Advanced modular system assembly

A case study in the Dutch superyacht industry

Master thesis report
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An advanced modular system assembly strategy for complex-shipbuilding

A case study in the Dutch super yacht industry

By
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Preface

Dear reader,

This master thesis is conducted in order to obtain a master's degree in Marine Technology at Delft University of Technology. I was able to perform my research at and in close collaboration with Royal Van Lent Shipyard, a renown Dutch superyacht manufacturer. The guidance of my supervisors of the TU Delft from a theoretical perspective and the assistance of many employees at Royal Van Lent Shipyard for the practical aspects were of great importance for me and my research. Employees from many departments took plenty of time to share their rich experience in shipbuilding in order to help me with by graduation research. There was a lot of genuine interest from Royal Van Lent Shipyard in my research and they are already taking measures to implement some of the results. Altogether it was an amazing and educational experience.

I would like to express my gratitude towards Royal Van Lent Shipyard to be able to conduct my graduation research with them. In particular, I want to thank Wilma van Rijn for supervising me for the past nine months. Besides Wilma, I want to thank Jeroen Kortenoeven for inviting me to management meetings which related to my research. Last but not least, I want to thank Ton Spruit for sharing the experience he gained in the building of over 90 yachts for Royal Van Lent Shipyard. All my practical questions could be answered by someone at Royal Van Lent Shipyard.

For the theoretical and academic aspects, I could get support at the TU Delft. My research has affection with shipbuilding, but also with process optimization. Dr. Ir. J.M.G. Coenen was my supervisor for the shipbuilding aspects in my thesis. Her academic career in combination with her practical experience from many shipbuilding companies and her willingness to share this with me was helpful. Dr. W.W.A. Beelaerts van Blokland was my daily supervisor. He helped me to maintain a helicopter view over the project and to dissociate my research from the general shipbuilding practices. The experience Dr. W.W.A. Beelaerts van Blokland has in the automotive, aerospace and in the lean practices were key for my research. I Would like to thank them for the assistance with my graduation.

Lastly, I would like to thank my family for supporting me during my nine month graduation research period. In particular I would like to thank my father with whom I could discuss practices in the oil & gas construction industry, where modular construction is common practice.

Please enjoy reading,

M. Schoonhoven
Delft, August 2018

Summary

The demand for super yachts is high, only a number of shipyards are participating in this expanding market. The core production process in complex-shipbuilding are the outfit activities Since the steel construction becomes less important in comparison with the outfit activities, substantial gains can be achieved in optimizing the outfit process. The length of the yachts is increasing, more man hours are used to complete the yacht. A significant increase in Time-To-Market is not accepted by the customers. There is a need for optimization in the production process of super yachts. A significant improvement in the assembly process of cars is established with a modular strategy. This strategy was evolved from various optimizations of the Toyota Production System. Besides the car manufacturing industry, modularization has improved the production process of aircraft manufacturing. A modular outfit strategy might be effective for the shipbuilding and more specific the super yacht assembly process as well. The next paragraph elaborates on the differences between conventional shipbuilding and super yacht building at RVLS.

The production of a super yacht has many similarities with conventional shipbuilding. roughly the same phases in the engineering process were found. The names of the phases is different, the overall content is practically equivalent. The hull construction both start with panel construction, then section assembly. In the standard process was pre-outfitting mentioned, this strategy is not used by RVLS (yet). The blocks in a standard process are painted before the erection section, this cannot and is not done at RVLS due to the straightening (Dutch: strekken) of the hull. In both processes takes the outfit process place after the block erection. In the RVLS process the yacht is painted just before the launch at the hull production yard. In the standard process the ship is launched and then the final outfit activities are done at the ship along a quay. After the launch in the RVLS process the ship is transported to the yard in Amsterdam where the outfitting is finished and the interior is installed. The outside of the hull is painted several times, the yacht is launched for a second time and the final outfitting and testing is done along a quay. The next paragraph further reviews the modular strategies in other industries.

Modular assembly a branch developed form the Lean theory. Ford introduced the moving assembly line, this was optimized by Toyota to the Toyota Production System (TPS). This strategy was researched by MIT and named Lean Manufacturing. Lean has been question to be applicable in different industries than the car manufacturing industry. The super yacht industry may even be in an advantage, since the it is close the lean ideal of single piece flow, Built-To-Order (BTO). Another market which is BTO is the aircraft manufacturing industry. Suppliers in the aircraft manufacturing industry are involved in the co-development and production of entire functions of the aeroplane, The core competency of the Large Scale Systems Integrator like Boeing is the integration of these systems. It should be aimed for to minimize the complexity of this integration in order to make co-innovation possible. In the current aerospace market the driving factor for success or failure is the network a company operates in. Lean has proven itself in the car manufacturing and the aerospace manufacturing industries. It should be aimed for in the super yacht system assembly to reduce to complexity to make it possible to design effective modules. These modules can optimize the assembly process, this can lead to a better value flow for RVLS, the LSSI. Moreover, Further improvement can be achieved when using a design for assembly approach.

The three effects are expected due to modularization and design for assembly. The first order of effect is the on-board assembly complexity. The number of components are analysed and lead to the System Coupling Level Index for shipbuilding, this is used to measure this complexity of the on-board assembly complexity. It is expected that this reduced complexity will result in a reduced Human Effort on-board. The second order of effect is the time-value shift. The value shift towards the supply chain i.e. co-production, which can be measured the

Production Multiplier. It is expected that the supplier can assemble the module more efficient than the LSSI on-board. This efficiency increase will result in a higher Gross Margin for the LSSI. The time effect can be explained as followed: the number of people in the engine room is limited, the human effort on-board will decrease due to modularization, the engine room can be completed earlier. This effect expresses itself in the Time-To-Market. Moreover, the lead time for the module will be longer in comparison with the current situation. It should be aimed for to postpone the procurement, thus the placement of equipment. Another benefit of this would be that the risk of damaging equipment will reduce. This effect could be expressed with the idle time of equipment, the moment of placement until the commissioning.

The System Coupling Level index should be minizmized by reducing the number of components to be installed on-boar. The human effort will move from on board to a workshop, which will likely result in a lower human effort overall. The modules are outsourced since the production of these modules is not a core competency of RVLS. It is expected that the Gross Margin for the yard will increase. Moreover, due to the a lower on-board necessary human effort this can exploited to reduce the Time-To-Market. Different assembly strategies should be design to postpone the placement of equipment in the engine room. The current design of the fuel oil systems should be optimized in terms of assemblability. This can be done by reducing the interface complexity according to the SCLI, by reducing the number of components to be installed on-board. It is expected that the effect mentioned earlier this paragraph will be further positively affected.

The modules which are determined are closely related to the corresponding system. Many components could be installed in a workshop in the module, instead of on-board assembly. This could reduce the complexity of on-board assembly process significantly. This effect is observed in the human effort necessary for the on-board assembly of the systems. In the current process, a lot of work needs to be done on-board, thus the human effort directly results in the time-to-market for the engine room. The engine room is the most critical technical room in the yacht. The modular approach can reduce the outfit, and commisioning with 19 weeks, thus the yacht could be delivered earlier from an engine room perspective. It should be noted that the interior and paiting also play an important role in the entire process, this should be done in a shorted time as well. Due to the shift from on-board to a workshop, the LSSI is enabled to outsource the production of these modules since this is not a core competence. The production multiplier is increased due to the shift to the supply chain. This increase in outsourcing results in a higher gross margin for the yacht, since the bits and pieces i.e. valves, appendices, and sensors can be installed much more efficient in a workshop. The redesign of the fuel oil system predominantly concerns the way of transferring fuel between the unit in the engine room and the bunker tanks. This used to be done with a manifold in the engine room, this resulted in nine pipes from all tanks to the engine room. The future state uses a feed-return pipeline with branches close to the designtated tank. This drastically reduced the complexity, and the piping and thus further reduced the human effort. The Production Multiplier rose, hence the Gross Margin.

It can be seen that the modularization drastically reduces the on-board complexity. This effect can be seen in on-board necessary human effort. The shift from on-board to suppliers has a value-time effects on the system assembly process. The Production Multiplier can be increased, hence the Gross Margin. The Time-To-Market can be shortened with 19 weeks. A different machinery install strategy should be used to postpone the installment of equipment. Altogether all KPIs (used in this preliminary model) are positively affected by the modularization. The fuel oil system is redesigned with an design for assembly approach. The complexity could be further reduced which reduced the human effort even more. The redesign substantialy reduced the piping in the system, this is the main factor of the significant reduced human effort. The Production Multiplier, and Gross Marging are increased in comparison with the modular system, and even more in comparison with the current state of the fuel oil system. Thus, the modularization of systems should be aimed for at RVLS. The redesign of the system, design for assembly, should be aimed for. The method is beneficial for one yacht. Howover, when the standaridzed units can be used in multiple yacht the effects will even be more significant.

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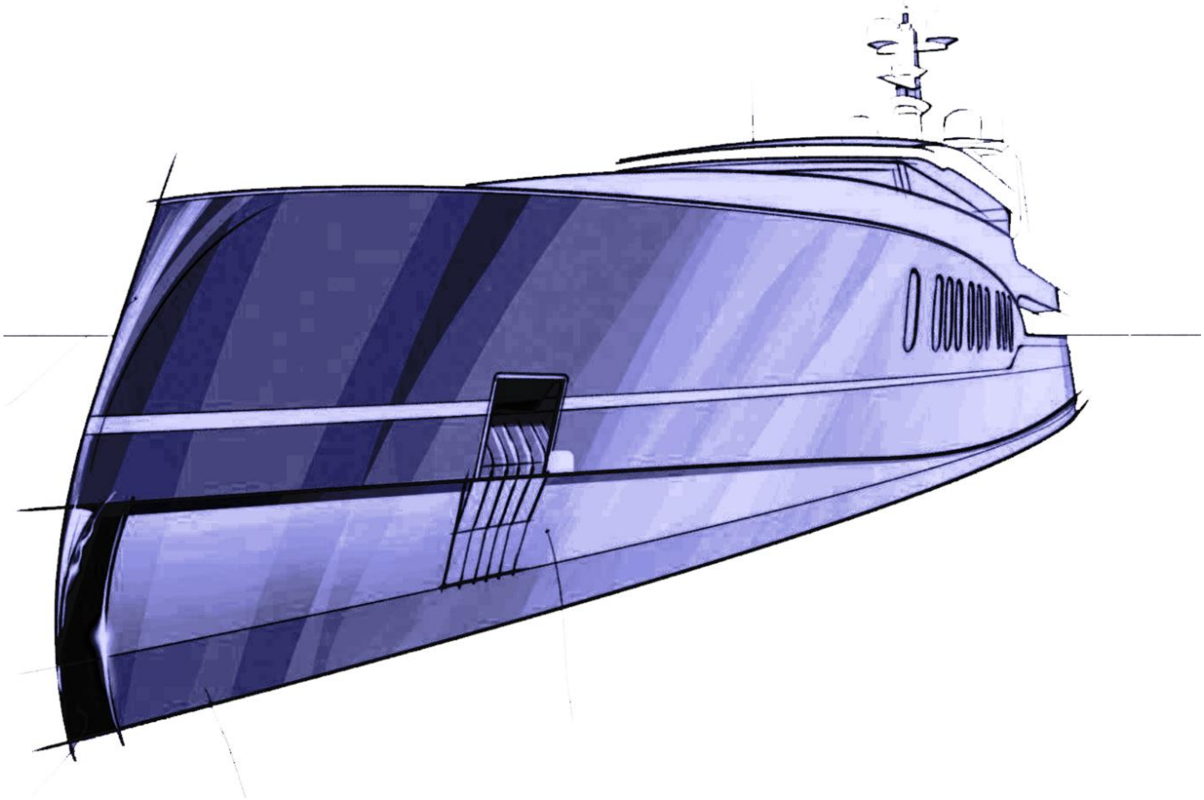
List of abbreviations

Abbreviation	Meaning
AC	Air-Conditioning
BF	On-block factor
BGWS	Black & Grey Water System
BET	Break Even Time
BWS	Bilge Water System
CA	Customer Attributes
CE	Concurrent Engineering
DRIFT	Do it Right the First Time
DVNA	De Voogt Naval Architects
DWS	Domestic Water System
ETO	Engineer To Order
EVM	Earning Value Management
FFS	Firefighting System
FOS	Fuel Oil System
HOQ	House Of Quality
HVAC	Heath, Ventilation & Air-Conditioning
IMP	Investment Multiplier
JIT	Just In Time
KDVS	Koninklijke De Vries Scheepsbouw
LOS	Lubrication Oil System
LPP	Lean Project Planning
LSSI	Large Scale Systems Integrator
MS	Market Share
OEM	Original Equipment Manufacturer
OF	On-board Factor
PMP	Production Multiplier
QFD	Quality Function Deployment
RVLS	Royal Van Lent Shipyard
SCLI	System Coupling Level Index
SWS	Sea Water System
TEI	Total Existing Interfaces
TM	Possible level of modular outfitting
TPI	Total Possible Interfaces
TTM	Time To Market
TPS	Toyota Production System
TR	Technical Requirements
UF	On-unit Factor
VSM	Value Stream Mapping
WIP	Work In Progress

I

DEFINE



1. Introduction

The first chapter of this thesis introduces the topic of this research, an advanced modular system assembly approach for superyacht building. The first section will elaborate on the problem identification by describing the current state of the company. Once the problem is made clear, challenges arise from this problem. These challenges are reviewed and stated in the second section on the research objectives. It will not be possible to solve all challenges in the timeframe of a graduation project. Therefore, it is important to define the scope of this research, which is given in section three. The fourth part of the introduction presents the sub-research questions. Chapter 1.5 explains the research design used to solve the research objectives.

1.1 Research context and field

In order to be able to identify the problem, a description of the company and the market where the company operates in is given. Feadship is a worldwide player in the design, and production of luxury super yachts. Every yacht is uniquely designed, and built according to the specific wishes of the customer. Each new Feadship is an innovation itself, since Feadship constantly strives to redefine the perception of perfection. Every Feadship is better than the last one in terms of construction, and technology (Feadship, 2018).

More than 1800 employees work among different locations in the Netherlands. The employees are stationed at “Koninklijke De Vries Scheepsbouw” (KDVS), “Royal Van Lent Shipyard” (RVLS), the architectural firm “De Voogt Naval Architects” (DVNA), and numerous subsidiaries. This thesis is conducted at De Kaag, the location of the Royal Van Lent Shipyard since 1849. The shipyard provides work to 400+ fixed employees spread over multiple departments. The superyacht industry is an expanding global market where only a number of players are involved in. The shipyard acts as lead supplier, many suppliers are managed by a project manager for the final delivery of the superyacht (Leybourne, 2010). Since the demand for superyachts is high, it is favourable for Royal Van Lent Shipyard to increase the production at the yard while profit is made.

In order to cope with the demand of custom super yachts, RVLS is expanding their production facilities. Currently there are two dry-docks, and two (smaller) slipways available to build the yachts. Through the construction of a third dry-dock at a new location in Amsterdam, the number of building slots increases. An additional change for the yard is an increase in feasible building length of up to 160m, the largest yacht currently built at the RVLS is “merely” 101.5m. If the size of the yacht increases, the total labour necessary to complete the yacht also increases. It is not accepted by the customers of RVLS that the building of the yacht takes significantly longer. The increase in length of the yachts combined with the extra production facility brings along production challenges. An optimization of the current production process at the RVLS is required. The necessity for optimization is also recognized by the management of the shipyard. Effort is has already been made in the optimization of the production processes.

First of all, an engineering department has emerged at the yard. In the old situation, the yard would contact the Naval Architect, and they would thereafter contact an engineering firm to execute the detailed engineering process. This long route of information transfer did not positively contribute to a short model development time. In the current situation, (lead-) engineers are positioned at the yard. This change has numerous benefits. The first benefit is that Royal Van Lent has more control on the engineering process, which makes it possible to finish the design, and engineering process earlier, and thus reduce the overall Time-To-Market (TTM). Another benefit is the communication between engineers, and production workers. In an early stage, the experience of foremen can be used. This will reduce the complexity of the production, improve the efficiency of production, and reduce the amount of rework.

The second change made in the organization is the rise of a supply chain management (SCM) department. In the old situation, procurement of equipment used to be done by the project management, however, due to their tight schedule insufficient effort was put into this in order to make an efficient production process feasible. The SCM department makes it possible to have a better supply chain structure with suppliers. Hence, it is possible to achieve a better production process. Further elaboration on the importance of SCM is given in the literature review in chapter 2.5.

Thirdly, customer management is key for an efficient yacht building process. The philosophy of Feadship is "Carte Blanche", which means: "starting from a blank sheet, and the assumption that everything is possible." Starting from a blank sheet, and close collaboration with the owner makes the first memory of the Feadship experience the actual building process itself (Feadship, 2018). The aforementioned philosophy is stated to emphasize the market Feadship operates in. The philosophy of Feadship makes it of utmost importance to convert the customers' wishes into technical design requirements (Park & Kwang-Jae, 1998). The management of the customer is a continual process of optimization at van Lent, since the customer management aspect in the yacht production process is crucial in the total efficiency of the production process. RVLS has introduced a toll gating concept for a better customer management process, this concept is maintained by the project management. It is of utmost importance to determine where the priority of the customer lies and how these used to optimize the production process.

To summarize, RVLS is increasing the production capacity through the construction of a new yard. The extra yard in combination with the larger yachts will require a better production process. Effort has been made by RVLS in the engineering, supply chain management and customer management phases in order to achieve a better production process. However, challenges still remain, the challenges are presented in the next section.

1.2 Research objectives

The three above mentioned changes can serve as a foundation for an improvement strategy in the production process at Royal Van Lent Shipyard. All three changes improve the quality and the timeliness of information, the start of an efficient production process. The next step is to develop a strategy for improvement in the production of super yachts.

The core production process within complex shipbuilding is the outfitting of the ship (Costa, 2012). Outfitting tasks include placement of pipes, cable trays, ducts, equipment, and installing insulation. Up to 70% of a modern complex ship's value comes from outfitting processes (LeaderSHIP 2020, 2013). The current outfitting at the yard is based upon large scale outfitting works performed during the building berth stage or when the ship is in a dry-dock. Ventilation ducts, pipe spools, cable trays, foundations etc. are fabricated in internal, and external workshops. The components are sent to the outfitting location on large pallets, followed up by the installation. Since the steel construction becomes less important in comparison with the outfitting activities for complex ships, substantial gains can be achieved in optimizing the outfitting activities (Rose, 2017).

Various other industries have faced similar challenges in optimizing production processes. Examples of these industries are the car manufacturing industry, the aerospace industry, and the shipbuilding industry in general. The development of optimized production processes in these sectors might offer solutions for outfit process in superyacht building even though there are (major) differences in the processes. In the beginning of the 20th century, the assembly line was introduced by Henry Ford in the car manufacturing industry. Various other optimization programs in the following years have been conducted in this industry, including the Lean principles. In the aircraft manufacturing industry improvement has been established by using these same Lean strategies. A key principle of Lean is continuous flow in a production process. The use of "building blocks" or "modules" is derived from this continuous flow. The method is used in the aircraft industry, car manufacturing industry, the shipbuilding industry, and many more. The author of this paper thinks further improvement is possible in the production process of superyachts by using these Lean principles, more specifically the use of modular system assemblies produced in workshops.

The current production process is not optimized for a modular system assembly strategy. The pieces of equipment are placed via building hatches or doors, this results in little movement space for the relatively large modules in a section. Therefore it is currently favoured by the production departments to install relatively small modules in the outfit phase. The challenge is to develop a production strategy where the advantages of large modules can be exploited. This thesis is aimed at the development, and quantification of the effects of a modular system assembly strategy.

1.3 Problem definition and scope

Up until now, no quantitative data are available on the effect of applying modular system assembly strategies in ETO-shipbuilding. But the results in Nieuwenhuis (2013) are promising in the sense that an approach is feasible from a design perspective, this sugeests that advantages could achieved for the production process.

The first step in this research is to analyse the current design of the systems and determine what can be pre-assembled in a workshop. This is done to make the assembly process inside the ship less complex and less time consuming. A measure should be sought to quantify the current complexity of the assembly process. Thereafter, the on-board assembly complexity should be minimized.

The second objective concerns the outsourcing of pre-assembled. Since the modules can be built in a workshop it is possible to outsource the modules to suppliers who are specialised in such systems. For example Rolls-Royce is specialized in the production of turbine engines for the Boeing 787. The goal is to find the best supply chain strategy. Due to the shift towards the supply chain it will likely result in longer delivery times for the equipment. Moreover, the longer the equipment is in the crowded engine room it is likely to be damaged. A different machinery instalment strategy might be better than the current strategy. Measures should be sought to quantify the current process, the new process should be designed to be better.

The last topic in this research concerns the design of the system. A modular system assembly strategy with the current design is likely to be beneficial. However, if the system is designed for easy assembly in the engine room, the results could be further elevated. It should be made clear what the definition of design for assembly is and how this can be used in shipbuilding. Moreover, the effects should be quantified, the differences between the current design, the modular strategy, design for assembly strategy should be made clear. A redesign of all systems would be too much work for a master thesis, one suitable system is redesigned instead.

The scope of the research has been given above, the consecutive step is to present the developed main research question:

To which extent can an advanced modular system assembly strategy improve the current ship building process?

1.4 Research questions

The following sub-research question are developed to answer the main research question:

1. *How does the production process at RVLS relate to a conventional shipbuilding process?*

2. *What can be learned from other industries from a modular perspective in order to optimize the assembly process of systems in a super yacht?*

3. *What research lacks for an effective modular strategy in the ETO-shipbuilding?*

4. *What are the Key Performance Indicators for the system assembly process?*

5. *What are the Key Performance Indicators for an effective modular design in terms of assemblability?*

6. *What is the current performance of the system assembly process?*

7. *What can be learned from the current state of the assembly process in the engine room?*

8. *What can be learned from the current state of the fuel oil system design in terms of assemblability?*

9. *What system modules can be determined and what is the effect on the assembly processs?*

10. *What value time effects can be exploited due to modularization?*

11. *How should a system be designed for an efficient on-board assembly process?*

12. *What system installment process should be aimed for by the shipyard?*

1.5 Research design

It is clear by now that this research has a strong relation with process optimization. The structure of this thesis is adopted from a renowned project management strategy, namely Six Sigma. The strategy is aimed at process optimization. Six Sigma is a management strategy originally developed by Motorola in 1986. The strategy is developed in order to optimize processes by reducing the variation in a process. DMAIC is a project methodology within Six Sigma, used for optimizing existing processes. The Six Sigma strategy also offers a methodology for product design (DMADV) with the reduction of defects as goal (Pzydek & Keller, 2014). This method has far more potential than DMAIC, since it is used in an early stage of product development (Thakore, Dave, Parsana, & Solanki, 2014). The structure used in this thesis is a combination of the above mentioned methods, this result in the method DMADE (Design, Measure, Analyse, Design, Evaluate). The structure is already used in the development of a Lean business process by Beelaerts et al. (2008). An brief elaboration on each phase is given below. Thereafter, the phases are related to the corresponding chapters in Table 1-1.

***D**efine*

The define section is the introduction, and the method. This section identifies, defines the problem, and provides a literature review. The last sub-chapter of the literature review provides the literature gap which this research aims to reduce. The chapter 2.2 provides a future model to measure the performance of the system assembly process.

***M**easure*

This section assesses the current performance according to the Key Performance Indicators, developed in chapter 3. A case study at the yard is used to find the current performance of the process. A elaboration is given later this chapter. First, the current complexity of the assembly process is given. Second, the supply chain strategy is analysed. Third the current strategy to install machinery is assessed. Fourth, the current design in assessed in terms of assemblability.

***A**nalyse*

The performance indicators and the current state have been determined. The next step is to analyse the data and determine what are the bottlenecks in the current process. The goal of analysis phase is to ensure enough knowledge is obtained to not waste any time in the design phase.

***D**esign*

The first part of this section is devoted to the new design of the engine room system assembly process. The knowledge gathered in the analysis section is used to design a better process. The second part is the design optimization of a system.

***E**valuate*

This phase consists of several sections. The first section is the performance assessment of the newly designed process. The second step concerns the conclusion of the research. The sub-research question are answered and will lead to an answer to the main research question. Thereafter are the recommendations given, for RVLS, and for future academic research. The last chapter of this section is the discussion.

Tabel 1-1 an overview of the structure in this report

DMADE Stage	Chapter	Sub-research question(s)	Source
Define	Introduction		Literature
	Literature Review	1, 2 & 3	Literature
	Preliminary future model	4 & 5	Litearture
Measure	Current state performance	6	Case study
Analysis	Assembly process complexity	7	Case study
	Value time effect	7	Case study
	Design optimization	8	Case study
Design	Module design	9	Case study
	Engine room assembly design	10	Case study
	Fuel oil system design	11	Case study
Evaluate	Performance assessment	12	Case study
	Conclusion		Case study
	Recommendations		Case study
	Discussion		Case study

The structure of the thesis is given above and related to the SRQ's, the next step is to determine the casestudy boundaries of this thesis in order to answer the main research question and test the developed method.

Casestudy description

The first decision to be made is the ship that is used for the case study. The phylosophy of Feadship is a one of a kind superyacht, however there are many similarities in the technical systems on board a yacht. The aim should be on a specific yacht which is representable for a generic technical system arrangement for a Feadship. The modular system assembly strategy can be used for all technical rooms, however the focus in this thesis is on one, the most complex one. The section selection is elaborated on. Lastly a system is needed for the redesign for the sake of assemblability as the last step in this thesis.

Yacht selection
The yacht used in this study is BN816, the engine room configuration is representable for a "standard" feadship. As mentioned in the introduction, the engineering department has changed a lot since a year. BN816 is the first yacht engineered by this department, therefore much information is available in a CAD environment which makes information provision less complex.

Section selection
The section that should be explored should be the one with the highest modularization potential. Many of the systems in the yacht are in the engine room, the engine room is critical in both labour hours, and is on the critical path of the building process. These three reasons indicate a high modularization potential, and is therefore chosen in this case study. This is confirmed by the research of Fafandjel et al. (2008) who state that the engine room has the highest modularization potential for modular system assemblies for various types of ships, since most of the systems are in the engine room.

System selection
The modularization of systems are influenced by the following aspects. First of all, the cost of labour that is used to assemble the systems. A cost of labour reduction for the assembly of the system should have a signification impact on the overal costs. Secondly, the system distribution must be reviewed. If the system is predominantly present in a single section e.g. the engine room it is easier to modularize than a system distributed over the entire ship. Thirdly, the potential to standardize should be taken into account. Since the focus in this study is on customer superyacht, systems can be one of a kind. Standardized modules offer a better solution if systems among different ships have similar customer requirements. In terms of costs of labour, distribution on board, standardization potential, and current state of the systems, the fuel oil system is chosen. An overview of the system determination is given in Appendix I.

Yacht	-	BN816
Section	-	Engine Room
System	-	Fuel oil system

2. Method

This chapter provides a theoretical analysis of the research question. The theoretical background is sought by answering sub-research questions 1, 2 & 3. This theoretical framework will result in a preliminary model.

2.1 Literature Review

Sub research questions:

1. *How does the production process at RVLS relate to a conventional shipbuilding process?*

2. *What can be learned from other industries from a modular perspective in order to optimize the assembly process of systems in a super yacht?*

3. *What research lacks for an effective modular strategy in the ETO-shipbuilding?*

First of all, a description of a generic shipbuilding process is given, and compared to the shipbuilding process at RVLS in chapter 2.1. This sub-chapter includes an elaboration on the necessity for optimization in the outfitting process. In the second sub-chapter various optimization strategies are given, many of these strategies originate from the car manufacturing industry. The strategies are given since these might offer solutions in the shipbuilding process. On first sight this might not be logical since the produced volumes are immensely different, however these car manufacturing strategies. A strategy resulting from these improvement methodologies is the modular strategy. Chapter 2.3 presents the literature behind a modular strategy. A modular strategy has a strong connection with the supply chain network of the company. Supply chain strategies related to a modular strategy are given in chapter 2.4. The fifth sub-chapter elaborates on the topic design for assembly (DFA). Design for assembly incorporates the assembly ease in the design of the system, modularization and DFA can further improve the assembly process of the systems in the engine room. The aerospace in a more advanced stadium in terms of modular assembly than super yacht building. The differences are discussed, and the valuable lessons from the aerospace manufacturing industry are given. In the seventh subchapter, a current state-of-the art on modular shipbuilding is given, providing a start for the development of the new method. In chapter 2.8 is the literature gap given which thereafter results in the preliminary method (chapter 3).

2.1.1	Conventional shipbuilding	SRQ 1
2.1.2	Improvement methodologies	SRQ 2
2.1.3	Modularization strategies	SRQ 2
2.1.4	Supply chain management	SRQ 2
2.1.5	Design for assembly	SRQ 2
2.1.6	Modular aircraft manufacturing	SRQ 2
2.1.7	Modular shipbuilding	SRQ 2
2.1.8	Literature gap	SRQ 3

2.1.1 Conventional Shipbuilding

The emphasis in this thesis is on the outfitting process, this process has important relations with other stages in the shipbuilding process. Therefore, the first thing that should be explained is the process of building ship. Three main groups within the ship production process can be identified, Hull (structural body), outfit, and painting (Storch & Lim, 1999). In the super yacht production, interior can be seen as a main group as well, however the engine room is not affected by the interior process, therefore not elaborated on. A standard building process is obtained from literature (Rose, 2017) and is related to the building process at RVLS. A general concept of both processes is given in the Table X-X. A more comprehensive structure of the shipbuilding value chain can be found in Koenig & Kuegelgen (1999). Once the process is clear, the need for optimization is elaborated on.

Design & Engineering

The design and engineering process is the specification of a ship to meet the desired needs of the customer. It is an iterative decision-making process, where the basic science, mathematics, and engineering sciences are applied to optimally convert resources used for meeting the stated objective (University of Nevada, Las Vegas, 2018).

- The basic design or design development is a phase where the yard, owner, co-makers etc. define the requirements, capabilities, and expectations of the ship. A preliminary 3D model of the hull structures is developed. The technical, and layout issues are finalized in the basic design.
- In the function design or final design 1 phase, the systems are schematically defined. These diagrams are used to create a materials list, get the owner's approval, and obtain class approval.
- The transition design or final design 2 phase is a combination of geometric modelling, and engineering. It helps to generate digital models in the early design cycle. The models can be continually validated for form, fit, and function.
- The detailed engineering phase is the development of a high detailed integrated 3D model, including: construction, piping, equipment, interior. The model should include information sufficient for the work planner to make worklist, and purchase material.
- The work instruction design makes the ship design suitable for production. Construction drawings are produced. At RVLS the work instructions are made by the production department. Material is purchased by the procurement department.

Hull construction

The construction phase in the shipbuilding process concerns the building of the hull. A brief description of the construction process is given below.

- The panels are produced during the panel construction phase. The panels consist of welded steel plates, and various kinds of stiffeners as can be seen in Figure 2-2
- During the section assembly, the panels are combined to form sections.
- These sections are thereafter combined to form building blocks.
- The building blocks are then combined to form the hull of the ship. (Figure 2-1)

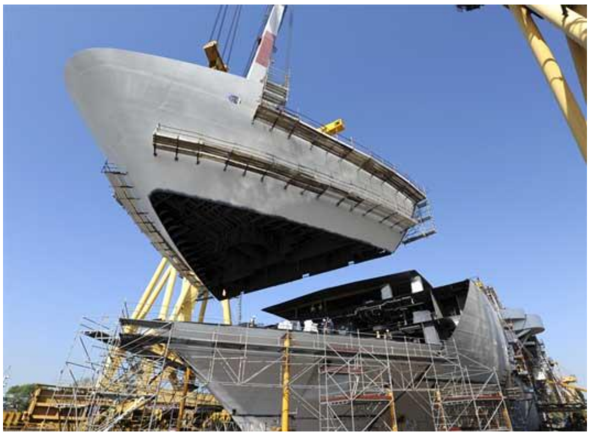


Figure 2-1 Block erection during the construction of a cruise ship

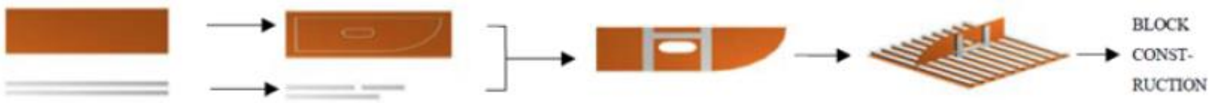


Figure 2-2 Panel construction

Outfitting

The main characteristics of the outfitting process are further described in this sub-chapter. Clear phases do exist in the design, engineering and hull construction phase, this is not the case for the outfit processes. The activities listed below are categorized as outfit activities. It will later be explained why there is no clear process for the outfit activities.

- Piping
- HVAC ducting
- Cable trays
- Foundations, supports & drip trays
- Floors
- Installations & commissioning of equipment

Outfitting activities can take place during the construction of the sections, this is called pre-outfitting. These building blocks are erected to form the hull. From this point outfitting work is called slipway or dry-dock outfitting. When the building block erection is completed, the hull is painted, and then launched. It should be noted that pre-outfitting does not happen at RVLS yet. The yacht is then transported to De Kaag to finish the outfitting activities, and completion of the building process. Outfitting done during the (partly) assembled hull is not efficient. The workers have to move to the dry-dock or slipway with their tools. Welding machines have to be lifted on-board with a crane. Moreover, the work conditions are not optimal due to difficult access, limited space and difficult working positions for example overhead welding. Besides the low efficiency, the congested workplace can result in hazardous conditions. This can be seen on the right side of Figure 2-3. The outfitting process is briefly described above. The next section addresses the painting of the yacht.

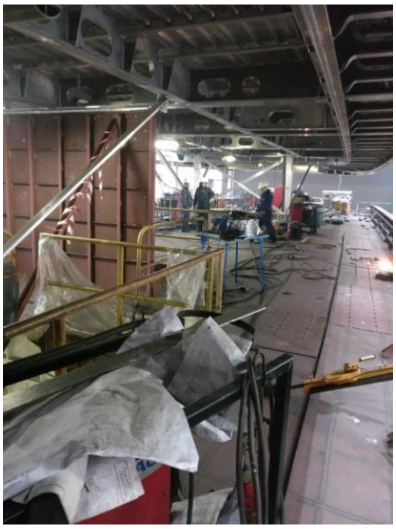


Figure 2-3 pre-outfit (left), and dry-dock outfit (right)

Painting

The paint process of a yacht and a conventional ship is different, and will be discussed in this section. In conventional shipbuilding the pre-outfitted sections can be painted prior to block erection. During the outfitting on-board, two types of painting take place: final painting of compartments and the painting of the outside of the ship before launching.

The painting process at RVLS is more complex. Painting during pre-outfit does not happen. During the erection of the sections, the sections will deform due to the welding. In order to make a hull within the tolerances of RVLS it is necessary to straighten the hull. A picture of the hull straightening can be seen in Figure 2-4. Due to the straightening it is not possible to paint the sections in the pre-outfit process.

The first layer of paint on the hull is applied just prior to the launch of the yacht at the casco yard (Figure 2-5). Once the ship has arrived at De Kaag, the hull of the yacht is faired (to ensure a smooth surface within the pre-defined tolerances. Afterwards, up to seven layer are applied to the hull.

Figure 2-4

Figure 2-5

Table 2-1

	Standard process	RVLS process
1	Basic design	Design development
2	Functional design	Final design 1
3	Transition design	Final design 2
4	Work instruction design	Work preparation & detailed engineering
5	Panel construction (a)	Panel construction
6	Section assembly (b)	Section assembly
7	Pre-outfitting (c)	-
8	Painting (d)	-
9	Block building (e)	Block building
10	Block erection (f)	Block erection
11	Slipway outfitting (g)	Slipway outfitting (at hull production yard)
12	-	Painting phase 1
13	Launch (h)	Launch at hull production yard
14	Quay outfitting (i)	Dry dock outfitting
15	-	Painting phase 2
16	-	Launch
17	-	Mast erection
18	-	Quay outfitting

Sub research conclusion:

1. *How does the production process at RVLS relate to a conventional shipbuilding process?*

To summarize, the design and engineering process are similar to a general ETO ship. The outfit activities and painting differ more for super yacht building and general ETO ship building. The outfit does not happen in a pre-outfit phase, and due to the straightening the sections cannot be painted during the pre-outfit phase. Moreover, the quality for the final paint layer is much higher, the number of paint layers is therefore higher. The painting process is more dominant in super yacht building than in conventional shipbuilding. The two processes are related to each other in Table 2-1, and visualized in Figure 2-6. The current process is clear, the next objective is to determine the drivers to optimize the process, this will be discussed in the next section.

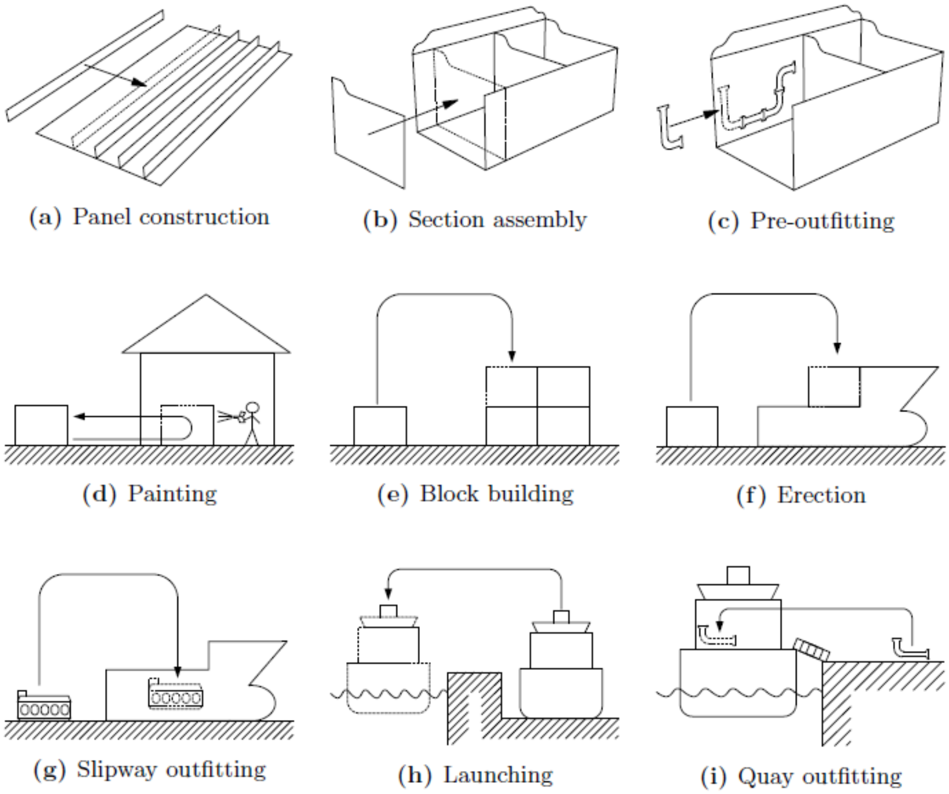


Figure 2-6 Schematic representation of the production of a conventional ship (Wei & Nienhuis, 2012)

Drivers for optimization in the outfit assembly process

It is important to understand the need for optimization in the outfitting process in complex ship building. As aforementioned the outfitting process makes up a substantial part of work in the entire production process, reducing the waste in this process therefore can have a major impact on the entire process. Three main drivers for the optimization of the production process in the superyacht industry are identified and given below.

The first one is shortening the TTM. Superyachts at RVLS are completely bespoke. The market demand for this category of superyachts is growing to the extent that only a few building slots are available in the next few years (Leybourne, 2010). Due to the high demand for these kinds of custom superyachts, and the limited number of buildings slots, it is important to shorten the TTM to gain a competitive advantage. Modular outfitting of technical systems can offer a reduction in the TTM.

The second driver is cost reduction, an inefficient production process leads to high production costs, and minimizes the profit for the yard. Lean teaches us about added value, customers are not willing to pay for waste in a process. An improvement in the production process can increase the profit of the shipyard (Fafandjel, Rubesa, & Mrakovcic, 2008). The costs can be divided in cost for human effort and the investment costs (Yu & Ishida, 2001).

The third reason for optimization in the ship production process is a technical one. The size of the superyachts tends to increase the coming years. Feadship strives for the same quality applicable in today's smaller yachts to be accomplished in the larger yachts. Optimization of production processes is needed to make this vision possible to achieve. It is now clear why there is need for optimization of the assembly process of a super yacht. From conventional shipbuilding three relevant measures could be found

- Human effort (Yu & Ishida, 2001)
- Cost (Fafandjel, Rubesa, & Mrakovcic, 2008)

- Time-To-Market (Leybourne, 2010) & (Beelaerts van Blokland et al, 2008)

The next question is how optimization can be achieved. In the next subchapter an overview is given of the current literature of improvement methodologies which might offer an efficiency improvement in super yacht building.

2.1.2 Improvement Methodologies

The drivers for optimization in the outfit process for shipbuilding have been given in chapter 2.1. This chapter elaborates on the improvement methodologies related to modular assembly. Since many of the improvements (including modular strategies) in assembly processes originate from the lean philosophy, the key principles of lean are given. Lean originates from the car manufacturing industry, therefore the car manufacturing industry is related to shipbuilding and the bottlenecks and opportunities are given. The third paragraph elaborates on the possibilities and implications of Lean in shipbuilding. An improvement methodology closely related to modular outfit is Just In Time (JIT), the effects of JIT on the car manufacturing industry are given and the possibility of JIT in shipbuilding is given.

Toyota Production System

Starting at the roots, the Toyota Production System (TPS) is the best way to understand lean manufacturing. TPS was researched by Massachusetts Institute of Technology (MIT), and was named lean manufacturing in the 1990s (Beelaerts van Blokland, Santema, & Curran, 2010). The basic principles were set out with the moving assembly line by Henry Ford. The importance of creating continuous material flow, eliminating waste, and standardizing processes were preached by Ford (Liker & Lamb, 2002). Ford had built a system that was good for the large American market. However the market for the Japanese carmakers was different. Taiichi Ohno, a valued engineer at Toyota whose mission was to catch up with the American auto industry in three years lead to the Toyota Production System (TPS) (Murman, et al., 2002) A more comprehensive description of lean and other improvement methodologies can be found in Appendix II

Comparison car-manufacturing & shipbuilding

Clearly, shipbuilding differs from automotive production. In the automotive industry, every minute a car comes from the assembly line. In a superyacht shipyard this is in the order of months. Super yachts are engineer-to-order (ETO), and are highly customized. Cars are divided in models, customers can choose options to customize the car, the options are far more limited in terms of customization. Super yacht manufacturing, and car manufacturing are different, however giving customers what they want with shortened lead times by eliminating waste applies to any process (Liker & Lamb, 2002). The authors of the book, the machine that changed the world, a book about how lean production revolutionized the global car wars state: “The adoption of lean production inevitable spreads beyond the auto industry, will change everything in almost every industry – choices for consumers, the nature of work, the fortune of companies, and ultimately, the fate of nations” (Womack, Daniel, & Roos, 1990). It is therefore likely to offer solutions for super yacht building.

Lean in shipbuilding

Every shipyard across the world operates in their own manner, Japanese shipyards are in a more advanced stadium in terms of lean manufacturing than shipyards in Europe, and the United States. The Japanese shipyards use relatively standardized, modular designs, there is a constant flow of material, in most cases on moving lines (Liker & Lamb, 2002). These ships are different from the yachts made at Royal Van Lent Shipyard. In the Japanese shipyards a routine design is used, the production process can be optimized for this design. At Royal Van Lent Shipyard this is not the case, (almost) everything is custom. The interior is the most important aspect for the super yacht owner and should be completely bespoke. A fairly standard routine design could be used for the systems in the engine room and is the trend within the company. A dedicated module supplier is optimized for producing system A, and can therefore more effectively become lean. Through economies of Scale, the manufacturing costs per unit decreases (Tung, 1991) . The implementation of lean manufacturing in shipbuilding could shorten the TTM, and increase productivity with at least 50 percent (Liker & Lamb, 2002). The focus should be of eliminating the non-value added work. A general block production process is analysed. The waste as well as the value added activities are given in Figure 2-7. It can be seen that the waste contributes to a significant part of the entire duration. For a modular outfit assembly the time the equipment is idle in the engine room can be considered as a waste as well.

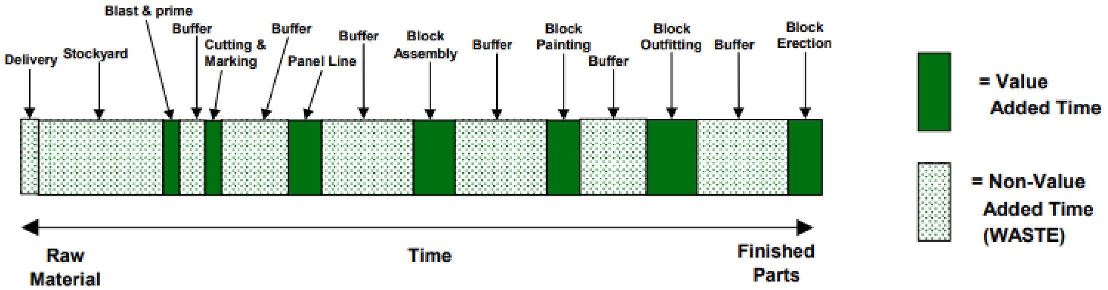


Figure 2-7 Elements of product lead-time

- Idle time of equipment in the engine room

Just-In-Time

Just In Time (JIT) is a production or management system created by the Toyota. In recent years, modular production is introduced in the production of automobiles. The modules are delivered JIT to the assembly factory. JIT encourages the suppliers to settle in areas around car assembly plants. This results in (1) reduced transportation costs, (2) easy exchange of information, (3) relationships of trust between customers and suppliers, and (4) specialized labour markets are and business-to-business networks are formed (Kaneko & Wataru, 2008). Most literature of JIT strategies in shipbuilding concern the panel construction (Phogat, 2013). The idea adapted from the car manufacturing industry is to let the modular system be delivered JIT in to the shipyard so it can be placed JIT on-board.

To summarize, the car manufacturing is in a far more advanced stadium in terms of process optimization. Theories like Lean, JIT, and many more have been developed and proven themselves over the years. It is argued by Liker & Lamb (2002) that Lean can eliminate at least 50% of the waste in shipbuilding. A collaboration with a supplier which is optimized in producing a certain module will result positively in reducing waste. For the shipyard it would be beneficial to send sub-assemblies or modules Just-in-Time to the outfit location. The next sub-chapter elaborates on the various modularization objectives and strategies and how effective modules can be made for shipbuilding.

2.1.3 Modularization

In this sub-chapter a method is developed to determine the building modules. Once the technical requirements are obtained, modules can be chosen accordingly. In broadest terms, modularity is an approach for efficient design, and production of complex products (Baldwin & Clark, 2004). Complex tasks are decomposed into simpler elements so that they can be managed independently, and yet operate together as a whole (Mikkola, 2003).

Background on modularization

Many industries use modularization strategies for example the computer hardware industry. Internal memory from brand A can be used with a motherboard from brand B. the interfaces between these modules are standard resulting in an almost infinite number of possible PC configurations. Also car manufacturers use modularization methods. It is recognized by skoda, and Volkswagen there is a need to move beyon JIT with a new approach called Modular Consortia. This means, the module supplier has te responsibility to assemble the module directly on the assembly line of the car manufacturer (Bennett & Klug, 2010).

It is not clear on first sight what the difference between a module and a system is, and how these relate. The difference between a system, and a module is given by Collins et al. (1997). A module is a physical subassembly, a system is a functional aggregate of components not necessarily delivered as one physical unit. modularity from the perspective of a system is the degree to which a system's components can be disassembled, and recombined.

Modularization can be applied with different objectives in mind. Each modular design objective requires a unique set of factors to be considered. Gu et al. (1997) present a method to form modules, a case study is performed on a vacuum cleaner. The factors that determine the modularization of a vacuum cleaner are different from a system in a complex ship. The following section elaborates on the different modularization objectives in shipbuilding.

Modularization objectives

As mentioned above a clear modularization objective is needed. The modular lifecycle objectives listed below can be identified from literature. The focus in this thesis will be on assembly ease of the engine room, the other objectives are given for the sake of completeness. The assembly of the engine room will be less complex simply because there are fewer tasks to be performed. Moreover the quality increases thourgh facilitation of rework and testing. Each individual module can be tested as a separate entity and repairs can be made while it is still cost effective to do so (Tung, 1991).

- *Maintenance & repair ease (Gu, Hashemian, & Sosale, 1997)*
- *Redundancy (Ertugrul, Soong, Dostal, & Saxon, 2002).*
- *Assembly ease (Wei & Nienhuis, 2012), (Tung, 1991)*
- *Quality improvement (Comm & Mathaisel, 2000)*
- *Cost reduction (Collins, Bechler, & Pires, 1997)*
- *Standardization (Nieuwenhuis, 2013)*
- *Innovation (Mikkola, 2003)*

Modularization approaches

The different modularization objectives for complex shipbuilding have been identified, these objectives can be reached with different modularization approaches. In this section these different modularization approaches obtained from literature (Fricke & Schulz, 2005) (Huang & Kusiak, 1998). The list below provides the different modularization approaches with an example. The approaches are illustrated in Figure 2-8.

- Component swapping modularity: Different pump sizes on module
- Component sharing modularity: Same sensor in different modules
- Fabricate-to-fit modularity: Scalable standard module
- Bus modularity: place modules on standard foundations
- Sectional modularity: different combinations for different

A wide variety of products can be developed with the given modularization approaches. Which approach is best suitable for the module depends on the use of the system. Research has been done on the product architecture, and product platforms, important aspects of modularization. A brief review is given below.

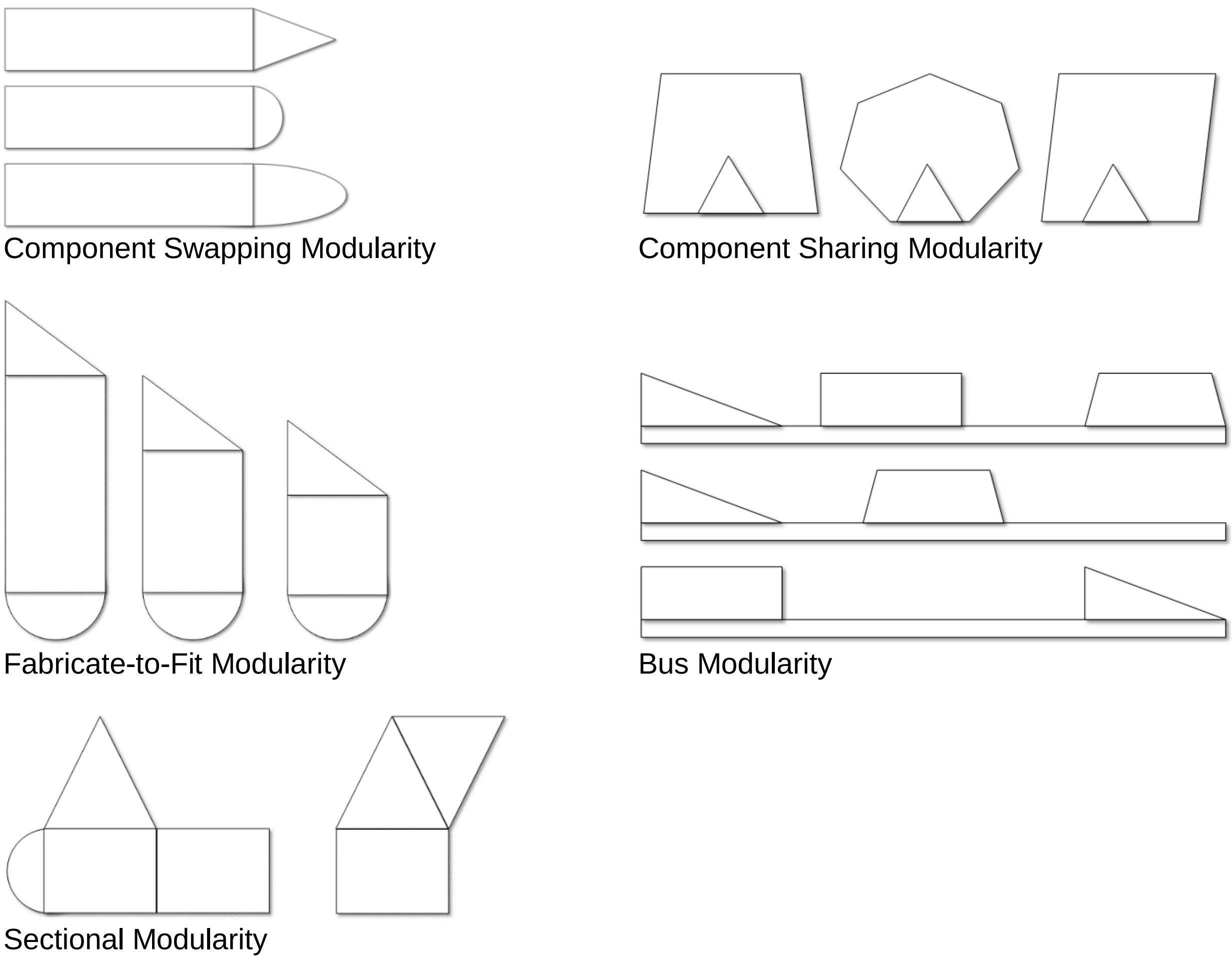


Figure 2-8 An illustration of different modularization approaches

Product platform & architecture

The modularization concept is closely related to several other concepts and technologies, including, product platforms, and product architectures. The first paragraph elaborates on the product platforms, the second paragraph concerns product architecture. The third paragraph explains the relation between the product architecture and the next sub-chapter: design for assembly.

During the 1990's, many industries have moved from designing "one-of-a-kind" products, towards developing product platforms from which a large number of variants or customized products can be configured. Through a product platforms, mass customization can be achieved. It should be made clear what a product platform is. A definition of the product platform is adopted from Erikstad (2009). A product platform can be defined as: "a structured coherent collection of resources, including systems and template hierarchies, textual components, variants, rules and interface definitions, from which a range of customized product definitions can be derived". Product platforms are related to modularization since the modules are the building block from which the product platform is built (Erikstad, 2009). The next step is to incorporate the interfaces of the product families, this is done with the product architecture.

The product architecture is important for the modularization process as well. The purpose of the product architecture is to define the basic physical building blocks of the product in terms of both what they do, and what their interfaces are with the rest of the device. The costs of customized components is high because improvement in functional performance of the system cannot be achieved without making changes to other components due to the many interfaces between the modules. If the interfaces of the customized components become standardized, alterations to the product architecture can be localized, and made without incurring costly changes to other components, making outsourcing possible (Nieuwenhuis, 2013).

Modular strategies are used in the computer hardware industries, automotive industries, and many more. Modular designs are useful for mean of managing complexity (Ethiraj & Levinthal, 2004). Different modularization objectives can be achieved with different modularization approaches. Product platforms and architectures can be developed with modular assembly strategies. The product platform is the various configuration of modules to obtain different designs, the product architecture concerns the connection of these module. The higher the level of modularization, and the better the product architecture, the easier it is to outsource manufacturing of its constituent components. Modular product architectures require that interfaces shared amongst components to be loosely coupled, hence promoting competition among suppliers.

2.1.4 Design for Assembly

The previous chapter elaborates on the modularization of systems to reduce the number of components to be installed on board. Benefits are expected in terms of human effort on board, and cost reduction. However, the author of this reports thinks the performance of the assembly process can be further elevated if design for assembly strategies are incorporated besides a modular strategy.

Background on design for assembly

First, the definition of design for assembly should be made clear. The definition adopted for design for assembly is: “the design of the product for ease of assembly”, where assembly is both acquisition and the insertion of the part (Boothroyd & Alting, 1992). In some literature design for assembly means the design of the system for performing assembly work, this definition is not relevant for this report.

The final cost of a product largely determined during the design of the product; the designer should incorporate manufacturing into account from the design phase. The altitude of designers “we design it – you built it” is called an “over the wall design”, the design is separated from production so that the manufacturing engineer has to cope with problems created by the designer. It is clear this will not lead to an efficient production process, and thus high costs for the company. It is important that designers clearly understand the influence of their decisions during preliminary design on assembly and costs.

Design for assembly introduced a revolution in design practices, even beyond the assembly costs. DFA simplifies the structure of the product, hence reduces the number of parts and thereby the total cost of the parts. In additions, any reduction is parts results in a cascade of effects in costs reductions e.g. less drawings & specifications, less vendors, less inventory. These aspects will ultimately have an important effect on the overhead costs. This line of reasoning is argued by Boothroyd et al. (1992) to be applicable for low volume production, so it might be beneficial for shipbuilding as well. The question rises how can this be applicable in shipbuilding?

The objective should be to simplify the product structure to reduce assembly cost and reduce the total part cost. Boothroyd et al. (1992) & Giusti et al. (1991) emphasizes the importance of the part count reduction. Moreover the connection interfaces should be simplified for a simpler assembly of the system (Giusti, Santochi, & Dini, 1991). The complexity in terms of components is used for the module design as well. A measure for the interface complexity is given by Jeong et al. (2011) which is discussed in the next section.

Interface complexity

Complexity in general is a highly sophisticated topic, especially a quantitative definition of the interface complexity. The lack of a specific metric to measure complexity was acknowledged by Jeong & Philips (2011). An equation is developed in order to define the complexity of a system as a ration between the total existing process relations, and the maximum amount of process relations. The developed method was used by Bosschaart et al. (2013) to develop a lean engineering design process for a rail way interlocking system. The SCLI is used as an indicator to define the complexity of the interfaces in a system. The SCLI is given in Equation 2-1, where TEI is the total existing interfaces and TPI is the total possible interfaces.

$$SCLI = \frac{TEI}{TPI} \qquad (2\text{-}1)$$

Where,

SCLI	=	*System Coupling Level Index*
TEI	=	*Total Existing Interfaces*
TPI	=	*Total Possible Interfaces*

2.1.5 Supply Chain Management

Supply chain management is an important aspect in modular strategies. The term supply chain management is defined as "managing the entire chain of raw material supply, manufacture, assembly, and distribution to end customer". A modular assembly strategy shifts the responsibility from the LSSI to the suppliers, therefore promoting competition among module suppliers. For instance, multiple car manufacturers involve their suppliers in the design of modules or an entire system an example of this strategy is the Volkswagen truck, and bus plant in Brazil (Pires, 1998). An efficient supply chain management strategy is key for the success of a LSSI, particularly if modular strategies are used.

Supplier categories

Suppliers in the supplier network of a LSSI can be categorized in three categories, the tiers I, II, and III. A tier I company delivers directly to the LSSI. Tier I suppliers usually work for multiple LSSIs, however, they are often tightly coupled to one or two LSSIs. There are many parts the LSSI uses, many of them are not directly purchased by the LSSI themselves. The companies that do not directly sell to the LSSI are called tier II companies. The tier III categories suppliers deliver raw materials e.g. steel.

Product development strategies

A LSSI basically faces three alternatives to manage the development of new components: (1) in-house sourcing, (2) co-production, and (3) co-development. In the co-development strategy the supplier, and LSSI join forces, this is justified when technologies are so expensive that individual firms cannot afford to develop them alone. The above mentioned strategies can result in three kinds of parts (Mikkola, 2003):

1. *Detail-controlled parts* are parts that are developed entirely by assemblers including functional specification, and detailed engineering.
2. *Supplier propriety parts* are parts which are developed entirely by parts supplier including functional specification, and detailed engineering.
3. *Black-box parts* are those parts whose functional specification is done by assemblers while detailed engineering is carried out by parts suppliers. Black box parts enable

assemblers to utilize supplier's engineering expertise, and manpower while maintaining control of basic design, and total system integrity.

The underlying assumption is that modular product architecture allows the decomposition of a complex system or process into smaller sub-systems. Based on product architecture, components can be categorized as a supplier proprietary part, a detailed-controlled part or a black box part. This component category is closely related to the product development strategy. Makers of complex systems are delegating more product development responsibilities to suppliers. Another trend going on is the reduction of the number of suppliers. This makes it possible for the LSSI to focus on effective purchasing, supply chain management, and other core competencies of the LSSI. The reduction of suppliers means that the assembler has to find innovative ways to cooperate with suppliers, and carefully devise product architecture strategies. Outside suppliers can perform many activities at lower cost, and with higher value added than a fully integrated company.

Outsourcing can only be realized when a system can be decomposed in such a way that interfaces of the components are well specified, which is a central focus in modularization strategies. It is clear that outsourcing strategies can result in a better performance of the LSSI. Another benefit of outsourcing is innovation. The following section will elaborate on co-innovation between a LSSI, and the supplier.

Co-production, -development & -innovation

The supply chain is a major player in the business operation strategy. The improvement of business operation allows companies to focus on growth strategies, and employ capital more efficient. Co-development, and co-production strategies, where multiple partners work together can reduce the development risk, and the TTM. Innovation used to be performed entirely in-house. A new environment of internal, and external pressures resulted in new ways for companies to innovate. One of these ways is used by Beelaerts van Blokland & Santema (2006), namely, co-innovation.

Co-innovation combines the assets, and resources of strategic partners. The partners work toghether rather than compete with one another. With a co-development strategy, different configurations can be used, and different results can be reached. The results of co-development is first of all, a lower TTM. Secondly, a knowledge premium can be reached. The two results would defenitely be befinicial in super yacht building. Co-innovation is an even stronger colabration with the supplier where the LSSI and the Tier I supplier innovate together.

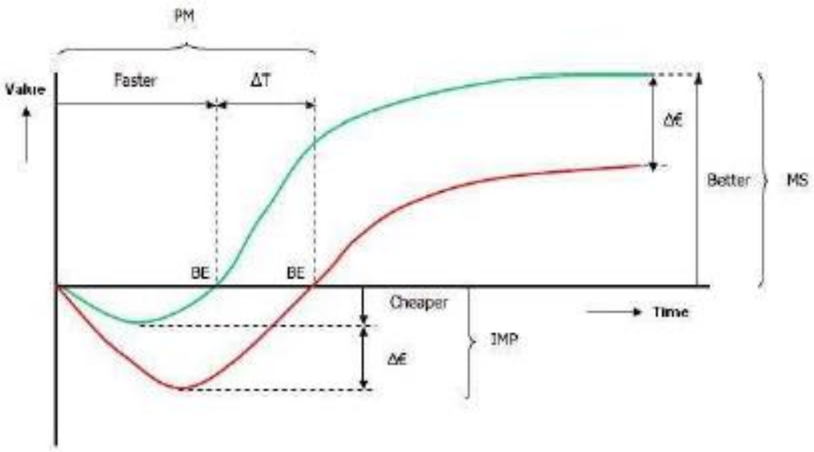
The use of more outsourced modules will drastically change the cashflow of the shipyard. More investments need to be made in a earlier stage of the project, and development costs will transfer to the suppliers. Beelaerts et al. (2007) used a value - time curve to visualize the shift in development costs, and earned revenues versus the time. The curve can be used for the change in cashflow of the shipyard aswell. A general concept of the value time curve is given in Figure 2-2. The first part of the curve represents the development costs of the product. The second increasing path represents the cash flow generated with the sales of the product. The 3C model is developed to quantify the effects of the value shift towards the suppliers (Beelaerts van Blokland, Verhagen, & Santema, 2008).

The 3C model links co-innovation, Lean value, and the supply chain to one another. Lean value, and supply chain have been discussed, however it is dignified to elaborate on co-innovation. Co-innovation emphasizes creation of customer value by co-developing engineering subsystems at a concurrent manner. The value drivers of the 3C model are; continuation, conception, and configuration (Beelaerts van Blokland & Santema, 2006).

- *Continuation* is the accessibility to and focus on customer satisfaction, Customers adopt the innovation, and generate value, thus ensuring continuity.

- *Conception* is the effect of co-development on the innovation investment costs of the LSSI, The engineering costs for the LSSI will reduce. This effect is indicated with the Investment Multiplier (IMP).
- *Configuration* is the configuration of the supply chain. Effective sub-contracting leads to co-production, which can lead to a higher overall profit.

The 3C model embodies the principles of Concurrent Engineering (CE). CE is a philosophy to perform tasks in parallel in order to reduce development times, improve product quality. lower development costs, and production costs (Yassine & Braha, 2003). The 3C model provides two measures to quantify co-production and co-innovation. The measure for co-production is the Production Multiplier (PM), the measure for co-innovation is the Innovation Investment multiplier (IMP). The results of co-innovation can be a shorted time-to-market, and a larger market share (Beelaerts van Blokland, Verhagen, & Santema, 2008). The results are visualized in Figure X-X.



Figuur 2-9 The changes on the value-time curve due to co-innovation

2.1.6 State-of-the-art in modular aircraft manufacturing

The current shipbuilding process has been elaborated on in chapter 2.1, the driver for optimization have been given. The following chapters (2.2-2.5) elaborated on optimization strategies, many of which originate from the car-manufacturing industry. It has been made clear the car manufacturing industry significantly differs from ETO-shipbuilding. An intermediate step between car manufacturing and ETO-shipbuilding is the aerospace manufacturing industry. Various improvement methods have been successfully implemented and the results are astonishing. This chapter is dedicated to analyse to which extent the aircraft manufacturing offers solutions for the system assembly process for ETO-shipbuilding. First the drivers and goals for optimization and aircraft manufacturing industry are given. Second, the current state-of-the-art is given for aerospace manufacturing. Lastly, a comparison is given between aerospace and shipbuilding industries.

Drivers & goals for optimization in the aircraft manufacturing industry

Crute et al. (2003) identified three main events for the introduction of lean in the aerospace industry, the first one being the end of the cold war. The end of the cold war resulted in drastic reductions in defence procurement budgets resulting in reduced military markets. The second reason is the gulf war, passenger demand fell drastically. This drop in passenger demand forced airlines to cancel or postpone civil aircraft orders. The third reason, in common with other industries, globalization has become a central feature. Such major events are currently not applicable to the super yacht industry. However, James-Moore & Gibbon (1997) identified 5 core drivers for lean in civil aerospace companies which can be related to super yacht building, namely:

1. The company should be more responsive to customer needs
2. The costs of the development, and production of the products should be reduced
3. The quality expected by the customer should be met
4. People should be used more effectively
5. The management of partnerships should be improved

The customer's wishes for super yachts change continuously, customers tend to desire the best products available on the market. In every company a reduction of development, and production costs is favourable, provided that the quality of the development, and production is maintained or increases. Customer satisfaction is of utmost importance in custom super yacht building, where extraordinary wishes are customary. It is clear that using people more effectively, and improved partnership management is beneficial for any kind of company.

Boeing formed goals to improve their production process (Crute, Ward, & Graves, 2003). The goals defined by Boeing are given below:

1. Achieve greater quality on first pass throughout Boeing – goal is 90% improvement in manufacturing quality
2. Organize corporate-wide work teams that are fully accountable for their work product, and that all have the metrics they need to measure their performance
3. Create a culture that encourages employees to propose better ways of meeting performance goals
4. Move up the value chain i.e. focus on core competencies
5. Reduce the company's cost structure substantially
6. Globalize to a greater degree

Better quality at the first time would be beneficial in shipbuilding as indicated by Liker & Lamb (2002). The reduction of the company's cost structure is beneficial for any company, and thus a shipyard. Treating a shipyard as a LSSI would imply that a shipyard has to focus on the core comptencies, which is in line with point four of the summation.

The applicability of Lean practices in sectors other than automotive has been questioned (James-Moore & Gibbon, 1997). The contrast between a high volume setting, and a low volume industry is enormous. However, the aerospace & super yacht sector may even be at an advantage over automotive in terms of applying Lean principles. The lower number of final products means that they are closer to the Lean ideal of single piece flow than the automotive sector. The aerospace sector is already "build-to-order", only producing aircrafts that are required by their customers. Built-to-order is the essence of a lean, a pull system. The problems of implementing Lean with aerospace are not, necessarily, more difficult than that of implementing Lean within high volume sectors, including automobiles. The challenges are different but not more difficult (James-Moore & Gibbon, 1997). Many years of optimization lead to the current state of the art, a brief summary is given in the next section.

State-of-the-art in the aerospace manufacturing industry

In this part the state of the art in aircraft manufacturing industry is given. Continuous flow is important in assembly process definition. A method to achieve continuous flow is the moving assembly line. The moving assembly line slowly moves products from one team to the other, resulting in a steady pace production line. Using assembly lines with the accompanying Lean techniques enhance the quality, and efficiency of production processes (Barbosa & Carvalho, 2014).

Nowadays in the aircraft manufacturing industry, suppliers are involved in the co-development of entire functions of the aeroplane e.g. wings, fuselage etc. This involvement of suppliers causes value to shift from the aerospace original equipment manufacturer (OEM) towards the supply chain. The OEM focuses on concept design, certification, testing, services, marketing, global supply chain management, and integration (the core activities). The suppliers are highly involved in the design, and production of parts, and subassemblies (Beelaerts van Blokland, Santema, & Curran, 2010). Since the suppliers are highly involved in the process, the network a company operates in becomes increasingly more the driving factor to success or failure.

Three major challenges for OEM arise from this. The first challenge is building the best value supply network. The building of an effective knowledge sharing network is the second challenge. Thirdly, it is a challenge to manage a successful cooperation within the network to innovate, and compete. If these challenges were successfully adopted by the aerospace companies, they are able to leverage value on suppliers and thus create value to flow more efficiently (Beelaerts van Blokland, Santema, & Curran, 2010). Royal Van Lent can be seen as a LSSI similar to aircraft manufacturers. Beelaerts (2010) defines the core competencies of the integrator as sharing knowledge, collaboration skills, product vision ,and market knowledge. This leads to a transition of risk, responsibility, and revenues upstream the supply chain.

One of the core principles of the integrator must be open innovation in a supply network. (Beelaerts van Blokland, Santema, & Curran, 2010) Co-development and co-production lead to a shorter break-even time, lower investments, and a higher growth of value. The development of the Boeing B787, and Eurocopter, show that when effective supply chain management is used, the high complexity of aircraft design, and production can be effectively managed. The effects of co-innovation, co-development, and co-production can be seen in Figure 2-10. The different sub-assemblies are developed and produced by various suppliers at various locations all over the world.

The implementation of lean practices can be evidently found in the UK, and the US. 1999 was declared by Lockheed Martin’s Aeronautics Sector as the ‘year of Lean’, and is rigorously applying Lean techniques to the F-16, F-22, and the C-130J military aircraft. Another aircraft manufacturer that has been heavily involved in employing lean practices is BAE Systems. The company’s flagship manufacturing site in Samlesbury, England, believed that Lean manufacturing was central to controlling costs on the Eurofighter programme. BAE Systems however perceives that the aerospace industry is 10-15 years behind the automotive sector in implementing Lean ideas (Crute, Ward, & Graves, 2003). It can be concluded that Lean is widely used in the aerospace industry but the car manufacturing industry is in a more advanced stadium. The question arises: “how does aircraft manufacturing relate to super yacht building and what techniques can be used?”.

Comparison aircraft manufacturing, and super yacht building

The first similarity between aerospace, and complex ship manufacturing is the order of the TTM. The TTM for a complex ship, in particular a custom superyacht is approximately three years. An aeroplane needs to be ordered by the customer at least one year in advance (Marsh, 2014). In comparison with the TTM for cars, this is a substantial increase. For both industries it is important to meet the upfront agreed delivery date, otherwise the manufacturers have to pay large sums of penalty money. The reliability of the production process is therefore highly important. The implementation of Lean has proven itself in reducing the TTM, and the deviation in the production process in the automotive industry, and is becoming more popular in the aircraft manufacturing industry. A reduction of the TTM will not only result in the elimination of penalties but will also give the company a competitive advantage in both the aerospace, and complex shipbuilding industry.

The second similarity is the role both the shipyard, and the aircraft manufacturer play in the production cycle. This role can be described as “Large Scale Systems Integrator”, the manufacturer is specialized in the assembly of the sub-systems. OEM’s (Original Equipment manufacturer) should focus on the core competencies while outsourcing non-core production (Petrick, 2007). The large number of suppliers in both the super yacht market, and the aerospace market therefore make supply chain management of utmost importance.

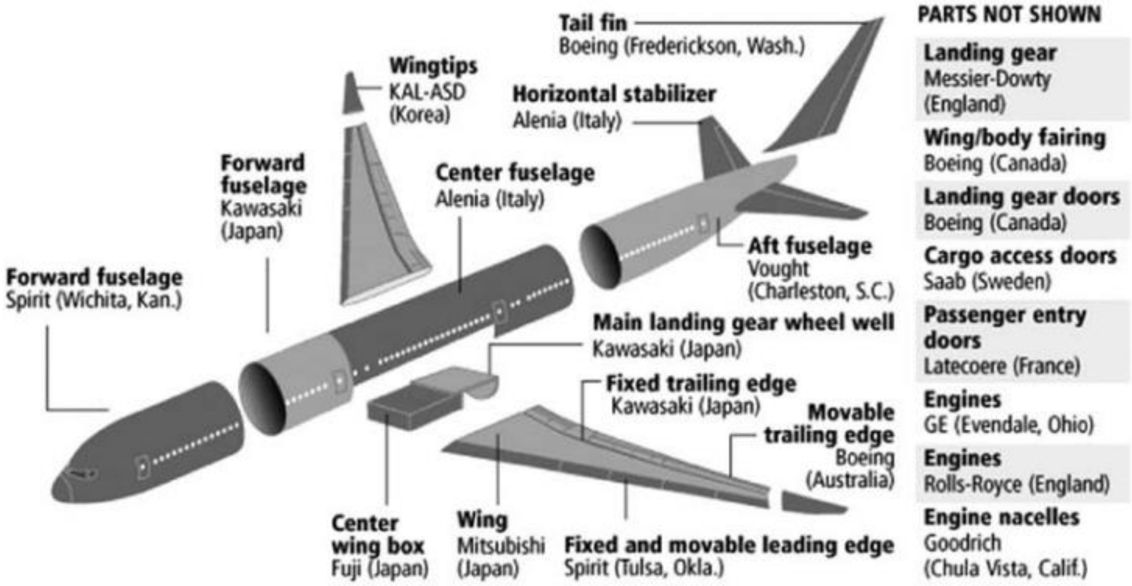


Figure 2-10 (Tang, Zimmerman, & Nelson, 2009)

The first dissimilarity identified is the level of customization. The level of customization is lower in the aerospace industry. The Large Scale Systems Integrator (LSSI) has a standard model with customizable options. These relatively standard final products lead to an engineering model that is final when production starts. This complete model helps to prevent rework in the production stage since there will be no changes in the design when production has started. Another benefit of the finished 3D model is that the production process is performed separately from the engineering process, therefore the production process can be optimized independently from the engineering process. In custom shipbuilding every ship is bespoke, and therefore the engineering has to be done for each individual ship. The study of Wei & Nienhuis (2012) shows that “the production starts before the entire ship is completely engineered. Pipes are placed when engineering is not final, resulting in up to 50% of rework”. The start of production before engineering is final is seen at RVLS as well. This production method is done to meet the milestones set at contract design whether this is the most efficient strategy is debatable. Liker & lamb (2002) show that reduction of costs, and improvement of quality can be realized by focussing on quality, doing it right the first time. The high level of customization brings challenges in shortening the TTM in custom shipbuilding.

The second difference between shipbuilding, and aircraft manufacturing is the total number of final products delivered. In the past five years the average number of orders at Boeing, and Airbus, the two largest aircraft manufacturers was more than 1000 aircrafts each per year (Statista, 2018). For super yacht shipyard like RVLS this is much lower, where only a few ships leave the shipyard each year. The low number of final products brings challenges in the optimization of the production process. The budget for optimization can only be distributed over a small number of final products.

It can be concluded that shipbuilding, and aircraft manufacturing do have important similarities. An overview of the differences and similarities is given in Table X-X

Table 2-2 Comparison between complex shipbuilding, and aircraft manufacturing

Similarities	Differences
Long Time-To-Market in both industries	Higher level of customization in Complex shipbuilding
Large Scale Systems integrator is the role of the OEM in both industries	Higher number of final products in aircraft manufacturing

The drivers, and goals for optimization in aircraft manufacturing relate to customer needs, development costs, quality, effective use of employees, and partnerships, this is also applicable to superyacht manufacturing. Aircraft manufacturing is in a more advanced stadium in terms of Lean, not much research has been conducted in Lean practices in the shipyard industry (Hordijk, Van Rooijen, & Schildtkamp, 2014). The research that has been done in lean shipbuilding is given tin the next sub-chapter.

2.1.7 State-of-the-art of modular system assembly in shipbuilding

The general concepts of a modular strategy have been explained, an elaboration on modular aerospace manufacturing has been given. The logical next step is to discuss the state-of-the-art in modular shipbuilding. It should be clear that a modular strategy has a strong relation with lean theory. A brief explanation of modular shipbuilding is given in the first section. Thereafter the focus is on the literature on modular system assembly in shipbuilding.

Modular shipbuilding

The ultimate goal of Lean is cost reduction via elimination of waste. It is complex to reduce waste from the perspective of building an entire ship. Defining interim products, and optimizing the assembly of these products is less complex, hence better manageable. Using these interim products within a ship makes it possible to define, and organize appropriate production work instructions. (Storch & Lim, 1999). The Japanese shipyards production is already primarily based on the flow of blocks. The potential benefits of “flow” are immense as shown by Koenig, Narita, & Baba (2002). One-piece flow is ideal from a Just in Time (JIT) point of view. The building blocks arrive exactly when needed at the slipway or dry-dock to be assembled onto the other blocks. Ideally families of parts that go through the same set of processes are produced on a production line dedicated to each product family (Osterholt, 2014).

The “takt” time in the car manufacturing industry is important, it is not clear at first sight that this principle is applicable in shipbuilding since the TTM is much longer. However, when the ship is conceived as a collection of smaller units thinking about takt time makes more sense. Individual blocks are scheduled just in time to construct the grand block, which are completed JIT for the final ship construction.

Since Lean production requires uniform, and continuous process flows, build strategies must be established, and followed which describe the proper breakdown of work within the blocks. The expense of design convenience should be considered in order to improve to assemblability, design for assembly. This section is on the building of an entire ship, the assembly of systems is a specific topic in shipbuilding. The next section therefore further elaborated on the state-of-the-art in modular system assembly.

Modular system assembly

The assembly of systems can be caterogirzed in the outfit part of shipbuilding. It is strongly recommended by Ozkok & Helvacioglu (2013), Rose (2017) & Wei (2012) to perform outfitting operations during the construction of the section i.e. pre-outfit. Fafandjel et al. (2008) showed that labour costs on-board can be on average 3-5 times higher than equivalent work done in the shop or on the platform. During the design, and engineering phase, it should be made sure the equipment can be build in a workshops, and easily assembled on board.

A method to shorten the TTM, improve work efficiency, and improve cost performance is the use of modular outfitting concept (Rubesa, Fafandjel, & Kolic, 2011). Using these building blocks has a great impact on the amount of work in the design, engineering, procurement, manufacturing, and assembly stages. The modular outfitting process is involved in many stages of the ship building process. The goal of the concept is to find the largest possible assembly which are subject to the following constraints: It must be feasible to assemble the components, and equipment in a workshop concurrently with the hull construction. The assembly must be easy to lift without exceeding the maximum crane capacity. The entire module layout must be confirmed by the preliminary system routing (Rubesa, Fafandjel, & Kolic, 2011). The goal for the shipyard is to let subsystems flow in “just in time” (JIT) according to Lean principles.

The modular outfitting approach does require changes in the design, and technological processes. A higher effort in designing, documentation preparation, engineering, quality assurance, and a higher level of design standard is necessary in order to minimize the interferences, and disconnections (Fan, Lin, & Zhuoshang, 2007). From a LSSI perspective, the engineering of these modules is not a core competence. The modules can be bought from suppliers, it reduces the complexity of engineering, procurement, production, and assembly, hence the overall complexity of the shipbuilding process. The LSSI should focus on the integration, and overall assembly strategy for these blocks.

The research done by Rubesa et al. (2011) provides a work breakdown structure of the outfitting process. The data is obtained from the building of a chemical and oil product tanker of 47,300 tdw. It gives an estimation of the present level of modular outfitting (PM), the total possible level of modular outfitting (TM), and the on-board factor (OF), the on block factor (BF), and the on-unit factor (UF). It can be seen in Table 2-3 that the on board factor is taken as one, since this is benchmark for the estimation. It can be seen that the cost can be reduced with a factor 5 for the Bilge water system, and Sea water system. The ventilation cost saving factor has the lowest potential, it can be decreased with a factor 2,5. It can be concluded from the research that a substaintial cost saving can be reached by using the modular outfitting approach.

It should be noted that it is important to avoid rework when using the modular outfitting approach. The costs of rework will be higher when the modular outfitting concept is used. Do it right the first time (DRIFT) should be practiced, and can be done by minimizing the overlap between basic, conceptual, and detailed design and the actual production should not start before the applicable space, phase, and stage are completed (Rubesa, Fafandjel, & Kolic, 2011).

It can be seen that suppliers deliver their system in a module, however the integration of the module on-board requires many additional pieces of equipment, pumps, valves appendices, and sensors. An example of such a module can be seen in Figure 2-11. It is observed that it is favoured by the yard to use smaller modules or no modules at all, since the movement space in the engine room is little. The use of smaller components makes it easier to assemble the system on-board. Moreover, it is easier to dissemble the system if there is not enough space to perform other outfit activities near the system.

Table 2-3 Cost saving factors for various stages of the outfitting process (Fafandjel, Rubesa, & Mrakovcic, 2008)

Work Breakdown Structure	PM (%)	TM (%)	OF	BF	UF
Sea water system (SWS)	40	80	1	0,4	0,2
Domestic water system (DWS)	30	75	1	0,4	0,25
Black & Grey water system (BGWS)	n.a.	n.a.	n.a.	n.a.	n.a.
Fuel oil system (FOS)	25	70	1	0,4	0,35
Lubrication oil system (LOS)	25	70	1	0,4	0,3
Bilge water system (BWS)	25	65	1	0,4	0,2
Firefighting system (FFS)	25	70	1	0,4	0,3
Ventilation	0	50	1	0,6	0,4
Air-conditioning (AC)	5	70	1	0,5	0,3

Legend:

Present level of modular outfit (PM)	Existing percentage of modular outfitting in relation with all outfitting work
Total level of modular outfit (TM)	Estimated maximum percentage of work that can be modularised
On-board factor (OF)	Labour cost factor at on-board stage of construction
On-block factor (BF)	Labour cost factor for on-block work relative to on-board cost
On-unit Factor (UF)	Labour cost factor for on-unit work to on-board cost

Figuur 2-11 An example of a water maker module

Sub research question:

2. *What can be learned from other industries from a modular perspective in order to optimize the assembly process of systems in a super yacht?*

In short, research has been done on the use of blocks or modules in the shipbuilding process. Shipyards in Japan, where a lot of series production is done use modular shipbuilding strategies in the hull construction. Little research has been done on the use of modular system assembly in shipbuilding, especially in the ETO-shipbuilding industry.

2.1.8 Literature gap

In this paragraph an elaboration will be given on the research gap. In the car manufacturing and aerospace manufacturing industries modular strategies are widely used, and substantiated with scientific literature. Modular concepts are used, and quantified in terms of hull construction. It can be seen in ETO-shipbuilding that suppliers deliver system modules, or skids, however at RVLS this is not favoured over assembling the system on board (yet).

Sub research question:

3. *What research lacks for an effective modular strategy in the ETO-shipbuilding?*

Modular system assembly
The quantification of the benefits in assembly time on-board can neither be found in literature not at the yard. The modular outfitting concept cannot be used in the same manner for different shipyards, this makes it difficult to quantify the benefits in a general manner. This is due to the fact that obstacles such as lack of space, constraints of lifting crane capacities, and transport vehicles are different in each shipyard. Therefore the modular system assembly is concept is widely seen a concept where considerable progress is possible to avoid the above mentioned obstacles (Rubesa, Fafandjel, & Kolic, 2011). Larger standardised unitised, typified, and pre-assembled in workshops can be used to further improve the outfitting of ships. The standardization of these modules can result in cost, and schedule benefits since the efficiency increases from repetitive manufacturing. Moreover, the modular strategy is aimed at reducing the complexity of the on-board assembly process. A measure has been found from an assembly line example, however this is not directly applicable to shipbuilding, The SCLI should be adapted for shipbuilding. This research is aimed at the quantification of the effects of a modular system assembly strategy on the shipbuilding process.

Design for assembly
An addition to a modular system assembly strategy it to use design for assembly method. No literature has been found the design for assembly of systems for a modular system assembly strategy in shipbuilding. The author thinks the combination of design for assembly and a modular system assembly strategy can further improve the system assembly process on board of ships. The literature from other industries suggest the complexity of the design should be limited. This can be done by minimizing the number of components that need to be installed on board and simplifying the interfaces between the modules.

The next chapter elaborates on the model developed to analyse these problems. First the model the quantify the effects of the modular system assembly strategy is presented. Thereafter, the model is adjusted and improved to be able to quantify the effects of the design for assembly method. Moreover, it is mentioned in the chapter 2.

2.2 Preliminary model

The introduction, and literature have been given, the third chapter of this thesis is about the measures for the research. The quote of DeMarco emphasizes the importance of this section for this thesis, and for controlling a process in general.

You cannot control what you cannot measure. (DeMarco, 1982)

In order to be able to measure the performance, the Key Performance Indicators (KPIs) for the process should be defined. This research is aimed to improve the production process of the yacht with modular assembly of systems. In order to do so, assumptions need to be made about the modular systems. It expected that the developed modular system assembly strategy has 4 orders of effects.

Sub research question:

4. What are the Key Performance Indicators for the system assembly process?

5. What are the Key Performance Indicators for an effective modular design in terms of assemblability?

2.2.1 Design of the preliminary model

The first order of effect is the reduction of the on-board complexity. The assembly complexity can be measured with the System Coupling Level Index (SCLI). For example a pump has 3 interfaces, in, out, and an electrical one. This is also what needs to be attached to the pump during the assembly process. So the equipment interfaces needs to be determined, but for the pumps, valves, sensors, and appendices the interfaces is predefined. The result of the less complex on-board assembly can be seen in the human effort necessary on board.

The second order of effect is the value shift towards the supply chain, i.e. co-production. The transfer of assembly complexity from board to a workshop enables the LSSI to outsource the production of the modular system. The expertise of the Tier I supplier can be used. The supplier is likely to more effectively produce the module, due to the advantages of repetitive manufacturing. The reduction of human effort on-board will transfer the value towards the supply chain. The hypothesis is that the costs of the entire production process will reduce. By doing so, the time value curve of the engine room assembly process can be optimized. The 3C model shows that co-production results in a shorter time-to-market in the production of aeroplanes. The same result is expected in the production of ETO-ships. The system is longer in the value chain of the supplier, different loading strategies could enable LSSI to install the module in a later stadium in the shipbuilding process. The result will likely indicate a postponement in purchase costs for equipment, moreover a shorter time on board for the module during production of the ship will reduce the risk of damage to the equipment.

The third order of effect concerns the co-development and design for assembly of systems. The co-production of modules in close collaboration with the supplier can result in the co-development of modules. It is stated in chapter 2.5 on supply chain management that the interfaces between systems is crucial for effective co-development of a system. The lower the complexity of the system, the easier it is to effectively co-develop them. Moreover, Giusti et al. (1991) argue that the complexity of interfaces significantly impact the ease of assembly. The hypothesis of the fourth effect is therefore as follows: the redesign of the systems with a lower interface complexity will elevate the performance of the conventional modular system assembly strategy.

1. Reduce the on-board human effort by reducing the on-board complexity
2. Improve the value-time curve of the assembly process of the ship
3. Design optimization (design for assembly) with a lower interface complexity to enable co-development, thus further elevate the performance of the modular system assembly strategy

2.2.2 Key Performance Indicators

The Key Performance Indicators are structured according to the three orders of effects. First, the assembly process complexity. Second, the value-time shift, and lastly the design optimization in terms of interface complexity. The headers are the effects, the numbering of the KPI's is continuous from 1 till 6. Lastly a table is given to show the relation between the order of effect, the KPI's and the relevant literature.

Assembly process complexity

1. System Coupling Level Index

The first indicator for the complexity of the assembly process is the SCLI. The index is adopted from Jeong et al. (2011) is used in the modular design of an assembly line for fire extinguishers. Moreover, the index is used in a railway interlocking system problem to measure and optimize the performance in terms of complexity (Bosschaart, Beelaerts van Blokland, & Tavasszy, 2013). This thesis is basically aimed at lowering the on-board assembly complexity. Jeong et al. proposed the formula 2-2 as the complexity measure.

$$SCLI = \frac{TEI}{TPI} \qquad (2\text{-}2)$$

Where,

$SCLI$ = *System Coupling Level Index*

TEI = *Total Existing Interfaces*

TPI = *Total Possible Interfaces*

They treat each station of the assembly line as a module and can in theory be connected to all other stations. If there are five station, this would result in fifteen possible interfaces. This in not applicable for the assembly process in shipbuilding. This can best be explained with an example. A pump has an inflow and an outflow, and an electrical input, thus three connections. A sensor is attached to a pipeline or equipment, and has an electrical output, thus two connections. A valve has an inflow and an outflow, thus two connections (valves with three connections are rarely seen in the yacht). The appendices for example a strainer also has two connections. It does not make sense to use the total possible interfaces for the system assembly process of the engine room. The following method to quantify the complexity is used instead. The total existing interfaces can be determined for each system, and thus for all systems together (Equation 2-3). The current complexity for all system assemblies is benchmarked at one, see Equation 2-4. It is expected that the total existing interfaces will reduce, thus the complexity of the system. If all total existing interfaces will decrease the entire complexity of the system assembly will hence decrease.

$$SCLI\ (n) = \frac{Interfaces\ system\ (n)}{Total\ interfaces} \qquad (2\text{-}3)$$

$$\sum_{1}^{n} SCLI(n) = 1\ (current\ situation) \qquad (2\text{-}4)$$

An example is given in Table 2-4. System A-D are considered with a total number of interfaces. The current case is compared to a illustrative future case.

Table 2-4 An example of the SCLI for the system assembly complexity in shipbuilding

	Current		Future	
System	**Interfaces**	**SCLI**	**Interfaces**	**SCLI**
A	85	0.28	65	0.22
B	35	0.12	20	0.07
C	70	0.23	40	0.13
D	110	0.37	60	0.20
Total	**300**	**1**	**185**	**0.62**

2. Human effort

The second KPI is the human effort expressed in man hours necessary to complete the engine room. Five different departments are involved in the engine room production process. Engineering, construction, mechanical, yacht painters, and electrical. The mechanical department is predominantly involved in the assembly of the systems. The reduction of components installed on-board will result in a reduction of human effort on-board. The hours should be calculated per system, so the effect on each system can be determined. The shift of human effort on-board to a supplier will result in a value shift towards the supply chain, the KPI showing this value shift is elaborated on in the next section. The human effort necessary for the system assembly is retrieved from interviews with experts from the company.

Value time effect

3. Production multiplier

The third KPI is the production multiplier. The measure is adopted from a method developed for the car manufacturing, and aerospace manufacturing industry, the 3C model. The production multiplier (PMP) is used in the 3C model in order to measure the value creation due to the co-production of the system. The focus of the 3C model is co-production, co-development and even co-innovation, which is strived for in a modular system assembly approach. The first step towards co-innovation is from in-house sources to outsourcing of production, this is called co-production. The increase in co-production can be indicated with the ratio of the added value by the supply chain, and the total added value. The equation is given in Equation X-X

$$PMP = \frac{Added\ value\ total}{Added\ value\ in\ LSSI} \qquad \text{(X-X)}$$

4. Gross margin

The fourth KPI is the gross margin. The goal of a company is to maximize margin of profit within each activity. The gross margin is defined as Equation X-X. The revenue is the amount the customer has paid. The costs are the yard has invested. The costs can be divided in co-production costs, and co-innovation costs. These can be measured with the innovation investment multiplier (IMP), and the production multiplier (PMP) respectively. Insight in the process of the supplier is necessary, the effort the supplier puts in the development of a product needs to be known. This information could not be obtained, however the price for the development costs is incorporated in the price for parts or components. For this analysis the price for the customer is kept identical, a reduction of costs is aimed for.

$$Gross\ margin\ (\%) = \frac{Revenue - costs}{Revenue} \qquad \text{(X-X)}$$

5. Time-to-market

The fifth KPI for the production of the systems is the lead time. The lead time can be determined for a system, however, it is not a performance indicator which RVLS seeks to minimize (yet). It is expected that the co-production of systems can result in a shorted time to market, this is what happened in the car manufacturing and aerospace manufacturing industries. The design and engineering of the system starts during the design development phase. The production activities start with the fabrication of the foundation during the building of the hull. The commissioning of the system is finished just before the sea trials start. A lead time of more than three years can be the result, which can often be seen for the systems.

A short time to market for the systems should be aimed for, since this can contribute to a short time to market for the entire yacht and a better controllable process. A detailed planning for the system production and assembly currently lacks, the production and assembly systems is primarily guided with the experience of the Assistant managers and the foremen. The lower complexity due to modularization will likely result in a better manageable process. Moreover, a modular strategy will result in less human effort needed on board, leaving the equipment idle on-board can result in damage and unnecessary pressure on the schedule. The next KPI concerns the moment of placement of equipment in the engine room.

6. *Idle time of equipment in the engine room*

The sixth KPI is the idle time of the equipment in the engine room. The KPI is derived from the Just-In-Time methodology. From the most general JIT perspective, the module is necessary in the yacht during the commissioning of the entire system just prior to sea-trials. In the current production process, a substantial human effort is necessary to assembly the system. In a modular system assembly approach the module is pre-tested in the factory, and ideally be installed in a “plug-and-play” manner. Less human effort is necessary on-board thus the module can be placed in a later hull construction phase. A benefit of this is the reduction of risk of damage e.g. welding sparks.

The time effects can be visualized in the value time curve, the value flow of the engine room can be seen. The time to market is visualized as well as the loading of equipment due to the large investment of equipment being made.

Design optimization for a lower interface complexity

The last step is to quanitfy the effects of design for assembly with a lower complexity of the design. A general accepted metric for complexity lacks, this was acknowledges by Jeong & Philips (2011). An equation is developed in order to define the complexity of a system. This index is adapted for an application in shipbuidling, and has been discussed earlier this chapter. In this research the design optimization is only done for the fuel oil system. The interface complexity is minimized, it is expected that this will further elevate the performance of the modular assembly strategy. So the fourth effect, a redesign for the fuel oil system with a lower interface complexity, should be analysed in the KPI’s 1-4. The journey from in-house sourcing to co-production, co-development, and co-innovation is a continuous process. The first five measures are focussed on the shift from in-house sourcing towards co-production. The design optimization is the co-development of the module with a supplier. Once the co-developed product works, a more intense collaboration can result in co-innovation for the system in the yachts to follow. The Table below provides the relation between the order of effects, the KPI, and the relevant literature.

Sub research conclusion:

3. What are the Key Performance Indicators for the engine room assembly process?

4. What are the Key Performance Indicators for an effective modular design in terms of assemblability?

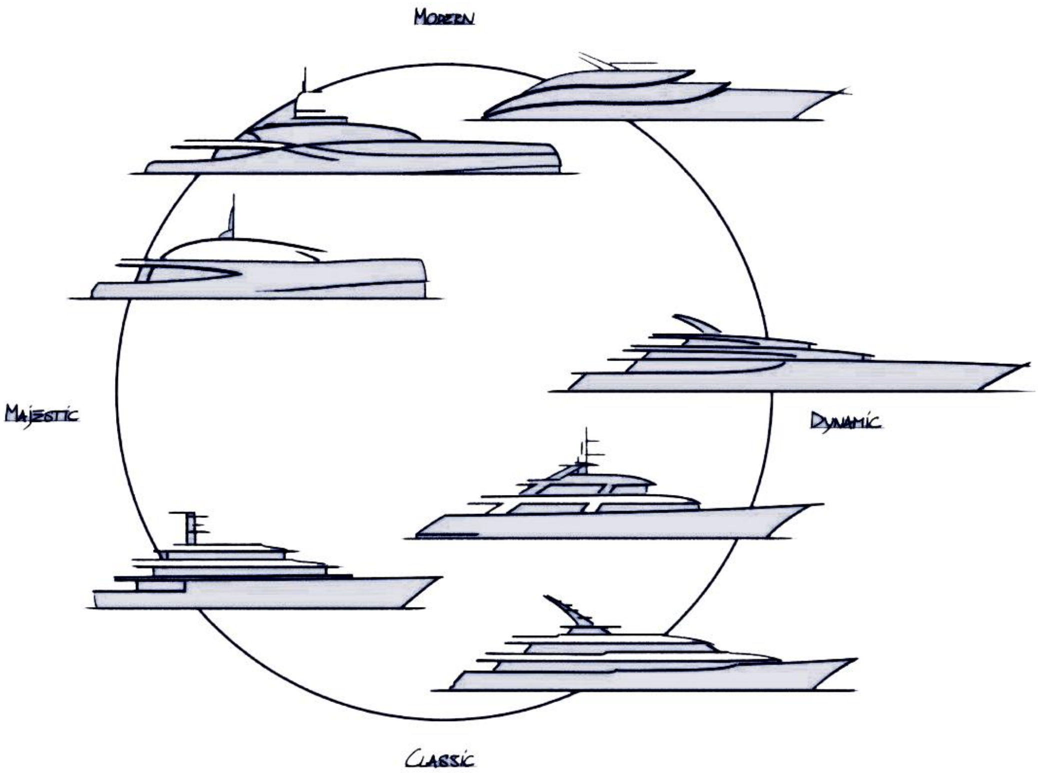
The answer to these sub-research questions is given in Table 2-5. The KPI’s are given for the assembly process, the value-time effect, and the design optimization.

Table 2-5 An overview of the preliminary model, the KPI's and their corresponding source

Order of Effect	KPI	Literature
1) Assembly process	1) SCLI	Jeong & Phillips (2011) Bosschaart et al. (2013)
	2) Human Effort	Wei & Nienhuis (2012) Tung (1991)
2) Value-time effect	3) Production multiplier	Beelaerts van Blokland et al. (2006) Beelaerts van Blokland et al. (2008) Beelaerts van Blokland et al. (2010)
	4) Gross Margin	Beelaerts van Blokland et al. (2008)
	5) Time-to-market	Rubesa et al. (2011) Leybourne et al. (2010) Beelaerts van Blokland et al. (2008)
	6) Idle time of equipment	Kaneko et al. (2008)
3) Design optimization	1) SCLI	Jeong & Phillips (2011) Bosschaart et al. (2013)
	2) Human Effort	Wei & Nienhuis (2012) Tung (1991)
	3) Production multiplier	Beelaerts van Blokland et al. (2006) Beelaerts van Blokland et al. (2008) Beelaerts van Blokland et al. (2010)
	4) Gross Margin	Beelaerts van Blokland et al. (2008)

II

MEASURE



3. Current state performance

This performance assessment will result in the performance of the current state in the production process of the engine room. The Key performance indicators of the production process have been given and discussed in chapter 3. This chapter concerns the current performance of the engine room assembly process according to the derived KPI's. The structure of this chapter is given in Table 3-1. The KPI's for the first two orders of effect are given for all systems. The last effect is only assessed and optimized for the fuel oil system (FOS). The effects are determined for the case study. This chapter is aimed as answering the following sub-question:

Sub research question:

6. *What is the current performance of the engine room assembly process?*

Table 3-1 An overview of which KPI's are determined for which system(s)

Order of Effect	KPI	System(s)
1) Assembly complexity	1) System Coupling Level Index	All
	2) Human Effort	All
2) Value time effect	3) Production multiplier	All
	4) Gross margin	All
	5) Time-to-market	All
	6) Idle time of equipment	All
3) Design optimization	1) System Coupling Level Index	FOS
	2) Human Effort	FOS
	3) Production multiplier	FOS
	4) Gross-margin	FOS

3.1 Current on-board assembly process

This section will indicate the current performance of the assembly process of the systems in the engine room. First, an short description of the system is given including a 3D render of the CAD model of the yacht. The description and the render provides insight in the current situation. Thereafter, the number of components are given and categorized. It should be noted that not for all systems this list can be made, such as the main engines. They are delivered by one supplier and not engineered by RVLS. For the sake of completeness they are included in the analysis. This list of components can be translated in the on-board complexity of the assembly process. Lastly, the resulting human effort necessary to complete the system is given, this includes all systems including the main engines for the sake of completeness. The systems are numbered according to the following list, it is also indicated which information is available in Table 3-2.

Table 3-2 An overview of the available information of the systems

System	SCLI	Human Effort
1. Bilge & firefight system	Yes	Yes
2. Fuel oil system	Yes	Yes
3. Sea water system	Yes	Yes
4. Domestic water system	Yes	Yes
5. Black & greywater system	Yes	Yes
6. Lubrication oil system	Yes	Yes
7. Working air system	Yes	Yes
8. AC & ventilation system	No	Yes
9. Propulsion system	No	Yes
10. Generator system	No	Yes
11. Ironwork & Cable trays	No	Yes

3.1.1 Bilge & firefighting system

Bilge water system

The bilge water system ensures that the bilge is emptied when necessary. The bilge is the lowest compartment of the ship, it is a residual collection tank of liquids due to rain, rough seas leaks in the hull or interior spillage. Bilge water can be a mixture of multiple substances i.e. fresh water, sea water, oil, chemicals and various other liquids. The bilge must be drainable, this can be done with the bilge system. Before the water can be thrown overboard it must be processed by a bilge water separator in order to meet regulatory obligations. When the ship takes on water due to for example a crash, the bilge pump can throw the water overboard to prevent the ship from sinking.

Firefighting system

Two firefighting systems are present in the yacht, the Hi-Fog unit, and a firefight installation using seawater. For safety, and regulatory reasons the Hi-Fog unit cannot be in the engine room. One of the two firefight pumps is installed in the engine room to provide all fire hydrants from seawater. The second is installed in a different room than the engine room. The Firefight pump and the Bilge water separator are indicated in the 3D render of the engine room (Figure 3-1). In Table 3-3 are the components and interfaces given for the entire system. In Table 3-4 is the complexity given, and in Table 3-5 the necessary human effort in total and for the engine room specifically.

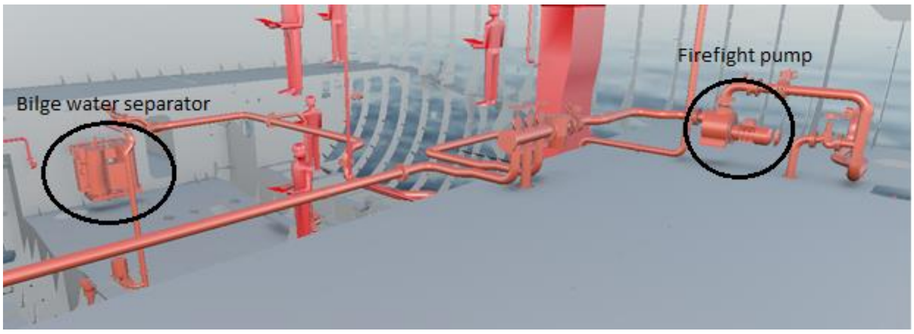


Figure 3-1 A 3D render of the bilge & firefighting system

Table 3-3 Components and interfaces in the bilge & firefighting system

Group	Amount [-]	Interfaces [-]
Equipment	4	16
Pumps	7	21
Appendices	45	90
Sensors	52	104
Valves	125	250

Table 3-4 Assembly complexity of the bilge & firefighting system

	Value
Total Existing Interfaces	481

Table 3-5 Human effort for the bilge & firefighting system

	Total	Engine room
Human effort [hr]	2181	981

3.1.2 Fuel oil system

The fuel oil system ensures fuel is supplied to the main engines, generators, and various other systems conform quality standards. The fuel oil system can be divided into three subsystems. The *fuel oil transfer system* which delivers fuel to the tanks, and transfers the fuel in between tanks. The *fuel oil treatment* system cleanses the fuel to the requirements set by the engine manufacturer. The *fuel oil supply system* delivers fuel to the main engines, generators, and other equipment. A 3D of the current state of the fuel oil system can be seen in Figure 3-2. Table 3-6 provides the number of components and the interfaces. Table 3-7 shows the complexity, and Table 3-8 the total human effort necessary in total and in the engine room.

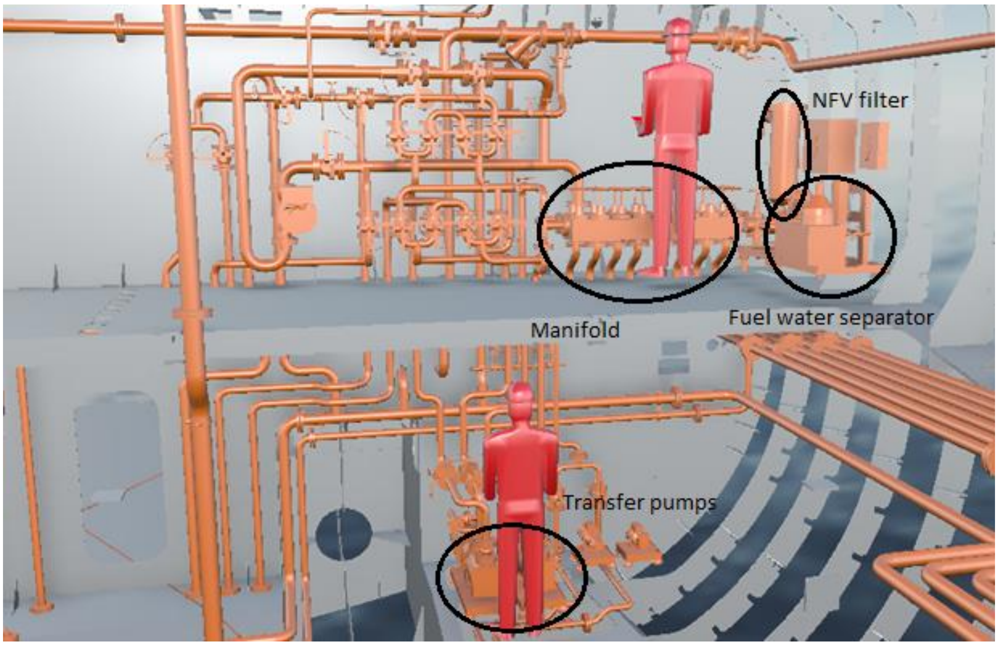


Figure 3-2 A 3D render of the fuel oil system

Table 3-6 Components and interfaces in the fuel oil system

Group	Amount [-]	Interfaces [-]
Equipment	11	30
Pumps	9	27
Appendices	38	76
Sensors	22	44
Valves	108	216

Table 3-7 Assembly complexity of the fuel oil system

	Value
Total Existing Interfaces	393

Table 3-8 Human effort for the fuel oil system

	Total	Engine room
Human effort [hr]	4500	2950

3.1.3 Seawater system

The third system is the seawater system. The Sea Water System is used for cooling of equipment, provides water for the water maker and can be used for firefighting. The water enters the vessel at the seawater inlet, two inlets are placed in case of constipation of one inlet. The inlets are protected with a system that prevents the attack of algae. The two inlets are connected with a crossover pipe, equipped with a mud strainer. Large pumps are used for the cooling of equipment; main engines, gearboxes, thrust bearing, generators and a freshwater heat exchanger. Moreover, it provides seawater for the chiller unit which cools water for the AC system. The chiller unit, seawater pumps, and the inlets are indicated in Figure 3-3. The number and type of components, and the interfaces are given in Table 3-9, the complexity is given in Table 3-10, and the human effort necessary is given in Table 3-11.

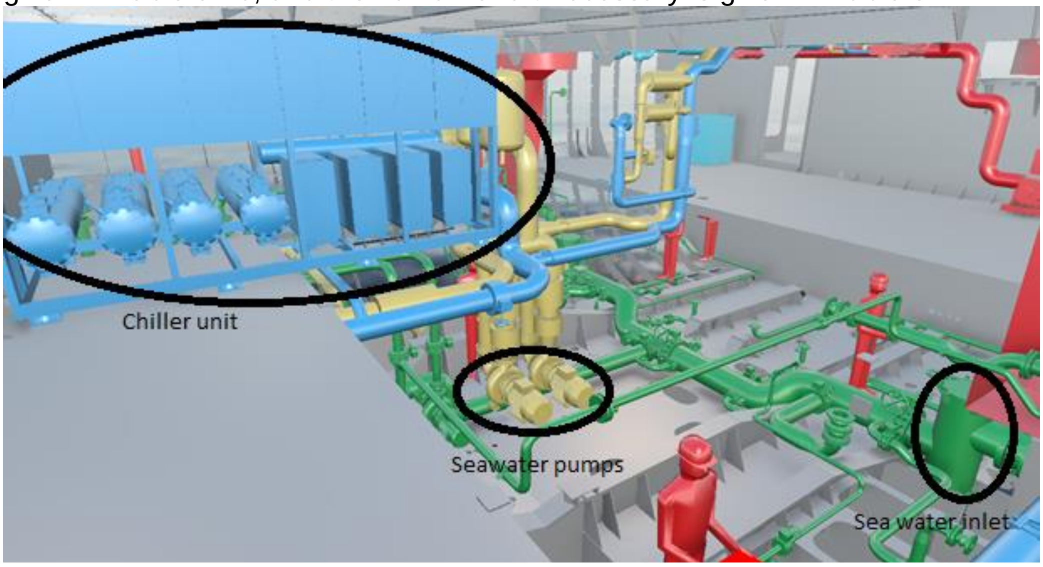


Figure 3-3 A 3D render of the sea water system

Table 3-9 Components and interfaces in the sea water system

Group	**Amount [-]**	**Interfaces [-]**
Equipment	3	9
Pumps	9	27
Appendices	68	136
Sensors	23	46
Valves	70	140

Table 3-10 Assembly complexity of the sea water system

	Value
Total Existing Interfaces	358

Table 3-11 Human effort for the sea water system

	Total	**Engine room**
Human effort [hr]	5060	4050

3.1.4 Domestic water system

The domestic water system is a complex system which can be basically be split up in two parts. The freshwater system, and the deck wash system. Fresh water can be obtained via three ways. The first way is to process seawater to fresh water. The second option is to acquire fresh water from a bunker vessel via the filling station. The last option is a fresh water shore connection. The seawater is lead to the water makers (reverse osmosis) and then stored in the freshwater tanks. Water acquired from the shore connected is lead to a water softener since the quality of the water is different quality in the world. The deck wash system is present in order to clean the outside of the yacht. This is done with demineralized and heated water. Various connections are available on-board the yacht so the yacht can easily be cleaned. The systems are visualized in Figure 3-4, 3-5 respectively. The water maker, boilers, and the water treatment unit are indicated in the first Figure. The Water purifier and the boilers are indicated in the second Figure. The number and type of components, and the interfaces is given Table 3-12. The complexity of the assembly is given in Table 3-13. The human effort necessary is given in Table 3-14.

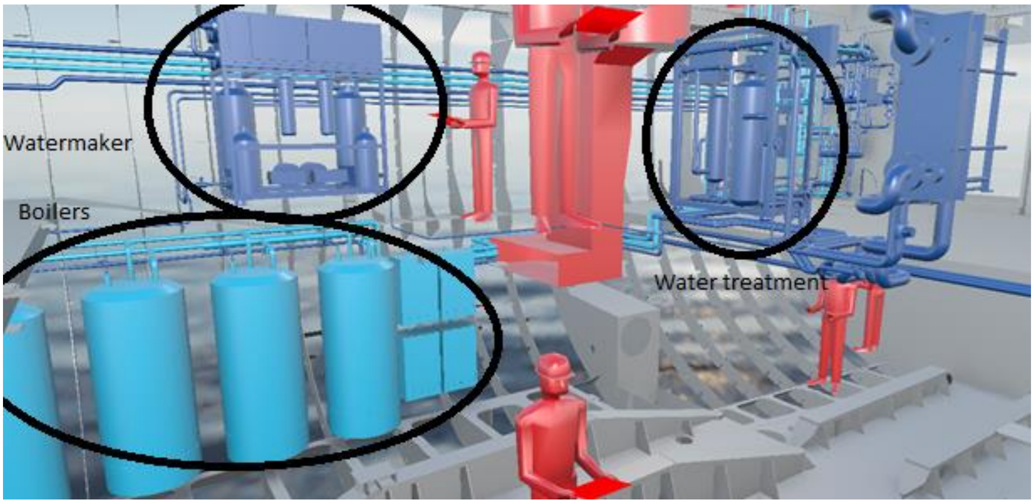


Figure 3-4 A 3D render of the domestic water system

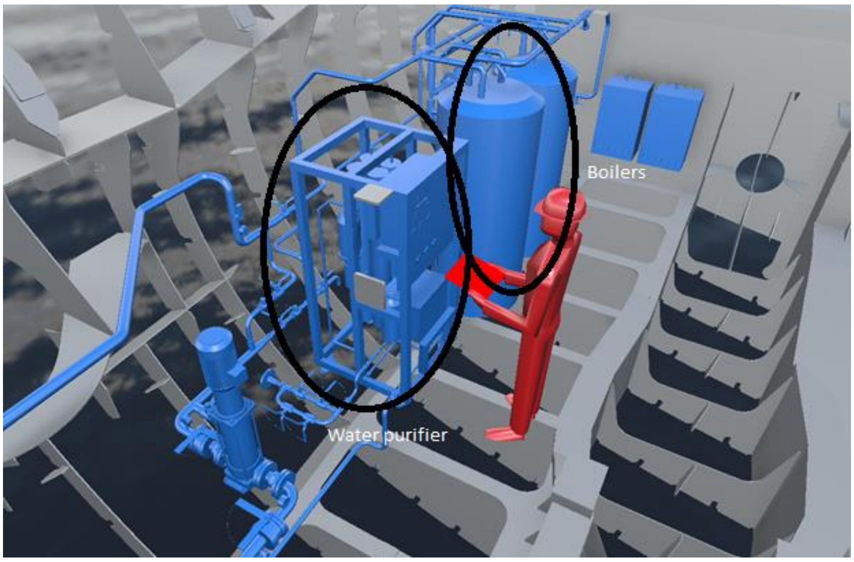


Figure 3-5 A 3D render of the deck wash part of the domestic water system

Table 3-12 Components and interfaces in the domestic water system

Group	Amount [-]	Interfaces [-]
Equipment	20	47
Pumps	8	24
Appendices	25	50
Sensors	44	88
Valves	169	338

Table 3-13 Assembly complexity of the domestic water system

Total Existing Interfaces	547

Table 3-14 Human effort for the sea water system

	Total	Engine room
Human effort [hr]	6045	2418

3.1.5 Black- & grey-water system

Blackwater is wastewater from toilets, it can contain bodily waste and toilet paper. Greywater comes from household equipment other than toilets, this includes water from showers and sinks. The black & grey water system processes this waste. The Treatment unit and the vacuum pumps are shown in Figure 3-6. The number and type of components, and the human effort necessary are given in Table 3-15. The complexity of the assembly is given in Table 3-16. The human effort necessary is given in Table 3-17.

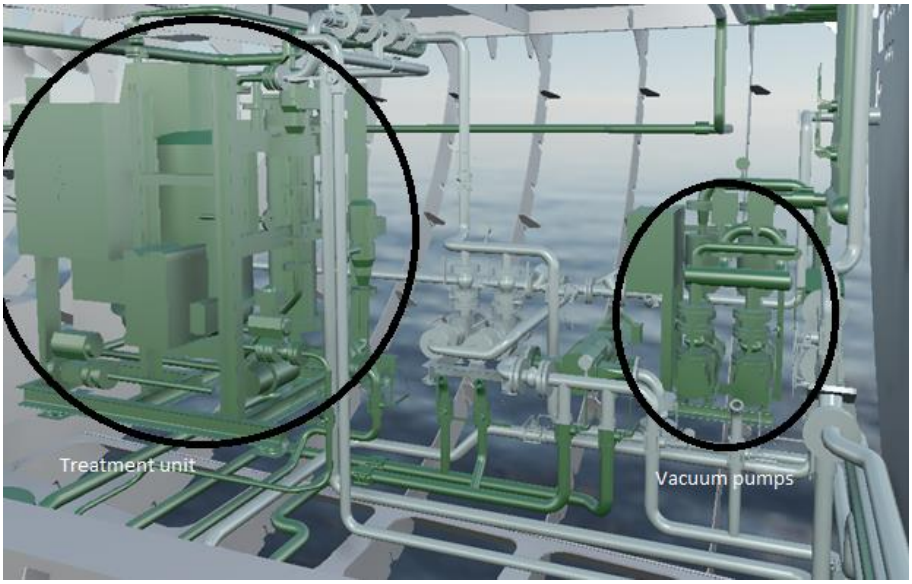


Figure 3-6 A 3D render of the black-& grey-water water system

Table 3-15 Components and interfaces in the black- & grey-water system

Group	Amount [-]	Interfaces [-]
Equipment	6	22
Pumps	3	6
Appendices	26	52
Sensors	16	32
Valves	67	134

Table 3-16 Assembly complexity of the black- & grey-water system

	Value
Total Existing Interfaces	246

Table 3-17 Human effort for the black- & grey-water system

	Total	Engine room
Human effort [hr]	7540	3770

3.1.6 Lubrication oil system

The lubrication oil system transfers clean oil to a connection in the engine room and the generator room. The Engines, gearboxes and generators can be filled via the filling cap through a hose with pistol. The dirty lubrication oil can be transferred from the engines and generators to a connection in the engine room and generator room via a hose. From the connection the dirty lubrication oil is transferred to the dirty lubrication oil tank. The clean lubrication oil is obtained via the filling station from a bunker vessel. The number and type of components, and the human effort necessary are given in Tabel 3-18. The complexity of the assembly is given in Table 3-19. The human effort necessary is given in Table 3-20.

Table 3-18 Components and interfaces in the lubrication oil system

Group	Amount [-]	Interfaces [-]
Equipment	0	0
Pumps	2	6
Appendices	24	48
Sensors	6	12
Valves	21	42

Table 3-19 Assembly complexity of the lubrication oil system

	Value
Total Existing Interfaces	108

Table 3-20 Assembly complexity of the lubcrication system

	Total	Engine room
Human effort [hr]	1493	1493

3.1.7 Working air system

The working air system is present to provide working air in the desired rooms of the yacht. In the engine room it is used to clean equipment etc. Table 3-21 provides the number of components, and the human effort in total and in the engine room respectively. The complexity of the assembly is given in Table 3-22. The human effort necessary is given in Table 3-23. A 3D render is nog helpful.

Table 3-21 Components and interfaces in the working air system

Group	Amount [-]	Interfaces [-]
Equipment	3	9
Pumps	3	9
Appendices	25	50
Sensors	2	4
Valves	21	42

Table 3-22 Assembly complexity of the working air system

	Value
Total Existing Interfaces	114

Table 3-23 Human effort for the working air system

	Total	Engine room
Human effort [hr]	1248	125

3.1.8 AC & ventilation system

The AC & ventilation system is extremely important in the yacht. The temperature and humidity in owner and guest accommodations should be perfectly regulated. Various AC-units are distributed along the yacht. The chiller unit provides cold water for these AC-units. Besides the accommodation the engine rooms should be ventilated as well. An external company is responsible for the AC & ventilation so the number of components could not be obtained, the human effort necessary to complete the system is available, and given in Table 3-24. The 3D render of the ventilation in the engine room does not provide much insight in the assembly process, and is therefore not included.

Table 3-24 Human effort for the AC & ventilation system

	Total	**Engine room**
Human effort [hr]	8786	1757

3.1.9 Propulsion system

The propulsion system consists of duplex form of the propeller shafts, the gearboxes and the main engines. the number of components is low, and could not be determined since they are provided by external suppliers. The human effort necessary to complete the system is available, and given in Table 3-25. A 3D render of the propulsion system is given in Figure 3-7.

Table 3-25 Human effort for the propulsion system

	Total	**Engine room**
Human effort [hr]	1493	1493

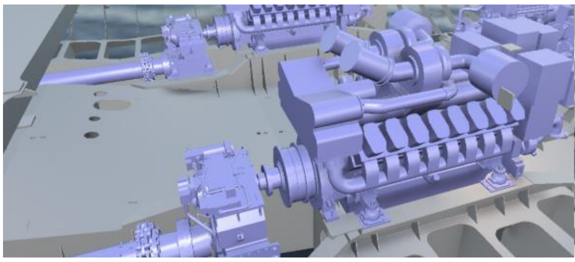


Figure 3-7 Render of the propulsion system

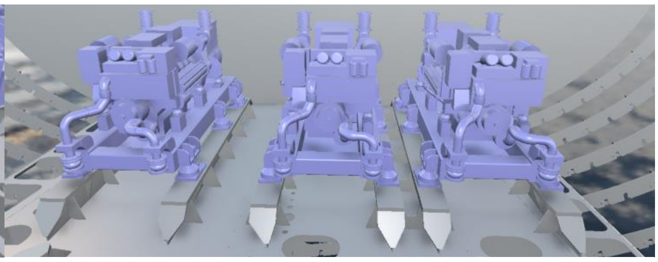


Figure 3-8 Render of the generating system

3.1.10 Generator set

Three generators can be used to power the yacht. The same reasoning is applicable for the generators as for the main engines. The number of components is not given, the human effort is in Table 3-26. A 3D render is given in Figure 3-8

Table 3-26 Human effort for the generator set

	Total	**Engine room**
Human effort [hr]	422	338

3.1.11 Ironwork & cable trays

The remaining category is the Ironwork & cable trays. Only the human effort is available, this given in Table 3-27.

Table 3-27 Human effort for the ironwork & cable trays

	Total	**Engine room**
Human effort [hr]	36505	12777

3.2 Current value time assessment

This part of the current state performance concerns the value time effect due to modularization. The co-production of the system is determined with production multiplier. Thereafter is the current gross margin given, since the customer pays for the entire yacht and not a system specifically a benchmark is set instead. Third, the current schedule is given and the resulting time to market. Fourth time current idle time of the equipment in the engine room is given.

3.2.1 Production multiplier

The production multiplier for the systems can be found in Table 3-28. The production multiplier is the value of the product added by the value chain divided by the total value of the product. It can be seen that the generator set and the propulsion system have a relatively high PMP, these units are bought from the supplier almost complete, and are expensive. The lowest PMP is the lubrication oil system. The investments for this system is low, the human effort in contrary is high.

Table 3-28 The production multiplier (PMP) per system

System exc. Piping	**PMP**
1) Bilge & Firefight system	1.58
2) Fuel oil system	1.70
3) Seawater cooling system	1.12
4) Domestic water system	2.50
5) Black & greywater system	1.87
6) Lubrication oil system	1.05
7) Working air system	5.65
8) AC & ventilation system	7.54
9) Propulsion system	8.16
10) Generator set	44.9
11) Ironwork & Cable trays	N.A.
Total	**3.26**

3.2.2 Gross margin

The ultimate goal for a company is to make a profit on their sales. The measure has been explained in the previous chapter. The yacht is sold as a whole it is therefore difficult to determine the exact gross margin made on a system. The exact gross margin is from the modularization perspective not extremely important, the difference in gross margin that can be achieved is. The gross margin of the current system is benchmarked at ten percent, see Table 3-29. This can be used to measure the change in performance due to the redesign later.

Table 3-29 The gross margin per system

System	**Gross margin**
1) Bilge & Firefight system	10%
2) Fuel oil system	10%
3) Seawater cooling system	10%
4) Domestic water system	10%
5) Black & greywater system	10%
6) Lubrication oil system	10%
7) Working air system	10%
8) AC & ventilation system	10%
9) Propulsion system	10%
10) Generator set	10%
11) Ironwork & cable trays	10%
Total	10%

3.2.3 Time-to-market

The current system assembly method is based on large scale outfit processes inside the engine room. This leads to schedule as shown in Table 3-30. A modular approach can significantly impact the time-to-market of the yacht construction. The current outfit process is currently 100 weeks, so almost two years followed up with 35 weeks of commissioning of the systems. It is expected that a modular system assembly approach can significantly reduce these durations.

Table 3-30 The schedule for the yacht in the case study

Activity	Start	Finish	Duration
DD, DO1	W1	W45	45 weeks
DO2	W91	W102	11 weeks
DE	W103	W119	16 weeks
Outfit	W137	W237	100 weeks
Delivery of equipment	W152	W153	1 week
Commissioning	W238	W273	36 weeks
Delivery		W274	

3.2.4 Idle time of equipment in engine room

The last indicator for the value time effect is the idle time of equipment in the engine room. If the equipment is installed in the engine room it takes up a lot of space making it more difficult for the workers to do their work. Moreover, the equipment in the engine room is susceptible for damage. Damage to equipment is reported due to welding, people standing on the equipment and breaking it, and many more examples. Another aspects is the delivery time of equipment. In a modular approach the value shift towards the supply chain, longer delivery times are expected. A shorter time of equipment in the engine room gives the supply chain more time the produce the modules. From an financial point of view, large investment can be postponed which result in a better value flow for the company. The current idle time of equipment is given in Table 3-31 below. The idle time is the moment of placement until the commissioning of the system.

Table 3-31 The idle time of equipment in the engine room

System	Idle time [weeks]
1) Bilge & Firefight system	86
2) Fuel oil system	86
3) Seawater cooling system	96
4) Domestic water system	86
5) Black & greywater system	86
6) Lubrication oil system	96
7) Working air system	86
8) AC & ventilation system	86
9) Propulsion system	86
10) Generator set	86
11) Ironwork & cable trays	N.A.

3.2.5 Value time curve

The indicators discussed in 3.2.1-3.2.4 all concern the value time effect. This section provides a schematic representation of this effect. The orange line in the Figure 3-9 represents the investment paid by customer. The payments are obtained from the total cost of the equipment and human effort with the ten percent gross margin. The payments are made on certain milestones according the specification made in the contract. The blue line is the investments made by the yard, around week 152 a large investment can be seen, this is the loading of equipment in the engine room. The cost of human effort is the constant linear line. The difference between the orange and blue line is the value flow.

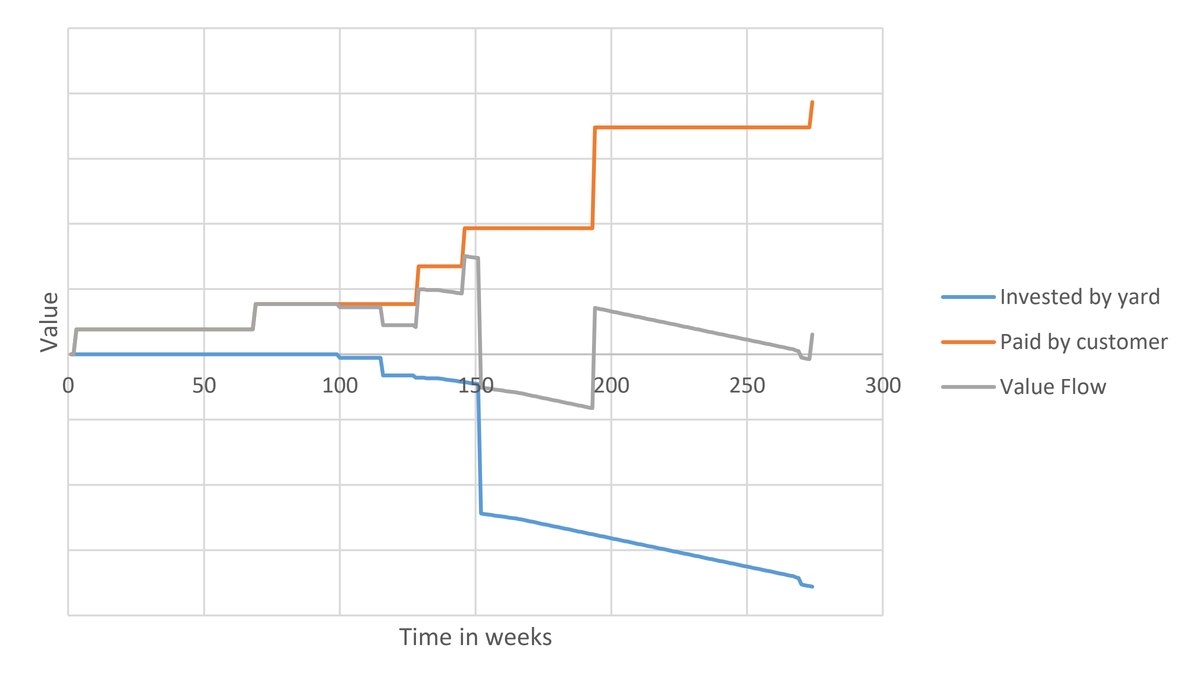


Figure 3-9 value time curve of the current engine room system assembly process

Sub research conclusion:

5. What is the current performance of the system assembly process?

In summary, the components of the systems are analysed. Based on this, the complexity of the interfaces could be determined, and thus the complexity of the assembly process in the engine room. The complexity is given in Table 3-32, where the total complexity is taken as one. Third, this complexity is related to the human effort for the yacht, and the engine room. This an overview of the human effort is given in third column of Table 3-32 The interfaces and thus the complexity cannot directly be related to human effort, since different systems have different requirements and thus different relations between complexity and human effort. This is the current performance of the on-board assembly process.

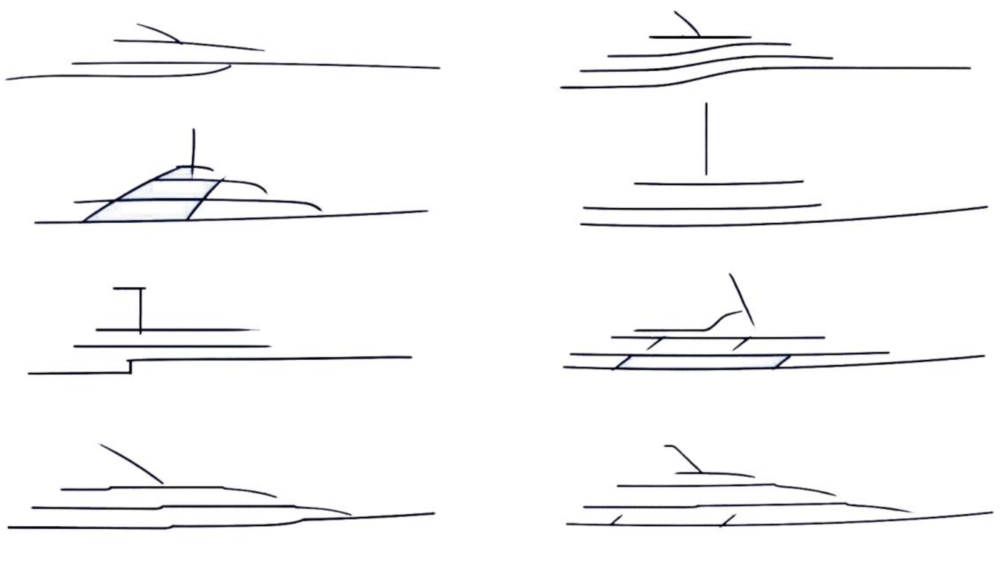
The second aspect is the supply chain of the current process. The current production multipliers have been given, this indicates the co-production of the systems. The gross margin has been explained and the Idle time of the equipment has been given, and related to the modular system assembly approach. All indicators are summarized in Table 3-32.

Table 3-32 The current performance of the system assembly in the engine room

System exc. Piping	**SCLI [-]**	**HE [hr]**	**PMP [-]**	**GM [%]**	**IT [wks]**
1) Bilge & Firefight system	0.22	981	1.58	10%	86
2) Fuel oil system	0.17	2950	1.70	10%	86
3) Seawater cooling system	0.16	4050	1.12	10%	76
4) Domestic water system	0.24	2420	2.50	10%	86
5) Black & greywater system	0.11	3770	1.87	10%	86
6) Lubrication oil system	0.05	1493	1.05	10%	76
7) Working air system	0.05	125	5.65	10%	86
8) AC & ventilation system	N.A.	1757	7.54	10%	86
9) Propulsion system	N.A.	1500	8.16	10%	86
10) Generator set	N.A.	338	44.9	10%	86
11) ironwork & cable trays	N.A.	12777	N.A.	10%	N.A.
Total	**1**	**32189**	**3.26**	10%	**N.A.**

III

ANALYSE



4. Current state analysis

The measurements given in chapter 4 indicate that the process can be optimized. The next step is an analysis of the bottle necks or constraints in the current process is performed. First the current state of the engine room assembly process is analysed to answer the seventh sub research question. Chapter 5.1 is devoted to the complexity of the engine room assembly. Second the value shift aspects is analysed. Third, different machinery install strategies are reviewed. These three chapter provide an answer to the seventh research question. Fourth, the current design for fuel oil system specifically is analysed in terms of assemblability. This analysis in chapter 5.4 provides an answer to sub research question 8.

Sub research question:

7. *What can be learned from the current state of the system assembly process in the engine room?*

8. *What can be learned from the current state of the fuel oil system design in terms of assemblability?*

4.1 System assembly analysis

For most systems there is a supplier who delivers the main component of the system. An example is this is the water maker for the domestic water system. The current way RVLS implements this unit in the system is completely custom. The remaining pumps are bought from a different suppliers, the same goes for the valves, appendices, and sensors. This leads to a high amount of components that needs to be installed on board, which can for each system be seen in chapter 4.1. Some of the remaining components cannot be installed in a modular form due to regulatory reasons. For example some of the valves should be in a certain compartment to ensure safety in the case of damage.

The complexity of certain assemblies is illustrated in Figure 4-1. Electrical cabinet is installed separately, Various piping is unnecessarily installed on board. Moreover this part of the bilge water system is installed close to the entrance of the engine room, the mechanical engineer who assembles the system is interrupted by other workers who need to pass. The engineer needs all his tools in the engine room, which takes time to bring them there. The restroom for employees is not on-board, the same goes for the restaurant for lunch breaks. In terms of lean this is not efficient.

The example in Figure X-X can be optimized and has already been done. The electrical cabinet, the monitor etc. can be installed on the skid at the workshop of the supplier. A lot less work is necessary on-board, which is aimed for.

A module where many of the piping, valves and sensors is already pre-assembled in a workshop would be highly beneficial. At RVLS there is not such a workshop yet available to build these modules. The carpenters have a workshop where they can make the interior. The mechanical department has a small workshop where only small ironwork such as support can be made. As is made clear in the literature it is not a core competency of RVLS to make the system modules. The next point of the analysis concerns the value shift towards the supply chain.

Figure 4-1 The complex version (left), and modular version (right)

4.2 Value time anlysis

The measure to quantify the co-production is the production multiplier. For the generators and main engines this production multiplier is extremely high. The supplier delivers the expensive system almost complete. For many other systems (bilge water system, fuel oil system, sea water system, domestic water system lubrication oil system, and the black & grey water system) it can be seen that the production multiplier is low. This means that RVLS does the largest part of the added value activities for these systems themselves. A closer collaboration with the suppliers can result in a higher production multiplier for these systems as well. By doing so, RVLS can focus more on their core competencies, and thus optimize their shipbuilding process.

In the current state performance the profit on each system, and thus the entire engine room is benchmarked at 10%. It is expected that the higher efficiency of the production process at the supplier will result in a cheaper system of the same quality. The profit for the shipyard will therefore increase. The value shift towards the supply chain will lead to longer lead times of the equipment. One solution would be to advance the order date of the equipment. Another possibility is to postpone the install moment of the equipment. This postponement will have various implications on the entire process, the next chapter will elaborate on this effect.

The shipbuilding process is a highly intergrated one. It is stated by Da Xu et al. (2012) that the assembly planning has a significant impact on the product delivery time, cost, quality, durability, and maintenance. During the planning of the production process, blocks are predefined. Limitations or other conditions which relate to the effectiveness of a particular shipyard are considered. Such considerations include the need to:

- Block erection process
- Strategy to install machinery in the engine room

To understand the engine room erection process, it should be made clear where in the shipbuilding process this takes place. Chapter 5.1.1 is included to elaborate on the engine room in the entire erection process. The erection process itself is taken as a hard constraint in the future state design of the engine room assembly process, since this is out of the scope of the reasearch. Chapter 5.1.2 elaborated on the second point, the strategy to install machinery in the engine room, this is of great importance in the research.

4.2.1 Erection strategy

This sub chapter elaboration on the erection strategy of the engine room. In Figure 4-2 are all sections of the yacht illustrated. The engine room, section 300 & 301 are indicated with a red circle. The building process officially starts with the Skeg, however this is purely for regulations, and is not used for months after construction. The actual block erection process starts with the foreship. Section 400 is the first section placed, sections are erected forward till section 700 & 7011. Thereafter, the section of the foreship (section 400) is connected to the engine room. The engine room itself is coded as section 300, the section aft the engine room is section 200. An overview of the relevant sections can be seen in Figure 4 – 2. The section with S100-S800 are made from steel, section S3-mast are made from aluminium.

Each section consists of "blocks", block 10 is the double bottom including tank deck, block 20 starts from the tankdeck up to, and including the intermediate deck or lower deck, and block 30 is from the intermediate up to, and including the maindeck as can be seen in Figure 4-3. The same annotations are used from now on in the report.

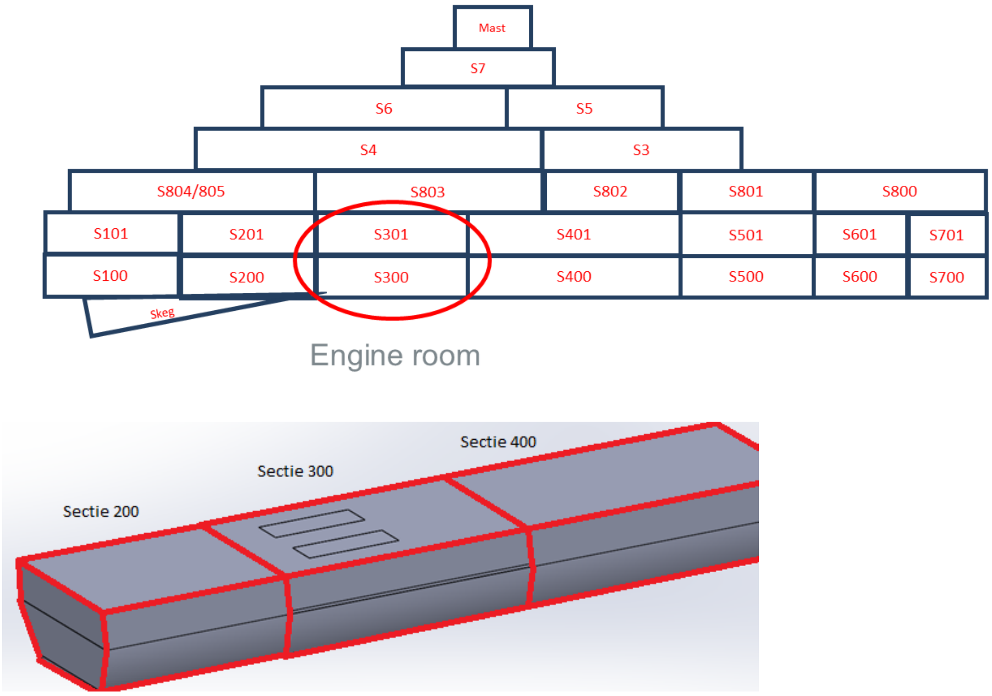


Figure 4-2 An overview of the sections (upper), where section 300 is the engine room, section 400 is part of the fore ship, and section 200 is aft the engine room (lower).

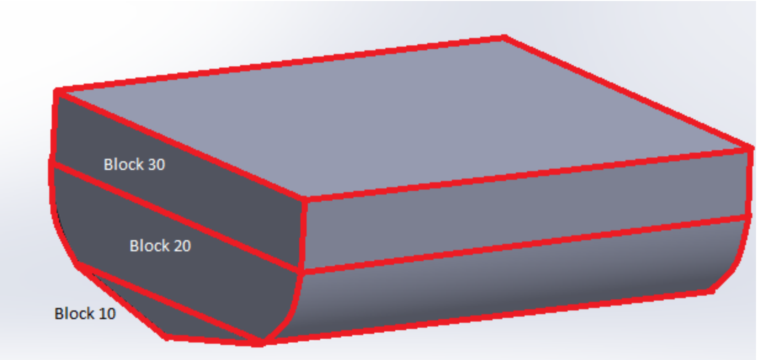


Figure 4-3 An overview of the blocks in the engine room, where block 10 is the double bottom, block 20 the lower deck, and block 30 the main deck.

Below (Figure 4-4) is a schematic diagram of the integrated erection, and the assembly of the engine room according to the current process. The production starts with the fore ship, the engine room is produced in a separate workshop, some of the hot work in the tanks is already done. The engine room section (300) is connected to the fore ship. Afterwards, section 200 block 10 is connected to the engine room. Now the tanks in the engine room can be tested for leaks, and the tank deck can be straightened. Thereafter, hot work phase 1 in the engine room can start. Hot work phase 1 consists of placing the foundations of the equipment, welding the insulation pins, cutting and welding the penetrations in the hull and bulkheads. After the hot work phase 1 is finished, painting phase 1 can start. Painting phase 1 consist of the painting of the foundations of the equipment, painting the engine room which needs to be insulated. Once the bulwark is placed, the entire hull can be straightened. After the straightening of the hull the tanks can be painted and the propeller shaft construction can be aligned. Then the engine room is loaded with equipment. Once the engine room is loaded, the superstructure can be placed. The main deck can be straightened, remaining hot work can be done on the main deck including the placement of the piping. Lastly the commissioning of the systems can start. The next chapter further elaborates on the machinery install strategies.

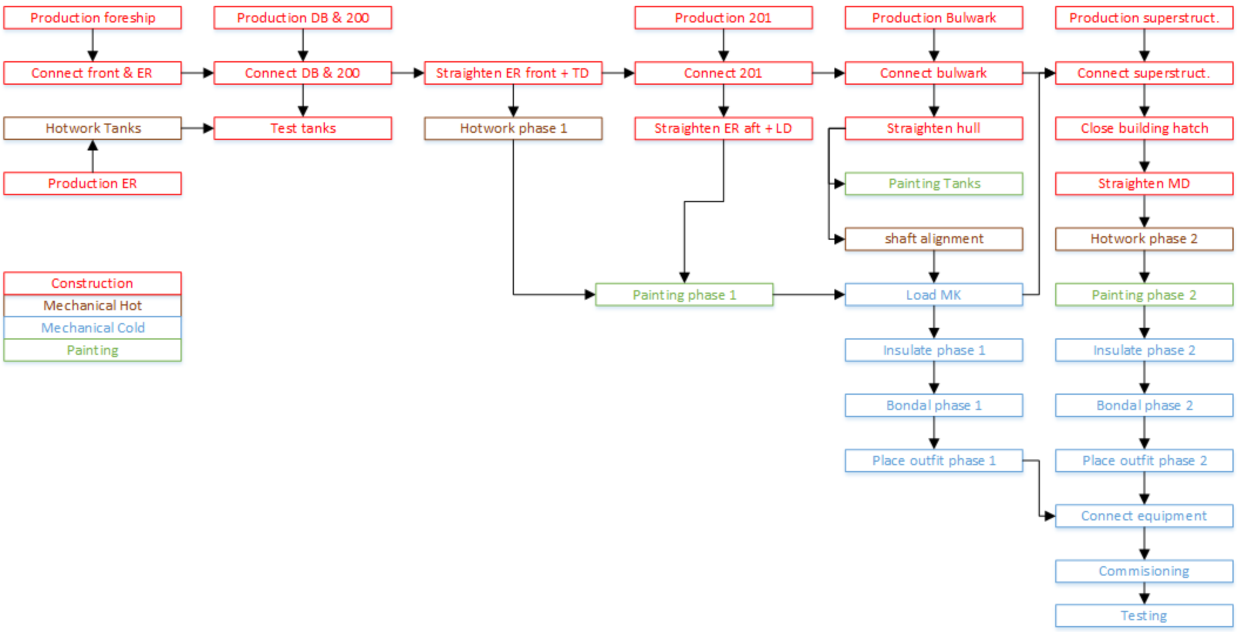


Figure 4-4 schematic overview of the current engine room assembly process

4.2.2 Machinery install strategies

The main challenge in the new production is the increased size of the outfit blocks. In the current production process at RVLS, most equipment is assembled on board. In the new strategy the building modules are significantly larger, the installment of equipment needs to be reviewed in order to place the larger modules. The following bottlenecks are found in the current production process: The protection of equipment, maximum module size, the limited movement space in the engine room, and some other attention points.

Protection of the equipment

In the current process a lot of hotwork is done when expensive equipment e.g. the generators and main engines are inside the engine room. When hotwork activities are performed near this equipment there is a significant risk to damage the equipment, therefore protection is needed. The generators and main engines are protected with welding blankets as can be seen in Figure 4-5. The rest of the equipment is protected with their original packaging or multiplex. The welding blankets can cost up to €10,000. For the other equipment the process is labor-intensive, the original packaging is removed, then the equipment is placed in the engine room, thereafter the packaging is placed again to protect the equipment. Moreover, even when te equipment is protected there is still a change to damage the equipment. A shortened time of equipment in the engine room will reduce the costs of damage.

Maximum module size

In the current process the hatches are the size of the main engines. Therefore the maximum module size is currently the size of the main engines. Once larger modules are used, different engine room loading strategies should be thought of. A picture of the current loading procedure of a generator is shown in Figure 4-6. The main engine will probabily still be the largest module but it should be kept in mind when determining the loading strategy.

Figure 4-5 A generator protected by a welding blanket

Figure 4-6 A generator is loaded in the engine room through the building hatch for the main engine

Limited movement space

Another sub-obtimal characteristic of the current process is the limited movement space for the equipment during the loading operations. As can be seen in Figure 4-7 the large module is manoevred to the final position in the engine room through narrow openings. When more equipment is placed in the engine room there is even less space for the remaining equipment.

A assembly sequence should be defined to ensure enough movement space in the engine room for the equipment to be placed.

Figure 4-7 Manoeuvring a generator to its final position in the engine room

Attention points
After the erection, and production of the sections, the hull straightness is not within the tolerances due to the welding. Especially at the frames, deformations happen due to the energy that has been put into the metal during welding. A method to smooth the hull is to straighten it (heat the material at specific placed, the material will shrink, and thus smoothen the hull). Other activities that should be done are the installation of the watertight doors in the watertight bulkhead. pressurizing of the tanks to test whether the tanks are leaking, cut the skin penetrations, weld the appendages, and various outfit activities.

Modules are already used in the current RVLS process, for example the main engines, generators, and watermaker. These large modules can't be placed via the existing hatches for the doors in the bulkhead. A dedicated building hatch has to be made in order to place these modules. The modules are transported within the engine room casco with the use of lifting eyes. Currently at RVLS, the size of the building modules is kept small so most equipment can be installed via the existing hatches in the bulkhead, independent from the temporary building hatch. More large modules will make the lifting schedule more complex,since there is not much space to move the modules.

Once the large modules have been placed, the hatches are closed. Currently this is done with a weld, since a welded hatch contributes to the stiffness of the construction. There are some drawbacks to a welded hatch, since it does affect the production process negatively because activities like painting, insulation etc. are postponed due to the heat input. An alternative is a bolded hatch, an elaboration on a bolted hatch can be found in the evaluation.

4.3 Design analysis of the Fuel Oil System

The fuel oil system ensures fuel is supplied to the main engines, generators, and various other systems conform quality standards determined in the design development phase. The fuel oil system can be divided into three subsystems. The *fuel oil transfer system* which delivers fuel to the tanks, and transfers the fuel in between tanks. The *fuel oil treatment* system cleanses the fuel to the requirements set by the engine manufacturer. The *fuel oil supply system* delivers fuel to the main engines, generators, and other equipment. A schematic overview of the supply, transfer and treatment system and their interfaces is given below in Figure 4-8. A 3D of the current state of a piece of the fuel oil system has been given in chapter 4. The bunker tanks are connected to the treatment units and transfer pumps via a manifold. After the treatment the fuel can go to a bunker tank or the service tanks. From the service tanks the fuel is distributed to the users.

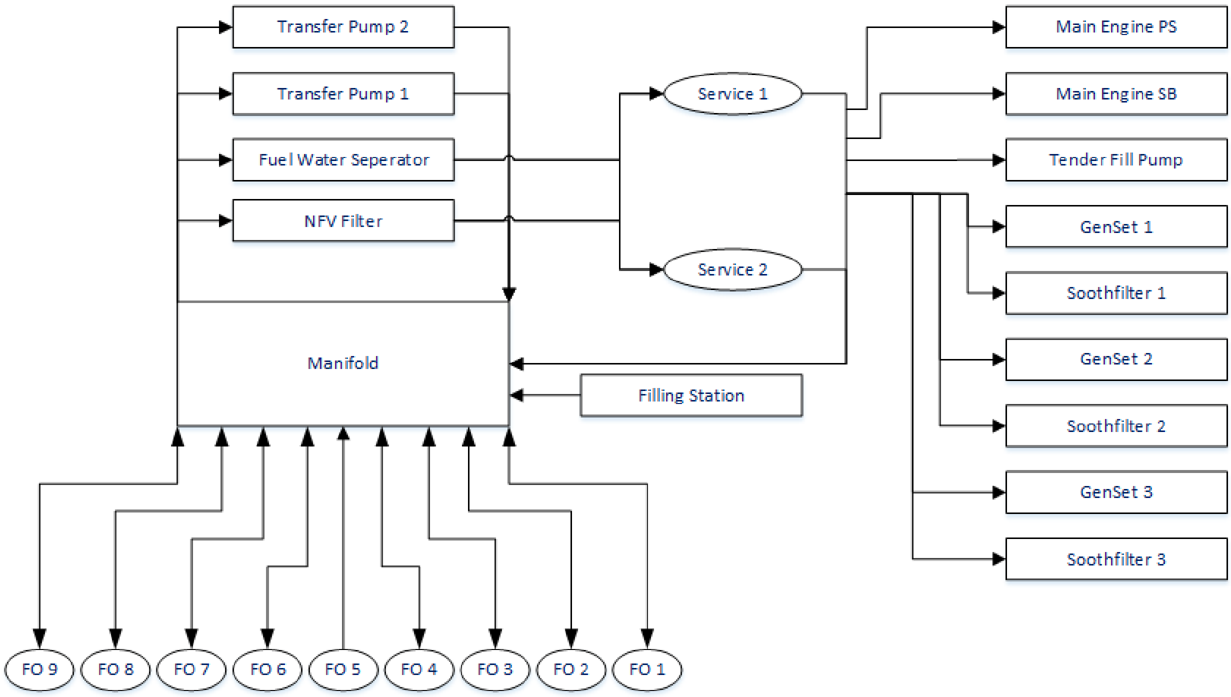


Figure 4-8 Schematic representation of the Fuel oil transfer, treatment and supply system.

Three main constraints can be found for an efficient fuel oil system assembly process. The first one being the many interfaces inside the complex engine room. This is complex in the engineering phase but also in the assembly phase. A lower number of interfaces in general and especially in the engine room would positively contribute to an efficient assembly process for the systems in the engine room. The second constraint is that many components like pumps, appendices etc. need to be installed on-board. It is stated in the literature review an eight times higher efficiency can be achieved inside a workshop. The third constraint is for two stakeholders inefficient. First of all for the mechanical engineers but also for the users of the engine room. The inefficiency is due to a multi-level system, the fuel oil system is partly on the tank deck and partly on the lower deck, from an operational perspective it would be beneficial to have the fuel system components close to one another.

Interfaces
The interfaces between the different components in the engine room given for the current state of the system are given in chapter 4-1. A total of 39 interfaces are present in the engine room, a lower number of interfaces should be aimed for in the future state. A lower number of interfaces will reduce the pipe routing in the engineering phase, and will reduce the human effort necessary for the assembly of the system. Currently, all bunker tanks are connected to the system via a manifold in the engine room. The manifold (Figure 4-9) is basically the hub in the fuel distribution network, an alternative should be sought to eliminate the manifold.

Components
Currently the fuel oil system consists of multiple sub-systems, two of them are predominantly in the engine room. These two sub-systems are analysed in this thesis namely the fuel oil transfer and the fuel oil supply system. It should be aimed for in the future state to limit the number of components, an place as much equipment, pumps, etc. as possible on the module. The higher efficiency of production workers in a workshop can be exploited.

The remaining systems are analysed in a less extensive manner. The main goal for the remaining systems is to minimize the number of components to be installed on board. For all systems a brief description of the major equipment is given. The number of all components in the system are given as well.

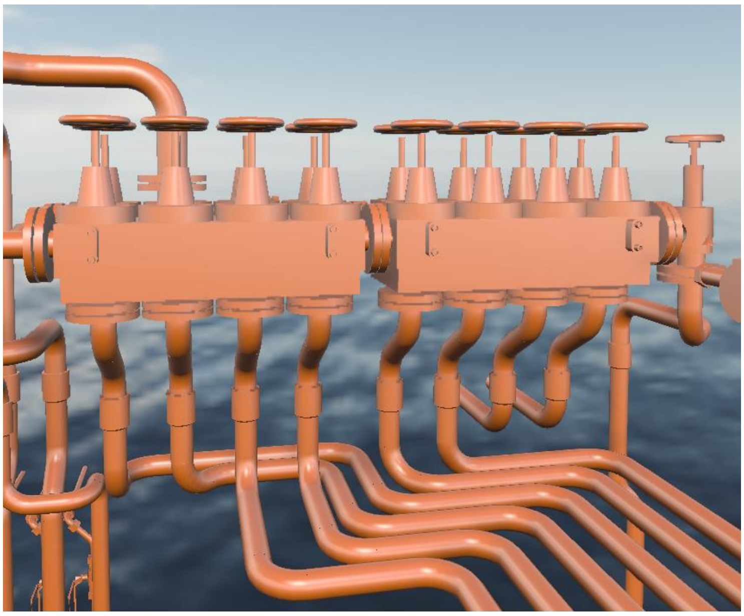


Figure 4-9 Manifold of the fuel oil system

Sub research conclusion:

7. *What can be learned from the current state of the system assembly process in the engine room?*

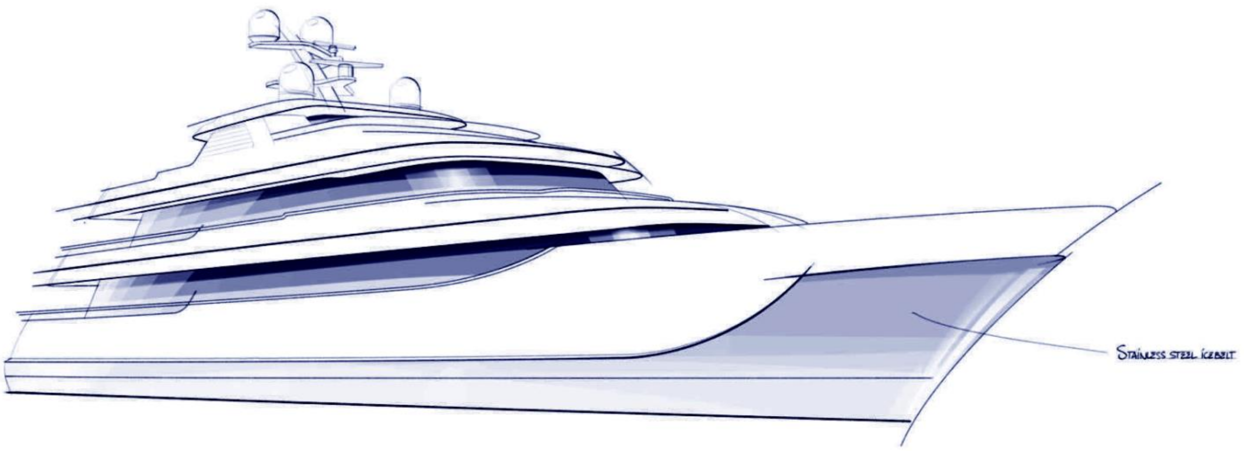
   The number of components to be installed on-board should be minimized. The human effort will move from on board to a workshop, which will likely result in a lower human effort overall. The modules are outsourced since this is not a core competency of RVLS. It is expected that the Gross Margin for the yard will increase. Lastly different assembly strategies should be design to postpone the placement of equipment in the engine room.

8. *What can be learned from the current state of the fuel oil system design in terms of assemblability?*

   The current design of the fuel oil systems should be optimzed in terms of assemblability. This can be done by reducing the interface complexity according to the SCLI, by reducing the number of components to be installed on-board. It is expected that the effect mentioned in sub research conclusion will be positively be affected.

IV

DESIGN



5. Design of the preliminary future state

The analysis of the current situation is done. The next step is to design the future state of the system assembly process. The first step in this chapter (5.1) is the determination of the modules, and the effects of them in terms of complexity and the human effort on-board. Thereafter (5.2), the value time effect of modularization is analysed. Here the effect of the co-production, the gross margin, the time-to-market and the idle time of equipment is determined. The last sub-chapter (5.3) is concerns the effect of a design for assembly on the fuel oil system.

Sub research questions:

9. *What system modules can be determined and what is the effect on the assembly processs?*

10. *What value time effects can be exploited due to modularization?*

11. *How should a system be designed for an efficient on-board assembly process?*

5.1 System assembly design

Some of the system are modularized, other are not. For the sake of completeness all systems are given, in Table 5-1 is an overview of what data is used for each system. For example the main engine is almost completely bought from an supplier, the parts and pieces could not be determined, the modularization is almost completely done and is therefore not (re-)modularized. The same reasoning is applicable for the AC & ventilation system, and the generators). The human effort and other investments for these systems is incorporated in the analysis so the evaluation is complete. The remaining systems are modularized by analysing the schematics and thereafter determining what can be put in the “module” or “skid”. The number of the subchapter is in line with the numbering in Table 5-1.

Table 5-1 Modularization (yes/no) of the systems in the engine room

System	Modularization	Human Effort
1. Bilge & firefight system	Yes	Yes
2. Fuel oil system	Yes	Yes
3. Sea water system	Yes	Yes
4. Domestic water system	Yes	Yes
5. Black & greywater system	Yes	Yes
6. Lubrication oil system	Yes	Yes
7. Working air system	Yes	Yes
8. AC & ventilation system	No	Yes
9. Propulsion system	No	Yes
10. Generator system	No	Yes
11. Ironwork & Cable trays	No	Yes

5.1.1 Bilge & firefight system

The first system is the bilge & firefighting system. Due to regulatory issues not all pumps and equipment could be installed on the module. For example there should be two firefighting pumps one of which cannot be in the engine room. It is therefore impossible to place this pump on a skid in the engine room. The components that can be put on the module are given in Table 5-2.

Table 5-2 Difference in components due to modularization on the bilge & firefight system

Group	Current [-]	New [-]	Δ [-]
Equipment	4	4	0
Pumps	4	2	-2
Appendices	40	32	-8
Sensors	48	43	-5
Valves	80	66	-14

The reduction in parts leads to a reduction in interfaces or connections that need to be installed on-board. First the Total Existing Interfaces are determined, thereafter the SCLI is calculated. This information is used to determine the necessary human effort. This information is for the entire system, later this is interpolated to the engine room specifically since the modules are placed in the engine room. The resulting interfaces, SCLI are given in Table 5-3.

Table 5-3 Difference in complexity and human effort due to modularization on the bilge & firefight system

	Current	New	Δ
TEI	481	421	-60
SCLI	0.22	0.19	-12.5%
Human Effort	2181 [hr]	1881 [hr]	-300 [hr]

5.1.2 Fuel oil system

The second system is the fuel oil system. This is a combination of the fill & transfer system, the fuel oil supply system, stripping system and de-aeration & overflow system. The last two systems mentioned is primarily pipeline, only a single pump is in these two systems. The reduction in components is predominantly impact by the fill & transfer system, and the supply system. The pumps, manifold, fuel water separator, etc. are placed on the skid. The results on the components is given in Table 5-4.

Table 5-4 Difference in components due to modularization on the fuel oil system

Group	Current [-]	New [-]	Δ [-]
Equipment	11	2	-9
Pumps	9	4	-5
Appendices	38	25	-10
Sensors	22	13	-9
Valves	108	53	-35

The reduction of components leads to a reduction in the complexity of the on-board assembly of the system. The effects on the fuel oil system are given in Table 5-5 below.

Table 5-5 Difference in complexity and human effort due to modularization on the fuel oil system

	Current	New	Δ
TEI	393	243	-150
SCLI	0.17	0.11	-38.2%
Human Effort	4500 [hr]	4100 [hr]	-400 [hr]

5.1.3 Seawater system

The third system is the seawater system. This system has many valves in the hull to control the flow of seawater in the yacht, obviously these valves cannot be placed on a skid in the engine room. The most important items that can be put on a skid are the large seawater pump to pump the water to the chiller unit of the yacht. These pumps and the accompanying valves, appendices and sensors can be put on the skid as well. The results are given in Table 5-6.

Table 5-6 Difference in components due to modularization on the sea water system

Group	Current [-]	New [-]	Δ [-]
Equipment	3	3	0
Pumps	9	5	-4
Appendices	68	52	-16
Sensors	23	7	-16
Valves	70	50	-20

The reduction of components, especially due to the four pumps can be seen in the complexity as well. The pumps, sensors etc. are assembled in a workshop, this reduces the on-board complexity of the assembly significantly, see Table 5-7. The total effect is a reduction of 400 human effort hours in the engine room.

Table 5-7 Difference in complexity and human effort due to modularization on the sea water system

	Current	New	Δ
TEI	358	242	116
SCLI	0.16	0.11	-32.4%
Human Effort	5060 [hr]	4660 [hr]	-400 [hr]

5.1.4 Domestic water system

The equipment of the domestic water system is predominantly in the engine room. The boilers, the water maker, the water treatment unit are all in the engine room. It should be noted this is not always the case, in some yacht this system is in a separate technical room. The four boilers installed, but all piping, heater elements etc. are installed on board. Substantial gains could be achieved by combining these. The water maker and water treatment unit are delivered as a unit but a lot of piping, sensors, valves are installed on-board to make the system fully functional. In this area of the system could significant part reduction be achieved. The total components that need to be installed on-board is given in Table 5-8.

Table 5-8 Difference in components due to modularization on the domestic water system

Group	Current [-]	New [-]	Δ [-]
Equipment	20	3	-17
Pumps	8	4	-4
Appendices	25	15	-10
Sensors	44	11	-33
Valves	169	71	-98

The domestic water system can basically divided in two system, the water used in the rooms etc. and the deck wash system to clean to yacht. The treatment, and heating of the water is in the engine room. The water is distributed to the rest of the yacht via a manifold in the engine room. A substantial reduction could be achieved of the complexity in the engine room. The results on the interfaces, complexity, and human effort is given in Table 5-9.

Table 5-9 Difference in complexity and human effort due to modularization on the domestic water system

	Current [-]	New [-]	Δ
TEI	547	202	-345
SCLI	0.24	0.09	-63.1%
Human Effort	6045 [hr]	5045 [hr]	-1000 [hr]

5.1.5 Black- & grey-water system

The fifth system is the black- & grey-water system. The water and other waste from the showers, toilets etc. is processed with this system. The waste is transferred from the accommodations to the engine room. The treatment unit, and pumps etc. are installed in the engine room, this location for the system is basic practice. The distribution network of the waste to the engine room cannot be modularized, but substantial gains can be achieved in the engine room. The treatment unit is delivered as a module in the current situation however, the valves, sensors etc. that are not delivered with the module are installed on-board. The most significant part count reduction is achieved with incorporated these components in the module. The effect on the components is given in Table 5-10.

Table 5-10 Difference in components due to modularization on the black- & grey-water system

Group	Current [-]	New [-]	Δ [-]
Equipment	6	4	-2
Pumps	3	0	-3
Appendices	26	15	-11
Sensors	16	14	-2
Valves	67	35	-32

The impact of modularization of the black- & grey-water system on the assembly complexity is given in Table 5-11, the reasoning for this reduction is similar to the domestic water system.

Table 5-11 Difference in complexity and human effort due to modularization on the black- & grey-water system

	Current	New	Δ
TEI	246	141	-105
SCLI	0.11	0.06	-42.7%
Human Effort	7540 [hr]	7040 [hr]	-500 [hr]

5.1.6 Lubrication oil system

The lubrication oil system is less interesting from a modularization perspective. The system is basically two pumps with some valves, pipelines etc. The part count reduction is given in Table 5-12.

Table 5-12 Difference in components due to modularization on the lubrication oil system

Group	Current [-]	New [-]	Δ [-]
Equipment	0	1	+1
Pumps	2	0	-2
Appendices	24	17	-7
Sensors	6	4	-2
Valves	21	11	-10

Although the system the least complex system, a significant reduction of the complexity could be achieved. However, the most effort for this system is in the pipelines. The results in the human effort are therefore less promising see Table 5-13.

Table 5-13 Difference in complexity and human effort due to modularization on the lubrication oil system

	Current	New	Δ
TEI	108	77	-31
SCLI	0.05	0.03	-29.7%
Human Effort	1493 [hr]	1443	-50

5.1.7 Working air system

The working air system is two compressors with a pressure vessel. The working air is distributed all over the yacht e.g. the air horn in the mast, and the connections in the engine room. Most of the system is pipelines, thus the most human effort is used for these pipelines, see Table 5-14.

Table 5-14 Difference in components due to modularization on the working air system

Group	Current [-]	New [-]	Δ [-]
Equipment	3	3	0
Pumps	3	1	-2
Appendices	25	23	-2
Sensors	2	0	-2
Valves	95	85	-10

Some of the valves, pumps, etc. could be placed in a module. This reduced the complexity of the system quite strong (Table 5-15), however, the human effort did not decrease significantly. Most of the human effort is in the distribution network.

Table 5-15 Difference in complexity and human effort due to modularization on the working air system

	Current [-]	New [-]	Δ
TEI	114	80	-34
SCLI	0.05	0.04	-29.8%
Human Effort	1248 [hr]	1218 [hr]	-30 [hr]

The systems bellow were not modularized, the reasoning is given in the beginning of chapter 5.1. for the sake of completeness the human effort is given below in Table 5-16, 5-17, 5-18, & 5-19.

5.1.8 AC & ventilation system

Table 5-16 Human effort for the AC & ventilation system

	Current [-]	New [-]	Δ
Human Effort	8786	8786	0

5.1.9 Propulsion system

Table 5-17 Human effort for the AC & ventilation system

	Current [-]	New [-]	Δ
Human Effort	1500	1500	0

5.1.10 Generator set

Table 5-18 Human effort for the AC & ventilation system

	Current [-]	New [-]	Δ
Human Effort	422	422	0

5.1.11 Ironwork & cable trays

Table 5-19 Human effort for the AC & ventilation system

	Current [-]	New [-]	Δ
Human Effort	36505	34505	-2000

A summary of the human effort necessary in the entire yacht for each system. The third column gives the human effort for each system in the engine room specifically is given in Table 5-20.

The fourth column gives the human effort the future modular state in the engine room, since all modules are in the engine room.

Table 5-20 An overview of the effect on human effort on-board due to modularization

System exc. Piping	Current tot. HE [hr]	Current ER. HE[hr]	Future ER HE [hr]
1) Bilge & firefight system	2181	981	681
2) Fuel oil system	4500	2950	2550
3) Sea water system	5060	4050	3650
4) Domestic water system	6045	2418	1418
5) Black & greywater system	7540	3770	3270
6) Lubrication oil system	1493	1493	1443
7) Working air system	1248	125	95
8) AC & ventilation system	8786	1757	1757
9) Propulsion system	1500	1500	1500
10) Generator system	422	338	338
11) Ironwork & Cable trays	36505	12777	10777
Total	75273	36868	31788

5.2 Value time effect

The effect on the on-board assembly process has been given. The second effect is the value time effect. The key peformance indicator change due to the modularization approach is given in the same manner as described in chapter 2, the method. First the production multiplier is given. Second the gross margin change is given. Third the time-to-market is given, and fourth a different machinery loading strategy is designed to postpone the placement of equipment.

5.2.1 Production multiplier

The produciton multiplier of the entire system assembly process in the engine room was 3.26, this increased with ten percent to 3.58. The highest increase in the production multiplier was achieved for the domestic water system. A large part of the system is installed in the engine room, the system could effectively be modularized. The shift from on-board to a workshop enables the LSSI to outsource the equipment. An overview of the produciton multiplier for the current case, future case, and the percental increase is given in Table 5-21.

Table 5-21 the production multiplier (PMP) for the current, and future system assembly process

System exc. Piping	Current PMP	Future PMP	Δ
1) Bilge & firefight system	1.58	2.09	32%
2) Fuel oil system	1.70	1.77	4%
3) Sea water system	1.12	1.18	5%
4) Domestic water system	2.50	3.80	51%
5) Black & greywater system	1.87	2.11	13%
6) Lubrication oil system	1.05	1.08	2%
7) Working air system	5.65	6.17	9%
8) AC & ventilation system	7.54	7.54	0%
9) Propulsion system	8.16	8.16	0%
10) Generator system	44.9	44.9	0%
11) Ironwork & Cable trays	N.A.	N.A.	0%
Total	**3.26**	**3.58**	**10%**

5.2.2 Gross margin

The second value time effect is the change in gross margin. It is expected that the increase of work efficiency due to specializiation can be seen in a lower cost for the system for the LSSI. The functionality of identicial is identical is therefore reasonable to assume the price the customer pays is also indentical. It could be argued that a modular approach will reduce the time-to-market, which would make it reasonable for the LSSI to charge more to the customer. For this analysis the price for the customer is kept identical. The price for the fuel oil system is determined with a supplier. The other prices for the systems are based on interviews with experts in the company. The highest gross margin increase is for the ironwork & cable trays. The investment costs for this category is really low, but the human effort is costly. A modular outfit approach will result in less pipeline supports, and less foundations. The highest effect of gross margin for a system is the domestic water system which is inline with the observation in the production multiplier. A large part can be outsources, thus a large part can be made in the efficicent workshop, thus the price off the equipment will reduce. The effect on each system is given in Table 5-22. The increase of gross margin of merely 2% is due to the main engines, the price for the main engines is extremely high, the impact of the other systems is therefore lower.

Table 5-22 the gross margin for the current, and future system assembly process

System exc. Piping	Current GM	Future GM
1) Bilge & firefight system	10%	21%
2) Fuel oil system	10%	13%
3) Sea water system	10%	16%
4) Domestic water system	10%	23%
5) Black & greywater system	10%	12%
6) Lubrication oil system	10%	11%
7) Working air system	10%	1%
8) AC & ventilation system	10%	10%
9) Propulsion system	10%	10%
10) Generator system	10%	10%
11) Ironwork & Cable trays	10%	30%
Total	10%	12%

5.2.3 Time-to-market

The third indicator of the value time effect is the time-to-market. The effect is analysed for the outfit and assembly phase. The modularization has a effect on the design phase, this was out of the scope. The engine room in a Feadship is small, especially when the equipment is installed. The number of people in the engine room is a bottle neck in this process. Using more workers would result in higher inefficiencies, even worse work conditions etc. The reduction of human effort is extraploted to the outfit and commisioning schedule. The outfit duration decreased from 100 to 86 weeks, the commisioning duration from 36 to 31 weeks. The total time-to-market could be reduced from 274 weeks to 255, a reduction of seven percent. The schedule for the future state can be seen in Table 5-23. It should be noted that this is the effect on the engine room, the interior, and yacht painters play an important role in the time-to-market of the entire yacht. It is however a good start which offers possibilities.

Table 5-23 the schedule for the future state of the engine room assembly process

Activity	Start	Finish	Duration
DD, DO1	W1	W45	45 weeks
DO2	W91	W102	11 weeks
DE	W103	W119	16 weeks
Outfit	W137	W223	86 weeks
Delivery of equipment	W152	W153	1 week
Commissioning	W223	W254	31 weeks
Delivery		W255	

5.2.4 Idle time of equipment in the engine room

The fourth indicators of the value time effect is the idle time of the equipment in the engine room, thus the time from the installment till the time of the commisioning. Currently the equipment is placed via two hatches in the main deck. As aforementioned, the added value activities shift towards the supply chain, thus the delivery times increase, thus the information for the suppliers needs to be available earlier. It would be benificial for the supplier, hence the

LSSI to postpone the placement of equipment. Another benefit of the later placement of equipment is reduced risk of damage of equipment. Currently the equipment is placed at the hull production yard, welding activities occur close to the equipment which could damage them if not protected properly. The next section will further elaborate on the possible strategies to install machinery.

Machinery install strategy

Two types of loading strategies could be identified, the current one via the main deck (MD), and the second one via the the main deck, and owners deck (MD+OD). Other strategies were analysed, however this resulted in an earlier installment date, this is not aimed for. First the current situation (MD) is described, second the MD+OD hatch is analysed.

Main deck hatch

Figure 5-1 illustrates the current building hatches in the main deck to load the equipment. The size of the hatches is based on the size of the main engines and are located right above the place of the main engines. The hull at the moment of the equipment loading is given in Figure 5-2. The arrow is the place of the engine room, Section 300, and 301.

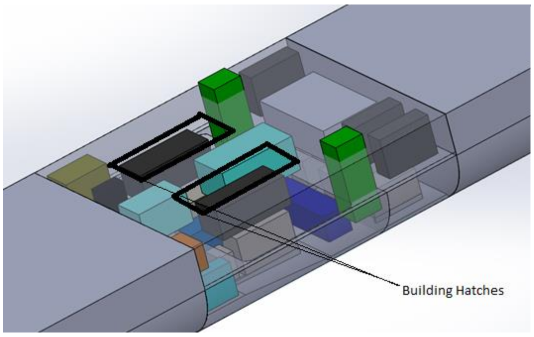


Figure 5-1 Modules in the engine room placed via a building hatch in the main deck.

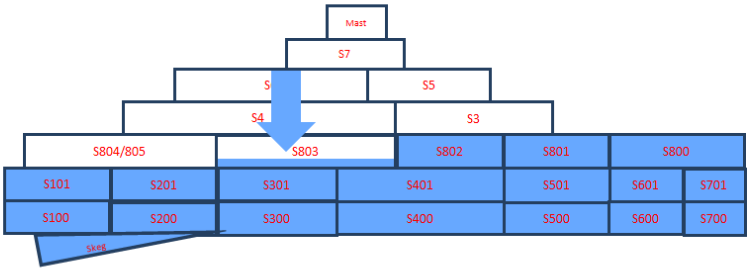


Figure 5-2 Hull stage when the equipment is loaded in the engine room with a building hatch in the main deck

Main deck & owners deck hatch

A loading strategy designed to delay the placement of the equipment for a better cashflow is with a building hatch in the main deck and the owners deck. More time is available for outfit activities before the loading activities which enables the yard to paint more before the equipment is placed, this results in better work conditions for the yacht painters. The hull stage when the equipment is loaded in the engine room is for this loading strategy is given in Figure 5-3. The equipment installweek could be postponed with 13 weeks. The results are given in Table 5-24

Table 5-24 The effect on the equipment placement week of different machinery loading strategies

Hatch	**Equipment install week**	**Idle time [weeks]**
Current	152	86
MD	152	71
MD+OD	165	58

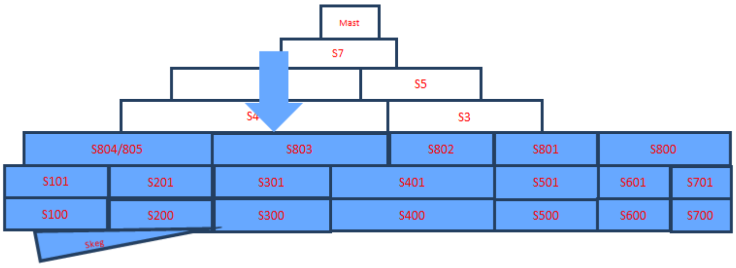
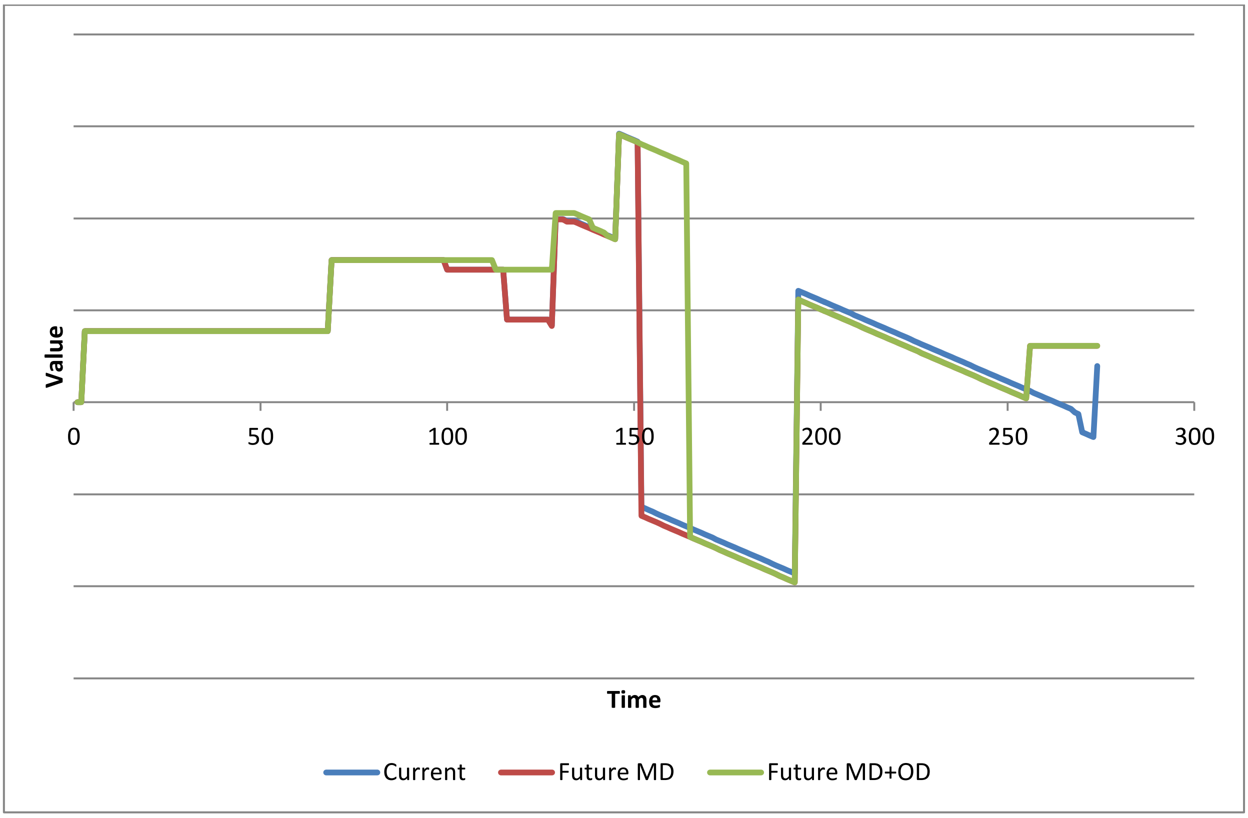


Figure 5-3 Hull stage when the equipment is loaded in the engine room with a building hatch in the main deck and owners deck

5.2.5 Value time curve

The value time effect can be visualized in the value time curve, see Figure 5-4 below. The postponement of the install moment of equipment results in a shortened negative cashflow for the company. It should be noted that the terms paid by the customer are extrapolated to system assembly costs, the other costs for example interior are not incororated thus it might not be a negative cash flow. However, in financial terms it is beneficial to delay large investements. The blue line is the current situation, The production takes until week 274. The red line is the same install strategy but now with the modules. The investment is slightly larger but the engine room is finished earlier, and cheaper. The green line is a different loading strategy of the modules. The equipment is loaded via the main deck, and owners deck, this results in a shorted time for the equipment in the engine room which is beneficial.

Figure 5-4 The value time curve of the engine room system assembly process of the current state, future state with a main deck hatch and main deck + owner deck hatch



5.3 Design for assembly of the fuel oil system

The last part of the design is the redesign of the fuel oil system from an assembly perspective. As shown in part 5.1, a reduction in complexity will result in a reduction of human effort on board. Chapter 5.2 showed that the outsourcing is beneficial. This chapter is devoted to elevate the performance of these two effects even more. First the interfaces in the engine room are optimized. The modularization in chapter 5.1, and 5.2 does not incorporate the purchase cost of piping, this analysis does. Moreover, the fuel oil system in 5.1, and 5.2 does include the de-aeration, and stripping system. This analysis does only include the transfer, and supply system.

Interfaces

The first constraints mentioned in the analysis is the high number of interfaces in the engine room. One important factor in this is that all piping of the bunker tanks is lead to the manifold inside the engine room. This is requires more time in the pipe routing in the engine room, the piping in the engine room is expensive due to the many bends in the pipes, and it is requires more time to assemble the pipes in the engine room. The following piping is designed in order to reduce the number of interfaces in the engine room as can be seen in Figure 5-5. Only two pipelines, a feed and a return line come from the bunker tanks to the fuel oil module in the engine room in contrast to the original 9. How the transfer pipelines are designed in the case study yacht can be seen in Figure 5-6. A side effect is that the valves are close to the tanks, thus they need to be remotely controllable from the alarm, monitoring, and control system. A manual mode is available in case of failure of the electric system, however the valves are only accessible via manholes which makes it difficult to operate them manually.

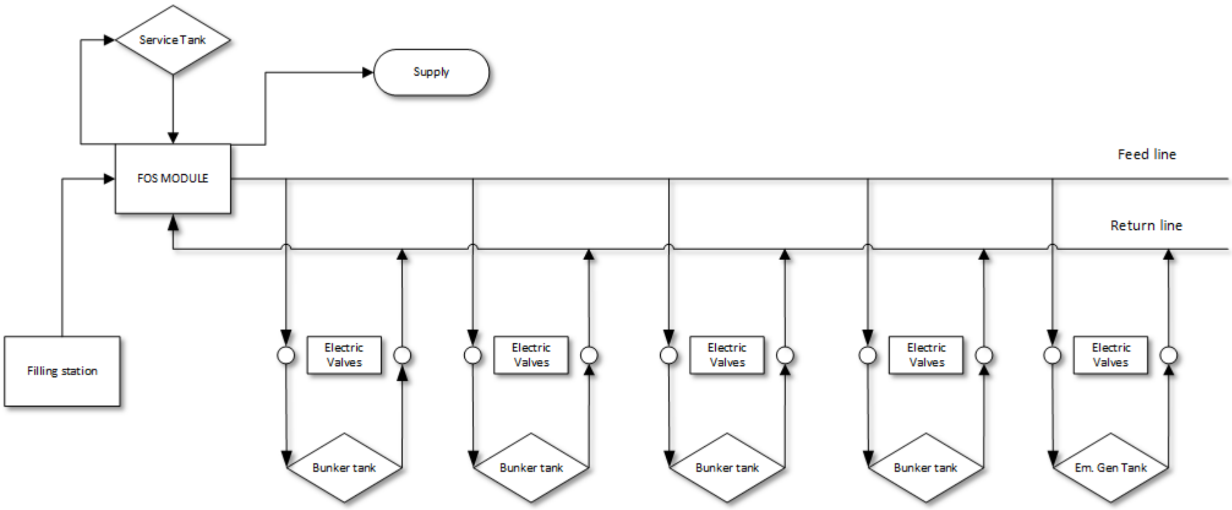


Figure 5-5 A schematic drawing of the future state fuel oil pipeline design

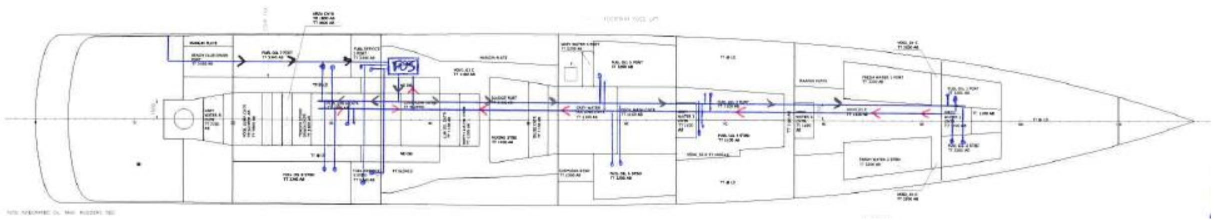


Figure 5-6 A schematic drawing of the future state pipeline design in the case study yacht

Components on the skid

In order to minimize the number of components the schematics of the fuel transfer & fuel supply are thoroughly analysed and discussed with engineers. The fuel transfer and supply system could be placed on one module. A significant reduction of components can be seen. This reduction is achieved by combining the pumps, equipment etc. on a module or skid. The skid is designed in close collaboration with a renowned company in the production of fuel oil treatment systems. The main component of the treatment unit, the fuel separator, was already bought by this company. A schematic drawing of the module with equipment, pumps and interfaces is given in Figure 5-7.

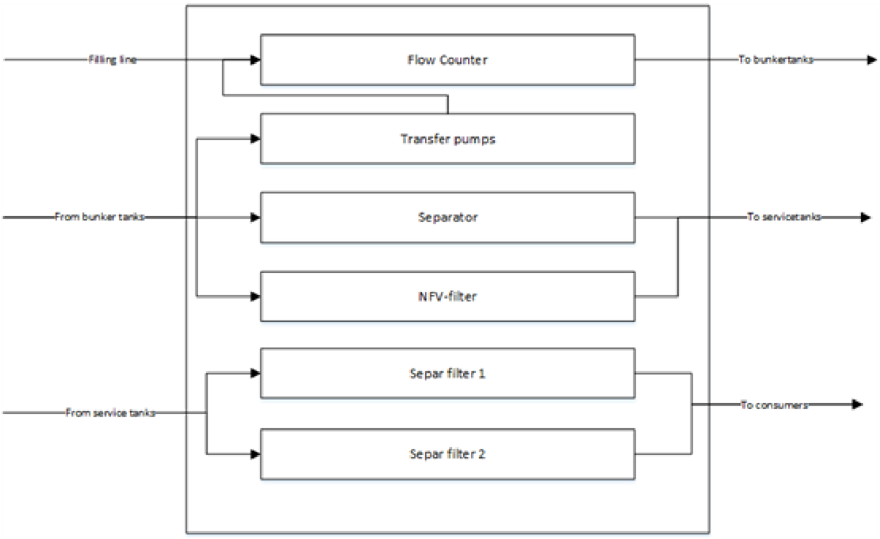


Figure 5-7 The future state module design of the fuel oil system

A feasibility study has been done, it is possible to make the skid 2500 X 1000 X 1600 mm. The footprint is thus 2,5 m^2, in comparison with approximately 4 m^2 in the current design. This is mainly due to the manifold. The result is shown in Figure 5-8, piping should still be routed. The electrical cabinet should be modelled as well. The cabinet can be placed on a high position in the skid, thus this will not cause any trouble. The fuel water separator, NFV-filter, NFV pump, Duplex-filters, tender pomp, fuel counter, and two transfer pumps are modelled (left to right).

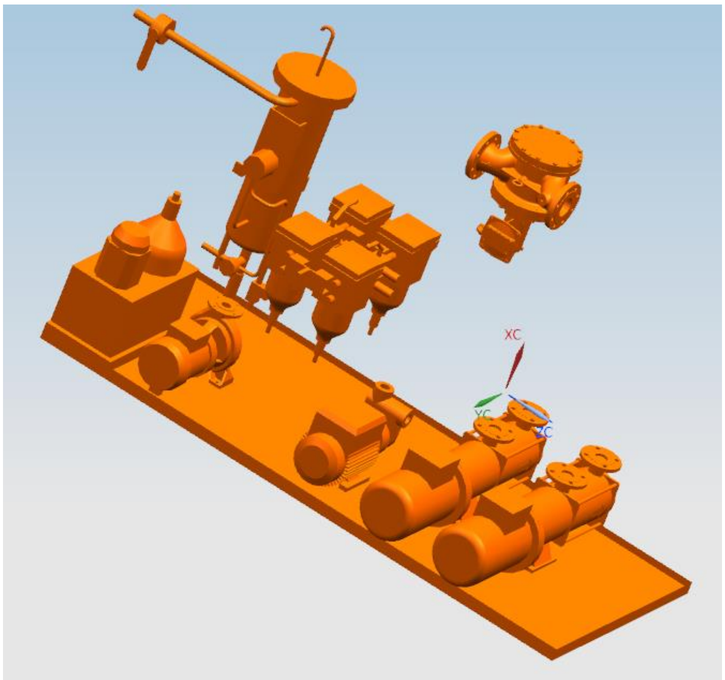


Figure 5-8 The 3D model of the preliminary future state of the fuel oil system.

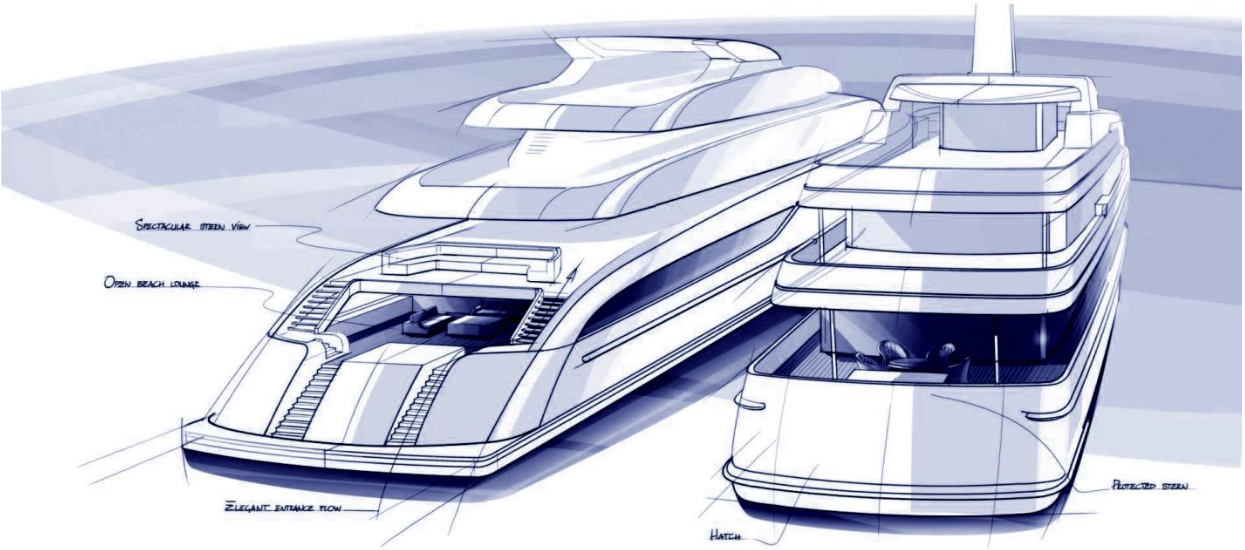
The first effect is the reduced complexity on-board, this could be reduced with 43%. The human effort decrease drastically since there is far less pipelines in the yacht. The production multiplier increases significantly, thus profit as well. The results and a comparison of the current and future state can be seen in Table 5-25.

5-25 the results of the redesign in terms of the KPI's

	Current	**Future Mod.**	**Future DFA**
1) SCLI	1	0.62	0.57
2) Human Effort	3980 [hr]	3480 [hr]	3080 [hr]
3) PMP	2.12	2.45	2.57
4) Gross Margin	10%	14%	19%

V

Evaluation



6. Performance assessment

The designed future state(s) can now be compared to the current state. The answer to sub-research questions 9-11 provides the comparison between the current and future state.

Sub research conclusion:

9. *What system modules can be determined and what is the effect on the assembly processs?*

The modules which are determined are closely related to the corresponding system. Many components could be installed in a workshop in the module, instead of on-board assembly. This could reduce the complexity of on-board assembly process significantly. This effect is observed in the human effort necessary for the on-board assembly of the systems. The results for each system are given in Table 6-1.

Table 6-1 The System Coupling Level Index, and the human effort for the on-board system assembly process

	SCLI		**Human Effort**	
	Current	*Future*	*Current*	*Future*
1) Bilge & firefight system	0.22	0.19	981	681
2) Fuel oil system	0.17	0.11	2950	2550
3) Seawater cooling system	0.16	0.11	4050	3650
4) Domestic water system	0.24	0.09	2418	1418
5) Black & greywater system	0.11	0.06	3770	3270
6) Lubcrication oil system	0.05	0.03	1493	1443
7) Working air system	0.05	0.04	125	95
8) AC & Ventilation system	N.A.	N.A.	1757	1757
9) Propulsion system	N.A.	N.A.	1500	1500
10) Generating system	N.A.	N.A.	338	338
11) Ironwork & cable trays	N.A.	N.A.	12777	10777
Total	**1**	**0.63**	**36868**	**31788**

10. *What value time effects can be exploited due to modularization?*

In the current process, a lot of work needs to be done on-board, thus the human effort directly results in the time-to-market for the engine room. The engine room is the most critical technical room in the yacht. The modular approach can reduce the outfit, and commisioning with 19 weeks, thus the yacht could be delivered from an engine room perspective. It should be noted that the interior and paiting also play an important role in the entire process, this should be done in a shorted time as well. The results for the Time-to-market, and the different machinery install strategies is given in Tabel 6-2.

Table 6-2 The time-effect, a comparison between the current, future main deck hatch, and future main deck + owners deck hatch.

	Current (MD)	**Future (MD)**	**Future (MD + OD)**
Delivery of equipment	W152	W152	W165
Time-To-Market	W274	W255	W255
Idle time of equipment	86 weeks	71 weeks	58 weeks

Due to the shift from on-board to a workshop, the LSSI is enabled to outsource the production of these modules since this is not a core comptence. The production multiplier is increased due to the shift to the supply chain. This increase in outsourcing results in a higher gross margin for the yacht. The bits and pieces i.e. valves, appendices, and sensors can be installed much more efficient in a workshop. The results of these different value asepcts can be seen in Table 6-3.

Table 6-3 The value-effect, a comparison of the current and future state in terms of the Production Multiplier (PMP), and the Gross Margin (GM).

	PMP		**GM**	
	Current	*Future*	*Current*	*Future*
1) Bilge & firefight system	1.58	2.09	10%	21%
2) Fuel oil system	1.70	1.77	10%	13%
3) Seawater cooling system	1.12	1.18	10%	16%
4) Domestic water system	2.50	3.80	10%	23%
5) Black & greywater system	1.87	2.11	10%	12%
6) Lubcrication oil system	1.05	1.08	10%	11%
7) Working air system	5.65	6.17	10%	1%
8) AC & Ventilation system	7.54	7.54	10%	10%
9) Propulsion system	8.16	8.16	10%	10%
10) Generating system	44.9	44.9	10%	10%
11) Ironwork & cable trays	N.A.	N.A.	10%	10%
Total	**3.26**	**3.58**	**10%**	**12%**

11. How should a system be designed for an efficient on-board assembly process?

The redsign of the fuel oil system predominantly concerns the way of transferring fuel between the unit in the engine room and the bunker tanks. This used to be done with a manifold in the engine room, this resulted in nine pipes from all tanks to the engine room. The future state uses a feed-return pipeline with branches close to the designtated tank. This drastically reduced the complexity, and the piping and thus further reduced the human effort. The Production Multiplier rose, hence the Gross Margin, the results can be seen in Table 6-4. It should be noted that the fuel oil system modular in SRQ 9 & 10 does not incororate the purchase costs of piping, and does incorporate the stripping and de-aeration. The DFA does include piping, and only the supply,and transfer system.

Table 6-4 Design for assembly of the transfer, and supply of the fuel oil system in comparison with the current, and the modular state.

	Current	**Future Mod.**	**Future DFA**
1) SCLI	1	0.62	0.57
2) Human Effort	3980 [hr]	3480 [hr]	3080 [hr]
3) PMP	2.12	2.45	2.57
4) Gross Margin	10%	14%	19%

7. Conclusion

This chapter presents the conclusion of this research. This research started since Royal Van Lent Shipyard recognizes the necessity to optimize their production process. The tendency of the increased size of the yachts, and an extra production facility in Amsterdam emphasise the need for optimization. Modular outfit has proven itself in the car manufacturing and the aircraft manufacturing industries. Therefore the following main research question was developed:

To which extent can an advanced modular system assembly strategy improve the current ship building process?

In order to answer this question, different sub-research question have been developed. The question and the answers to these questions are given below.

1. *How does the production process at RVLS relate to a conventional shipbuilding process?*

   The production of a super yacht has many similarities with conventional shipbuilding. The roughly the same phases in the engineering process were found. The names of the phases is different, the overall content is practically equivalent. The hull construction both start with panel construction and then section assembly. In the standard process was pre-outfitting mentioned, this strategy is not used by RVLS (yet). The blocks in a standard process are painted before the erection section, this can and is not done at RVLS due to the straightening (Dutch: strekken) of the hull. In both processes takes the outfit process place after the block erection. In the RVLS process the yacht is painted just before the launch at the hull production yard. In the standard process the ship is launched and then the final outfit activities are done with the ship along a quay. After the launch in the RVLS process the ship is transported to the yard in Amsterdam where the outfitting is finished and the interior is installed. The outside of the hull is painted several times, the yacht is launched for a second time and the final outfitting and testing is done along a quay.

2. *What can be learned from other industries from a modular perspective in order to optimize the assembly process of systems in a super yacht?*

   Modular assembly a branch developed form the Lean theory. Ford introduced the moving assembly line, this was optimized by Toyota to the Toyota Production System (TPS). This strategy was researched by MIT and named Lean Manufacturing. Lean has been question to be applicable in different industries than the car manufacturing industry. The super yacht industry may even be in an advantage, since the it is close the lean ideal of single piece flow, Built-To-Order (BTO). Another market which is BTO is the aircraft manufacturing industry. Suppliers in the aircraft manufacturing industry are involved in the co-development and production of entire functions of the aeroplane, The core competency of the Large Scale Systems Integrator like Boeing is the integration of these systems. It should be aimed for to minimize the complexity of this integration in order to make co-innovation possible. In the current aerospace market the driving factor for success or failure is the network a company operates in. Lean has proven itself in the car manufacturing and the aerospace manufacturing industries. It should be aimed for in the super yacht system assembly to reduce to complexity to make it possible to design effective modules. These modules can optimize the assembly process, this can lead to a better value flow for RVLS, the LSSI.

3. *What research lacks for an effective modular strategy in the ETO-shipbuilding?*

The quantification of the benefits in assembly time on-board can neither be found in literature not at the yard. The modular outfitting concept cannot be used in the same manner for different shipyards, this makes it difficult to quantify the benefits in a general manner. Therefore the modular system assembly is concept is widely seen a concept where considerable progress is possible to avoid the above mentioned obstacles. Larger standardised unitised, typified, and pre-assembled in workshops can be used to further improve the outfitting of ships. This research is aimed at the quantification of the effects of a modular system assembly strategy on the shipbuilding process. An addition to a modular system assembly strategy it to use design for assembly method. No literature has been found the design for assembly of systems for a modular system assembly strategy in shipbuilding. It is expected that the combination of design for assembly and a modular system assembly strategy can further improve the system assembly process on board of ships.

4. *What are the Key Performance Indicators for the system assembly process?*

The first order of effect is the on-board assembly complexity. The number of components are analysed, each components has a certain complexity in terms of the interfaces. The **(1) System Coupling Level Index** adapted for shipbuilding is used to measure this complexity. It is expected that this reduced complexity will result in a reduced **(2) Human Effort (HE)** on-board. The second order of effect is the time-value shift. The value shift towards the supply chain i.e. co-production. The measure for co-production is the **(3) Production Multiplier (PMP)**. It is expected that the supplier can assemble the module more efficient than the LSSI on-board. This efficiency increase will result in a higher **(4) Gross Margin (GM)** for the LSSI. The time effect can be explained as followed: the number of people on-board is limited, the human effort on-board will decrease due to modularization, the engine room can be completed earlier. This effect expresses itself in the **(5) Time-To-Market (TTM)**. Moreover, the lead time for the module will be longer in comparison with the current situation. It should be aimed for to postpone the procurement, thus the placement of equipment. Another benefit of this would be that the risk of damaging equipment will reduce. This effect could be expressed with the **(6) idle time of equipment**, the moment of placement until the commissioning.

5. *What are the Key Performance Indicators for an effective modular design in terms of assemblability?*

The third explained can be seen as an elevation of the future modular performance by using design for assembly. It is expected that the modularization strategy itself will elevate the performance of the current process. The current design is not optimized for the assembly yet. By reducing the interface complexity of the fuel oil system (transfer & supply) in a redesign, it is expected that the KPIs 1-4 (SCLI, HE, PMP, and GM) can be further improved.

6. *What is the current performance of the system assembly process?*

The first thing that should be measured is the complexity, this can be done with the SCLI. The SCLI is benchmarked for the current situation as one, this is the result of 2247 interfaces. The human effort necessary in the current situation is 368688 hours. The Production Multiplier of the current situation is 3.26. The Gross Margin could per system could not be retrieved for the systems, the current process is benchmarked at a 10% Gross Margin. The idle time of equipment in the engine room is generally speaking 86 weeks, some systems do not to be lifted during the install moment of machinery, the idle time of these is 76 weeks.

7. *What can be learned from the current state of the assembly process in the engine room?*

The number of components to be installed on-board should be minimized. The human effort will move from on board to a workshop, which will likely result in a lower human effort overall. The modules are outsourced since this is not a core competency of RVLS. It is expected that the Gross Margin for the yard will increase. Moreover, due to the a lower on-board necessary human effort this can exploited to reduce the Time-To-Market. Lastly different assembly strategies should be design to postpone the placement of equipment in the engine room.

8. *What can be learned from the current state of the fuel oil system design in terms of assemblability?*

The current design of the fuel oil systems should be optimzed in terms of assemblability. This can be done by reducing the interface complexity according to the SCLI, by reducing the number of components to be installed on-board. It is expected that the effect mentioned in sub research conclusion will be positively be affected.

9. *What system modules can be determined and what is the effect on the assembly processs?*

The modules which are determined are closely related to the corresponding system. Many components could be installed in a workshop in the module, instead of on-board assembly. This could reduce the complexity of on-board assembly process significantly. This effect is observed in the human effort necessary for the on-board assembly of the systems.

10. *What value time effects can be exploited due to modularization?*

In the current process, a lot of work needs to be done on-board, thus the human effort directly results in the time-to-market for the engine room. The engine room is the most critical technical room in the yacht. The modular approach can reduce the outfit, and commisioning with 19 weeks, thus the yacht could be delivered ealier from an engine room perspective. It should be noted that the interior and paiting also play an important role in the entire process, this should be done in a shorted time as well.

Due to the shift from on-board to a workshop, the LSSI is enabled to outsource the production of these modules since this is not a core competence. The production multiplier is increased due to the shift to the supply chain. This increase in outsourcing results in a higher gross margin for the yacht. The bits and pieces i.e. valves, appendices, and sensors can be installed much more efficient in a workshop.

11. *How should a system be designed for an efficient on-board assembly process?*

The redesign of the fuel oil system predominantly concerns the way of transferring fuel between the unit in the engine room and the bunker tanks. This used to be done with a manifold in the engine room, this resulted in nine pipes from all tanks to the engine room. The future state uses a feed-return pipeline with branches close to the designtated tank. This drastically reduced the complexity, and the piping and thus further reduced the human effort. The Production Multiplier rose, hence the Gross Margin. It should be noted that the fuel oil system modular in SRQ 9 & 10 does not incororate the purchase costs of piping, and does incorporate the stripping and de-aeration. The DFA does include piping, and only the supply,and transfer system.

12. What system installment process should be aimed for by the shipyard?
It can be seen that the modularization drastically reduces the on-board complexity. This effect can be seen in on-board necessary human effort. The shift from on-board to suppliers has a value-time effects on the system assembly process. The Production Multiplier can be increased, hence the Gross Margin. The Time-To-Market can be shortened with 19 weeks. A different machinery install strategy should be used to postpone the installment of equipment. Altogether all KPIs (used in this preliminary model) are positively affected by the modularization. The fuel oil system is redesigned with an design for assembly approach. The complexity could be further reduced which reduced the human effort even more. The redesign substantialy reduced the piping in the system, this is the main factor of the significant reduced human effort. The Production Multiplier, and Gross Marging are increased in comparison with the modular system, and even more in comparison with the current state of the fuel oil system. Thus, the modularization of systems should be aimed for at RVLS. The machinery should be installed via two hatches in the main deck and owners deck, instead of only the main deck. The redesign of the system, design for assembly, should be aimed for. The method is beneficial for one yacht. However, when the standaridzed units can be used in multiple yacht the effects will even be more significant.

The above given answers lead to an answer to the main research question. *To which extent can an advanced modular system assembly strategy improve the current ship building process?* A modular system assembly strategy results in a better assembly process. The first effect, a reduction of complexity in the engine room, indicated by the System Coupling Level Index, results in less human effort on-board. The value-time curve can be optimized when the effects of modularization are exploited. The effects of modularization can be further improved when design for assembly is used. A redesign of the fuel oil system has shown this.

8. Recommendations

The recommendation in this thesis is built up in two parts. The first part is the recommendations for future scientific research. The second part is the recommendations for RVLS.

8. 1 Recommendations for scientific research

Reliable data
An advanced planning model is developed (PERT) in this thesis, however due to the lack of reliable data it could not be used. The current process is too use such a model. Since modularization reduces the complexity of the process, the process can be better manageable. More research should be done in order to obtain reliable data for the activities. This is challenging since all shipyard operate in their own manner, therefore the data should be shipyard specific. Even within the shipyard a large variance can be seen in the installation of a “simple” component like a foundation. Another consequence of the lack of reliable data is the testing of the model. The developed model is not tested with reliable data. A verification is needed for practical use of the model, hence it is not used in this thesis yet. In the future it could be useful to manage the assembly process. Moreover, the human effort estimates are obtained from experts within the company. These are thus not the actual benefits, the effects should be measured carefully when the method is used in practice.

More case studies
The current analysis is done for one super yacht, and a particular focus on one particular system. An analysis on more yachts or even other complex-ships can provide better insight in the benefits of modularization in shipbuilding. A better analysis can be done for the other systems in the engine room, with the focus on reducing complexity. This can create broader support for a modular outfit strategy in complex-shipbuilding

Design perspective
This thesis was focused of the assembly process in the yacht. The reduction of complexity of the interfaces can result in a more efficient assembly process. The size of the fuel oil system module could be reduced by removing the manifold from the engine room, so the size of the module is not an issue (for the fuel oil system). For the other systems this analysis is not done, the impact on design for assembly on the engine room lay-out should be researched for all systems.

8.2 Recommendations for Royal Van Lent Shipyard

The developed strategies are assessed according to the key performance indicators. Not all effects of the strategies are included in this analysis. A modular strategy will affect production process in more aspects discussed in this research. The important aspects are given below with a short elaboration on further research for Royal Van Lent Shipyard.

Hatch type
The first effect discussed is the type of hatch used for the loading of equipment. In strategy 1, 3,4, and 8 the hatches are welded. A program at RVLS which is performed at RVLS at the time of writing is the “heetwerk vrij” program, in English “hot work free”. The goal is to finish all hot work activities when the hull enters the RVLS yard. Another option is to bolt he two hatches. The elimination of welding the hatches after the equipment is placed has three advantages. The first one has been said, the reduction of hot work in the engine room. The second is the reduction risk to damage the with the sparks of welding. The third benefit could be during a refit. If the main engines are replaced, a hole is cut in the hull, with a bolted hatch this might not be necessary, however further research is necessary to conform this reasoning. The major

drawback of a bolted hatch is the fact that it does not contribute to rigidness in the construction, in contrary to a welded hatch. In the engineering of the construction of the engine room it should be taken into account that there are two holes present above the main engines, with the size a main engine.

Foundation of equipment
In the current process the equipment is placed on the foundation and is kept in place with temporarily straps, so it will not moves during the transport to Amsterdam. In Amsterdam the equipment is lifted and threaded plates are welded so the equipment can be bolted to the foundation. The foundation can be painted only when the plates are welded to the foundation, otherwise toxic fumes will come free due to the burned paint. A method should be sought to directly bolt the equipment to the already painted foundation, this would reduce a lot of waste in the process.

Shaft alignment procedure
The shaft alignment procedure has been mentioned in the thesis, it was assumed that either a one-phase or a two-phase procedure can be used. The two-phase procedure is used to ensure the bearing are perfectly aligned with propeller shaft in order to minimize vibrations and thus noise. The one-phase shaft alignment is used in other super yacht yards, but an analysis on the impact should be done.

Customer management
If more modules are used in the engine room assembly, the customer must make decisions in an earlier stage of the project. Certain decisions for the fuel oil system should be made in the design development stage, the person who guides the development of this system for the customer, the chief engineer, is not always appointed in this stage of the process.

9. Discussion

The limitation of the research are discussed in this chapter. The first the role of the piping is discussed in the system and how this is used in the thesis. Second, the reliability for the human effort estimates is discussed. Third some assumptions are made on the cost of this human effort, these are elaborated on. Lastly the implications on the module sizes are discussed.

Piping
The piping system in the yacht is built up in spools. The spool drawings were not available for the yacht yet when this thesis was conducted. Each spool has two connection, the inflow and the outflow. These are not incorporated in the model (yet), for both the current and future state. The modular strategy, and more so the design for assembly strategy will reduce to number of piping installed on-board. The complexity will further reduce when this is incorporated in the model. Since the costs of piping is not yet available for the yacht and a it is difficult to make good assumptions on the effect of modularizations for this, this is not incorporated in the investment costs for the yacht. For the modular strategy the piping used will remain practically the same, thus will the investment costs. The reduction of human effort on-board due to the piping is incorporated based on the experience of expert at RVLS. The effect on the piping due to design for assembly is incorporated in the model, The reduced complexity significantly reduced the amount of pipe spools, thus the investment and instalment costs for piping.

Reliability human effort estimates
Another point of discussion is reliability of the estimates in human effort on-board. The opinion of experts is used to find the human effort estimated of the modular state, and the design for assembly effects. There are two factors identified that could question the reliability of these estimates. First of all, it has been mentioned that Royal Van Lent built customer yachts. The estimations by the yard for the human effort are good, but not perfect. The yacht has not yet been built so both the current performance as well as the future performance is estimated to the best of their knowledge by experts at the yard. A better estimate would be provided by the exact “as built” human effort, this is how ever not possible. A direct comparison of the same yacht with the current strategy and the future strategy is not possible since every yacht is custom. Second, there probably is a difference in work efficiency and quality of the workers at Royal Van Lent Shipyard at Kaag and the workers at the hull production yard, but the experts are familiar with this difference. However, the case study yacht is not built at Kaag but in Amsterdam. The case study yacht has not been built yet, the data is based on experience of people at De Kaag, the work conditions could be different in Amsterdam, which could lead to a different amount of work. Examples of the differences could be, other walking distances for the employees, a better accessible yacht, a different lay-out of the yard. These effects are not taken into account.

Reliability cost estimation human effort
Different activities can be done by different suppliers, and at different yards. The price for human effort could thus be different for all activities, moreover the price could be different tomorrow. The price for all human effort is kept identical in this research. The reliability of the real cost of human effort could be better if the human effort is contracted with suppliers. It should be noted that a modular system assembly strategy will reduce human effort, more equipment is bought directly from the supplier. It is easier to get insight in the total costs of the entire products.

Reliability cost estimation modules
The cost of the equipment is analysed with the invoices of the equipment, thus reliable estimates, or even exact. The price of the module is discussed with the supplier of the fuel oil system, it is not on exact but a good estimate. The price for the remaining modules is estimated with experts from RVLS, the experts have a lot of experience with suppliers. The estimates are

good estimations but cannot directly be used. The cost should be discussed and negotiated with the relevant suppliers.

Module size
A drawback of modularization from literature is the increased size of the modules. A indicative analysis was done on the sizes of the modules with the help of experts to prove the feasibility of modularization for the specific yacht. Currently every system is designed for each specific yacht, of more standardized modules are used with less interfaces on-board. More effect can be put into the design, thus a compacted system can be achieved. This analysis is done for the fuel oil system and was proven to positively impact the size of the system. The analysis should be done for the other systems as well.

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Appendices

Appendix I: Modularization potential

System	Labour costs system/ total labour costs	Distribution rating	Standardization potential
Bilge	5%	2	2
Firefighting	11%	4	2
Fuel oil	10%	2	1
Seawater	10%	1	1
Fresh water	17%	4	2
Black & grey water	9%	4	2
Lubcrication oil	2%	1	1
Compressed air	3%	3	3
HVAC	17%	4	3
Remaining	15%	n.a.	n.a.

Appendix II: Improvement methodology literature

Three main objectives of the Toyota Production System (TPS) are to eliminate the three M's:

1. *Muri* – design out overburden. When operators or machines are overloaded, it can result in machine breakdowns, and illness among employees which is highly undesirable.
2. *Mura* – remove inconsistency. The goal should be to systematically decrease variation in a production process.
3. *Muda* – eliminate waste, the waste in a process can be categorized in the following seven categories.
    1. *Overproduction* – more products are made than demanded by customers.
    2. *Waiting* – periods of inactivity in a downstream process when upstream processes have not delivered on time.
    3. *Transport* – Unnecessary motion or movement of materials
    4. *Over processing* – operations such as rework, reprocessing, handling or storage due to defects, overproduction or excess inventory
    5. *Inventory* – raw material, work-in-progress, and finished goods that are not directly required to fulfil
    6. *Motion* – the extra movement that employees, and equipment make to accommodate inefficient layout, reprocessing, overproduction or excess inventory
    7. *Defects* – Finished goods or services not conform the specification

The Toyota production process is schematically illustrated in Figure 1. All steps will be elaborated on in the following numeration:

- *Just-in-time* – Is a methodology primarily aimed at reduction of flow times within a production as well response time from suppliers. Making exactly what is needed, exactly when it is needed, and exactly the amount that is needed
- *Jidoka* – means automatic implementation of quality in order to produce defect free products
- *Takt time* – is the average time between start of production of one unit, and the start of production of the next unit
- *Pull flow* – means produce a product only when it is demanded by the next production step or customer
- *Man-machine separation* – if machines can stop themselves in the case of a problem there is no need for a human to stand, and watch machines. Man-machine separation frees people on the work floor.
- *Heijunka* – this is a Japanese term which refers to a system which levels the production in order to get a more constant flow.
- *Standard working* – the standardized work is well specified takt time, precise work sequence and, inventory. Improving standardized work is a never-ending process.
- *5S* – the letter S is the first letter of five Japanese which translate in English to: sort, set in order, shine, standardize and, sustain. The method describes ow to organize a workspace effective by identifying and, storing the items used, maintaining the area and, sustaining the new order
- *Kaizen* – this word means improvement in English. It refers to continuously improvements of all kinds, large and, small over a long period (Dinero, 2005).
- *Stability* – all of the above mentioned principles lead to a stable work process, which is highly desirable

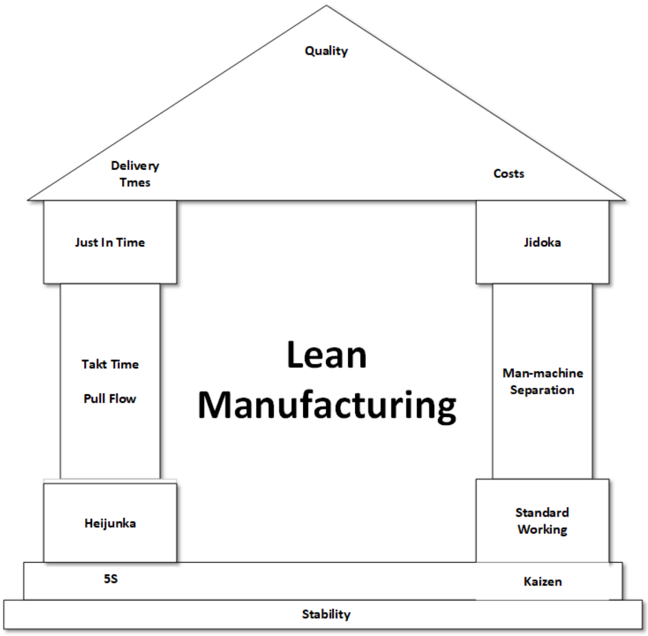

Figure 1 the house of Lean Manufacturing

A more comprehensive theory of Lean production is Lean thinking. This philosophy involves eliminating waste and, links the steps that create value. The five key principles of lean thinking are given below:

1. Precisely specify value by a specific product
2. Identify the 'value stream', the set of all specific actions required to bring the product to market
3. Make value flow without interruption
4. Let the customer 'pull' value from the producer
5. Pursue 'perfection'

In conclusion the philosophy of Lean is about building effective supply and, demand networks to produce products. (Beelaerts van Blokland, Santema, & Curran, 2010)

Value stream mapping
Value Stream Mapping (VSM) is a method that maps the flow of the transformation of raw materials into the final product. The premise of the VSM is to understand the customer's perspective, improve throughput, reduce the cycle time, and help design a production system (Jeong & Phillips, 2011). In this method the supervisor, foremen etc. are an integral part of the process planning. The planning facilitates the planning process, does the managing of the planning tool, analyses reports etc. However he does not set dates, defines no durations, and gives no hours consumption estimates.

Theory of Constraints
Theory of Constraints (TOC) is developed by Eli Goldratt in the mid-1980s. A constraint is anything that prevents the system from achieving its goal. Every system has a constraint, if not the profit would be infinite. The constraints labelled as negative, but as positive since constraints are opportunities for improvement (Goldratt, 1988). The main assumption of TOC can be measured, and checked with the following three factors.

1. *Throughput* – the speed that the entire production process generates money
2. *Inventory* – the money that has been invested in purchasing things which it intends to sell
3. *Operating expense* – The money that is spent to turn inventory into throughput

The constraints can be removed in with the following five steps given below, and illustrated in Figure 2:

1. *Identify* the system's constraint(s), and prioritize them according to their impact on the goal(s) of the organization.
2. *Decide* how to exploit the system's constraint(s). For physical constraints the objective is to make the constraint as effective as possible. For a managerial constraint the goal should be to eliminate it, and replace it with a policy which will support increased throughput.
3. *Subordinate* everything else to the above decision. In other words, every other component of the system must be adjusted to support the maximum effectiveness of the constraint. Because throughput is dictated by the firm's constraints. The most effective manner of resource utilization is obtained when the resources are synchronized with the constraint. If non-constraint resources are used beyond their productive capacity to support the constraint, they do not improve throughput but increase unnecessary inventory (Lockamy & Cox, 1994).
4. *Elevate* the system's constraint(s). The overall system performance can only be improved by eliminating the constraint in the critical path. This constraint should be optimized with rigorous improvement efforts until it no longer the constraint of the system.
5. *Repeat* the steps, if a constraint is broken. Do not let inertia become the next constraint. The first part of this step makes TOC a continuous process. The second part is a reminder that no policy is appropriate for all time or in every situation. Since the environment changes, the policy of the business has to change as well. If this step is not implemented this may lead to an organization disaster (Graham, 2000), (Rahman, 1998).

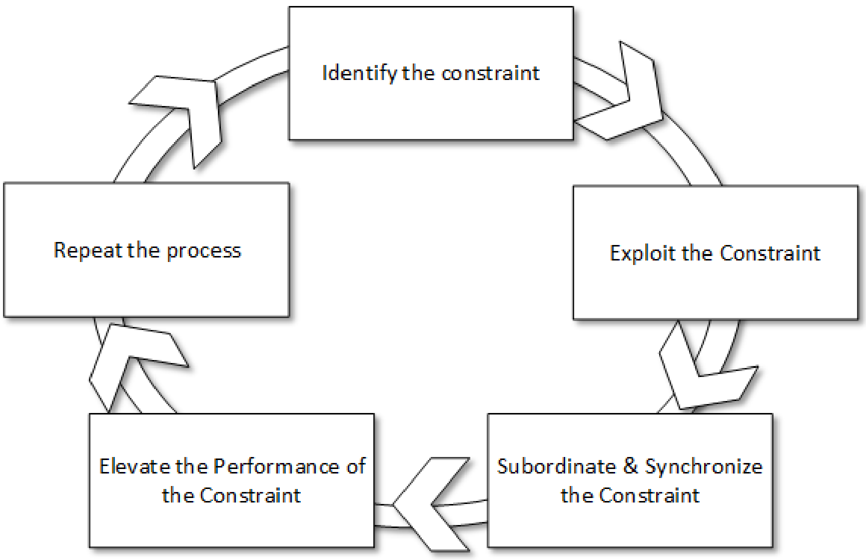

Figure 2 Theory of Constraints, optimization cycle

TOC identifies three types of (internal) constraints:

1. *Equipment* – the current (use of) equipment limits the system to produce more products
2. *People* – Lack of skilled people limits the system
3. *Policy* – A policy either written or unwritten prevents the system to produce more products

Appendix III: Scientific paper

An advanced modular system assembly strategy for complex-shipbuilding

A Case study in the Dutch super yacht industry

M. Schoonhoven, Dr. W.W.A Beelaerts van Blokland, Dr. Ir. J.M.G. Coenen

Abstract* – A strategy is necessary to improve the assembly process of super yachts. Literature on improvement methodologies from different industries suggest that a reduction of system complexity can lead to a more efficient assembly process. A less complex system in terms of assemblability can be achieved by modularization of these systems. Literature suggest that the performance of a modular strategy can be further elevated by with a strategy called "design for assembly". The System Coupling Level Index is adapted for shipbuilding. A reduction in the complexity results in less human effort on-board. This enables the LSSI (Large Scale System Integrator) to positively change the value-time curve of the assembly process. The shift from on-board to a workshop enables the LSSI to outsource the production of the modules, this is indicated with the Production Multiplier (PMP) adapted from the 3C model. The outsourcing of these modules leads to a higher Gross Margin (GM) on the system for the LSSI. Moreover, the time effect is a reduced lead time of the engine room. A different machine install strategy can reduce the idle time of equipment in the engine room. This reduces the risk on damage of equipment and gives the suppliers more time to produce the modules.

I. Define

This section consist of the introduction and the method. The introduction identifies, defines the problem. The method provides a literature review and the preliminary future model to measure the performance of the system assembly process.

1) Introduction

The demand for superyachts is high, only a number of shipyards are participating in this expanding market [1]. A superyacht can be seen as a complex-ship, the ship is Engineering-To-Order (ETO) according to the specific wishes of the customer. The core production process (up to 70%) in complex-shipbuilding are the outfit activities [2][3]. Since the steel construction becomes less important in comparison with the outfit activities, substantial gains can be achieved in optimizing the outfit process [4]. The length of the yachts is increasing, more man hours are necessary to complete the yacht [1]. A significant increase in Time-To-Market (TTM) is not accepted by the customers. There is a need for optimization in the production of super yachts. Significant improvement in the assembly process of cars is established with a modular strategy. This strategy was evolved from various optimizations of the Toyota Production System. Besides the car manufacturing industry, modularization has improved the production process of aircraft manufacturing significantly. A modular outfit strategy might be effective for the super yacht assembly process as well, in particular the assembly of systems. This research is therefore aimed at answering the following main research question: *To which extent can an advanced modular system assembly strategy improve the current ship building process?* The structure of this research is adapted from the improvement methodology Six Sigma, DMAIC. This abbreviation stands for Define, Measure, Analyse, improve, and Control. The last two phases are changed to design, and evaluate respectively. The define part consists of the introduction.

2) Method

In order to optimize the super yacht assembly process, the process at the yard should be related to a conventional shipbuilding process. A conventional shipbuilding process is adopted from [4][5].The key differences are given below:

1. There is no pre-outfit done in the analysed process (outfit prior block erection)
2. Painting cannot be done prior block erection due to the straightening of the hull.
3. The hull is transported from the hull construction yard to the outfit dry-dock via sea.

Pre-outfit might be useful in a future assembly strategy. The straightening of the hull is a hard constraint with the current tolerances of the hull production. The transport of the hull is a hard constraint as well.

Various improvement methodologies have been developed [6][7][8]. Most of the methodologies originate from the car manufacturing industry, many of them have been proven to be beneficial in the aircraft manufacturing as well [7][9][10]. Similar to the aircraft manufacturing industry, the shipyard acts as Large Scale System Integrator. Two core competencies of a LSSI are (1) the integration of systems, and (2) creating the best supply chain network. The hypothesis that an advanced modular system assembly strategy will lead to the following three order of effects:

1. The on-board human effort can be reduced by reducing the on-board complexity.
2. Improve the value-time curve of the assembly process of the ship by outsourcing the modules and a different machinery install strategy.
3. Design optimization (design for assembly) can reduce the complexity further, thus further elevate the performance of the modular system assembly strategy

First the complexity should be measured. A measure has been developed for an assembly line of a fire extinguisher, the System Coupling Level Index (SCLI) [11]. The Total Existing Interfaces (TEI) is divided by the Total Possible Interfaces (TPI). It was assumed that every station in the line can be connected to every other station, so 5 modules leads to a TPI of 15 interfaces. This does not make sense when e.g. a pump is observed. The pump has an inflow, an outflow, and an electrical input, hence the Total Possible Interface definition is not applicable to shipbuilding. The Total Existing Interfaces does show potential to be used in interfaces since an interface is an assembly action. The total existing interfaces can be determined for each system, and thus for the all systems together. The current complexity for all systems complexity is benchmarked at one (Equation – 1). The complexity of the system is the interfaces of the system divided by the total interfaces (Equation – 2). It is expected that the total existing interface will reduce, thus the complexity of the system as well. The reduction of complexity on-board will result in a reduced human effort on-board which is expressed in man hours [12][13]. The human effort estimations are gathered via interview with experts on the shipyard.

$$SCLI(n) = \frac{Interfaces\ system\ (n)}{Total\ interfaces} \qquad (1)$$

$$\sum_{1}^{n} SCLI(n) = 1\ (current\ situation) \qquad (2)$$

Second, the value-time effect. The value shift towards the supply chain i.e. co-production, which can be measured the Production Multiplier (PMP) [14]. It is expected that the supplier can assemble the module more efficient than the LSSI on-board. This efficiency increase will result in a higher Gross Margin for the LSSI [7]. The time effect can be explained as followed: the number of people in the engine room is limited, the human effort on-board will decrease due to modularization, the engine room can be completed earlier. This effect expresses itself in the Time-To-Market [1][14][15]. Moreover, the lead time for the module will be longer in comparison with the current situation. It should be aimed for to postpone the procurement, thus the placement of equipment. Another benefit of this would be that the risk of damaging equipment will reduce. This effect could be expressed with the Idle Time of Equipment (ITE), the moment of placement until the commissioning [16].

The last step is to an elevation of the future modular performance by using design for assembly. It is expected that the modularization strategy itself will elevate the performance of the current process. The current design is not optimized for the assembly yet. By reducing the assembly complexity in a redesign it is expected that the SCLI, HE, PMP, and GM can be further improved. An overview of the preliminary model is given in Table 1

Table 1 An overview of the preliminary model

1) Assembly complexity	*SCLI*	[11]
	HE	[12][13]
2) Value-time effect	*PMP*	[7][14]
	GM	[14]
	TTM	[1][14][15]
	ITE	[16]
3) Design optimization	*SCLI*	[11]
	HE	[12][13]
	PMP	[7][14]
	GM	[14]

II. Measure

From this point on, the model is used on the case study. This chapter, the measure, provides the current performance of the engine room assembly process of the systems. First the current assembly process complexity is given, thereafter the value time aspects. The design optimization measures have been given, this is for the current situation unnecessary to repeat since they are given in the assembly complexity and value time aspects. The design optimization is elaborated on in the redesign of the system.

1) Assembly process complexity

The first thing that should be measured is the complexity, this can be done with the SCLI. The SCLI is benchmarked for the current situation as one, this is the result of 2247 interfaces. The human effort necessary in the current situation is 37000 hours. The results for each system is given in Table 2.

Table 2 the assembly process complexity of the engine room

System	TEI	SCLI	HE
Bilge & firefight (BFS)	481	0.22	981
Fuel oil (FOS)	393	0.17	2950
Seawater cooling (SWC)	358	0.16	4050
Domestic water (DWS)	547	0.24	2420
Black & greywater (BGS)	246	0.11	3770
Lubrication oil (LOS)	108	0.05	1493
Working air (WAS)	114	0.05	125
AC & ventilation (ACVS)	N.A.	N.A.	1757
Propulsion (PS)	N.A.	N.A.	1500
Generator (GS)	N.A.	N.A.	338
Ironwork & cable trays (ICT)	N.A.	N.A.	12777

2) Value time aspects

First the indicators of the value effects are given, then the indicators for the time effect. The value effect is the Production Multiplier, and gross margin. The results of the value effect (PMP & GM) are given per system in Table 3. The time effect is for the entire process equal, and thus not given per system but for the entire engine room as a whole. The Time-To-Market in the current assembly process is 274 weeks. The idle time of equipment in the engine room is generally speaking 86 weeks.

Table 3 The value indicators of the current engine room assembly

System	PMP	GM
Bilge & firefight	1.58	10%
Fuel oil	1.70	10%
Seawater cooling	1.12	10%
Domestic water	2.50	10%
Black & greywater	1.87	10%
Lubrication oil	1.05	10%
Working air	5.65	10%
AC & ventilation	7.54	10%
Propulsion	8.16	10%
Generator	44.9	10%
Ironwork & cable trays	N.A.	10%

The results are summarized in in Table 4, and illustrated in the value time curve in Figure 1.The blue line is the value invested by the yard, the orange line is the value paid by the customer. The grey line is the difference between these two, thus the value flow of the engine room.

Table 4 The current performance of the engine room assembly process.

KPI	Current
SCLI	1
HE	37000 [hr]
PMP	3.26
GM	10%
TTM	274 weeks
ITE	86 weeks

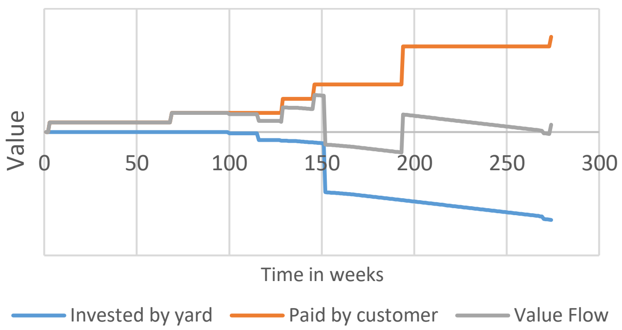

Figure 1 the value time curve of the current engine room assembly process

III. Analysis

The performance indicators and the current state performance have been determined. The next step is to analyse the data and determine what are the bottlenecks in the current process. The goal of analysis phase is to ensure enough knowledge is obtained to not waste any time in the design phase. First the assembly process is analysed. Second, the design of the fuel oil system is analysed.

1) System assembly process

Currently, many valves, appendices, sensors, etc. are installed on board. The number of components to be installed on-board should be minimized. This will result in a less complex assmebl progres, since many actions are eliminated on-board. The human effort will move from on board to a workshop, which will result in a lower human effort in terms of man hours. An example of this can be seen in Figure 2 & 3, Figure 2 is an complex, time consuming strategy to install the oil-water seapartor. Figure 3, is a more efficient strategy.

Figure 2 Complex oil-water separator

Figure 3 Modular oil-water separator

2) Value time aspects

The modules should be outsourced since this is not a core competency of RVLS, this will increase the Production Multiplier. It is expected that the Gross Margin for the yard will increase, since the supplier is specialized in the system, and can make the system in a workshop with a higher work efficiency. Moreover, due to the a lower on-board necessary human effort a shorted Time-To-Market can be achieved. The systems are devilvered more complete, so less work is necessary to be done on-board. The systems, thus the engine room can be finished earlier. Lastly different assembly strategies should be designed to postpone the placement of equipment in the engine room. Currently much works needs to be done in the engine room to finish the system. An outfit and assembly period of 130 weeks can be observed. Moreover, the work done by suppliers is more, hence the lead time for the equipment will be longer. Thus, a machinery install strategy should be sought which postpones the placement of equipment.

3) Design of the fuel oil system

The current design of the fuel oil systems should be optimzed in terms of assemblability. This can be done by reducing the interface complexity according to the SCLI, by reducing the number of components to be installed on-board. It is expected that the effect of "merely' modularization will be positively be affected. Figure 4 illustrates the current situation of the fuel oil system. All piping if the bunker tanks is transferred to the manifold in the engine room. From here it cleansed with the NFV filter, and fuel water separator, or it transferred to other bunker tanks with the transfer pump. The manifold is used as a distribution hub, this results in many interfaces in the engine room, a less complex method should be sought to distribute the fuel between the bunker tanks.

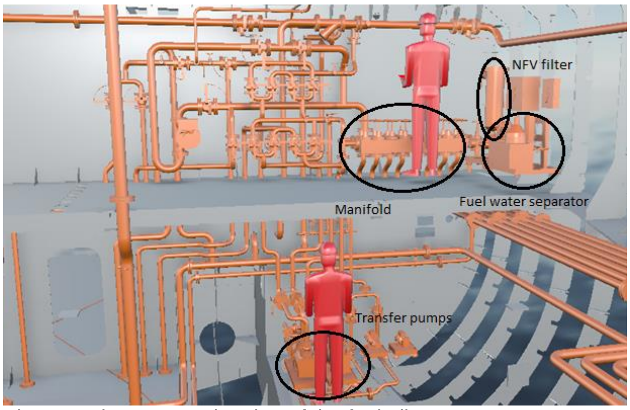

Figure 4 The current situation of the fuel oil system

IV. *Design*

The first part of this section is devoted to the new design of the engine room system assembly process. The knowledge gathered in the analysis section is used to design a better process. The second part is the design optimization of a system.

1) assembly process complexity

The modules which are determined are closely related to the corresponding system. The main component of the system was used as the start of the module, the schematics were analysed to increase the number components on the module. Many components could be installed in a workshop in the module, instead of on-board assembly. This could reduced the complexity of on-board assembly process significantly. This effect is observed in the human effort necessary for the on-board assembly of the systems. The results on the assembly complexity are given in Table 5.

Table 5 The complexity and human effort of the future modular state

System	SCLI		HE [hr]	
	Future	δ	Future	δ
BFF	0.19	-12.5%	681	-300
FOS	0.11	-38.2%	2950	-400
SWC	0.11	-32.4%	4050	-400
DWS	0.09	-63.1%	2420	-1000
BGS	0.06	-42.7%	3770	-500
LOS	0.03	-29.7%	1493	-50
WAS	0.04	-29.8%	125	-30
ACVS	N.A.	N.A.	1757	0
PS	N.A.	N.A.	1500	0
GS	N.A.	N.A.	338	0
ICT	N.A.	N.A.	12777	-2000

2) Value time effects

The value effects can be seen in Table 6. The AC & ventialation, propulsion system, generating system, and the ironwork & cable trays are not modularized, therefore these don't show any differences. The other system do show an increase in the production multiplier. This resulted in a higher profit for the yard for all system except for the working air system, here a decrease in Gross Margin is observed. The work on-board is extremely low in the engine room, a larger investment in equipment resulted in a lower gross margin for the yard.

Table 6 the value effect due to modularization

System	PMP		GM	
	Future	δ	Future	δ
BFF	2.09	+32.3%	21%	+11%
FOS	1.77	+4.1%	13%	+3%
SWC	1.18	+5.4%	16%	+6%
DWS	3.80	+52.0%	23%	+13%
BGS	2.11	+12.8%	12%	+12%
LOS	1.08	+2.9%	11%	+1%
WAS	6.17	+9.2%	1%	-9%
ACVS	7.54	0	10%	0%
PS	8.16	0	10%	0%
GS	44.90	0	10%	0%
ICT	N.A.	0	10%	0%

The time effects due to modularization can be split up in the Time-To-Market, and the Idle Time of Equipment. In the current process, a lot of work needs to be done on-board, thus the human effort directly results in the Time-To-Market for the engine room. The engine room is the most critical technical room in the yacht. The modular approach can reduce the outfit, and commisioning with 19 weeks, thus the yacht could be delivered earlier from an engine room perspective. The next step is to look at alternatives for the install strategy for machinery in the engine room. Various install strategies have been reviewed, only one could effectively postpone the placement of equipment. Figure 5 illustrates the current strategy of installing machinery, there are two hatches in the engine room above the main engines. Figure 6 displays the hull building progress.

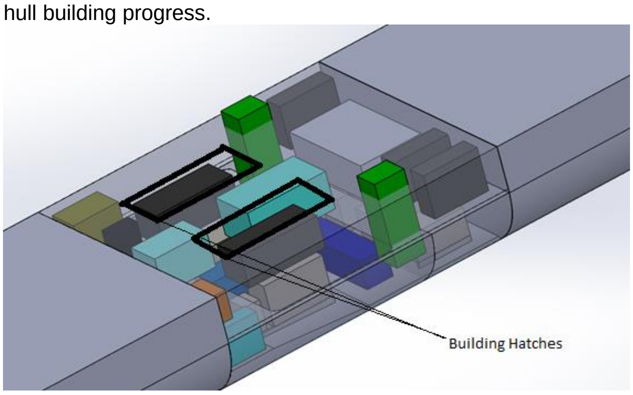

Figure 5 Illustration of the current equipment loading strategy

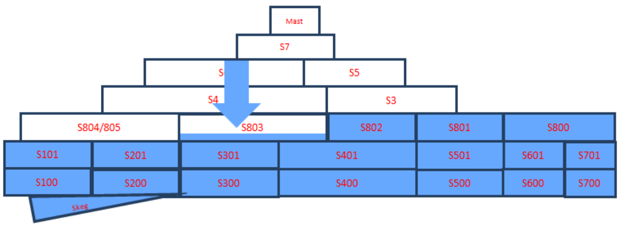

Figure 6 The hull building progress in the current situation, building hatch main deck

The strategy to postpone the Installment Week of Equipment (IWE), is via four hatches, two in the main deck, and two in the owners deck. The hull building progress is given in Figure 7. The results on the Install Week of Equipment, Time-To-Market, and the Idle Time of Equipment is given in Table 7.

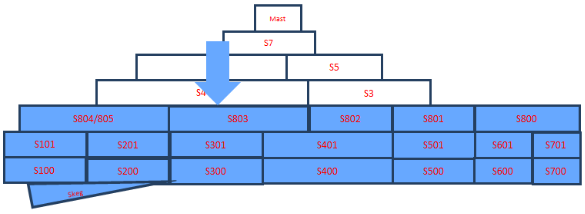

Figure 7 The hull building progress in the preliminary future situation, building hatch main deck, and owners deck

Table 7 The Install Week of Equipment (IWE), Time-To-Market (TTM), and Idle Time of Equipment (ITE) of two machine install strategies.

	Current (MD)	**Future** (MD)	**Future** (MD + OD)
IWE	W152	W152	W165
TTM	W274	W255	W255
ITE	86 weeks	71 weeks	58 weeks

3) Design optimization

The first constraints mentioned in the analysis is the high number of interfaces in the engine room. One important factor in this is that all piping of the bunker tanks is lead to the manifold inside the engine room. This is requires more time in the pipe routing in the engine room, the piping in the engine room is expensive due to the many bends in the pipes, and it is requires more time to assemble the pipes in the engine room. The following piping is designed in order to reduce the number of interfaces in the engine room as can be seen in Figure 8. The fuel oil module is connected to the filling station. Instead of the manifold, local electric valves at the tanks are used, this reduces the complexity significantly.

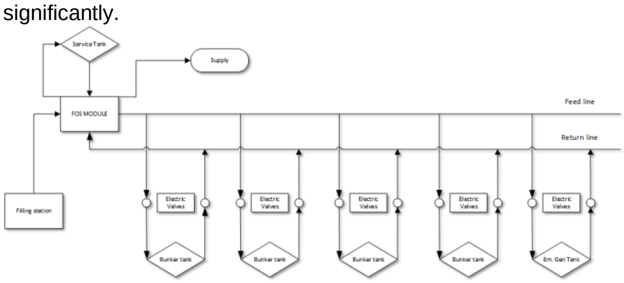

Figure 8 redesigned pipe routing of the fuel oil system

In order to minimize the number of components the schematics of the fuel transfer & fuel supply are thoroughly analysed and discussed with engineers. The fuel transfer and supply system could be placed on one module. A significant reduction of components can be seen. This reduction is achieved by combining the pumps, equipment etc. on a module or skid. The skid is designed in close collaboration with a renowned company in the production of fuel oil treatment systems. The main component of the treatment unit, the fuel separator, was already bought by this company. A schematic drawing of the module with equipment, pumps and interfaces is given in Figure 9. A preliminary design is made for the fuel oil module, this design is given in Figure 10. The current fuel oil system has a footprint of approximately 4 m^2 in the engine room. The preliminary future design has a footprint of approximately 2.5 m^2. The manifold could be removed, so the footprint could be reduced. The electrical cabinet should still be modelled. The cabinet can be placed on a high position in the skid, thus this will not cause any trouble. The fuel water separator, NFV-filter, NFV pump, separ-filters, tender pomp, fuel counter, and two transfer pumps are modelled (left to right).

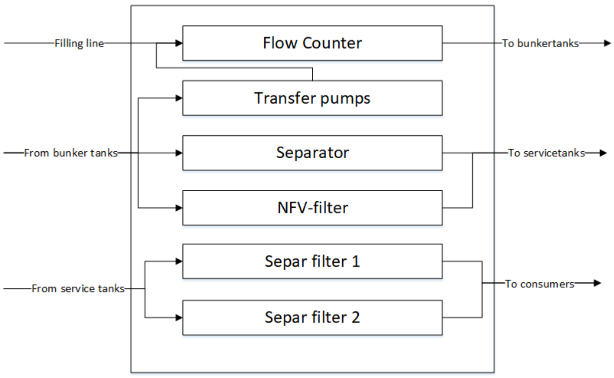

Figure 9 redesign of the fuel oil system module

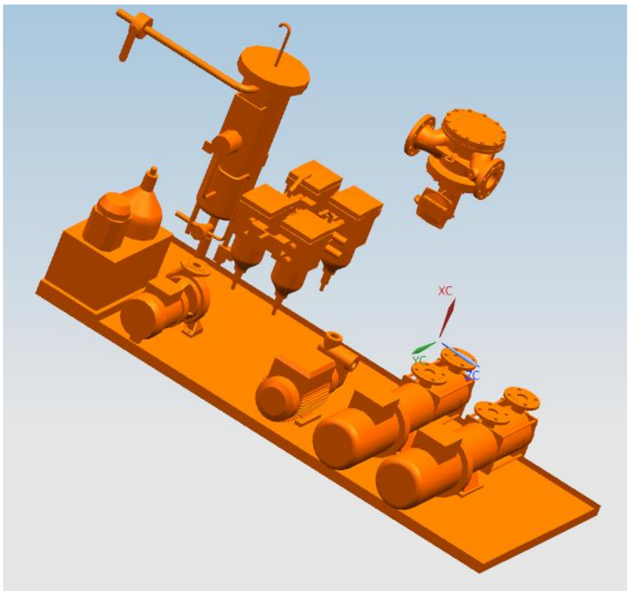
Figure 10 Render of the redesigned fuel oil system (Without piping)

The effects of the redesign with Design For Assembly (Future DAF) are given in Table 8, in comparison with the current situation and the Future modular situation (Future Mod.). The complexity of the modular method could further be reduced. This lead to even less human effort on-board. The suppliers could produce a larger part of the system, which can be seen in the Production Multiplier. Ultimately the gross margin rises for the LSSI.

Table 8 Comparison of the effects on the fuel oil system due to modularization, and design for assembly.

	Current	**Future Mod.**	**Future DFA**
SCLI	1	0.62	0.57
HE	3980	3480	3080
PMP	2.12	2.45	2.57
GM	10%	14%	19%

V. Evaluation

This phase consist of several sections. The first sections is the performance assessment of the newly designed process. The second step concerns the conclusion of the research. The sub-research question are answered and will lead to an answer to the main research question. Thereafter are the recommendations given, for RVLS, and for future academic research. The last chapter of this section is the discussion.

1) Performance Assessment

The modules which are determined are closely related to the corresponding system. Many components could be installed in a workshop in the module, instead of on-board assembly. This could reduce the complexity of on-board assembly process significantly. This effect is observed in the human effort necessary for the on-board assembly of the systems. Due to the shift from on-board to a workshop, the LSSI is enabled to outsource the production of these modules since this is not a core competence. The Production Multiplier is increased due to the shift to the supply chain. The bits and pieces i.e. valves, appendices, and sensors can be installed much more efficient in a workshop this results in a higher Gross Margin for the shipyard. Moreover, the Time-To-Market could be shortened. A different machinery install strategy enables the LSSI to postpone the placement of equipment. The results are given in Table 9.

Table 9, a comparison of the current and the future engine room system assembly process

	Current	**Future**
SCLI	1	0.63
HE	37000 [hr]	32000 [hr]
PMP	3.26	3.58
GM	10%	12%
TTM	274 weeks	255 weeks
ITE	86 weeks	58 weeks

The results can be visualized with the value time curve, this curve is given in Figure 11, below. The higher Gross Margin, the shorted Time-To-Market, and the reduced Idle Time of Equipment can be seen in the curve.

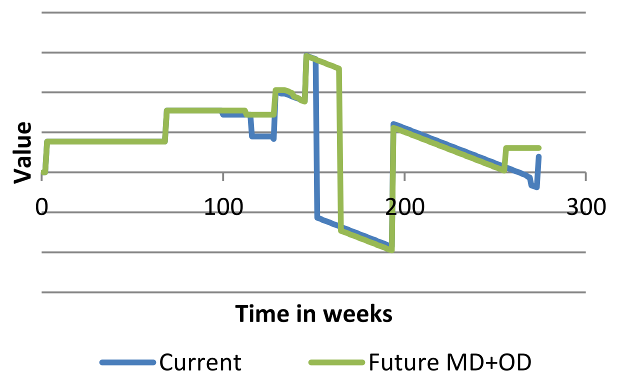

Figure 11 The value time curve of the current process, and the future process

2) Conclusion

The above given chapters lead to an answer to the main research question.

To which extent can an advanced modular system assembly strategy improve the current ship building process?

A modular system assembly strategy can result in a better assembly process. The first effect, a reduction of complexity in the engine room, indicated by the System Coupling Level Index, results in less human effort on-board. The value-time curve can be optimized when the effects of modularization are exploited. The effects of modularization can be further improved when design for assembly is used. A redesign of the fuel oil system has shown this.

3) Recommendations

The current analysis is done for one super yacht, and a particular focus on one particular system. An analysis on more yachts or even other complex-ships can provide better insight in the benefits of modularization in shipbuilding. A better analysis can be done for the other systems in the engine room, with the focus on reducing complexity. This can create broader support for a modular outfit strategy in complex-shipbuilding. Moreover, this research was focused of the assembly process in the yacht. The reduction of complexity of the interfaces can result in a more efficient assembly process. The size of the fuel oil system module could be reduced by removing the manifold from the engine room, so the size of the module is not an issue (for the fuel oil system). For the other systems this analysis is not done, the impact on design for assembly on the engine room lay-out should be researched for all systems.

4) Discussion

The limitation of the research are discussed in this chapter. The first the role of the piping is discussed in the system and how this is used in the thesis. Second, the reliability for the human effort estimates is discussed. Third some assumptions are made on the cost of this human effort, these are elaborated on. Lastly the implications on the module sizes are discussed.

Piping

The piping system in the yacht is built up in spools. The spool drawings were not available for the yacht yet when this research was conducted. Each spool has two connection, the inflow and the outflow. These are not incorporated in the model (yet), for both the current and future state. The modular strategy, and more so the design for assembly strategy will reduce to number of piping installed on-board. The complexity will further reduce when this is incorporated in the model. Since the costs of piping is not yet available for the yacht and a it is difficult to make good assumptions on the effect of modularizations for this, this is not incorporated in the investment costs for the yacht. For the modular strategy the piping used will remain practically the same, thus will the investment costs. The reduction of human effort on-board due to the piping is incorporated based on the experience of expert at RVLS. The effect on the piping due to design for assembly is incorporated in the model, The reduced complexity significantly reduced the amount of pipe spools, thus the investment and instalment costs for piping.

Reliability human effort estimates

Another point of discussion is reliability of the estimates in human effort on-board. The opinion of experts is used to find the human effort estimated of the modular state, and the design for assembly effects. There are two factors identified that could question the reliability of these estimates. First of all, it has been mentioned that Royal Van Lent built customer yachts. The estimations by the yard for the human effort are good, but not perfect. The yacht has not yet been built so both the current performance as well as the future performance is estimated to the best of their knowledge by experts at the yard. A better estimate would be provided by the exact “as built” human effort, this is how ever not possible. A direct comparison of the same yacht with the current strategy and the future strategy is not possible since every yacht is custom. Second, there probably is a difference in work efficiency and quality of the workers at Royal Van Lent Shipyard at Kaag and the workers at the hull production yard, but the experts are familiar with this difference. However, the case study yacht is not built at Kaag but in Amsterdam. The case study yacht has not been built yet, the data is based on experience of people at De Kaag, the work conditions could be different in Amsterdam, which could lead to a different amount of work. Examples of the differences could be, other walking distances for the employees, a better accessible yacht, a different lay-out of the yard. These effects are not taken into account.

Reliability cost estimation human effort

Different activities can be done by different suppliers, and at different yards. The price for human effort could thus be different for all activities, moreover the price could be different tomorrow. The price for all human effort is kept identical in this research. The reliability of the real cost of human effort could be better if the human effort is contracted with suppliers. It should be noted that a modular system assembly strategy will reduce human effort, more equipment is bought directly from the supplier. It is easier to get insight in the total costs of the entire products.

Reliability cost estimation modules

The cost of the equipment is analysed with the invoices of the equipment, thus reliable estimates, or even exact. The price of the module is discussed with the supplier of the fuel oil system, it is not on exact but a good estimate. The price for the remaining modules is estimated with experts from RVLS, the experts have a lot of experience with suppliers. The estimates are good estimations but cannot directly be used. The cost should be discussed and negotiated with the relevant suppliers.

Module size

A drawback of modularization from literature is the increased size of the modules. A indicative analysis was done on the sizes of the modules with the help of experts to prove the feasibility of modularization for the specific yacht. Currently every system is designed for each specific yacht, of more standardized modules are used with less interfaces on-board. More effect can be put into the design, thus a compacted system can be achieved. This analysis is done for the fuel oil system and was proven to positively impact the size of the system. The analysis should be done for the other systems as well.

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