of the module and not the section itself. The items belonging to sections that are no part at the modularized situation must be excluded from the BOM of these sections.

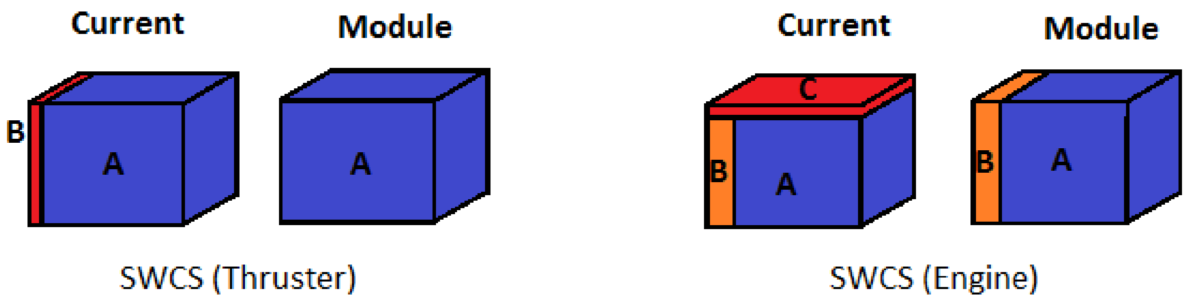

Figure 23: Sequence changes in section

Next to this densification of modularization, a proper planning model also fascilitates faster outfitting. Figure 24 shows the difference between the targeted end and the actual end of all section erections of the analysed pipe laying ship, where positive numbers can be interpreted as a delay and negative numbers are an early start. It can be seen that at the beginning the tasks are finished before the targeted and to the end tasks are finished after the targeted date. The last section has a delay of 70 days. When looking at the difference between the targeted start and the actual start of all section erections in Figure 25, it can be seen that the early finish of erection does not have the same impact on the start of the following section erection, especially at the beginning when all tasks finish earlier than targeted.

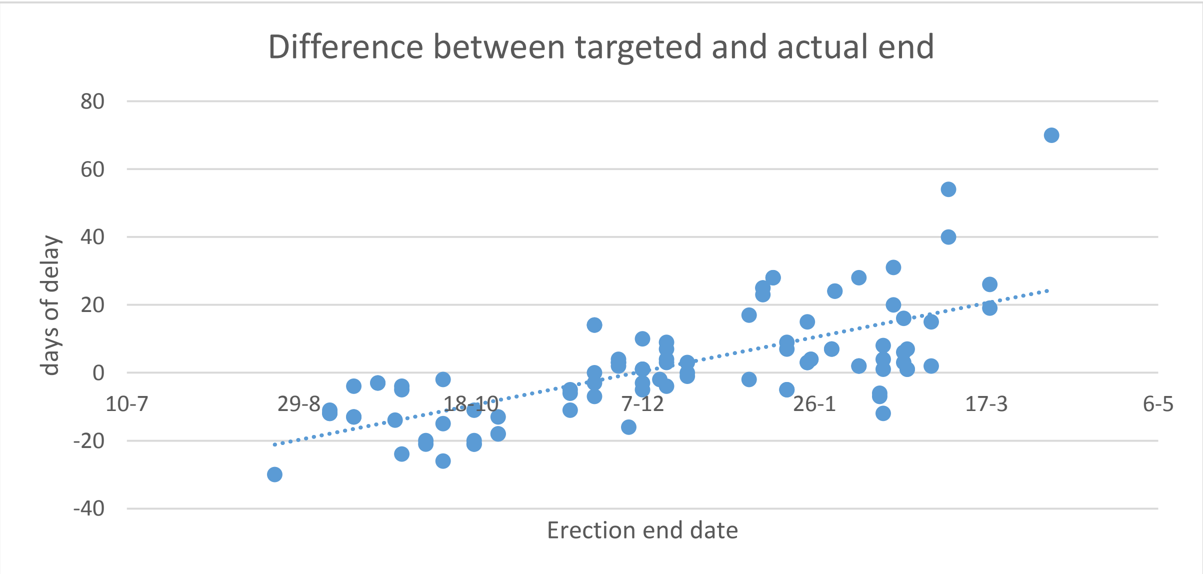

Figure 24: Targeted end vs. actual end

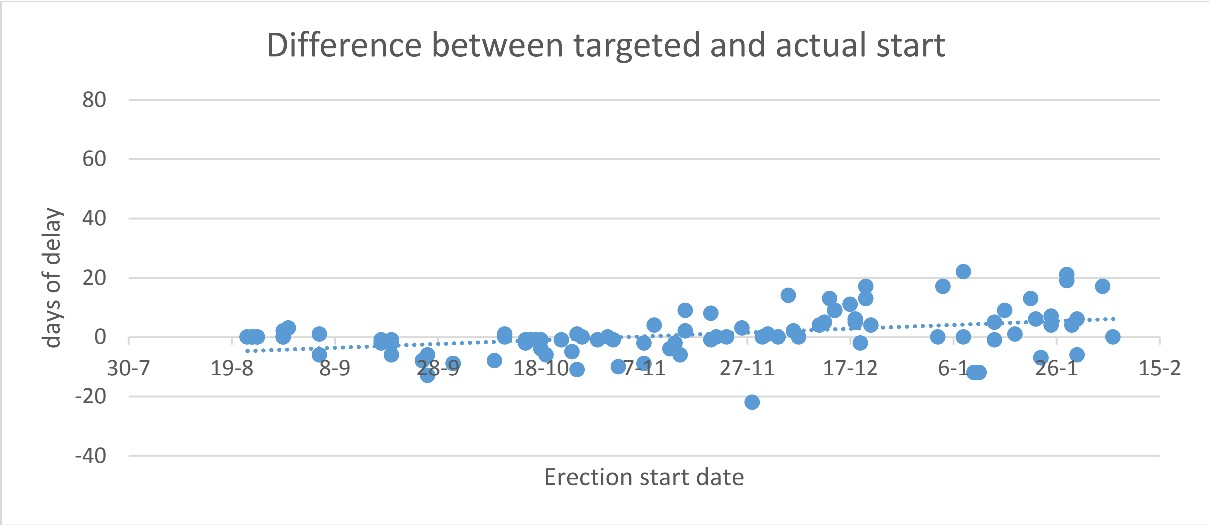

Figure 25: Targeted start vs. actual end

Practically it is not possible to trace the reasons for the delay for each section and as this is a single case it can not be concluded that it is a structural flaw of project management. It could have a reasonable explanation like more dependencies needed to start the task. But the fact is that the planning and/or the actual tasks are not synchronized in this case and it is open for optimization. This can be explained theoretically with the Parkinson's law. The law makes clear that when there is a specific time assigned to a task, the probability that it has a delay is significant while the probability that it starts earlier than planned is way lower. Goldratt uses the half of the initial engineers estimation as a rule of thumb for an aggressive estimation (Goldratt, 1997), but Royal IHC can use previous experiences to make a more reliable estimation by analysing multiple prior projects. This could also lead to better work distribution and better agreements with the customer at the design phase by identifying possible additional delays. To illustrate the effect of this, an example of a current planning and an aggressive planning are compared in Figure 26.

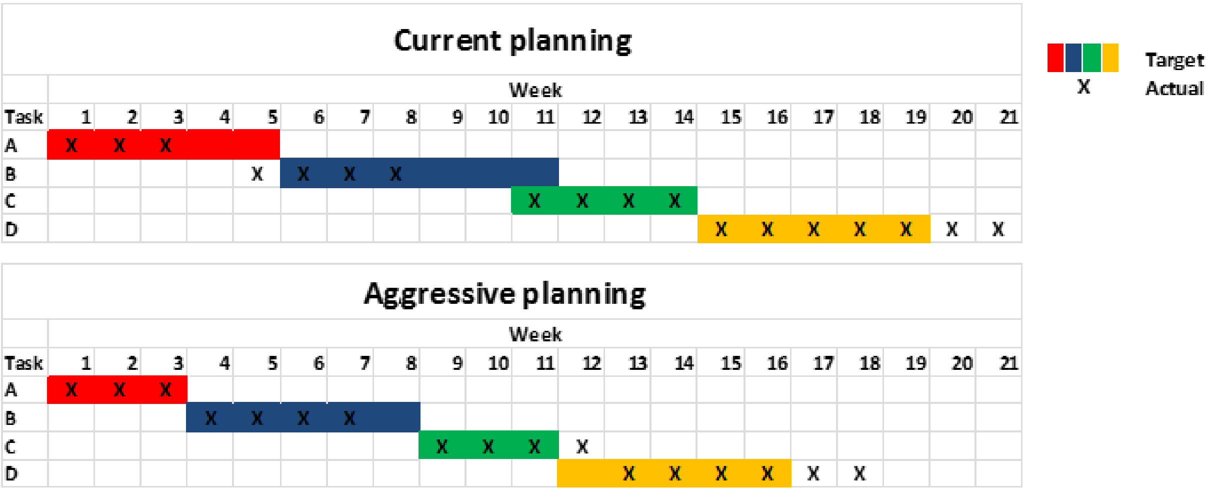

Figure 26: Aggressive planning

The actual week needed for a task is kept the same except for the last task D, in order to show the possible reduction using modules to the end as explained before. Even when the actual weeks are kept the same, there is a two week reduction of the total only by aggressive estimations.

The dependencies between elements in a system determines to a large extent the performance and efficiency of the system (Reinertsen, 1997). It can be concluded that reducing the complexity of outfitting at the later stage by reducing dependencies using modularization can have a positive impact on these delays. Less items on the outfitting BOM results also in less crane utilization which is convenient for scheduling. The observations of Wei (2012) show that there is an average of 25 minutes of waiting (delay) due to negotiation with the current user and waiting for the crane to transport heavy pipe spools at the section assembly area. The employee can wait or can continue with another non-scheduled task (engineer’s dillema). If the employee does not wait with the intention to avoid waste, but starts with another non-scheduled task, the probability that the task needs rework and thus waste increases as multitasking is not desired in Lean Manufacturing. Multitasking for employees caused by interruption by more urgent work increases the sharing of resources. Lower utilization of resources like cranes and forklifts reduces the probability of this interruption. It creates a bigger capacity buffer to handle variation and unplanned usage.

The aspects discussed in this chapter can be taken into account when planning and scheduling future projects, eventually including the relevant modularized cases, to create a more efficient scheduling and planning model.

9. Implementation and recommendations

The implementation of modularization is a complex field and entails factors like transaction cost, supply risk, supplier responsiveness and supplier innovation. These factors are discussed assuming the piping subcontractor of IHC as the module supplier. Also implications and recommendations are presented for both implementation and further research.

9.1 Impacts of supply base reduction

The transaction cost is defined by Choi and Krause (2005) as the frictional cost of doing business with suppliers and coordinating them, in order to obtain the needed inflow of material, parts and services. However, removing the walls between the information flow between piping subcontractor and other suppliers might lead to opportunistic behaviour like increasing prices. While the piping subcontractor is still functioning on the same supply tier, Royal IHC must be aware of the possible opportunistic behaviour. A thorough analysis and agreements must be done on this risk by Royal IHC before implementation. Royal IHC is already using modules for various systems, so it is expected that they are able to deal with this aspect. Less negotiation, fewer communication channels, less order placing and better tracing of problems are mentioned as reasons to lower transaction costs by reducing the supply base.

The level of interaction is very high for most of the cases, because the systems cannot be tested before all equipment are installed. By lowering the supplier numbers, the unreliability of delivering all items just in time to avoid delay is reduced, but the risk of delayed delivery of the whole module is increased. A delayed delivery of the whole module is way more risky than a standard single item which can be supplied from another supplier. The responsibilities with the module supplier must be clear. A half-finished module can also be a solution if the process is not yet mature. The maturity is explained in Chapter 9.2 Institutionalizing of modularization.

A close relationship and open communication between Royal IHC and the piping subcontractor is the essential factor leading to responsiveness. The fact that mounting and testing of some modules is no longer related to the milestones of section building inside the yard, the responsiveness is higher than the current situation. Next to that, standardizing by making modules is considered as the most influencing enabler affecting delivery speed and responsiveness to customer's performance (Jayaram, Vickery, & Droge, 2000). Jayaram et al. suggests further that concurrent engineering has a positive influence on manufacturing lead time and that value analysis affects timing in the key value generation activity of new product development. Concurrent engineering is realized by outsourcing products and services like testing and this study contributes to the valuing for a new product development in terms of making modules. As mentioned before, the design process is crucial and therefore Jayaram et al. emphasize the interaction of concurrent engineering with information technology with an empirical proof. This practice improves the time-based performance in manufacturing.

Instead of supplying items without knowing where it is used for, exchange of technological information increases the possibility of innovation. A small adjustment for the supplier can result in a key advantage for Royal IHC, who can use this to create value. Most of the innovative ideas leading to 25% cost savings for Honda came from the suppliers (Liker & Choi, 2004). This can also lead to standardisation which is highly desirable for improving and institutionalizing modularization. Obviously, this technological information should not be sensitive to share or a core business of Royal IHC.

Finally, reducing the supply base by modularization can lead to significant improvements unless the complexity and the behaviour of the current situation for Royal IHC is understood well. Instead of blindly lowering the supply base, an optimal number leads to more desirable results (Choi & Krause, 2005).

9.2 Institutionalizing of modularization

A study about institutionalizing modularity in ship technologies show that little effort has been expended to incorporate modular design in ship technologies and emphasizes that priorities should be given to mature the processes leading to implementation of modularization (Doerry N. H., 2014). This case study contributes to the maturation of the modularization process as explained in Chapter 2.2 Relevance and these efforts should be pursued in order to institutionalize it in the future. According to Doerry (2006), institutionalizing a technology is realized when:

1. An engineer has sufficient knowledge of the technology to predict its performance and impact on the product design at all stages of design;
2. An engineer has sufficient knowledge of the technology to predict the engineering effort required to integrate the technology into the product design in all stages of design;
3. An engineer has sufficient knowledge of the technology to predict the cost impact of the technology on the production cost of the end product;
4. An engineer is able to adequately specify the technology in a product specification to enable the producer to adequately bid a price and produce an acceptable product;
5. A customer is satisfied with the performance of the end product, having only characterized the performance requirements with relatively few parameters. In other words, customer expectations are met for product performance in areas that have not been explicitly specified.

In this case study, attention is primarily given to the third aspect of institutionalizing, but other aspects should also be considered to mature the modularization in shipbuilding further as far it is needed for Royal IHC. Again, it must be said that Royal IHC is already implementing modularization.

Finally, next to the improvements, there is also cost related to the implementation of modularization as the counterweight. There is a change engineering for all outfitting related employees and subcontractors of Royal IHC which must be managed well to achieve the desired performance. Detailed initial module design is necessary to avoid costly rework (Baade, Klinge, Lynaugh, Woronkowicz, & Seidler, 1998). Modules are heavier and often denser than conventional outfitting, so stronger supports and foundations might be required. The supplier of the module must be determined and possibly assisted. All these are worth a further research to compare it with the profits of modularization and to be able to value the modularity.

10. Conclusion

The goal of this study is to reduce (possible) wastes to increase the pre-outfitting percentage of outfitting and to facilitate modularization using relevant literature. In order to do that seven modularization cases are analysed and the Lean Manufacturing effects of the modularization on the outfitting process for Royal IHC are presented to answer the research question. These effects were determined using five variables: movement time, movement distance, storage area, storage time and transaction. The result of the analysis shows that there is a significant reduction of movement which can result in less confrontation of employees working on the shipyard and less interruption. Both reductions at the pre-outfitting and on board outfitting leads to the desired overall higher pre-outfitting percentage compared to all outfitting activities. This increases the pre-outfitting percentage, which is highly desirable at the relative long-lasting engine related outfitting. The slight increase in storage area can be avoided or even decreased with better naval engineering knowledge by concentrating the items in even a smaller area as observed at current modules of Royal IHC. Modularization increases ground storage and decrease shelve storage. The ratio between the occupancy of the shelve area and the ground area in the warehouse can be adjusted to have more efficient warehousing when the portion of modularization increases. The average storage time reduction of 40 days and the two cases with relatively long storage time and/or high value compared to the assumed three day storage situation are showing the necessity of applying Just in Time principle. Waste in form of Work In Progress inventory can be reduced using modules. The 78% reduction of items on the outfitting BOM is vast and one of the most significant improvement. This reduces the complexity in dependencies and resources and can decrease the probability of waste especially to the end of outfitting where delays are found. The correlation between the saved labour times for the foundation, equipment and piping of the modules facilitates a strategic approach to generate new modules in the future. More analysed cases can increase the reliability and can make more classifications of total savings, in weight or in amount of items on the outfitting BOM.

Modularization changes the installation sequence and the BOM of the systems and these changes needs to be taken into account right from the initial design process. It is found that an early finish of section erections do not have the same impact on an early start of the following section erection, especially at the beginning when all tasks finishes earlier than targeted. More aggressive estimations using lower bounds rather than averages of task durations at the start can compensate the increasing delays to the end. Better work distribution and agreements with the customer can be made at the design phase by identifying possible additional delays. These delays can also be mitigated by lowering the utilization of resources to create a bigger capacity buffer to handle variation and unplanned usage. These effects of modularization in this case study show the waste reduction that directly or indirectly facilitates a higher pre-outfitting percentage.

Not only the external suppliers, but also the internal suppliers on the shipyard is reduced allowing a better manageable Just in Time principle. This facilitates On-Time Performance of activities indicating the level of success of the shipbuilding. The installation process on board becomes considerably less complex and the possibility of a defect can be mitigated by testing before supply. The suppliers of the cases can be reduced to one, but this has influence on transaction cost, supply risk, supplier responsiveness and supplier innovation. Reducing the transaction with suppliers by reducing the amount of suppliers can lead to significant advantages unless the complexity and the behaviour of the current situation for Royal IHC is understood well. All cost related to these improvements, which worth a further research, can be compared with the Lean Manufacturing effects to value modularity. The integration of design and manufacturing and the interaction of information technology and concurrent engineering are the key factors for an efficient implementation of modularization. This practice improves the time-based performance in manufacturing. Royal IHC is already implementing modularization, but these aspects can be used effectively by Royal IHC where necessary. Even though there are significant improvements in this case study, modularization in shipbuilding is not yet institutionalized (Doerry N. H., 2014). These efforts should be pursued in order to institutionalize modularization in the future and more research to modularization possibilities in the shipbuilding like this case study will contribute to that goal. This research contributes theoretical and practical to the valuing of modularity with a Lean Manufacturing perspective by conducting a case study at one of the leading shipbuilding companies. The cost impact of the analysed cases is worth a further research to contribute to the valuing.

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Appendix A: Scientific paper

Lean Manufacturing effects of modularization on the outfitting process in shipbuilding: A case study of Royal IHC

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Abstract
Becoming competitive in the market and enhancing that position has been more challenging for European shipyards than their "low cost labour" competitors in the last decades (Wei, 2012)*. Next to the innovation of products, the innovation of production like modular outfitting is an area that requires attention. As modular outfitting is considered as an optimization of the outfitting, increasing the portion of modular outfitting can be used to increase efficiency and reduce cost* (Fafandjel, Rubesa, & Mrakovcic, 2008)*. Prior studies about modularization do not emphasize the Lean Manufacturing effects that can increase the efficiency by reducing waste. So, modularization of seven existing systems by reducing the items on the Bill of Materials is done to show these Lean Manufacturing effects. This is realized by doing a case study for Royal IHC, a leading Dutch shipbuilding company. Improvement areas at movements, storage, transaction and planning are found to reduce waste. The findings contribute to the valuing of modularization and gives insight on the benefits of modularization with a Lean Manufacturing perspective using relevant literature.*

Keywords: Modularization, Lean Manufacturing, Outfitting, Supply base, Royal IHC

Introduction

The innovation of production processes requires attention in order to enhance the competitiveness in shipbuilding. Production improvements are currently important for increasing the efficiency of shipbuilding, which can result in lower cost and reduced lead times. Wei (2012) suggests that the outfitting work can be done more efficiently by completing outfitting earlier and that strict milestones of the production are constraints for pre-outfitting. Several studies that tried to calculate cost factors at different outfitting stages suggest that outfitting at later stage involves more cost (e.g. Fafandjel, Rubesa, & Mrakovcic, 2008). As modular outfitting is considered as an optimization of the outfitting process, increasing the portion of modular outfitting can be used to increase efficiency and reduce overall cost according to Fafandjel et al. Modularization decreases the number of items on a Bill of Materials (BOM) by making pre-assembled items. Less items on a BOM can result in fewer suppliers, which lowers the transaction risk and costs while increases responsiveness (Meysen et al, 2009). There are prior studies about modularization in shipbuilding but there is no emphasis on the Lean Manufacturing aspect of modularization. Lean Manufacturing is a method to reduce waste in manufacturing with a systematic approach. Furthermore, there is no general guideline for the shipbuilding industry to estimate the possible labour savings by making modules for outfitting. If there is a specific section that has a low pre-outfitting rate, making modules of systems/parts on that section can facilitate faster outfitting and increase the portion of desirable pre-outfitting. This case study analyses several Lean Manufacturing effects of reducing the items on the BOM for outfitting using data of Royal IHC, a Dutch shipbuilding company. These effects give an insight on the benefits of modularization with a Lean Manufacturing perspective. The goal is to increase the pre-outfitting percentage by identifying (possible) wastes and to facilitate modularization in shipbuilding using relevant literature. So the following research question is answered in this research:

"What are the Lean Manufacturing effects of reducing the items on the Bill of Materials using modularization on the outfitting process for Royal IHC?"

Theoretical background

Royal IHC designs and constructs complex vessels for the maritime and offshore sector at multiple international locations. This case study uses data of a pipe-laying ship built in Krimpen aan den Ijssel. Royal IHC is already using modularization in ships with success, so increasing the portion of modularization will be discussed in this report.

The long lead time and high customization of ships can lead to late design changes and costly rework. The production cost can possibly increase to eight times of the current production cost (Rubesa, Fafandjel, & Kolic, 2011). Therefore, Rubesa et al. emphasize the importance of higher effort in better engineering, better quality assurance and a higher level of design standards to avoid rework. However, modularization is an exquisite way to deal with these design changes, because it provides flexibility lowering the impact on the total product (Gershenson & Prasad, 1997). One of the findings in the paper of Meysen et al. (2009) is the reduction of the supply base realized by modularization. Integrating the key supplier(s) to the production can result in higher efficiency as experienced by Lear. This company evolved from seat producer to entire interior systems by diversifying its productive process (Lara, Trujano, & Garcia-Garnica, 2005). This technological upgrading of key suppliers can also be applied in the shipbuilding industry and some modules can even be tested before supply to reduce defect probability. Taking this successful example into account, the piping subcontractor of IHC is assumed as the supplier of the generated modules in this research. The supplier is determined and assisted if necessary to expand so they can facilitate the modularization of your company in return. There are especially two processes that needs priority to mature this modularization process (Doerry N. H., 2014). The emphasis should be especially given to cost estimation and valuing modularity and flexibility as these are essential for the justification of modularization.

Lean Manufacturing is a method to reduce waste in manufacturing with a systematic approach. This study uses the Theory of Constraints (TOC) and Just in Time (JIT) as the main principles of Lean Manufacturing. The TOC of Goldratt focusses on the process that slows the speed of production and is essentially about change (Dettmer, 1997). This is used when generating possible modules effectively. The Just in Time principle is described as the process of producing the necessary parts at the necessary time and have on hand only the minimum stock necessary to hold the processes together (Sugimori, Kusunoki, Cho, & Uchikawa, 1977). The importance of JIT can be seen in the factor loadings at agile manufacturing strategies, which modularization is a part of (Shah & Ward, 2003). The biggest loading factor is at the JIT principle as shown in Table 1.

Table 1: Loading factors

Lean principles	Loading factors of Agile manufacturing strategies
Just in Time	0.552
Total Productive Maintenance	0.327
Total Quality Management	0.075
Human Resource Management	0.146

Method

Taking the current situation and the Theory of Constraints into account, modules for outfitting are generated inside a pipe-laying ship that is built at Royal IHC. It is known and experienced that data/information gathering can be slow in big companies. Also not all necessary data are available or exists thus some of them must be generated. Therefore and due to limited time for this research, the complexity in terms of number of items are balanced to get satisfying results. The CAD drawing, the outfitting BOM and the production flow are analysed in order to make an outfitting model of the current situation. The following variables are determined therefore: movement time, movement distance, storage area, storage time and transaction.

By making a VBA movement model of the shipyard map the movement time and movement distance are calculated. The storage is extracted by data of Royal IHC and the installation times are extracted from the data gathered by Wei or from expert opinion. The effects of modularization on the determined variables are analysed to obtain results.

The engine room accounts for 40% of the production hours and ship costs (Bertram, 2005). Mainly the engine room, but also other rooms of the ship are analysed to include "low hanging fruits". The following seven cases are chosen for this case study:

1. Auxiliary Sea Water Cooling System (Thruster)
2. Auxiliary Sea Water Cooling System (Engines)
3. Air compressor A
4. Air compressor B
5. Lubrication valve system
6. Oil reclaim tank
7. Fire extinguish system

Results

The Lean Manufacturing variables of the case results and the correlation of saved labour are discussed in order to determine the effects of modularization.

Movement time and distance

The total theoretical time saving of the seven modules is 7827 minutes, which is equal to 130 hours, as shown in Table 2.

Table 2: Loading factors

	SWCS (Thruster)	SWCS (Engine)	Air compr. A	Air compr. B	Lubrication valve system	Oil reclaim tank	Fire extinguisher system	Total
Time [min.]	492	2953	1036	1292	906	506	642	7827
Distance [m.]	1608	5342	1446	1342	729	729	2187	13381

The labour reduction results in a 0.24% labour hour reduction in the pre-outfitting and 0.64% labour hour reduction in the outfitting on board. This is a minor improvement, because small systems are analysed to have sufficient amount of cases taking the validity of the generated guideline into account. These numbers are very likely higher in practice because there are also movement times not taken into account like movements by employees who needs to walk to forklifts, get tools from workshops or other employees, missing items, rework etc. The distance savings due to modularization is 13 km. for foundation, equipment and piping movements. These are apart from the movements inside the ship, to and from the working area, travels during breaks etc. Employees who are working on the shipyard are less confronted and interrupted by other employees when they are working in the same area. This can reduce the waste, especially towards the end of outfitting where delays are found. The profit increase by reducing waste with a Lean perspective is shown in Figure 1.

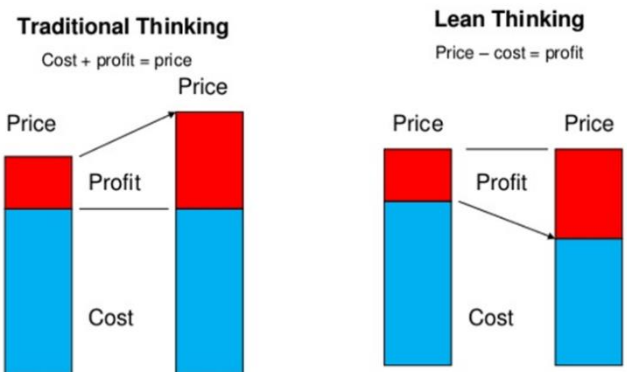

Figure 1: Traditional vs. Lean

Storage area

There is 0.73 m^2 increase in storage area of modules on the shipyard compared to loose items, however better naval engineering knowledge at module generation can result in denser modules and even decrease the necessary storage area. The main difference is the fact that there is a shift from shelve storage to ground storage. The densification of the system by modularization results in a reduction of 26 m^2 floor space inside the ship. This can facilitate to build smaller ships theoretically, but this not expected to be applied in short term as the ship has to be redesigned and has major interdependencies. Other purposes like improved accessibility or cargo/storage capacity can be created.

Storage time

Assuming a safety margin of three days, the average storage time reduction of all equipment inside the warehouse is 40 days. To express the concern of the storage time, the value of the items are also taken into account. It is assumed that storage in the warehouse of 3 days for the module is appropriate as a buffer. Equation 1 is used to express the *value-day factor* (F) as the magnitude of the concern of storage for every case. The higher the value and/or the stored days of the items compared to the three day storage at the modularized situation, the higher the factor F.

$$F = \frac{\sum_{i=1}^{n}(value_i \cdot storage_i)}{(value_i + value_{i+1} + \ldots + value_n) \cdot 3} \qquad (1)$$

F = value-day factor
$value_i$ = value of equipment i in euros
$storage_i$ = storage day of item i in days

Two cases have relatively long storage time and/or high value compared to the assumed three day storage situation as shown in Table 3.

Table 3: Value-day factor

Cases	Value-day factor
SWCS (Thruster)	19.8
SWCS (Engine)	1.9
Air compressor A	3.7
Air compressor B	3.7
Lubrication valve system	31.8
Oil reclaim tank	4.7
Fire extinguisher system	3.7

Transaction

The amount of items on the outfitting BOM is reduced on average 78%. The supplier transactions are reduced from six to one for two cases and four to one for the other five cases. Also the reduction of internal suppliers is a remarkable improvement, because JIT for internal supply facilitates On-Time Performance (OTP) and less dependencies results in a more manageable JIT.

Correlation of saved labour

A correlation between the saved times for foundation, equipment and piping is determined using equation 2.

$$S_{total} = S_f + S_e + S_p \qquad (2)$$

S_{total} = saved total minutes
S_f = saved foundation minutes
S_e = saved equipment minutes
S_p = saved piping minutes

Using a linear regression model, equation 3 is found for desired total savings above 492 minutes:

$$Stotal = Sf + Se + Sp = (-0{,}3443 \cdot Stotal) + (0{,}8813 \cdot Stotal) + (0{,}463 \cdot Stotal) \qquad (3)$$

Planning and scheduling model for outfitting

Modularization influences the outfitting sequence of several items and this must be taken into account from the design phase. When looking at the difference between the targeted start and the actual start of all section erections in Figure 2, it can be seen that the early finish of erection does not have the same impact on an early start of the following section erection, especially at the beginning when all tasks finish earlier than targeted. Practically it is not possible to trace the reasons for the delays, but the fact is that the planning and/or the actual tasks are not synchronized in this case and it is open for optimization. The delays can lead to undesirable multitasking of employees and unplanned usage of resources.

Figure 2: Targeted and actual erection dates

Implementation and recommendations

The implementation of modularization is a complex field and entails factors like transaction cost, supply risk, supplier responsiveness and supplier innovation. The frictional cost by doing business with suppliers can be reduced by lowering the supply base, however removing the walls between the information flow between the piping subcontractor and other suppliers might lead to opportunistic behaviour like increasing prices. By lowering the supplier numbers, the unreliability of delivering all items just in time to avoid delay is reduced, but the risk of delayed delivery of the whole module is increased. A close relationship and open communication between Royal IHC and the module supplier is the essential factor leading to high responsiveness. Next to that, standardizing by making modules is considered as the most influencing enabler affecting delivery speed and responsiveness to customer's performance (Jayaram, Vickery, & Droge, 2000). Instead of supplying items without knowing where it is used for, exchange of technological information with suppliers increases the possibility of innovation. A small adjustment for the supplier can result in a key advantage for Royal IHC, who can use this to create value. For example, most of the innovative ideas leading to 25% cost savings for Honda came from the suppliers (Liker & Choi, 2004).

A study about institutionalizing modularity in ship technologies show that little effort has been expended to incorporate modular design in ship technologies and emphasizes that priorities should be given to mature the processes leading to implementation of modularization (Doerry N. H., 2014). In this case study, attention is primarily given to the cost impact of the technology which is only one of the five aspects of institutionalizing according to Doerry (2006). Jayaram et al. also emphasize that the design-manufacturing integration and the information technology-concurrent engineering interaction are the key factors for an efficient implementation of modularization. Next to the improvements, there is also cost related to the implementation of modularization as the counterweight. There is a change engineering for all outfitting related employees and subcontractors of Royal IHC which must be managed well to achieve the desired performance. This is worth a further research to compare it with the profits of modularization and to be able to value the modularity.

Conclusion

The analysis of the Lean Manufacturing effects of modularization concludes that the reduction of movements leads to less confrontation and interruption of employees working on the shipyard and increases the overall pre-outfitting percentage compared to all outfitting activities. Accessibility inside the ship is increased using modules. The necessity of applying Just in Time principle to reduce waste in form of Work In Progress inventory becomes more perceptible when taking the storage time and the value of the items into account. Less items on the outfitting BOM reduces the complexity in dependencies and resources and can decrease the probability of waste especially towards the end of outfitting where delays are found. A guideline for a strategic approach to generate modules in the future is generated by finding a correlation between the saved labour times. However, more case analyses can increase the reliability and make different correlations for various classifications. More aggressive estimations using lower bounds rather than averages of task durations at the start of outfitting can compensate the increasing delays to the end. This provides better work distribution and agreements with the customer at the design phase by identifying possible additional delays. These delays can also be mitigated by lowering the utilization of resources to create a bigger capacity buffer to handle variation and unplanned usage. Not only the external suppliers, but also the internal suppliers on the shipyard is reduced allowing a better manageable Just in Time principle. Defect possibility can be mitigated by testing before supply if possible. These effects of modularization in this case study show the waste reduction that directly or indirectly facilitates a higher pre-outfitting percentage.

Implications and implementation aspects due to supplier reduction are presented using relevant literatures. Reducing supply base by modularization can lead to significant advantages unless the complexity and the behaviour of the current situation for Royal IHC is understood well. The cost related to these improvements, which is worth a further research, can be compared with these Lean Manufacturing to value modularity. Royal IHC is already implementing modularization, but these aspects can increase the efficiency. Even though there are significant improvements in this case study, modularization in shipbuilding is not yet institutionalized (Doerry N. H., 2014). Efforts and more research to modularization possibilities in the shipbuilding like this case study will contribute to the institutionalizing. This research contributes theoretical and practical to the valuing of modularity with a Lean Manufacturing perspective by conducting a case study at one of the leading shipbuilding companies. The cost impact of the analysed cases is worth a further research to contribute to the valuing.

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Appendix B: Map of IHC Krimpen aan den Ijssel

The huge indoor production hall of Royal IHC is coloured red in Figure 27. The relevant locations for the production are added also on the map and is used when analysing the items on the outfitting BOM.

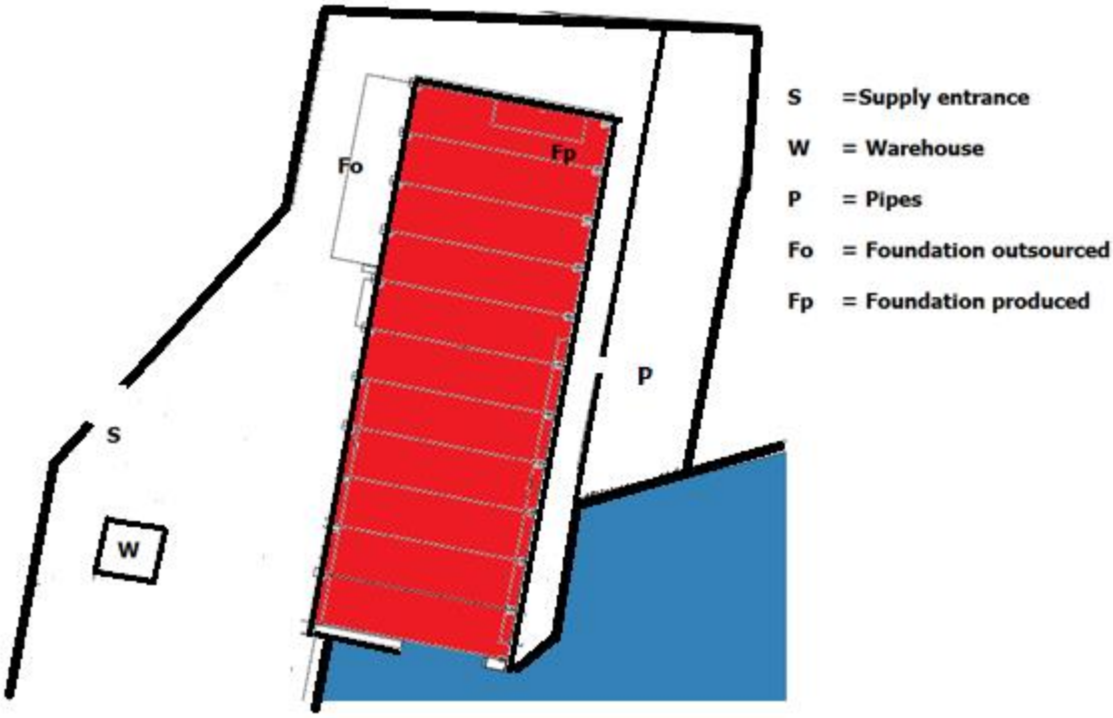


Figure 27: Map of Royal IHC, Krimpen aan den IJssel

The production hall of IHC is divided into two rough areas; the assembly area and the slipway area as can be seen in Figure 28. At the assembly area the pre-outfitting activities take place. The red line is showing the separation between the pre-erection area and the erection area. A part of the next ship, which is going to be built after the ship laying on the erection slipway, can already put on the pre-erection slipway to work on.

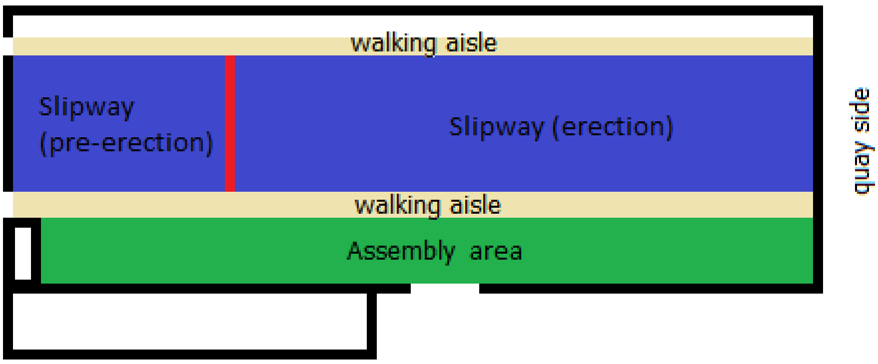


Figure 28: Indoor hall map

Appendix C: VBA movement model

In order to analyse the consumed time and covered distance related to the outfitting module, the production planning is analysed. To do this, a model of the shipyard has been created using Excel VBA. Figure 29 shows a screenshot of the model. The model calculates the distances between multiple spots on the yard and fills a distance matrix. This matrix is used to determine the covered distances for specific actions and multiplying the distance with movement speed shows the consumed time.

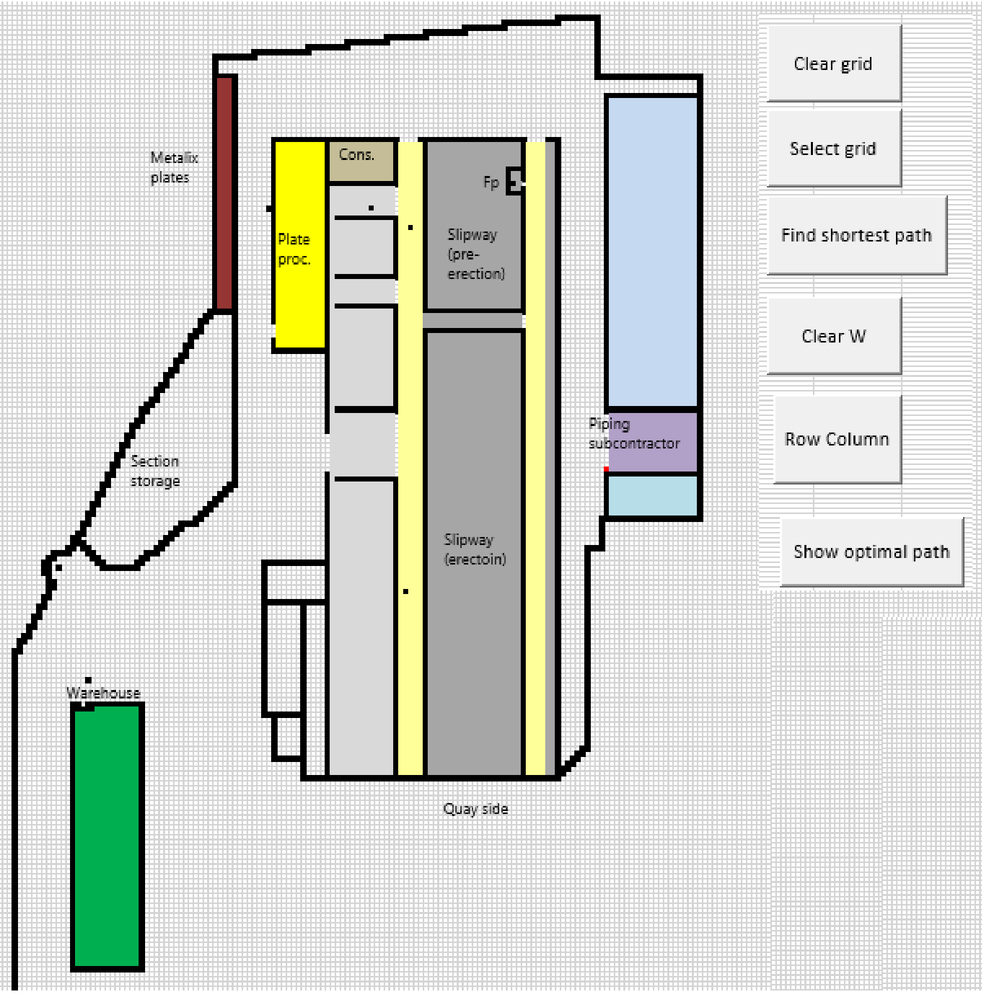


Figure 29: VBA model of the shipyard

The movement speed is a variable and depends on the transportation mode. Diagonal moves of 1.41 meters are included to be more realistic. To justify this an example of a path is chosen and the calculated and manually drawn shortest paths are compared. A part of the calculated route is shown in Figure 30. This is compared with the path using the Pythagoras equation which is the shortest theoretical path.

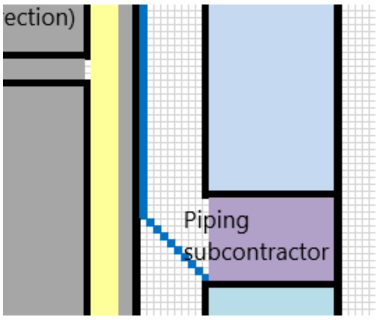


Figure 30: Example path for justification

The VBA model calculates 144.97 meters and the Pythagoras results in 141.97 meters. There is a difference of 2.1% and that is the maximum. As there are assigned paths for pedestrians and vehicles, the difference is expected to be lower than 2.1%.

The model can use heuristics for faster calculations, but the distance matrix needs to be filled once. The calculation time is not important in this case. Therefore, the heuristic is chosen zero which makes the VBA movement model use the Dijkstra's algorithm to guarantee the shortest path (Fu, Sun, & Rilett, 2005).

A simple example of a calculation is shown in Figure 31. An equipment arrives at the supply entrance and is immediately stored in the warehouse. When needed it is transported to the assembly area next to the pre-erection area. Adding locations to the list and clicking on calculate show the distance covered and the time consumed when movement speed is assumed 5 km/h (walking speed). The speed of the forklift is estimated as 20 km/h by a floor employee, but with a note that it is obviously dependent on the transported item. For this reason, the movement speed is assumed 10 km/h for heavy equipment above 1000 kg. This method is used to translate the movement times and covered distances for the current situation and for the future modularized situation later on.

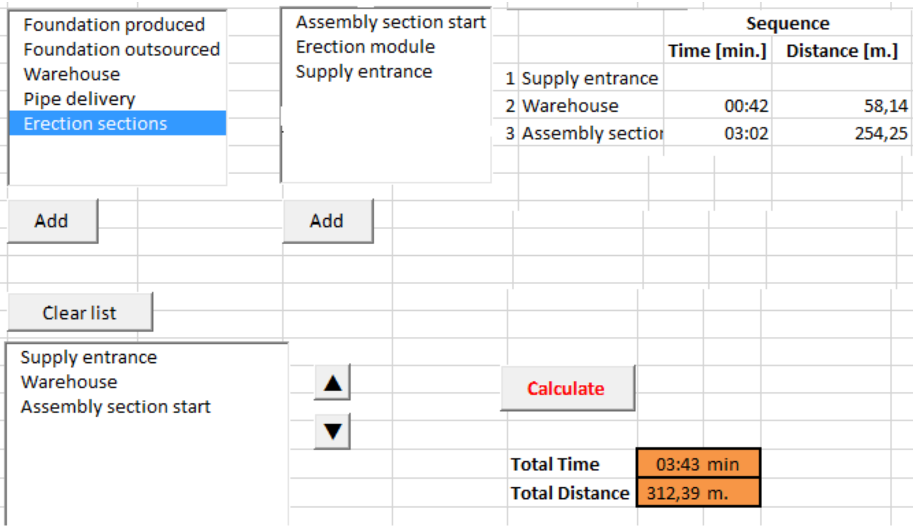


Figure 31: Example path calculation

Appendix D: Assumptions and calculations

List of assumptions

Several assumption that are taken into account are listed in Table 15.

Table 15: List of assumptions

		Source
Picking up and dropping down an item with a forklift	15 sec.	Assumption
Speed of forklift (<1000 kg)	20 km/h	Employee estimation
Speed of forklift (>1000 kg)	10 km/h	Assumed considering source for <1000 kg
Walking speed	5 km/h	(Browning, Baker, Herron, & Kram, 2006)

Used data and calculations

The generated data and the calculations that are made for estimations are listed in this appendix.

- **Foundation calculation**

This study uses estimations based on expert opinion of employees. Five foundations of existing modules were shown and an estimation of the total labour needed is estimated as 20 hours. The height of the foundations were all the same so that does not make a difference. Taking the expert opinion into account, the area of the top view of the foundation is assumed as the decisive factor to assign the labour hours. The 20 hours of labour is distributed as can be seen in Table 16. Also looking at the weight of the foundation, the estimations seem to be valid.

Table 16: Foundation data for estimation

Foundation	**Equipment weight (kg)**	**Foundation weight (kg)**	**Dimension lxb [m]**	**Area [m^2]**	**Labour [h]**
1	1800	395	1.7 x 1.2	2,04	2,48
2	2100	505	2.5 x 1.5	3,75	4,56
3	3400	526	3.8 x 1.2	4,56	5,54
4	550	83	1 x 0.85	0,85	1,03
5	3200	637	3.5 x 1.5	5,25	6,38

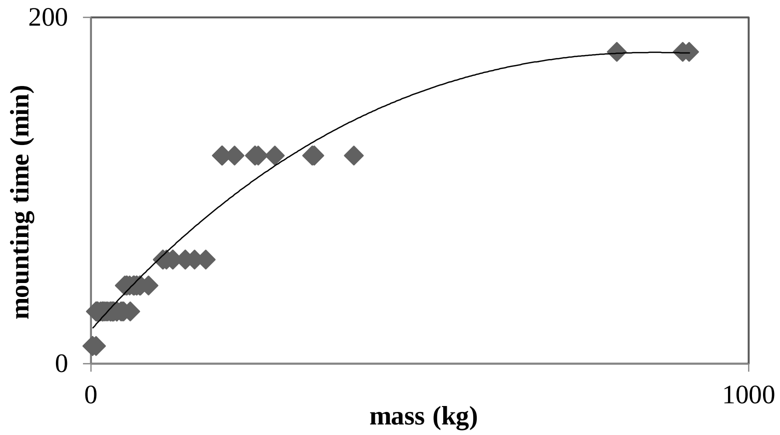
The mass of the new module foundations is determined using the top view area of the foundation. The resulting equation is as follows:

$$Labour = 72.948 \cdot Area \qquad (3)$$

Labour = amount of labour in minutes
Area = amount of area in m^2

- **Equipment time calculation**

Wei (2012) asked various outfitting workers to give their expert opinion on the required mounting time for roughly 130 pieces of equipment. These estimations are plotted by weight and a curve, as shown in Figure 32. Equation 4 is created to estimate the mounting time of equipment as shown below.



$$y = 7.86 \times 10^{-8} \cdot x^3 - 3.53 \times 10^{-4} \cdot x^2 + 19.43 \quad (4)$$

y =mounting time in minutes
x = mass of equipment in kg.

Figure 32: Mounting estimations of Wei (2012)

Considering all equipment Wei studied, the limited equipment above 1000 kg have a maximum mounting time of 240 minutes as can be seen in Figure 33. Therefore, it is assumed that equipment or modules above 1000 kg needs 240 minutes of mounting time.

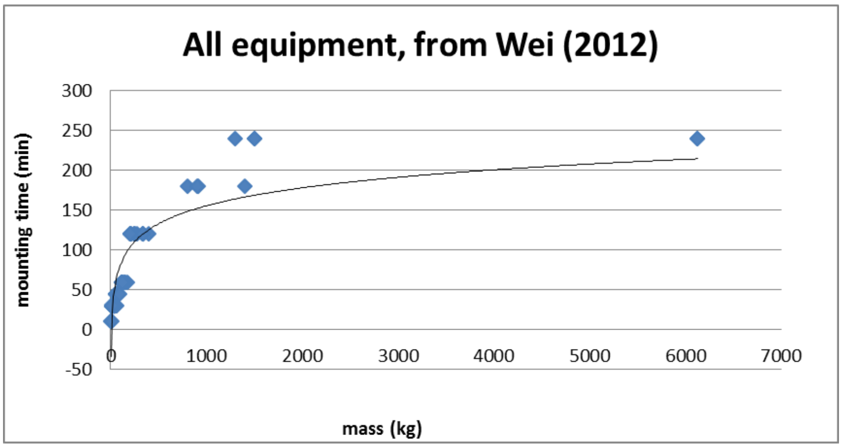


Figure 33: All mounting estimation data of Wei (2012)

- **Piping time calculation**

Wei observed the piping process one week a day for nine months and gathered valuable data as shown in Table 17. This data is used to estimate the labour needed for piping of new modules.

Table 17: Piping estimations of Wei (2012)

Item	Actions	Time on average [min.]
Prepare document/tools	1. Read 3d and 2d drawings	10
	2. Think and make the decision which is the next spool to be installed	10
	3. Search the spool in a pipe cradle	10
Transport a pipe spool	4. Negotiate with the current user of a crane	5

	5. Wait for the crane	20
	6. Transport the pipe spool from the cradle to a steel section and place the pipe spool on its position	15
Make one support	7. Figure out the position of this support	2
	8. Measure and write down the distance from the center of the pipe spool to its nearby steel structure	3
	9. Walk to a workshop and make the support	15
	10. Pick up bolts and nuts in a storehouse and walk back to the steel section	5
	11. Weld the support on the steel structure and put the pipe spool on the support	5

The transportation of pipe spools over 50 kg at the assembly area is done using a crane. The *transport a pipe spool section* in Table 17 is then used. The smaller spools are carried by employees. If the length of a pipe spool is less than 3000 mm, at least one support is needed. So the total length of pipe spools is divided by 3000 to calculate the necessary amount of supports.

The saved cradles transported from the piping area to the assembly area is determined using the volume of the cradle and the occupancy. The estimated dimension of one cradle is 0.8x1x4 meters, but he halve of this volume is taken into account because it is observed that there are a lot of empty places between the pipes on the cradle.

When the module is generated, the amount of interacting pipes are determined. These links are attached after the module is positioned and is assumed that it takes double the time of attaching at the assembly area (5 minutes) due to possible inconvenient positions for the employee while attaching. These pipes are already attached to the module package, so no transport is needed to the assembly area.

- **OF/POF calculation**

The total outfitting labour of the ship is 26464 man hours. This is the installation time of pipes, HVAC ducts, lights, cable trays, small ironworks and minor equipment (<1000 kg) and is collected with the same data collection method used in this research. These are only the installation times. To include the movement times, the ratio between installation and transportation times of the cases is analysed. The transportation times are on average 0.43% of the total time, so the total outfitting time of the ship including transportation results in 26578 hours. It is reasonable to assume that the pre-outfitting is 80% of the total outfitting for EU shipyards (Schank, 2005). Using the previously mentioned 1:3:5:7 ratio of outfitting work in later stages, the ratio between the final outfitting and section outfitting is 3:7 (Fafandjel, Rubesa, & Mrakovcic, 2008). The total outfitting times for pre-outfitting (POF) and the rest of the outfitting time (Non POF) is shown below in equation 5 and 6:

$$POF = 26578 \cdot 0.8 = 21262 \text{ hours} \qquad (5)$$

$$Non\ POF = 26578 \cdot 0{,}2 \cdot \frac{7}{3} = 12403 \text{ hours} \qquad (6)$$

- **Value-day calculation**

It is assumed that storage in the warehouse of 3 days for the module is appropriate as a buffer. Equation 7 is used to express the *value-day factor* (F) as the magnitude of the concern of storage for every case.

$$F = \frac{\sum_{i=1}^{n}(value_i \cdot storage_i)}{(value_i + value_{i+1} + \ldots + value_n) \cdot 3} \qquad (7)$$

F = value-day factor
$value_i$ = value of equipment i in euros
$storage_i$ = storage day of item i in days

- **Correlation calculation**

There are two strategies used for this calculation:

1. All cases except the lubrication valve system case
2. All cases except the lubrication valve system and fire extinguisher case

The reason to exclude the lubrication valve system is the fact that it has not a similar foundation to the rest of the cases. The zero change at the foundation saving distorts the distribution using the generated correlations. The reason to exclude also the fire extinguisher is that it is found after analysis that it has an outlying result and has also the smallest saving of all cases. It might be that the equation is more reliable for modules saving a total time above 492 minutes. These two strategies are applied to the following two methods.

The average method

The average method calculation takes the averages of the total saved time (S_{total}), the saved foundation time (S_f), the saved equipment time (S_e) and the saved piping time (S_p) to generate an equation. The resulting correlations can be seen in Table 18.

Table 18: Average method correlation

Correlation	Total	Foundation	Equipment	Piping
Strategy 1	1	-0.37	0.65	0.73
Strategy 2	1	-0.38	0.65	0.73

The total saved time is distributed over the foundation, equipment and piping using this correlation. The result is compared with the initial case distribution and the deviation in percentages are calculated. The mean value and the standard deviation of these are calculated for the foundation, equipment and piping as shown in Table 19.

Table 19: Mean and Std. dev. for average method

Strategy		Foundation	Equipment	Piping
1	**Mean**	21	28	-5
	Standard dev.	50.9	53.6	24.3
2	**Mean**	13	32	-9
	Standard dev.	51.5	59.0	24.3

The linear regression method

Before blindly applying the linear regression model and assuming that there is a linearity, the Pearson correlation is used to test the extent of linearity between the variables. For more detailed information about the Pearson correlation the paper of Rodgers & Nicewander (1988) can be studied. The Pearson correlation (*r*) is shown in equation 8.

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{(n\sum x^2 - (\sum x)^2)(n\sum y^2 - (\sum y)^2)}} \qquad (8)$$

r = Pearson correlation
n = amount of cases
x = total saved time in minutes
y = saved foundation time, saved equipment time **or** saved piping time in minutes

The Pearson correlations for foundation, equipment and piping for both strategies are shown in Table 20.

Table 20: Pearson correlation for linear regression model

Strategy	Foundation	Equipment	Piping
1	-0.925	0.964	0.963
2	-0.928	0.964	0.964

As the Pearson correlation for both strategies are very close to -1 or 1, there is a high linearity. A scatter plot and the trend lines are shown in Figure 34 and Figure 35 for both strategies.

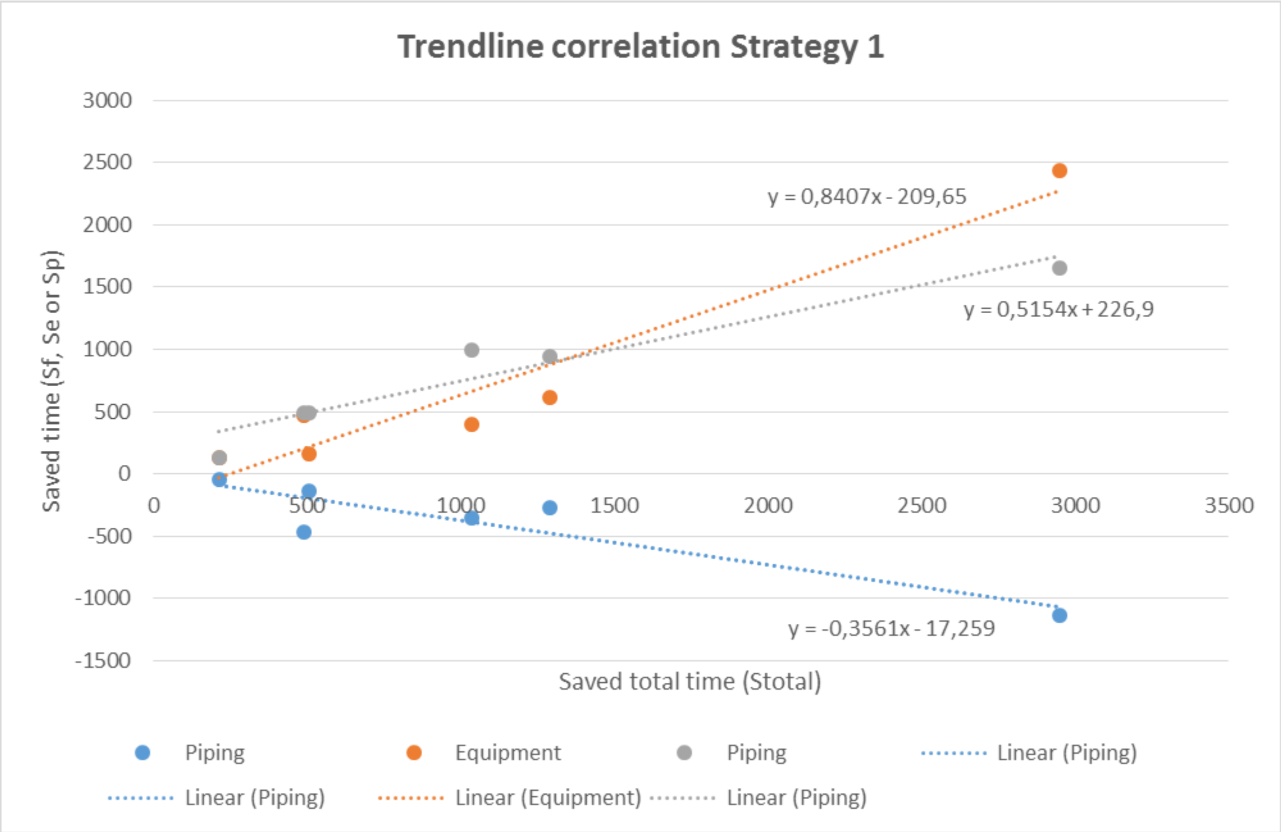


Figure 34: Trend line correlation for strategy 1

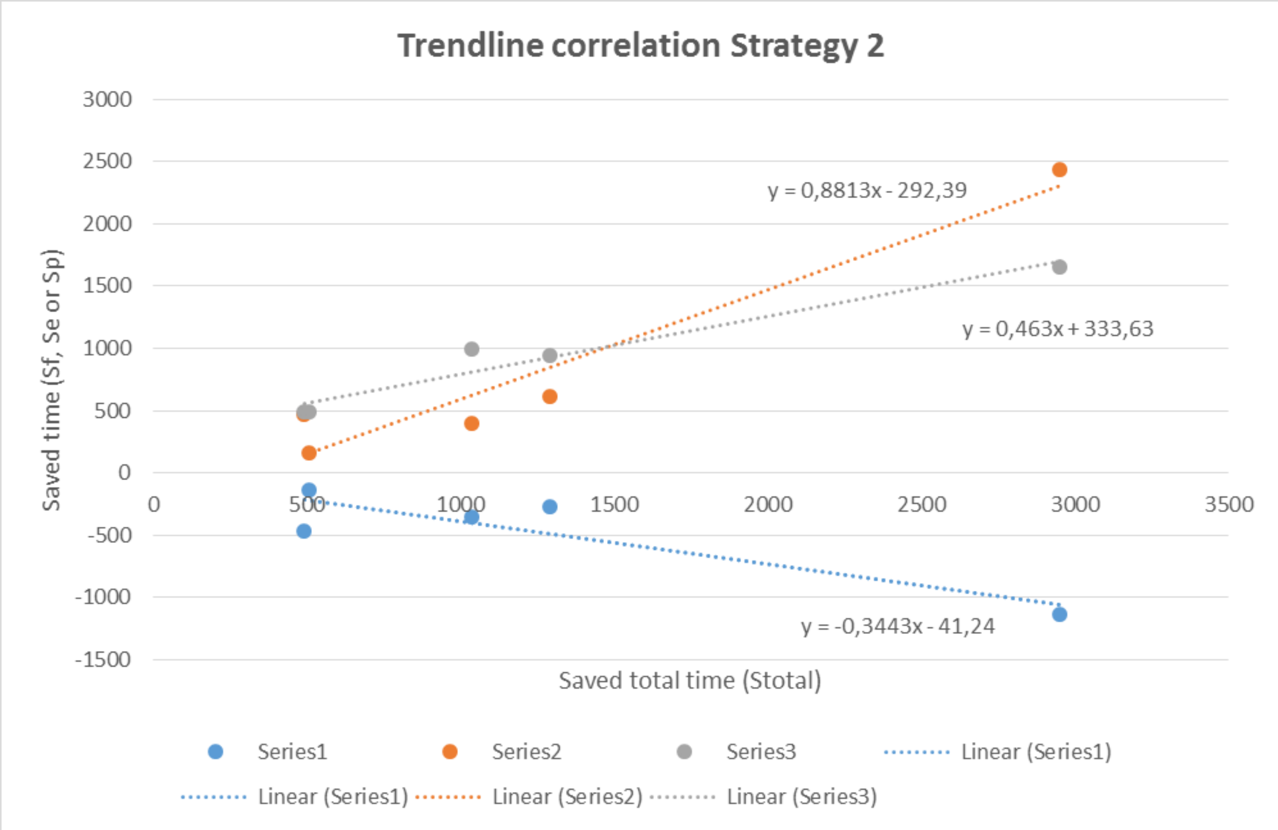


Figure 35: Trend line correlation for strategy 2

Using the trend line equations to generate the equation, again the total saved time is distributed over the foundation, equipment and piping. The result is compared with the initial case distribution and the deviation in percentages are calculated. The mean value and the standard deviation of these are calculated for the foundation, equipment and piping as shown in Table 21.

Table 21: Mean and Std. dev. for both strategies

Strategy		**Foundation**	**Equipment**	**Piping**
1	**Mean**	27	-7	21
	Standard dev.	57.0	71.8	66.0
2	**Mean**	17	3	3
	Standard dev.	52.4	49.0	13.9

Appendix E: Production model design