NTNU – Trondheim
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Small-Scale Automation in Shipbuilding

An Investment Study for Automated Hull
Production in High-cost Countries

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"If you follow in the footsteps of others, you will always be two steps behind." - *Unknown*

Preface

This report is the result of the M.Sc. Thesis in Marine Systems Design, written for The Department of Marine Technology at The Norwegian University of Science and Technology (NTNU) the spring of 2015. The work put in should reflect the 30 credits given.

The overall goal of this thesis was initially to investigate the possibilities for an increased level of automation in Norwegian yards. The focus was to investigate what impact it had on the organization of the production in-house, as well as decisions regarding administrative and commercial tasks. Ulstein Verft was brought in as a collaborator to help with key figures and shipbuilding expertise. Unfortunately, midway into the thesis collaboration it became clear that they wanted a different path for the thesis than the author. The collaboration ended, and naturally, the scope of the thesis needed adjustments to best facilitate a satisfying result. The adjusted goal of the thesis then became to create a case where a shipyard in a country with high-cost labour will make a strategic move from buying the hulls from other yards, to making them in-house. The hypothesis is that it will be too expensive to hire manual labour to perform the vast amount of construction work needed to complete a hull. It is a very labour-heavy task, and getting a large enough qualified workforce can prove difficult. The thesis will investigate if automation technology can be the means to reach the goal of taking back hull production.

It is notoriously difficult to gather data on the covered field, due to reticence in the industry. The case study is built on available data and estimates developed through conversations with the supervisor.

I would like to give special thanks to Arnulf Hagen, who has supervised the project. He has shared his insight in the shipbuilding industry, and been a great help to get the author past the bumps along the road to completion.

I would also like to thank Sjur S. Søndenaa for all the helpful discussions we have had about the subject in matter, and the people at the office, for contributing to a good working environment.

Trondheim, 10th June 2015

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Abstract

The globalized market enforces a great cost pressure on all the shipbuilding actors. Norwegian yards, representing countries with high local wages and prices, is under pressure to make changes if they want to keep up with the competition. Historically, ship owners have been willing to pay the extra price for Norwegian ships, given the reputation of good quality and deliverability, but this could change in the near future. Asian shipyards are becoming more skilled at building increasingly complex vessels. They have access to low-cost labour, and can usually offer a better price on the ships compared to Norwegian designs and builds.

The overall goal of this thesis is to investigate if modern automation technology can be applied in hull building to increase efficiency, and level the labour-cost differences between high labour-cost countries and low labour-cost countries. The framework for the thesis is a semi-integrated yard in a high labour-cost country who buys completed hulls abroad and now wish to make a strategic move towards becoming a fully integrated yard, performing more of their own steel work.

The hypothesis is that it will be too expensive to hire manual labour to perform the vast amount of construction work needed to complete a hull. It is a very labour-heavy task, and getting a large enough qualified workforce can prove difficult. The aim is to investigate if modern automation technology can be a viable investment to reach the goal of taking back more steel work of the hull production. The focus will be on identifying realistic operations to automate, and investigate what impact it has on the production efficiency.

A literature review focusing on the hull building process and modern automation technology identified several intelligent robotic configurations that could potentially increase the hull building efficiency, as well as eliminating the hazards associated with manual work task operation. In later years, the larger Asian yards have focused on building specialized robots for application at the shipyards. They are still prototypical, but show good test result.

A model is developed to evaluate the different elements affecting the investment decision regarding automation technology. The model can be used as a tool in the quantitative decision-making between the two options: invest in automation technology to make own hulls, or keep buying hulls abroad. The model depicts simple calculations that shed light on where the largest potential for improvement through automation lies, and whether or not the investment pays off. It consist of six basic steps:

- Step 1: Establish case data
- Step 2: Map process time consumption
- Step 3: Perform maximum investment calculations
- Step 4: Evaluate investment by Net Present Value
- Step 5: Sensitivity analysis
- Step 6: Scenario weighting with Quantitative Strategic Planning Matrix

Each step builds from the preceding step and applies the newly retrieved information into the next analysis.

The model is applied to a case study to test its validity. The case study is based on publically available key figures, as well as some qualified estimates. This study focus on the building of semi-advanced Platform Supply Vessels with a typical length of 75-90 meters, breadth of 17-20 meters and 3500 tons of steel weight. The case study yard can manage a throughput of four vessels of this kind each year.

The results from applying the model to the case study shows that modern automation technology can contribute to an increase in the hull building efficiency. Increasing the efficiency result in valuable time saved, and justifies a substantial investment in automation technology for each of the stages described in the hull building process.

In addition to increasing efficiency, the automation technology introduce several advantages that cannot be measured directly in monetary values. An example of such a factor is improved HSE. These elements are crucial to include in the decision-making process, as they can affect the long-term reputation of the given yard. Only by combining the conclusions from the qualitative and quantitative analysis is it possible to comprehend the total investment value.

Sammendrag

Det globaliserte markedet fører til et stort kostnadspress på alle skipsbyggingsaktører. Norske verft, som her representerer land med høye lokale lønninger og priser, er under stort press for å gjøre endringer om de ønsker å holde tritt med konkurransen. På grunn av ryktet om god kvalitet og leveringsdyktighet har skipseiere historisk sett vært villige til å betale ekstra for norske skip. Dette kan i fremtiden forandre seg. Asiatiske verft blir stadig mer dyktige til å bygge stadig mer komplekse fartøy. De har tilgang til lavkost arbeidskraft, og kan normalt sett tilby en bedre pris på skipene sammenlignet med norske design og konstruksjoner.

Det overordnede målet med denne avhandlingen er å undersøke om moderne automatiseringsteknikk kan brukes i skrogbyggingen for å øke effektiviteten og utjevne arbeidskostnadsforskjeller mellom høykostland og lavkostland. Rammene for avhandlingen er et semi-integrert verft i et høykostland som kjøper ferdige skrog i utlandet, og nå ønsker å gjøre et strategisk trekk mot å bli et fullintegrert verft som utfører mer av sitt eget stålarbeid.

Hypotesen er at det vil bli for dyrt å hyre manuell arbeidskraft til å utføre den enorme mengden av byggearbeider som trengs for å fullføre et skrog. Det er en oppgave som krever mye arbeidskraft, og det å finne en stor nok kvalifisert arbeidskraft kan bli vanskelig. Målet er å undersøke om moderne automasjonsteknologi kan være en levedyktig investering for å nå målet om å ta tilbake mer stålarbeid av skrogproduksjonen. Fokus vil være på å identifisere realistiske operasjoner som kan automatiseres, og undersøke hvilken innvirkning det har på produksjonseffektiviteten.

En litteraturgjennomgang med fokus på skrogbyggeprosessen og moderne automasjonsteknologi avdekket flere intelligente robot-konfigurasjoner som potensielt kan øke skrogbygningseffektiviteten, samt eliminere farene forbundet med manuell utførelse av arbeidsoppgaver. I senere år har de større asiatiske verftene fokusert på å bygge spesialiserte roboter for bruk ved skipsverft. Selv om de er prototypiske, kan de vise til gode testresultater.

En modell er utviklet for å evaluere de ulike elementene som påvirker investeringsbeslutningen om automasjonsteknologi. Modellen kan brukes som et verktøy i den kvantitative beslutningsprosessen mellom de to følgende alternativene: investere i automatiseringsteknologi for å lage egne skrog, eller fortsette å kjøpe skrog i utlandet. Modellen viser enkle beregninger som belyser hvor det største potensialet for forbedring gjennom automatisering ligger, og om investeringen er lønnsom. Den består av seks grunnleggende trinn:

- Trinn 1: Etablere case data
- Trinn 2: Kartlegge prosessenes tidsforbruk
- Trinn 3: Utføre beregninger av maksimal investering
- Trinn 4: Evaluer investeringer ved Net Present Value
- Trinn 5: Følsomhetsanalyse
- Trinn 6: Scenariovekting ved bruk av Quantitative Strategic Planning Matrix

Hvert trinn bygger videre fra det foregående trinn, og anvender den nye informasjonen som avdekkes i det neste trinns analysemetode.

Modellen er brukt på en case-studie for å teste dens gyldighet. Case-studiet er basert på offentlig tilgjengelige nøkkeltall, samt noen kvalifiserte anslag. Denne studien fokuserer på bygging av semi-avanserte forsyningsskip med en typisk lengde på 75-90 meter, bredde på 17-20 meter og 3500 tonn stålvekt. Verftet anvendt i case-studiet kan håndtere en gjennomstrømning på fire skip av denne typen hvert år.

Resultatene fra anvendelse av modellen på case-studiet viser at moderne automatiseringsteknikk kan bidra til en økning i skrogkonstruksjonseffektiviteten. Denne økningen i effektiviteten resulterer i verdifull innspart tid, og rettferdiggjør en betydelig investering i automatiseringsteknologi for hver av fasene beskrevet i skrogbyggeprosessen.

I tillegg til å øke effektiviteten, vil automatiseringsteknologi introdusere flere fordeler som ikke kan måles direkte i pengeverdier. Et eksempel på en slik fordel er forbedret HMS. Disse elementene er avgjørende å inkludere i beslutningsprosessen, ettersom de kan påvirke det langsiktige omdømmet til det gitte verftet. Bare ved å kombinere konklusjonene fra kvalitativ og kvantitativ analyse er det mulig å forstå den totale investeringsverdien.

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1. Introduction

The globalized market enforces a great cost pressure on all the shipbuilding actors. Norwegian yards, representing countries with high local wages and prices, is under pressure to make changes if they want to keep up with the competition. Historically, ship owners have been willing to pay the extra price for Norwegian ships, given the reputation of good quality and deliverability, but that could change in the near future. Asian shipyards are becoming more skilled with building increasingly complex vessels. They have access to low-cost labour, and can usually offer a better price on the ships compared to Norwegian designs and builds. To keep their global position, and to increase their market share, Norwegian yards must review which strategic changes that can increase their margins and give them the upper hand for the years to come. It becomes more important to produce smart and efficient. Buying hulls from abroad reduces the possibilities for early outfitting, pushing the work to a more inconvenient stage in the building process and makes the overall process more inefficient.

The continuous development of automation technology encourages Norwegian yards to investigate if this technology can take part in a restructuring of the shipbuilding production process, increasing the quality and efficiency of their production. The robotics have dropped in price and have become more flexible and intelligent. They can perform many different tasks related to hull building. This includes operations like cutting, bending, welding and painting, among others. In some cases, these tasks will represent a hazardous environment for a human resource. Operations in enclosed spaces is a good example where replacing a human resource with a robot can increase the health benefit of the human resource. Applied correctly in a production line it can potentially level the labour-cost differences, increase the continuity and quality of the product, and secure jobs in Norway for the years to come.

It is important to notice that the assessments and issues addressed in this thesis applies for shipbuilders in any high labour-cost nation. Norway is used as the example as they represent the extremity when it comes to labour-cost. The general goal of this thesis is to research the possibilities for semi-integrated yards in high labour-cost countries to take steps towards becoming fully integrated yards, doing all their own steel work. In particular, the report focuses on the hull building process.

Chapter 1 is the introduction to the thesis. It includes a background for the topic, as well as an historic walkthrough of the development in Norwegian shipbuilding and problematics concerning outsourcing of work. Next, it presents the research done in this thesis. It describes the research methods used, and contains the literature review. The literature review goes through all the essential background information, discuss the previous research performed in the field, and then moves towards the formulation of the research objective.

Chapter 2 presents the hull construction process. Both the historical development, and the present shipbuilding process strategies are discussed. The chapter defines the different stages of the process, which will be used further in the thesis.

Chapter 3 is a detailed description of the history of automation technology, as well as the different robotic configurations that modern technology has developed.

Chapter 4 focuses on identifying tasks in the hull production process that can be automated, and establish a robotic configuration fitting for each task.

Chapter 5 presents the different criteria that should be assessed when considering the investment decision. It involves both qualitative and quantitative factors that affect the final decision. Based on the criteria presented, a model is developed for assessing the investment.

Chapter 6 contains a case study established for testing the model developed in chapter 6. The case is based on the key figures available, as well as some qualified estimates developed.

Chapter 7 is the discussion chapter, where the results reached through the preceding chapters are analysed, commented and discussed.

Chapter 8 summarizes the discussion in the previous chapter, and draws some conclusions. In addition, it presents some subjects that should be reviewed for further work.

1.1 History

Shipbuilding is an industry with long and proud traditions. The industry is important for so many other business sectors. Transport of cargo by sea, offshore operations and subsea installations, none of these would have been possible without the development yards have made with shipbuilding technology.

In Norway, shipbuilding has been part of the history for quite some time. The first cases of shipbuilding dates back to early Viking age. However, few would had believed that it would lead to the competence one find in Norway today. The start of Norwegian shipbuilding as we know it is set around the early 1900s. There was a structural transition as the Norwegian fishing fleet moved from sail and rowing boats to motorized vessels. Mechanical shops to install and maintain the motors and equipment emerged along the coastline of Norway, close to the major trading cities. These mechanical shops laid the groundwork for the shipyards that have emerged throughout the 20th century.

It is common knowledge that Norway is one of the best in the world when it comes to building complex vessels. The Norwegian yards have highly educated people with the knowledge and skills to be innovative. These skills were not a given. They were highly driven by the discovery of oil on the Norwegian Continental Shelf. New ship designs where needed to support and supply this emerging industry.

The ability to restructure the yards were put to test, and Norwegian yards proved able to evolve better than the competition. New ship designs were necessary in order to perform the offshore operations that emerged from this discovery. A nation that previously were used to making fishing vessels made a strategic choice to rise to the occasion and grasp this new market. This development of the yards and the building of advanced offshore vessels gave Norwegian yards 40 years of head start.

Part of the reason for Norway's success with shipbuilding lies in the advantage of the marine cluster. Norway is in a unique position when it comes to local companies producing many of the sub-systems aboard the ships. These companies have a close relationship that stretches over several decades, and together they are able to out-compete several of the Asian competitors within shipbuilding despite the higher price. It has proven that ship owners are willing to pay extra to get the quality stamp "Made in Norway".

1.2 Outsourcing

To adjust for high labour-cost in Norway, as good as all yards chose to outsource steel work and hull construction in the late 90s. As hull building is a very labour-heavy part of shipbuilding, a large cost were cut by outsourcing to low labour-cost countries like Romania and Poland. The construction of the hull is considered a relatively simple task that foreign workers can perform without the need for higher education or close supervision from Norway. It was considered as a necessary strategic move in order to keep the prices at a competitive level in the global market throughout the turn of the century. Isolated, this action spares the yards from a high cost, but overall it affects other parts of the production planning, making the total picture more nuanced.

When the hull is constructed and assembled abroad, it presents several challenges for the company. First, the communication between the Norwegian company and the hull yard abroad must be good to ensure good coherence between product expectations and the delivered product. Changes to design, and adjustments made on behalf of the customer is important to share with all staff involved in the design and building phase. When the hull builders and the engineering design team is stationed in two different countries with different work culture, this kind of communication can often be a challenge. In some countries abroad, it is not uncommon that a worker tends to cover up mistakes, in fear of the personal consequence of reporting the mistake. This can lead to a product with inferior quality, thus harming the brand name of the given yard.

1.3 Research

This thesis had a known topic from the start, so a systematic search method was the best way to find relevant literature. A systematic search is usually used in electronic databases, where you can build a search profile from a set of key search phrases combined in different orders and create a systematic search strategy.

When performing the literature search for this project, the author made use of several scientific electronic databases, along with less scientific search engines. The following search methods and engines were used, listed roughly by order of usage:

- University Library, dept. of Marine Technical Centre
- DiVA
- Google Scholar
- NTNU BIBSYS
- Google search

The key search phrases used in the start was:

- Shipbuilding
- Automation
- Robot technology
- Efficient industry
- LEAN production
- Key figures

The phrases was combined in different orders to create a search result. After the thesis developed, the search phrases became more refined, and aimed towards specific segments of the research objective.

The literature search for this project report proved more difficult than expected. The search engines lacked scientific papers on the subject, and the key search phrases proved inefficient. Since the Norwegian shipbuilding is not directly comparable to shipbuilding abroad, it further reduced the material available. Kleven Verft and Ulstein Group was approached for experienced insight and key figures, but with little results. Experience from the thesis supervisor implies that key figures is notoriously difficult to get hold of in the shipbuilding industry. An example of this is “Nøkkeltall for produksjon på skipsverft”(Steinveg & Lønseth, 1995). The report establish a systemized and standardized way of gathering key figures from shipyards in order to improve the usability. What the report lacked however, was to actually retrieve any key figures from the shipyards.

As the research went on, better key search phrases emerged, and the literature became more relevant. In the absent of scientific papers, other sources were applied. Company presentations and conference Powerpoints like (Kleven Maritime, 2011) and (Grobæk, 2012) were used for insight in the mindset of the Norwegian shipbuilding industry. Thoughts on the cluster effect, and future automation is discussed, but sources for the data presented is lacking. Presumably, the data presented are the result of internally available studies from Kleven.

1.4 Literature Review

In order for the thesis to qualify as a contribution to the knowledge concerning small-scale automation in shipbuilding, it must present information not previously published, and fill a gap in the relevant body of knowledge. In order to do so, it is important with a thorough literature search to investigate existing knowledge available. Through a thorough literature study, it is also easier to get inspiration regarding issues that require further studies, and can be included in the research objective.

This chapter will provide a description of theory and methods relevant to automation of shipbuilding processes. Identifying background data relevant for the research objective is emphasised, along with a discussion of previous research in the field. The final section will present the research objective for this paper.

Essential background information

To be able to improve the efficiency and quality of operations in shipbuilding it is important to have a good understanding of how a ship is constructed, and how all the different parts of the organization interact. Only through a good understanding of all work tasks, can one suggest changes that can improve the existing procedure. In addition to shipbuilding knowledge, this thesis require an extensive knowledge of automation technology, the state of the art technology, and how it can be best applied to an industry. Understanding the possibilities and limitations for robots is essential.

Shipbuilding process

Although shipbuilders worldwide apply many different strategies to shipbuilding, the general approach is similar in all strategies. You start with producing small parts, and assemble them to increasingly larger elements, finally forming a ship hull. After the hull is completed, it is outfitted with the necessary equipment for its predefined purpose. (Eyres & Bruce, 2012) describe the complete process in a very detailed manner in the book “Ship Construction”. Apart from the structural build-up of a ship, it describes the techniques applied in all stages, as well materials used and dimensioning factors for ship design. Although the MARINOR reports in the series “Velutrustede og velorganiserte arbeidsplasser” (Hukkelberg, 1995b) focus is to organize and equip the workplace in yards properly, it confirms many of the work tasks assigned to the stages described in “Ship Construction”. By categorizing the work tasks related to each stage in the hull-building phase, it is possible to look at time consumption in each stage.

When researching factors that affect the efficiency, it is also necessary to look at processes upstream, as well as supply chain and general company strategies. For this purpose, (Hagen, 2014) provides interesting aspects on production philosophy and modularization of design that are relevant for the discussion on increasing construction building efficiency. Supply chain is not discussed extensively in this thesis.

Automation technology

It was easier to find scientific articles and information about the automation technology, as it is used in several other industries. In databases and search engines like BIBSYS and Google Scholar numerous hits emerged when combining the key search phrases. The challenge, however, was separating the shipbuilding related automation from the general automation technology more fitted for i.e. automobile industry. The book “Ship Construction” (Eyres & Bruce, 2012) provided a good basis for further research on specific automation technologies for each operation. Specifically, the book describes automated welding, along with automated plate and section preparation. These applications of automation show some of the possibilities, and displays key areas for further research.

The shipbuilding industry was not among the first to embrace the advantages of automation technology in production, but as the technology developed many yards saw a potential in the technology. Samsung, with its huge Geoje shipyard, have performed vast amounts of research on how automation technology can be applied to their yard. They have developed their own concepts, and have utilized existing robot designs. This has resulted in a 68% production automation rate, and a self-proclaimed title as “The World’s Highest Production Automation Rate Utilizing Robots” (Samsung, 2015).

The Norwegian company Kleven Group have also directed focus towards automation technology in the later years. They have an automated pipeshop at Kleven Verft, which has proven successful, and are currently enduring a project involving robots for welding with seam tracking, flake production and assembly.

Different prototypical solutions and established robot technology like automated plate bending in (Yoshihiko, 2011), and joining techniques in (F. Roland, Manzon, Kujala, Brede, & Weitzenböck, 2004) exist in numerous articles and shipbuilding journals. (Souto, Faiña, Deibe, Lopez-Peña, & Duro, 2012) and (Lee et al., 2010) present welding robots designed for shipbuilding industry, and methods used to improve the welding processes. Some papers are very technical, while some simply review the technology out there. The majority of the designs are a better fit for shipyards abroad, with more repetitive operations. However, as the intelligence and flexibility of the robots have improved over the years, many of the designs is stated to be functional in a one-of-a-kind industry as well.

Previous work in the field

The initial research reveals many studies investigating measures to increase efficiency in an industrial business. However, most studies have a more general approach to the topic, focusing on either identifying time-thieves or introducing LEAN production methods to the business, like (Ciobanu & Neupane, 2008). Another example is (Hukkelberg, 1995a), which seeks to increase productivity through streamlining the workplace, as well as educating the workers and investing in modern production equipment.

In (Hukkelberg, 2000), the focus was on possibilities for increasing productivity through station-oriented production for section building. No studies were found where automation technology has been studied as a mean to increase the overall efficiency in the shipbuilding industry, and by that bring more steel work in-house. It seems like most studies aiming to increase productivity at shipyards were conducted too long ago, when the modern automation technology did not exist as an alternative to manual labour.

As mentioned, technology-wise many of the findings are outdated. As automation technology studies has an economic and competitive aspect, the companies performing the studies tends to keep the updated studies confidential. This limits the insight in applied state of the art automation technology.

1.5 Primary Objective

A shipyard with high-cost labour will make a strategic move from buying the hulls from other yards, to making them in-house. This scenario is highly relevant for Norwegian yards, but can also be representative for any yard with only high-cost labour available. In order to make this transition as profitable as possible, the situation must be investigated thoroughly. Every investment scenario is measured in their potential profitability, as will this.

The hypothesis is that it will be too expensive to hire manual labour to perform the vast amount of construction work needed to complete a hull. It is a very labour-heavy task, and getting a large enough qualified workforce can prove difficult. The aim is to investigate if modern automation technology can be a viable investment to reach the goal of taking back more steel work of the hull production.

The focus will be on identifying realistic operations to automate, and investigate what impact it has on the production efficiency. The report will develop a model for assessing an investment in automation technology, and then test it on a case study.

Continuous improvements is the key to survival in a tougher market, and this study aims to investigate to what degree small-scale automation can be part of that improvement.

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2. Shipbuilding – Hull Construction

This chapter will introduce the different stages of construction when building a ship hull. It will describe the historical development of the methods used, and introduce some major changes made to the assembly strategies. The content of this chapter is based on chapter 14 in (Eyres & Bruce, 2012).

2.1 Historic Development

Ships have historically been constructed on a slipway piece by piece. Even though the building material changed from wood to steel, it made little difference to the construction process. Industrial innovation has often been driven by wars. Shipbuilding is no different.

The Second World War required a large number of ships to be built in a short period. This forced the yards to adapt their construction methods, introducing more welding in the shipyards and a turn towards mass production. Prefabrication of smaller ship units became a highly developed science.

The quality of welded ship hulls took a shot across the bow, as the well-known American cargo ships called Liberty, started experiencing hull cracks along the welding seams. It later proved to be the grade of steel used that suffered from embrittlement when exposed to extreme temperatures.

As the shipyards identified the potential benefits of prefabrication, they invested in assembly workshops and larger cranes fitted for prefabricated units. Increasing ship size and steel weight of the ships in the 1950s offered further motivation for unitization. Today, as good as all vessels are to a certain degree prefabricated. The construction of prefabricated units under cover offers an attractive advantage in Northern Europe, and in the hot climates. Not only because of working conditions, but also because it provides better conditions for welding. Central services as torch gas, compressed air and electricity are more easily available, and can be lain out where needed.

As the unit construction method developed, and ships continued to grow in size, the units grew larger. Eventually, the units were assembled into large block modules. This rapidly reduced the lead-time for hull construction. Nevertheless, as the ships grow bigger, they also grow more complex. The outfitting started becoming a bottle neck for the yards. To gain the advantages that faster construction time offered, they had to make the outfitting more efficient. This lead to outfit planning being made for each work zone individually, instead of the total ship. It facilitated pre-outfitting of each block module. In some cases, the pre-outfitting of a block may reach 85-90 %.

2.2 Shipbuilding Process Strategies

Shipyards have traditionally been where most value was added, in large from own labour force (Hagen, 2014). Gradually as the shipbuilding industry becomes more globalized and professionalized, the values are added by equipment procured from external suppliers. As Figure 1 shows, 47% of the project costs are related to procurement. The chart is representative for complex vessels built in Norway. An indicator of complexity is the share related to steel materials. The higher the complexity is, the lower is the expected share of steel material costs.

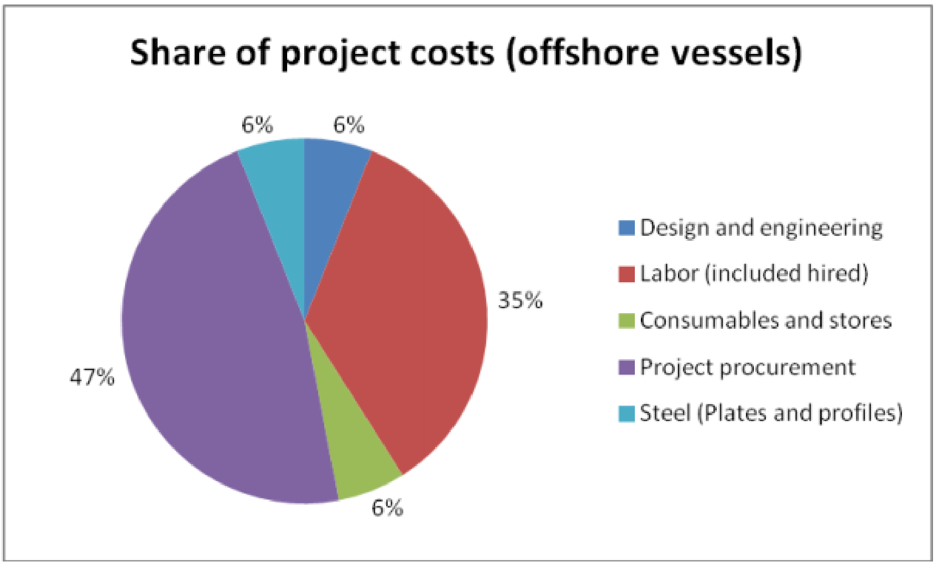

Figure 1 - Share of project costs for offshore vessels. Source: (Hagen, 2014).

Shipyards can be sorted in three different categories, depending on their level of in-house work. The three categories are:

- Fully integrated yard
- Semi-integrated yard
- Pure outfitting yard

Fully integrated yard:

The typical thing for a fully integrated yard is that it has its own steel production and makes a fair part of equipment in-house. With that, comes the capacity and ability to build own hulls. By making own hulls, it is easier to control quality and timeline of the production process. It also eliminates a large portion of the transportation cost, and makes it easier to increase the level of early outfitting on the blocks. The downturn with such yards is that they are more vulnerable to fluctuation in the market due to a higher number of fixed employees. A downturn will result in under-utilization of labour, quickly draining capital reserves.

The problem with keeping an internal workforce to produce equipment is that the effect of scale often makes it cheaper to buy equipment from specialized suppliers. With the professionalizing of the industry, the ship-owners tend to prefer equipment built by suppliers, as they are more reliant and renowned.

A fully integrated yard have all equipment needed for hull production and outfitting. This includes heavy-lift cranes and horizontal transportation systems, as well as dock or slipway.

Semi-integrated yard:

Compared to a fully integrated yard, the semi-integrated yard perform less work itself. A semi-integrated yard must constantly find the balance between what to buy and what to build. The chosen balance of outsourced work depends on the type of ship being built, and the degree of outfitting. Figure 2 from (Hagen, 2012) illustrates the relation for the decision regarding hull building.

The semi-integrated yards operate with both fixed and hired employees, making them less sensitive to fluctuations in the market.

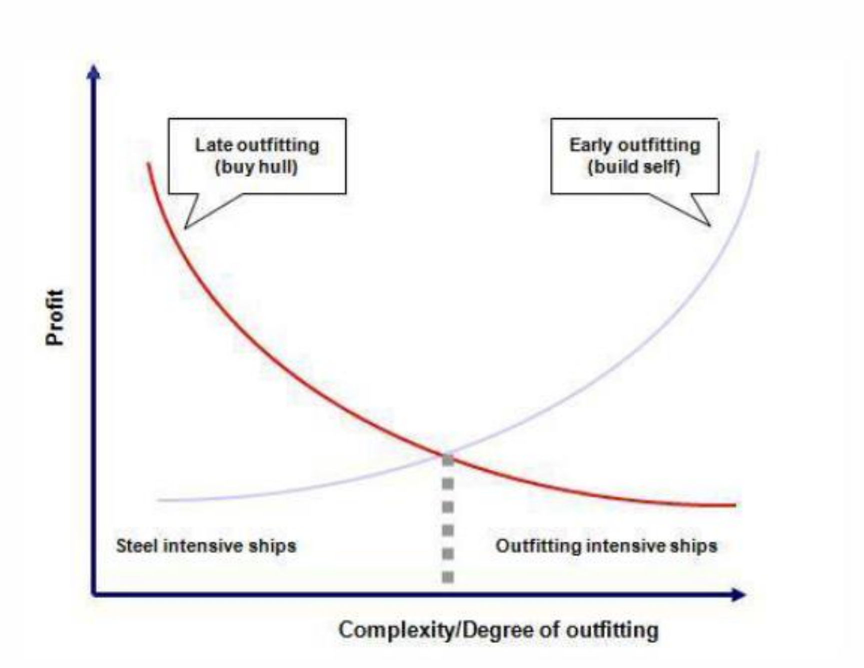

Figure 2 - To buy or build hull, depending on complexity of ship.

Pure outfitting yard:

The pure outfitting yards specialize in the completion part of ships, and has no facilities for hull building or extensive steel work. Outsourcing the hull building allows for higher efficiency and specialization of the yard, but also weakens the independency. The yard is constantly depending on hulls from a sub-supplier, risking delays as the process is out of their control. Such yards have a lower fixed cost, as the yard area can be reduced to quay areas. Indoor halls represent a large investment cost, and require much larger areas available.

A pure outfitting yard hire labour based on the needs on current projects. They have a low number of permanent workers, and can quickly adapt to a changing market. The downturn of such a strategy is that a larger portion of the profitability goes to suppliers, as they control the margins on the supplied product.

2.3 Construction Assembly

The hull construction assembly consist of several stages, putting together increasingly larger elements of the ship. The number of stages in this process vary with the different yards, ship designs, complexity and size of ships. In Norwegian shipbuilding it is hard to define a "typical" ship, and therefore hard to describe the different assembly stages accurately on a general basis. Nevertheless, the next paragraph will set a framework, describing four out of six general main stages of the construction assembly. In the case study in chapter 6, each stage will be analysed to identify the workload and automation opportunities related.

The six construction stages are presented in Figure 3. This report will only focus on direct steel work, thus eliminating surface treatment and outfitting on slipway. The description of work tasks in each stage is largely collected from (Hukkelberg, 1995a).

Figure 3 - Hull construction stages. Source: (Hukkelberg, 1995a).

Stage 1: Burning and cutting

This work stage consist of operations like:

- Burning
- Cutting
- Grouting
- Grinding
- Bending of plates, profiles and pipes

Steel plates come in on a horizontal conveyor to the burning table, where laser or other equivalent burning tool cuts out shapes. Plates are cut to correct size, grouted and grinded, before transported to the next stage. Plates, profiles and pipes that require multidimensional shapes are bent using appropriate bending machines.

Stage 2: Production of parts and prefabrication

In this context, production of parts refers to joining of structural elements such as flakes or panels. Prefabrication includes both prefabrication of steel outfitting, as well as piping. It can typically be smaller parts like brackets, girders and bulwarks. It is usually flat, two-dimensional work, with no more than five parts assembled together. The dimensional restrictions depend on i.e. ship design and construction yard, but typically 2 by 5 meters, and maximum 2 tonnes.

The work stage consist of operations like:

- Assembly
- Control
- Rectification
- Welding
- Grinding

Stage 3: Section and block building

This process consist of the construction of subsections and larger units, which are then assembled to form large blocks. The work is performed within the predefined areas set of for the specific sections.

The work stage consist of operations like:

- Assembly of parts
- Assembly of subsections
- Assembly of blocks
- Welding
- Grinding
- Control
- Rectification
- Assembly of prefabricated outfitting

In general all parts that are subsequently to be built into a larger three-dimensional unit prior to erection. Typically, subsections can be flat plate panels, curved shell units, matrix or "egg box" structures. Dimensional restrictions can typically be parts up to 12 by 12 meters, and weigh up to 20 tonnes.

The size of the larger units are usually decided on an early stage of the structural design phase. The dimensioning factors here is usually the facilities at the yard. Parameters like crane lifting capacity, size of block assembly lines and height under crane hook are just some of the dimensions the design engineers have to take into consideration. The size can typically be one or two panels with internal structure, weighing up to 60 tonnes.

The next step is to combine several units into a block. A typical unit can for instance be a double-hull section, while a block can combine several of these to form a complete double-bottom block over a plate length (Eyres & Bruce, 2012). The units are usually outfitted during assembly, and can contain necessary piping, foundations and equipment. This work is done at its most efficient location, being when the subassembly sections and units are open and available. Size of the blocks depends, as mentioned, on the particular yard facility. Big block modules can easily weigh up to 200 tonnes.

Stage 4: Surface treatment

One could argue that surface treatment should be included as part of the steel work, but it is not defined as such in this thesis.

Stage 5: Section/block assembly

This process consist of assembling sections or blocks together, forming the final hull in the slipway.

The work stage consist of operations like:

- Lift, placement and alignment/rectification
- Tagging and adapting
- Assembly
- Welding
- Grinding
- Assembling elements together
- Preparing parts for surface treatment in the joining area
- Surface treatment of the joining area.

When dividing a ship design into construction blocks, the smart thing is to make sure that complete systems are enclosed in one single block. This makes it easier to perform early outfitting of the blocks, and opens possibilities for testing systems before it is assembled at the erection site. By doing this, you avoid complicating the connection interfaces between blocks. The more systems that cross between two blocks, the more labour is required in the docks when assembling the blocks. Performing that kind of work on such a late level can affect the cost efficiency (Hagen, 2014).

3. Automation Technology

This chapter will describe the historic development of automation technology, as well as the state of the art technology available today. The chapter, in its entirety, is based on information collected in the project thesis (Kålås, 2014).

3.1 History of Automation Technology

The industrial revolution proved to be the beginning of an innovative thought process developing over several decades. Without it, the automation technology would never have developed into the resource it has proven to be today. Automation has been the major force when trying to streamline and optimize the production processes. (Wallén, 2008)

The main thought with automation technology was to have technical devices replacing human workforce on simple manual work. Simple and repetitive operations are mind numbing for a human, and can in time cause lack of concentration, leading to mistakes. With automation technology, one eliminates this factor, as it is very good at repetitive operations.

The first robot in Norwegian industry appeared in 1967. A Norwegian wheelbarrow company called Trallfa had trouble recruiting someone for the spray-painting job, due to very bad working environment. The solution would be to install a robot, but with a listing price of 600 000 NOK the Unimate was excessively expensive for such a small company. They decided to try to develop a cheaper robot, with a target price below 15 000 NOK. The result was an electro-hydraulic robot that could perform continuous movements, and was very easy to program.

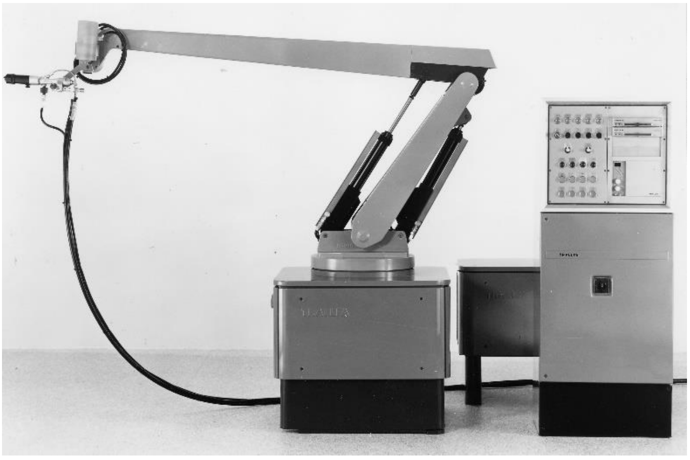

Figure 4 - The Trallfa robot.

The robot was only meant for internal use as a painting robot, but developed into a commercial success. In 1985, ASEA (later ABB) bought Trallfa, and the painting robots was incorporated in ASEA’s line of industrial robots. Several other companies developed individual robot solutions. By 1973, there were 71 different manufactures of industrial robots, with Unimation covering 30 % of the market.

The robots have changed a lot since the first prototype. The methods are similar, but the technology has had huge development. We have moved from simple, hydraulically controlled robots that can perform one single task, to flexible, electric robots that can be programmed to perform a number of different tasks. The table below shows some of the highlights through the history of industrial robots.

Table 1 - Robot development benchmarks.

Year	Event	Comment
1961	Unimation robot	The first hydraulically controlled robot designed for industrial use was invented. The prototype was tested at a GM factory.
1967	Trallfa robot	Trallfa invented the first electro-hydraulic robot. The robot was used for spray-painting wheelbarrows, and was the first robot ever used directly in the working process.
1973	ASEA robot	The first electrical robot (both the drive and the control systems).
1973	T_3 – The Tomorrow Tool	Cincinnati Milacron launched the first ever microcomputer controlled robot.

These historical moments were all a very important contributors to developing the robot. They continuously made the robot more efficient, more flexible and more intelligent. From the early 1980s, the focus was on developing advanced sensor systems. Digital vision, laser scanners and advanced optics further developed the robot to make it more intelligent. This has opened several new areas of appliance. Cutting, bending, painting and arc welding are just some of the tasks now possible. Tasks that accounts for a great portion of the manual labour in shipbuilding.

3.2 Industrial Robot Configurations

The industrial robots are defined and categorized by several different features. This chapter will describe the four major robot types, categorized by their mechanical structure and features:

- Articulated robots
- SCARA (Selective Compliance Assembly Robot Arm)
- Delta robots
- Cartesian robots

Articulated robots (McMahon, 2015):

The articulated robot is a robot fitted with rotary joints. It can range from a simple two-jointed structure to larger systems with 10 or more interaction joints. The rotary joints allow for full movements through several planes. The more joints, the more capabilities the robot has. The typical articulated robot design is a robotic arm with several joints. The flexibility of this robot allows it to perform numerous operations, as the arm can be fitted with many different tools.

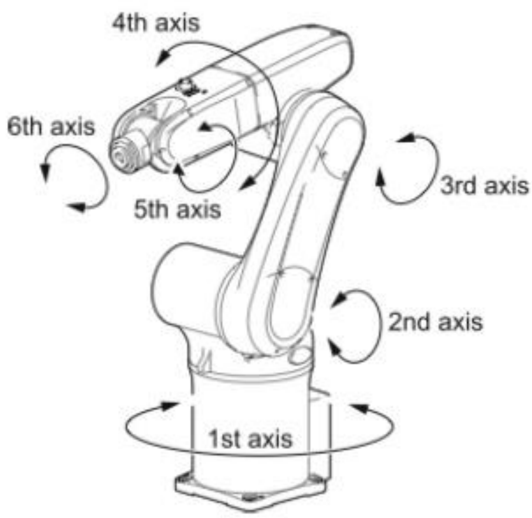

Figure 5 - Articulated robot configuration.

SCARA robots (P. Roland, 2015):

SCARA stands for Selective Compliance Assembly Robot Arm. The robot is rigid in the Z-axis and pliable in the XY-axis. This type of robot is designed for many types of assembly operations, where one of the attributes is the ability to extend into confined areas and then retract out of the way. SCARA robots are very fast and clean in the motion. They have a single pedestal mount, requiring little space and easy mounting.

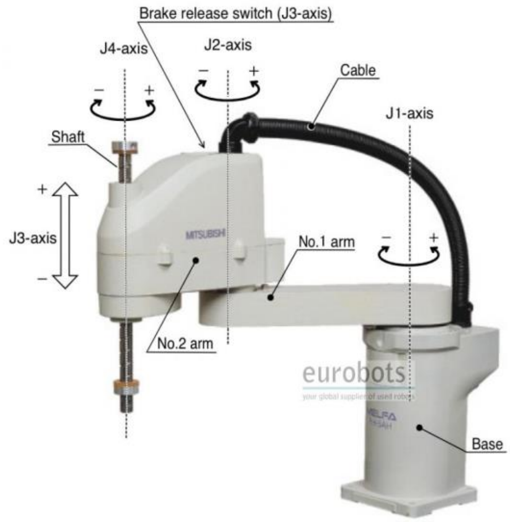

Figure 6 - SCARA robot configuration.

Delta robots (Oza, 2015):

The Delta robot is a type of parallel robot. The design consist of three arms connected to a universal joint at the base. They are very popular for picking and packing parts light and small objects in factories, as they are very fast. Some of the robots can perform up to 300 picks per minute.

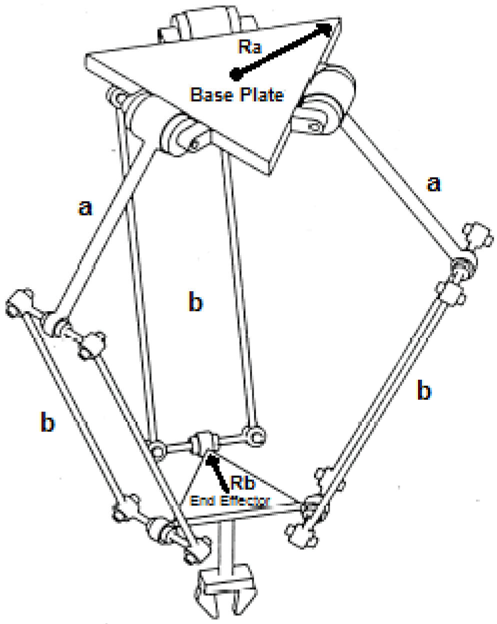

Figure 7 - Sketch of a Delta robot configuration.

Cartesian robots (Messmer, 2015):

The Cartesian robot got its name because it typically moves in a Cartesian frame. The robot can move along three axes that are coupled at right angles, making out an x-y-z coordinate system. Due to a very rigid structure, the robot offers good precision and repeatability. The Cartesian robot is the simplest type of industrial robot. The simplicity also makes it one of the cheapest solutions. The con is that it can perform a limited set of operations. The orientation of the tools are locked to the three-axis movements, thus limiting the work envelope. It is a good fit for pick and place work tasks.

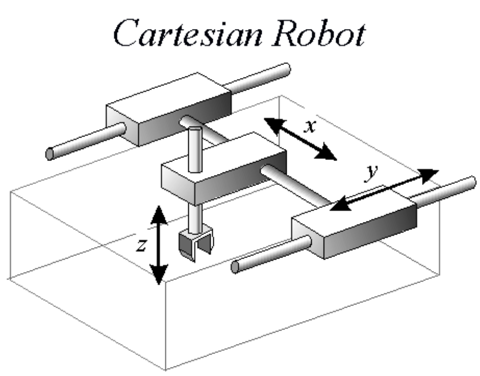

Figure 8 - Sketch of a Cartesian robot configuration.

A variation of the Cartesian robot is the Gantry robot. Like the Cartesian robot, it is able to move along three perpendicular axes. The difference is that this robot is placed on a gantry with two beams moving in the x-direction. It has a carriage that can move along the y-direction between the two beams, and a tool that can be lowered in the z-direction. This means that the z-axis and the tool is the only parts that interferes with the workspace. Unlike the standard Cartesian robot, the Gantry robot encloses its work envelope from the outside. It stands firmly on four legs, and if those legs are strong, the robot can potentially lift very heavy weights. One benefit worth mentioning is that the Gantry robot can be used as a platform for other robots. For instance, an articulated robot can be mounted upside down as the tool, opening for a wide range of applications. (Sunshine, 2015)

Figure 9 - 3D-model of a Gantry robot configuration.

Most of these robotic configurations have abilities that makes them applicable in shipbuilding. In some cases, two configurations are combined to construct a work envelope fitting for the given task. By identifying potential tasks for automation in chapter 4, the different robotic configurations can be assigned to the specific tasks.

4. Automation of Hull Construction

This chapter is based on the information collected in the project thesis (Kålås, 2014). The purpose is to identify tasks in the hull construction process that are candidates for automation.

Automation technology and robotics have come a long way in the last decades. It has opened possibilities for areas of application that previously was unheard of. The shipbuilding industry is one of these areas. A robot can potentially perform many tasks related to the steel work.

The tasks listed below are typical work related to hull construction that fall inside the range of the current automation technology. These are labour-heavy tasks representing a substantial amount of the hull building cost. Making such tasks more cost-efficient will eliminate some of the labour-cost differences between yards in high labour-cost countries and their competitors abroad. It will also reduce the human exposure to the environmental hazards related to the work tasks.

- Plate cutting
- Edge preparation
- Grinding of welds, plate and pipe finishing
- Bending of plates, profiles and pipes
- Welding, both plates, profiles and sections
- Assembly of smaller parts
- Surface treatment, both particle blasting and painting

The choice of robotic configuration depends on the application area. It is important to find a robotic configuration that has a work envelope matching the application, setting and part.

4.1 Plate Cutting

Steel plates and sections were mostly cut to shape using gas cutting technique. In recent time, the introduction of plasma-arc cutters proved competitive. It is now widely used. Alternative methods are laser cutting, which has been increasingly employed in a robotic configuration, and water jet cutting. The advantage of laser cutting compared to plasma cutting is that additional finishing operations is not required after laser. Regardless of the method, the operation can be highly automated.

When a plate is cut to the right shape, a profiling machine is used. The machine is fed CAD drawings from a computer, and cuts the plate to the desired shape. In addition to the shape, the computer also decides the start and stop location, the cutting speed to apply and what information to mark the part with.

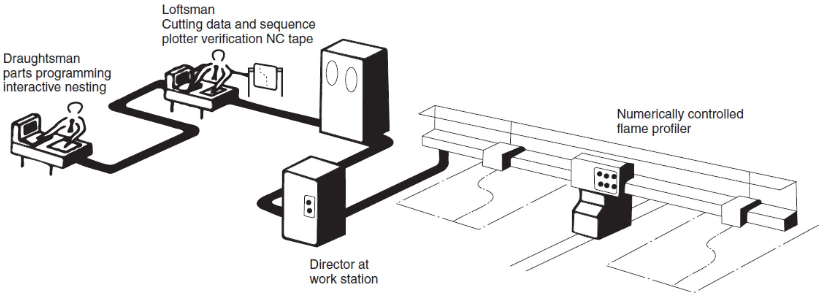

Figure 10 - Sketch showing the control flow for a flame cutting control system. Source: (Eyres & Bruce, 2012).

In the case of smaller one-off shapes as beam knees and brackets, the plates may be cut using a hydraulically operated guillotine. This is a task usually assisted manually.

A typical robot fitted for plate cutting is the gantry robot. Its tracks can be mounted alongside a conveyor system transporting the plates, and several laser burning heads can be mounted to increase cutting speed. The technology is well known, and the process is already automated at several yards with plasma cutting tools. The introduction of the laser-cutting tools in combination with modern robotics could prove favourable, even for yards who have older automated burning table technologies installed.

4.2 Edge Preparation

To improve the quality of coatings in shipbuilding, an IMO regulation requires plate edge preparation. This involves rounding of all plate edges to avoid the flaking of coating around edges.

Manually, the edge preparation can be very tedious and time demanding. By introducing an automated edge preparation system, the plate handling time is reduced, thus reducing the operation cost. An example of such a system is the Kranendonk solution illustrated in Figure 11. It can easily be implemented in an existing plate cutting line, and offers an intuitive touch screen interface (Kranendonk, 2013a).

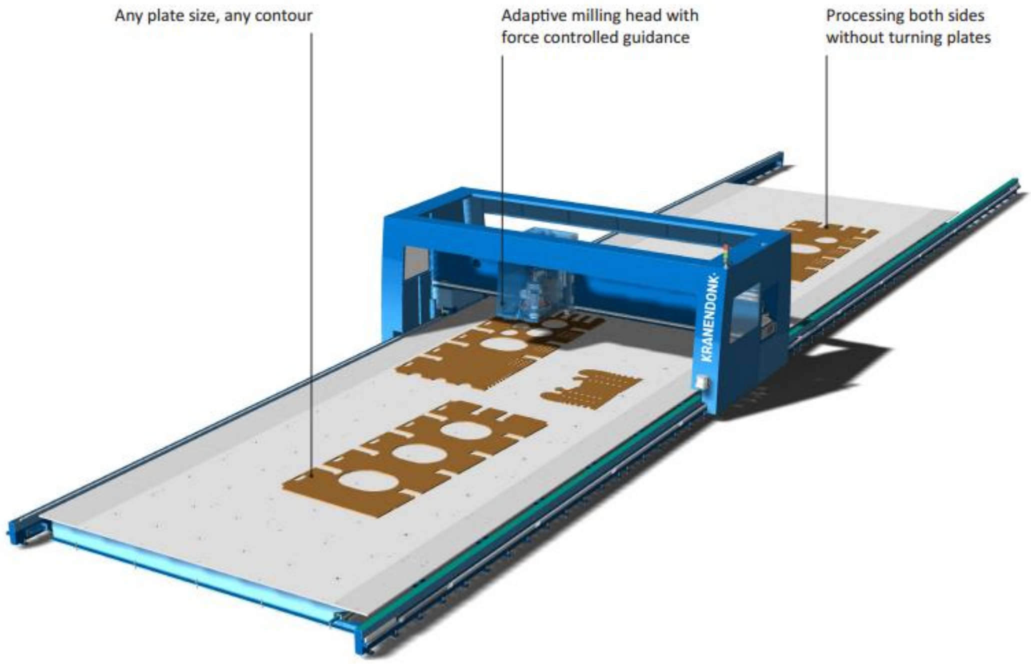

Figure 11 - Kranendonk Edge Preparation System. Source: (Kranendonk, 2013a).

4.3 Grinding of Welds, Plate and Pipe Finishing

Grinding is one of the shipbuilding related tasks most fatiguing for the manual operator.The work is carried out to remove excess material from the surface of welded and machined parts. It is static work, very noisy and the metal dust filling the air forms an unhealthy working environment for manual labour. By introducing a robot grinder, the manufacturing employees will not have to endure such hazardous working environment, and is relieved of the heavy back work.

Grinding robots are not necessarily a good fit for all grinding work in shipbuilding. Most configurations are designed for indoor robot cells where small to medium sized parts can be processed, thus most relevant for the second stage described in chapter 2.3.

Many companies produce robots for grinding. FANUC, Motoman and KUKA are some of the most renowned ones. The common nominator for most grinding robots is that they are based on the articulated robot configuration, described in chapter 3.2. This is because their rotary joints make a very flexible work envelope, as Figure 12 illustrates. This allows for easy access with the grinding tool on complex geometries.

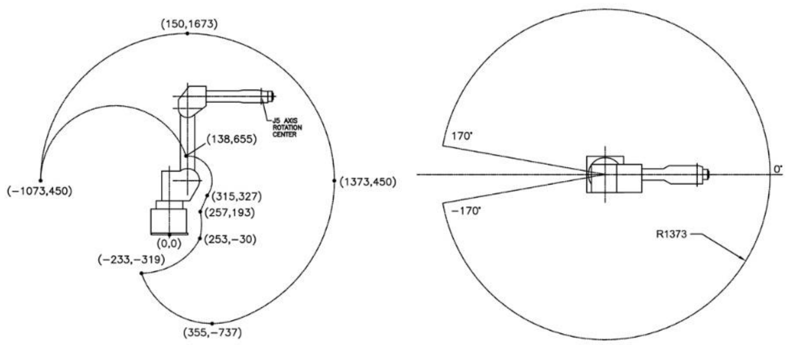

Figure 12 - FANUC robot work envelope.

The grinding robots come with pressure sensor technology to produce an accurate and consistent result. It can be desirable to have multiple robots operating together in a robot grinding cell. In these cases, one robot holds the tool while the other manoeuvres the part, increasing component handling time.

4.4 Bending of Plates, Profiles and Pipes

The information discussed in this chapter about plate bending is retrieved from (Hagen, 2014) and (Yoshihiko, 2011), along with general background information and illustrative pictures from (Eyres & Bruce, 2012).

When constructing the ship hull, the degree of parallel ship is important. One have to compromise between optimization for behaviour at sea, and optimization for efficient production. Put simply, surfaces with curvature is more time demanding to produce than flat surfaces. The aft and foreship usually contain larger areas of double curvature, while the midship sections can be flat or single curvature.

There exist two different solutions for shell plate bending in the industry. One is by use of plate rolls, while the other is by use of heat-line bending.

Plate rolls:
This method makes use of heavy-duty bending rolls. As Figure 13 shows, two lower rolls and one upper roller is used for this configuration. Load is applied to the upper roller, and distance between the rollers can be adjusted to reach desired curvature. This configuration is only applicable to single curvature bending. Modern bending rolls can bend plates up to 45 mm thick, with curvature up to a half circle. The method is highly automated, and plates are typically fed into the machine by a conveyor system.

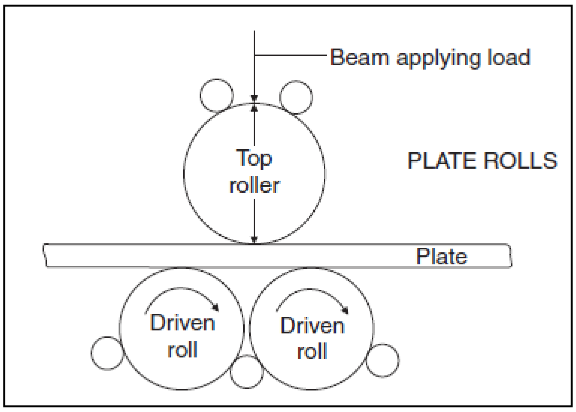

Figure 13 - Illustration of a plate bending roll configuration. Source: (Eyres & Bruce, 2012).

Heat-line bending:
This procedure is widely used to obtain curvature in the steel plates. Heat is applied in a line to the surface of a plate by a flame torch, and is immediately cooled by air or water. Used in the right way, one can make controlled distortions to obtain the correct shape of the steel plate. It has traditionally depended on highly skilled workers with long experience. They used to work without written instructions, making it hard to control cost and delivery time.

Figure 14 - Manual heat-line work, bending steel plates. Source: (Yoshihiko, 2011).

To make the task more predictable, the industry started projects towards mechanizing the process. In (Yoshihiko, 2011) a fully automated steel plate bending system is presented. The system is called “IHIMU-alpha”, and is a heat-line bending configuration that can operate continuously without human interaction.

Figure 15 - Automatic heat-line system called "IHIMU-alpha". Source: : (Yoshihiko, 2011).

Producing pipe spools is very complex and time consuming. By applying a fully automated pipe shop, production time can be reduced to minutes instead of hours per pipe (Kranendonk, 2013c). An automated pipe shop is a complete system that performs the entire operation related to pipe spool production. Cutting, welding, flange assembly and pipe bending are all carried out in the same station, reducing logistics and increasing efficiency. Vision technology is utilized to recognize pipe and flange location to ensure a correct assembly.

4.5 Welding Process

As stated in (F. Roland, Manzon, Kujala, Brede, & Weitzenböck, 2004), the joining processes are an important key factor for the competitiveness of European shipbuilders. In addition to representing a significant portion of the total man hour consumption in hull production and outfitting it also have an impact on non-productive work operations, such as straightening and fitting. Joining operations represents about 50 % of the total person hour consumption and building cost of ships[1], not only by direct cost attributed to joining operations, but also due to potential rework to adjust heat distortions. In some cases, these unproductive work operations can compose up to 30 % of the total efforts in hull production.

This shows how important it is to apply the right joining process. Studies referred to in (F. Roland, Manzon, Kujala, Brede, & Weitzenböck, 2004) have shown that laser hybrid welding can improve the fatigue performances of joints by up to 30 % as compared to arc welding. It therefore indicates that laser hybrid welding should be preferred over arc welding in future work operations.

[1] Excluding procurement cost.

Laser hybrid welding offers a number of advantages, such as:

- Significantly increased welding speed.
- Less heat distortion and rework.
- Reduced consumption of filler material.
- Improved quality, in particular in combination with mechanized equipment.

The way this technology has developed, it can be used for all applications in the preassembly phase of shipbuilding. To make it sustainable and economically viable for shipbuilding, there are, however, several factors to discuss. Unlike other industries, shipbuilding consist of several large structures with difficult accessibility for the welding equipment. This limits the possibilities for standardization. Even more so for Norwegian shipbuilding, which specializes in prototypical, advanced vessels.

The technical solution of laser hybrid welding is illustrated in Figure 16. It is excellent for flat components, like decks and bullkheads. These parts represent a significant portion of the structural elements in many modern ships. These parts are joined by long, straight butt- and fillet-welds. Such work can be carried out efficiently by a laser hybrid configuration, suspended from a gantry system. The parts can easily be attached at the end of a six-axis, articulated robot, making it more flexible. The efficiency of these gantry systems would also be improved by integrating peripheral work operations, like the edge preparation described in chapter 4.2, reducing transport operations and increasing the exploitation of the equipment.

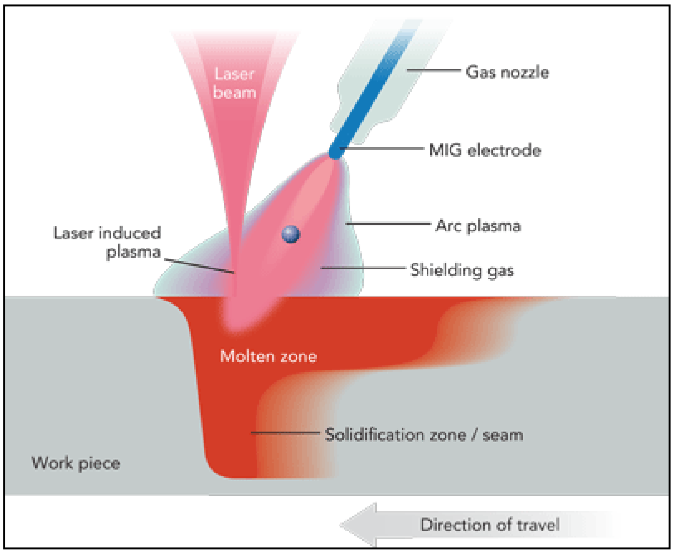

Figure 16 - Laser hybrid welding configuration. Source: www.industrial-lasers.com.

An example of a gantry robot configuration is the automated panel welding line from KRANENDONK, illustrated in Figure 17. It combines gantries with multiple suspended articulated robots to make the panel welding highly efficient. Thanks to an intelligent software that derives all production data from 3D CAD models, arc times over 90% per shift are realized (KRANENDONK, 2013b).

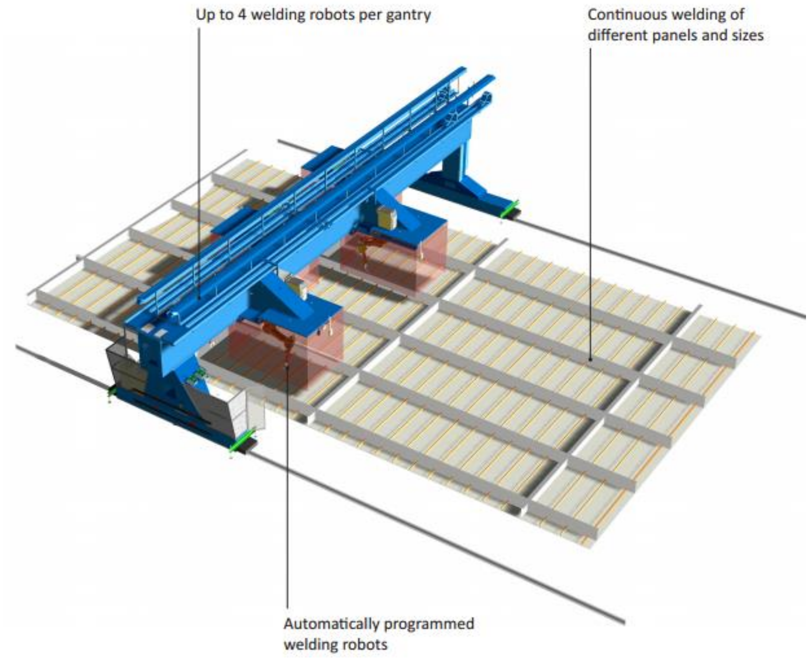

Figure 17 - KRANENDONK panel welding line.

In addition to flat panels, decks and bulkheads, automated gantry welding can be applied to double bottom hull sections and web welding with stiffeners or bulkheads up to 500 mm height.

While most of the automated welding robots are configured for operations in the early pre-assembly stages, projects are also carried out to automate the dock assembly. A project called DOCKLASER has developed an equipment concept for block and dock assembly, called DOCKWELDER, which can improve production automation of the final assembly process on the dock (Andritsos & Perez-Prat, 2000; DockLaser, 2002). The project group consist of shipbuilders, welding institutes, equipment suppliers, experts on work safety, and a leading classification society. The main objective of the project is to increase competitiveness in European shipbuilding by automating 30% of the welding tasks in the dock area, and thus increasing productivity by 10%. In addition, the project aimed to improve the working conditions, safety and health of the welders in the ship erection area. A simulation of the concept is shown in Figure 18 below.

The project was completed in 2005, and showed promising results. It produced better quality, more efficient, and improved the working conditions in the late assembly and outfitting stage. The application of laser processing reduced the heat distortions as well as damages in outfitting and surface treatment. In figures, the project provided the following results (Maritime Transport Research Database, 2010):

- 100% increase in welding speed as compared to arc welding.
- 33-50% heat input as compared to conventional processes, depending of DockLaser tool.
- 50% investment cost, when comparing tractor solution to gantry type laser systems.
- 25% reduction of emissions when using laser welding instead of arc welding.
- 50% space consumption in production line for tractor system, compared to gantries.

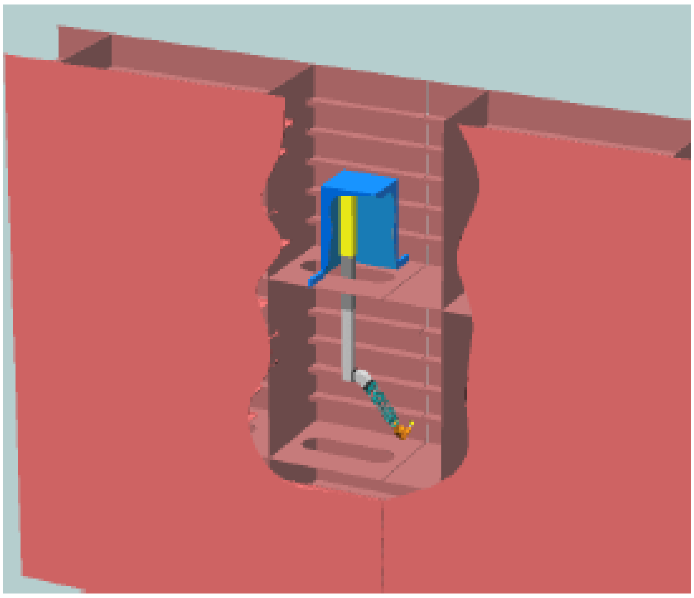

Figure 18 - Simulation of the DOCKWELDER concept. Source: (Andritsos & Perez-Prat, 2000).

4.6 Assembly

Assembly is defined as "any process that takes a number of steel piece parts, or larger structures, and combines them into a larger structure" (Eyres & Bruce, 2012). Assembly operations in the hull construction process vary depending on the stage in the process. Small parts are assembled in to incrementally larger constructions, lastly forming the complete hull. For robots, the contribution to hull assembly is limited. The robots are good at pick and place operations, as well as holding parts for i.e. welding operations. With a common payload of <25 kg, the robots are limited to assist in the lighter parts assembly.

In the early stages, typical assembly tasks are placing stiffeners, girders and brackets for tack welding, as well as placing plates for welding. Moving to the later stages, the steel parts be represented by completed panel structures, and larger three-dimensional parts. These are exceeding the mentioned payload, thus robots cannot contribute to the assembly process except from performing the actual welding operation of the parts.

Assembly robots are not limited to one type of robot configuration. Although the multiple axis articulated robot arm is the most versatile, both delta-robots and gantry configuration can perform simple pick and place operations. The advantages of the gantry configuration is its large work envelope, as well as the possibility to combine it with several articulated robots for handling parts.

4.7 Surface Treatment

Surface treatment is the collective term including both surface grit blasting and application of paint and coatings. This section will describe both automation of surface blasting and automation of the surface painting. While the surface blasting may take place in several stages of the building process, the surface painting is preferably only done once. To succeed with this strategy, it is important to complete all hot outfitting before the surfaces are painted. Hot outfitting performed after painting will only damage the paint, causing unnecessary rework in a stage where it is cumbersome.

Surface blasting

Surface blasting is a very tedious and time-consuming operation. It is environmentally unfriendly, but is required for preparing all metallic surfaces for painting operations (Souto et al., 2012). Operators are continuously exposed to the unhealthy and hazardous working environment, an unwanted side effect to the necessary operation. There exist two main relevant methods for surface preparation; one being abrasive blasting and the other being ultrahigh pressure water jet blasting. Abrasive blasting consists of small particles being blasted against the surface, removing any coating, corrosion or other elements that can affect the surface paint quality. The most common particles used are sand, or in shipbuilding, usually metals (grit blasting). These operations generate a lot of toxic waste. The operator is exposed to the blasting particles, along with any particles stripped of the surface. In addition to this, the surface treatment generates a lot of noise pollution.

To eliminate the unhealthy and hazardous working environment, and the effects it has on the operator, a robot can replace the operator and perform the surface blasting unsupervised. Several design attempts has been made over the last couple of years, and prototypes has been successfully tested on a small-scale basis.

Surface blasting is normally carried out in several stages. To keep a clean production line and unpolluted weld seams, the steel are blasted before utilized in the production. This cleans away any corrosion and oil that the plates may be covered by from milling and storage. The other stage where surface blasting is applied is right before the surface painting. Due to increasing demands regarding the environmental footprint and lifetime of paint coatings, proper blasting is necessary to ensure the adhesiveness of the coating. Any irregularities or sharp edges will result in uneven coating, and is a common cause of premature coating failure.

To ensure proper results, the surface treatment should be carried out in a separate surface treatment hall. Chemicals used in the surface treatment is environmentally unfriendly, and a controlled environment is necessary to limit the spread.

Figure 19 - Grit blasting robot design. Source: (Souto et al., 2012).

Figure 19 shows one of the robot prototypes designed for surface treatment. It is a grit blasting robot with magnetic feet, enabling attachment to the hull side for vertical operation. To enable movement across a curved hull, the design consist of two four-legged frames connected through complex joints, allowing the frames to move relative to each other. The robot legs is attached to the hull by the use of hollow permanent magnets with coils

inside them. This setup is chosen to make a simple mechanism for detaching the robot legs from the surface, as well as increasing attachment force when this is needed. When detached, the legs are simply demagnetized. This is advantageous, as it is easy to get rid of any ferromagnetic dust that may stick to the magnets during operation.

The grit blasting head and vision quality control are mounted on the lower module. One camera controls the path ahead of the blasting head, while the other mounted behind verifies that the surface has reached desired surface texture. In Figure 20 you can see the graphical user interface of the robot autonomous mode. The work area is drawn over the 3D model of the ship, and the best path is then chosen automatically. The trajectory is then translated into command sequences for the robot, where curvature and forbidden areas is taken into account. This robot is naturally adapted for the surface blasting of larger sections and complete hull parts, being blasted in the second surface blasting session described above. It needs a certain treatment area to be advantageous.

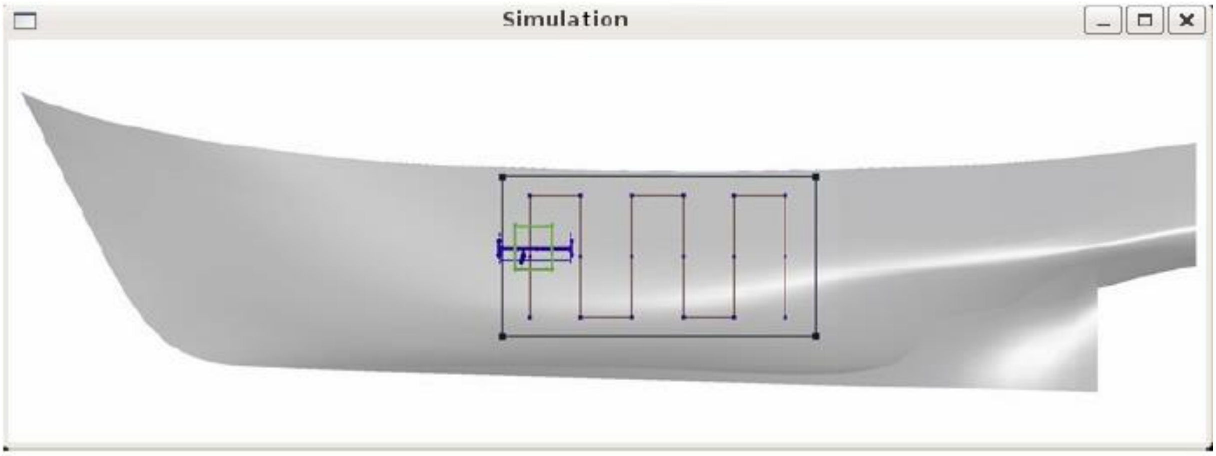

Figure 20 - Graphical robot user interface of the autonomous mode. Source: (Souto et al., 2012).

A different self-travelling robotic system has been designed for autonomous abrasive blast cleaning in the double-hulled structure of ships. The system consist of a 7-axis redundant manipulator and the established RRX mobile platform. The design has been field-tested to ensure the design quality, and it shows promising results. It successfully performed the upper-blasting motions, which is one of the most difficult tasks in the blast cleaning. It fits through a 600x800-mm access hole, and at velocities of 1.5 m/min and 1.875 m/min, it satisfied the required blasting quality, Sa 1.5. Figure 21 shows the entire work process of the design inside the double-hull (Lee et al., 2010).

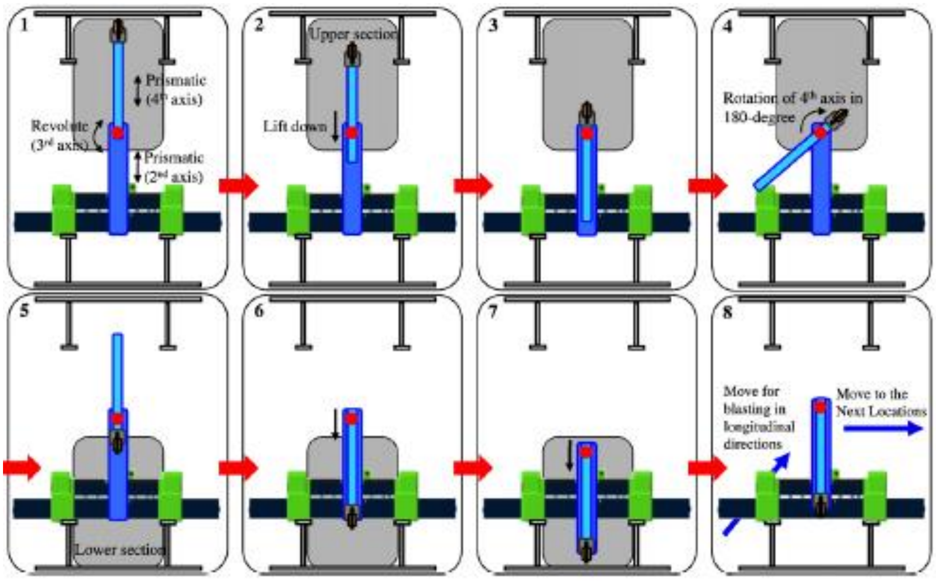

Figure 21 - Process of manipulation of the 7-axis manipulator for covering the entire workspace. Source: (Lee et al., 2010).

Surface painting

After the surface has been cleaned, and treated to reach a satisfying surface texture, it is ready for painting. As with the surface treatment, the painting operation have traditionally been carried out manually. Being as it is such a specialized task, the work is commonly outsourced to sub-suppliers specializing in paint jobs. All the fumes and chemicals provide a very hazardous working environment for the operator, and can have a large impact on the health and safety in the long run.

Figure 22 - Manual hull painting operation.

Replacing the operator with a painting robot can have several benefits. The product quality improves due to the robots precise movement and uniform dispensing abilities. It ensures that each part gets the exact amount of paint required for the expected quality. This also reduces the paint related costs, and applied correctly it can reduce time spent on surface painting. The robot is, needless to say, unaffected by the fumes, and can even operate in a combustible environment. The robot allows for easy access to normally hard to reach places. Different shaped painting tools and nozzles specializes the robot for each painting task.

For smaller parts, the multiple axis articulated robot arm is used. Its flexible movements allow for precise paint application, even at complex curved parts. For the larger sections and complete hull structures, wall-climbing robots like the grit blast robot described above can also be used for surface painting.

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5. Investment Decision Criteria

How an investment scenario is evaluated depends on the information available, and what type of investment it is. To make an educated decision there is a need to assess all ways the investment will affect the business, and base the decision on the total picture.

There are several different methods to apply for the solving of a research question. Two methods used extensively in this report is the qualitative and quantitative methodology. Normally, one use either one or the other to make a case, but this specific scenario can apply argumentation from both. The methods are shortly described below.

Qualitative method:

The qualitative method begins with the specific and moves towards the general. It is based on gathering experiences and opinions from several different sources, and then analyse these to identify a set of data patterns (DeVault, 2015).

Quantitative method:

The quantitative method looks at the general case and moves towards the specific. It is a deductive approach, that applies everything that is measurable. The gathering of numbers and known statistics often gives a more precise and verifiable conclusion than with the qualitative method. As the definition of a deductive approach shows below, it is a good fit for the solving of hypothesis.

Deductive method:

The deductive method act as a testing of an established hypothesis. The hypothesis bases of an existing theory, and then uses scientific observations to confirm or reject the hypothesis (Research Methodology, 2015). The method is best illustrated as shown in Figure 23 below.

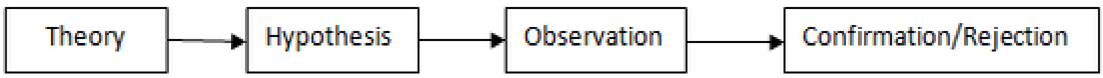

Figure 23 - Illustration of a deductive research method. Source: (Research Methodology, 2015)

The investment picture concerning automation technology is complex. It is not only a discussion about profitability, but also business strategy, technology optimism and several other factors that are not easily quantifiable. This makes it necessary to weigh in both the quantitative results and the qualitative results.

5.1 Qualitative Elements

The qualitative elements that affects an investment decision like this can be challenging to define. It relies on factors that cannot be measured in numbers, and requires extensive discussion to reach a conclusion. What is special about the qualitative research is that it does not necessarily reach an absolute truth regarding the investment in question. There are human factors involved that can give different "best practice" for companies in different situations. The following qualitative elements will be discussed in this report:

- HSE
- Quality and consistency
- Efficiency
- Construction weight and consumption of materials
- Flexibility
- Cost
- Technology optimism
- Restructuring of production line and supply chain

HSE

As (Hukkelberg, 2000) states, the most important resource in shipbuilding is not machines or equipment, but the people working in the production. HSE requires a double-sided focus. On one side, HSE can be improved by preventing negative effects. On the other, it can be improved by exploiting positive effects. The first involves preventing wear and tear, to take care of the human resource. The last one involves improving confidence and educating the human resource.

The importance of protecting the health, safety and environment of the workers has only grown throughout the years. Government rules strictly regulates the allowable working conditions in the yards. By introducing robots as a replacement resource for the tasks typically generating hazardous environment, you eliminate the health risk for the worker. This is part of preventing negative effects in HSE. Typical hazardous tasks in ship hull construction includes, but are not limited to:

- Working in enclosed areas, such as double-hulled structures.
- Grinding
- Painting/Surface treatment
- Welding in static positions.

Enclosed areas, like the double-hulled structure, are one of the toughest working environments to operate in. The area limitations forces the operator to work in fatiguing positions. The enclosed areas have limited feed of fresh air/oxygen, and toxic fumes can build up quickly, creating a hazardous environment for the worker.

In addition to preventing negative effects, the introduction of robotic technology can exploit positive effects. Welders and other yard operators can be further educated to robot technicians, and by that increase their feeling of accomplishment. Continous nurturing of the intellectual minds of workers is important to keep the working staff satisfied.

As Table 2 shows, the general accident rate in shipbuilding industry is high compared with the industry average (Ministry of Employment and Labor, 2010). High focus in the last couple of years has reduced the rate, but still has a way to go in order to reach the industry average. The mentioned robots are unaffected by fumes, enclosed space and other hazardous factors, and can be operated by workers at a safe distance from the harsh environment.

Table 2 - Industrial accident rate in the Korean shipbuilding industry. Source: (Ministry of Employment and Labor, 2010).

Year	**2006**	**2007**	**2008**	**2009**	**2010**
Shipbuilding industry					
Accident rate (%)	1.89	1.55	1.76	1.41	1.20
Industrial accident victims (person)	2240	2065	2375	2413	2122
Death toll (person)	48	46	45	53	47
Average accident rate for all industries (%)	0.77	0.72	0.71	0.70	0.69

Quality and consistency

The main factor influencing quality of robotic operation in the shipbuilding industry is the consistency. A robot will always perform the operation exactly as programmed. A welding robot will improve the quality of the welding seems, and reduce the use of welding wire, which then reduces the overall weight of the construction. Kleven reports as much as 80-90% reduction in welding wire consumption, as well as 10% deformation compared to conventional welding (Kleven Maritime, 2011). This consistent quality can also affect the throughput time at the yard. In some cases up to 30% of the total efforts in hull production is unproductive work. Rework to adjust for heat distortions is part of the problem, and can be eliminated by use of automation technology with modern welding equipment (F. Roland, Manzon, Kujala, Brede, & Weitzenböck, 2004).

Paint jobs will also be more consistent and paint related costs reduced. The robot has sensors detecting exactly when the desired result is reached, eliminating the variable human judgement call needed in manual labour.

The use of welding robots also enables thinner plating on the steel structure. Plates below 10 mm tend to cause problems during regular gas welding due to burn-through (Hagen, 2014). With robotized laser-hybrid welding this problem is close to resolved. It can facilitate the use of thinner plating, and lower the construction weight, particularly on superstructures. This is possible as most of the plates are not a load-carrying element. The choice of plate thickness is more influenced by the welding techniques traditionally used in the shipyards. The technology greatly reduces the heat distortion in the welds, due to a more concentrated heat source from the laser. Investigations have shown that laser hybrid welding can improve the fatigue performance of weld joints by up to 30% compared to arc welding (F. Roland, Manzon, Kujala, Brede, & Weitzenböck, 2004). This affects the expected maintenance cost, but also the expected lifetime of vessels built. All quality factors have a big impact on the competitiveness in a global market. A company known to deliver top quality can demand a higher asking price than their competitors.

Efficiency

In order for automation technology to make the shipbuilding industry more efficient, the whole production line must be re-organized. Several examples from history has shown failed attempts at increasing productivity by applying partial automation of a process. When the rest of the production line is not optimized to the change, it tends to cause more work, as operators has to continuously assist the automated processes.

With the technology development we have seen on the turn of the century, robotics have increased their flexibility in regards to numerous tasks. Where robots previously only managed repetitive operations, the new types are more intelligent, able to adapt to "one of a kind" processes. This development is key for Norwegian shipbuilding to be able to exploit the full potential of the technology.

Welding robots is a good example of the increased efficiency automation technology can offer. A presentation at Kleven Verft (2015) reported robot-welding speeds of 1.8 meters per minute. Compared to a manual welder, which can be expected to deliver 0.35-0.7 meters per minute (Johansen, 2007), a robot is clearly favourable under ideal circumstances. An example for a cruiseship with 400 km of welding seam will give a welding time of 3 704 hours with robot-welding speed, but 9 524 – 19 048 hours if done manually.

The efficiency rate is dependent on the amount of set-up time and non-productive work needed to prepare the operation. (Colton, 2009) reports a manual operator efficiency of 10-45 % for arc welding. This is affected by several factors:

- Personal breaks
- Set-up
- Change position
- Change electrodes
- De-slagging
- Removing residual stresses

Compared, semi-automatic efficiency is reported to be 25-60 %, with the following underlying arguments:

- No need to change electrodes, as wire is used.
- Higher currents and speed
- Some processes require no de-slagging

At last, a fully automatic efficiency is reported to be above 90%. This is highly dependent on the task in hand, and the example assumes small set-up time and de-slagging time.

An efficiency-related factor that is often forgotten, is the potential rework needed due to i.e. heat distortions. Such unproductive work operations can compose up to 30% of the total efforts in hull production (F. Roland, Manzon, Kujala, Brede, & Weitzenböck, 2004). As mentioned, the heat distortions is close to elimination by use of robotic laser-hybrid welding, thus drastically reducing the unproductive work.

One of the great efficiency factors weighing in favour of robots is the simple fact that they do not experience fatigue and tiredness. It does not need a lunch break, or a limited 8-hour shift to operate optimally. Given that the systems upstream and downstream can handle the workflow, the robot can operate 24/7.

A graphic from Kleven Maritime in Figure 24 shows the price per hour, adjusted for efficiency. As you can see, around 2003, robot production outcompeted manual production in Poland (Kleven Maritime, 2011). In order for the total to be profitable, the expected lifetime must be longer than the expected pay-off time on the investment. Such calculations will be included in the model developed in chapter 5.2.

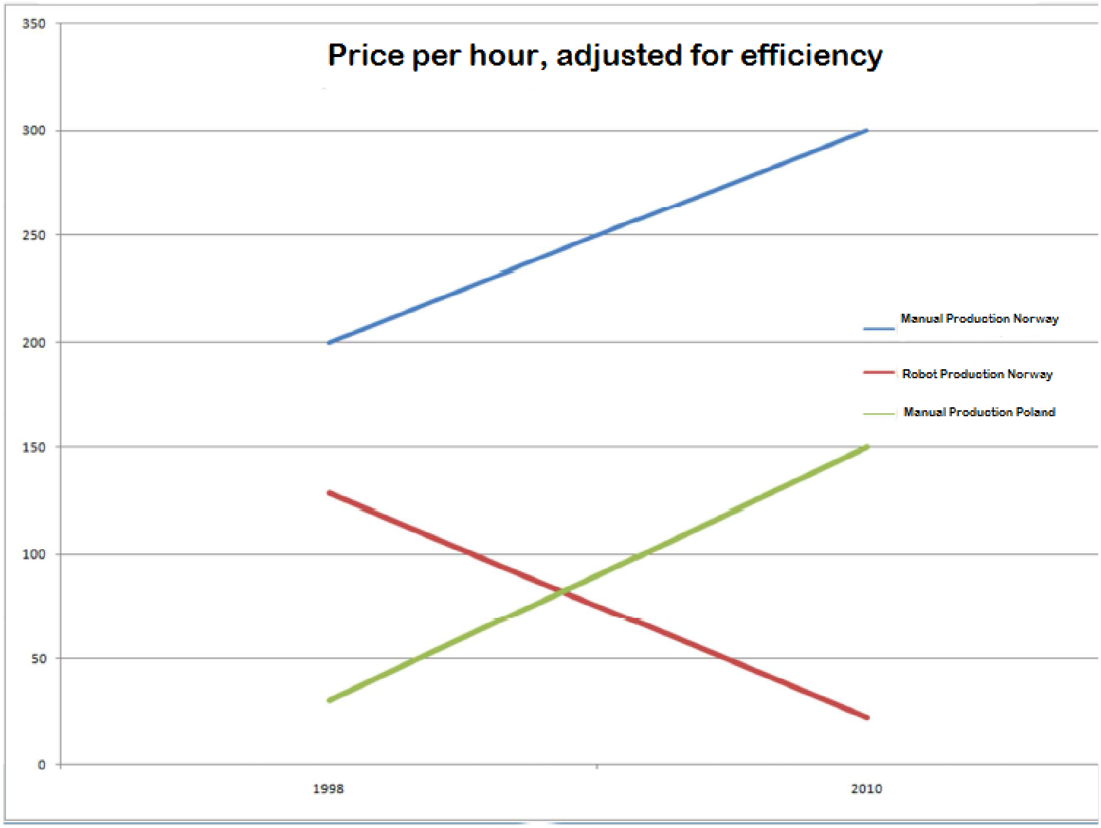

Figure 24 - Comparison of work price per hour [NOK] for robot production and manual production in Norway/Poland, adjusted for efficiency. Source: (Kleven Maritime, 2011).

Construction weight and consumption of materials

Keeping the construction weight as low as possible is always a challenge in shipbuilding. On one side, you need to ensure that the structural integrity of the construction is according to regulations. On the other side, you aim for as high payload as possible. The flexibility in design allows for easier adaption to new operations in an uncertain market, but also adds weight in the shape of extra fundaments. With the application of automation technology and modern welding methods, you can substantially reduce the construction weight, as well as the consumption of material. This is largely due to the elements listed in Table 3.

Table 3 - Elements that reduces the construction weight, and consumption of materials through automation.

Element	**Description**
Thinner plating	Robot welding with laser hybrid technology allows for thinner plating than today's standard/norm. The technology provides a more concentrated heat to the plates, and can weld thinner plates without risking burnthrough and buckling. This applies in particular to the superstructure, where less of the plating act as weight-carrying elements. [2]
Reduced consumption of filler material	With welding robots, the consumption of filler material is reduced. The robot is programmed to the exact feeding speed needed for the given plate thickness, avoiding overfilling. (F. Roland, Manzon, Kujala, Brede, & Weitzenbo, 2004)
Reduced offcuts	Introduction of cutting robots can facilitate the reduction of offcuts through computer optimization of cutting procedure. An example from (Hukkelberg, 1995b) assume that cutoffs accounts for 20% of the total materials used for plates, pipes and profiles. In addition to saving material cost, a more precise burning will reduce the amount of adaption in a later assembly stage.
Flexible robots allow for different production design	Ship designs are carried out with focus on both sea performance and manufacturability. With robot technology, the design can be more optimized, as the robot arm has flexible joints and tools that allow for operations that is difficult to do manually. This can allow for a hull design that minimizes the use of excess materials.

[2] Established through discussions with A.Hagen (2014).

Flexibility

The flexibility of the automation technology can speak both for and against it, depending on how you see it. The development within sensor technology and optics, along with programming technology, has increased the robots flexibility tenfold. The robots are now smaller, and can perform a numerous of tasks, with different tool attachments. The programming is simpler, where 3D-models can now be directly interpreted to robot operations. On the other hand, they will not be more flexible than manual labour when it comes to performing a variety of tasks.

Cost

The cost of automation technology can speak both for and against the case. In order to increase the profit of hull construction through automation you need several robots for several tasks. This requires a substantial capital investment, both in equipment and in hall area with the necessary infrastructure. However, the fact is that the price of automation technology has dropped significantly the last years due to the rapid development of the technology. Automation technology have experienced the same development as mobile phones, offering a more flexible, multipurpose solution for a lower price. This is one of the most important reasons as to why they can be considered as a replacement for manual labour in certain hull construction stages.

Technology optimism

It is hard to measure the values of this, but it is still an important factor from an investor point-of-view. This factor is about the importance for companies to be first, to lead the way in order to gain head on your competitors. Many companies insist on being among the first to apply new technology, and does so for a reason. If the company have a belief that the given technology can have a future, it is important to acquire the technology early to gain knowledge of its application. It takes time to adjust to any new technology, and by acquiring it early, you can take part in the continuous development and adjustment of the technology, to make it a best fit for the company. Technology optimists believe that the evolution of technology is the only way forward, while technology pessimists on the other hand, believe that there is no future, no perspective.

Kleven is known as the yard in Norway focusing on automation technology in their production. Through conversations with Tore Roppen, the Director Supply chain in Kleven, the author learned that those who first applied robots and modern production methods still have the greatest pace of change. Those who were late to apply such methods struggle to compete. The largest competitiveness will not be found where the labour is cheap, but where the pace of change is greatest.

It comes down to company strategy, whether or not you are technology optimists or pessimists. There is a risk factor related to both options, and several cases throughout history have examples that favours both options. If you are a technology optimist, the automation technology applicable to shipbuilding should be of interest regardless of the risk factor, given that the potential profit is proportional to the risk. If you are a technology pessimist, you will probably wait until others have proven the profitability of the technology, but then you also have to accept the risk of falling behind your competitors in the race of market share.

Restructuring of production line and supply chain

In order to utilize the full potential of introducing automation technology in a previously manual production line, the supply chain and production line needs restructuring. The material flow may not be identical, and parts may be needed at a different stage in the construction process. Work stations should be repositioned to best fit a new material flow. Several reasons suggest a restructuring:

- Robots need different infrastructure, and tools available compared to manual labour.
- Material flow may change, due to more work being done in a robot production cell.
- Storage should be placed close to automation, and be fitted with automated feeding of parts and material.
- Design should be optimized for robot production to maximize efficiency and profit.
- Suppliers must deliver a more consistent product to best facilitate the robots lack of ability to improvise.
- Drawings must be completed earlier, because operators need time to program the robots.

5.2 Quantitative Elements

The Quantitative elements is easier to define. It should depict which of the different scenarios that are most profitable, given the framework set in the case study. The problem, however, is getting a realistic picture of the entire economic impact each scenario gives. Companies are reluctant to share their key financials, as this is confidential data. They fear that they will lose some of their competitive advantage if this information becomes common knowledge. The case, as mentioned earlier, is thus based on the limited data available.

The two different scenarios that will be compared, are the following:

- Buying hulls produced manually in a low labour-cost country (Poland i.e.).
- Producing hulls with automation technology in a high labour-cost country (Norway i.e.).

That is, the calculations aims to investigate if automated production in a high labour-cost country can outcompete manual production in a low labour-cost country.

Developing a model

This chapter will describe a general model that can be used as a tool in the quantitative decision-making between the two scenarios. It should depict simple calculations that can help shed light on where the largest potential for improvement through automation lies. Several methods are included in the model, to shed light on different aspects of the investment decision. The model will follow these steps:

- Step 1: Establish case data
- Step 2: Map process time consumption
- Step 3: Perform maximum investment calculations
- Step 4: Evaluate investment by Net Present Value and Payback Period
- Step 5: Sensitivity analysis
- Step 6: Scenario weighting with Quantitative Strategic Planning Matrix

Step 1: Establish case data

This step should collect and establish all case data needed to create a framework for the rest of the calculations.

Step 2: Process time consumption mapping

In order to identify tasks where automation can increase the efficiency, it is necessary to map the processes involved in the existing production. This involves investigating where all manhours are applied in the process. This paper divides the hull building process into five stages, described in chapter 2.3. With these stages as the starting point, key figures from a relevant case can be used to establish the workload distribution for each stage. The next step, as the form in Table 4 depicts, is to distribute the manhours applied in each stage between the work tasks relevant for that particular stage. The table act as a general template, and stage related tasks should be adjusted for each individual yard or build project.

Table 4 - Workload distribution table template.

Portion of total amount hull related steel work:	0 %	0 %	0 %	0 %	0 %
	Stage 1 Burning and cutting	Stage 2 Part prod. And prefab	Stage 3 Section building	Stage 4 Surface treatment	Stage 5 Section assembly
Tasks:					
Burning	0 %				
Cutting	0 %				
Edge preparation	0 %				
Grinding	0 %	0 %	0 %		0 %
Bending of plates, profiles and pipes	0 %				
Assembly		0 %	0 %		0 %
Control		0 %	0 %		
Rectification		0 %	0 %		
Welding		0 %	0 %		0 %
Lift/placement					0 %
Alignment/rectification					0 %
Tagging and adapting					0 %
Prepare for surface treatment in joining area					0 %
Surface treatment of joining area					0 %
SUM	0 %	0 %	0 %		0 %

With a workload distribution table established, it is possible to calculate the time consumption related to all stages and all tasks in the hull building process using the following equations:

$$\begin{gathered} Original\ task\ time\ consumption = \\ Specific\ Task\ Rate[\%] \cdot Specific\ Stage\ Rate[\%] \cdot Total\ Manhours[h] \end{gathered} \tag{1}$$

$$\begin{gathered} Original\ task\ financial\ cost = \\ Original\ task\ time\ consumption \cdot Hourly\ Wage \end{gathered} \tag{2}$$

Once the complete hull building process is mapped, the results can be used to test the impact of efficiency change through automation. To do so, each task must first be coupled with its associated possible rate of automation. That is, how much of each task can be automated with current automation technology. Next, the expected change in task efficiency reached through automation is estimated. The table template is available in Table 5, and can be filled in using case study data for the relevant yard or project.

Table 5 - Template for estimated task rate of automation, and associated efficiency change.

	Assumed rate of work that can be automated	Assumed increased efficiency where robots are operating:
Tasks:		
Burning	0 %	0 %
Cutting	0 %	0 %
Grouting	0 %	0 %
Grinding	0 %	0 %
Bending of plates, profiles and pipes	0 %	0 %
Assembly	0 %	0 %
Control	0 %	0 %
Rectification	0 %	0 %
Welding	0 %	0 %
Lift/placement	0 %	0 %
Alignment/rectification	0 %	0 %
Tagging and adapting	0 %	0 %
Prepare for surface treatment in joining area	0 %	0 %
Surface treatment of joining area	0 %	0 %

By combining data from Table 4 and Table 5, potential time saved is calculated:

$$Potential\ time\ saved = Original\ time \cdot W \cdot E \tag{3}$$

$$Where\ W = \%\ work\ that\ can\ be\ automated$$
$$and\ E = \%\ increased\ efficiency\ from\ automating$$

Potential cost savings per build can then be calculated:

$$Potential\ cost\ savings = Potential\ time\ saved \cdot Hourly\ wage \tag{4}$$

Step 3: Maximum investment cost to break even

When the potential cost saved by applying automation technology is known, it is possible to perform calculations to find a justifiable magnitude of the investment. If the investment cost exceeds the expected savings throughout the lifetime of the investment, then it is a bad investment.

Maximum investment cost is calculated using the following equation:

$$Max\ investment = \frac{Potential\ savings}{year} \cdot \frac{depreciation\ period}{(1 + capital\ interest)^{depreciation\ period}} \tag{5}$$

To apply equation 5, the following case data is needed:

- The manhour consumption of one hull
- The annual hull throughput in the yard
- The depreciation period of the investment
- The capital interest p.a.

This equation calculates the maximum total investment for the investment to break even throughout the depreciation period. This should be calculated for each stage in the process to uncover individual differences. All the results from equation 5 should be presented in a table. A template is provided in Table 6.

Table 6 - Max investment cost to break even.

Stage	Savings/year		Max investment cost to break even	
1	NOK	-	NOK	-
2	NOK	-	NOK	-
3	NOK	-	NOK	-
5	NOK	-	NOK	-
TOTAL	NOK	-	NOK	-

Step 4: Net Present Value and Payback Period

A method that can assist in the decision-making is the Net Present Value (NPV) method. It is a formula used to determine the present value of an investment by the discounted sum of all cash flows received from the project. Put simply, it is an indicator of how much value an investment adds to the company. The procedure and description of the method is collected from (Baker, 2000).

The formula can be written:

$$NPV(r) = -C_0 + \sum_{i=0}^{T} \frac{C_i}{(1+r)^i} \tag{6}$$

Where

$$C_0 = Initial\ investment$$
$$C_i = Cash\ Flow$$
$$r = Discount\ Rate$$
$$T = Time$$

It is easily calculated using a table. See the steps in Table 7 for suggested set-up.

Table 7 - Net Present Value calculation template table.

Year	**Cash Flow**	**Present Value**
i=0	$-C_0$	$-C_0$
i=1	C_1	$\frac{C_1}{(1+r)^1}$
i=n	C_n	$\frac{C_n}{(1+r)^n}$
i=n+1	C_{n+1}	$\frac{C_{n+1}}{(1+r)^{n+1}}$
Total		$\boldsymbol{-C_0 + \sum_{i=0}^{T} \frac{C_i}{(1+r)^i}}$

What the resulting NPV tells us about the decision is:

- If NPV > 0, the investment will add value to the company, and the investment should be accepted.
- If NPV < 0, the investment will subtract value from the company, and the investment should be rejected.
- If NPV = 0, the investment will neither add value or subtract value, and the investment should be based on other criteria than financial.

Unlike the NPV, the Payback Period does not account for the present value of cash flows. With this method, the investment is accepted or rejected based on the length of the payback period. The payback period is simply defined as the period of time it takes for the project to recover the money invested in it. It can be calculated using the same cash flows as the NPV calculation.

$$Payback\ Period = \frac{Initial\ investment}{Annual\ cash\ flow} \tag{7}$$

Step 5: Sensitivity to change in key parameters

It is interesting to see how influencing different key factors are on the outcome of the calculations. That is, how much the outcome changes if a key parameter changes. This gives information about which factors that require extra attention.

The information can be presented through a number of different methods. One method chosen for this analysis is a Ranked Sensitivity Table. The table should display what impact different parameters has on the calculated maximum investment to break even, and be ranked by their impact. A 10% change in the key parameters is considered an appropriate change to uncover the impact.

The parameters chosen for further studies are:

Table 8 - Sensitivity Parameters chosen.

Parameter	Chosen because:
Polish wages	Hull building is very labour-heavy, thus a large part of the cost is related to wages. Changes in wages will therefore have a significant impact on the cost level.
Polish currency	Currency exchange rates for PLN have varied greatly over the last years, and affects the total cost in NOK.
Robot efficiency	Uncertainties in the estimates and local differences between yards makes it interesting to investigate how much robot efficiency affects the outcome.
Throughput	The planned throughput affects the total turnover for the yard, and by that, impacts the total investment limit. With lower throughput, the profit per unit throughput has to be higher to maintain the investment limit viable.

Other parameters could also have been included, but these are evaluated as the most relevant to investigate based on their fluctuating values. A template for the Ranked Sensitivity Table is presented in Table 9, where “Change in Total maximum investment” is calculated as:

$$\begin{gathered} Change\ in\ Total\ maximum\ investment = \\ New\ maximum\ investment - Original\ maximum\ investment \end{gathered} \tag{8}$$

Table 9 - Ranked Sensitivity Table template.

Key Parameter	Change in Total maximum investment	Rank, by magnitude of change
Polish wages +10%		
Polish currency +10%		
Robot efficiency +10%		
Throughput +10%		

This sensitivity differs for the different stages of construction. For some of the key parameters it can be interesting to investigate the impact on each individual stage.

Step 6: Scenario weighting with Quantitative Strategic Planning Matrix

The procedure for this method is largely collected from (Kasi, 2009; Maxi-Pedia, Not dated).

The Quantitative Strategic Planning Matrix (QSPM) is a strategic planning tool that can be used to evaluate possible strategies for a project or company. It provides an analytical method for comparing the different alternatives. It falls within the thirds stage of strategy formulation, called "The Decision Stage", and uses input from stage 1 and 2 analysis to decide objectively between the alternative strategies.

Stage 1, known as "The Input Stage", is based on the EFE (External Factor Evaluation) matrix and IFE (Internal Factor Evaluation) matrix. It is used to identify key strategic factors. The EFE matrix and IFE matrix are very similar. The major difference is that the IFE matrix focuses on internal strength and weakness of the company, while the EFE matrix focuses on the external opportunities and threats to the company. The EFE and IFE matrix are combined with a SWOT analysis from stage 2 "The Matching Stage", together forming the QSPM displayed in Table 12.

The concept of the QSPM is to determine the relative attractiveness of various strategies based on the extent to which key external and internal critical success factors are capitalized upon or improved. The relative attractiveness of each strategy is then computed by determining the cumulative impact of each external and internal critical success factor (Maxi-Pedia, Not dated). The Total Attractiveness Score listed in the bottom of Table 12 indicate the relative attractiveness of each alternative strategy. The higher the score is, the more attractive the strategic alternative is.

A limitation is that the QSPM can only be as good as the prerequisite information and matching analysis upon which it is based. It also requires good judgement in assigning fitting ratings. The advantage of the method is that it integrates the external and internal factors into the decision making process. It also makes an elsewise intuitive and subjective process more objective by methodizing it.

To assign weights to the factors, the factors are first ranked by assumed importance and then weighted subjectively. This must be done for internal and external factors respectively, as listed in Table 10 and Table 11. These weights could have been rounded off to the closest 5%, but it would make it difficult to separate the subjective priority of many factors.

Internal factors

Table 10 - Internal factor priority rank.

Priority Rank	Factor	Weight
1.	Quality of product	16%
2.	Skill set in-house	13%
3.	Work productivity	11%
4.	Worker’s unique skill set	10%
4.	Little early outfitting	10%
4.	Sensitive to oil prices	10%
7.	Location of business	9%
8.	Unique product	8%
8.	Difficult to lay off labour	8%
10.	Product logistics	5%

External factors

Table 11 - External factor priority rank.

Priority	Factor	Weight
1.	HSE	15%
2.	Increased throughput	14%
3.	Declining margins	12%
3.	Economic downturn	12%
5.	Construct lighter hulls	11%
6.	More competition	9%
6.	Climbing wages	9%
8.	Educate workers	7%
9.	Industry consolidation	6%
10.	Reduce bottlenecks	5%

The priority and weights can be adjusted to fit each individual company. The key is that the process is methodized. The finalized QSPM template is displayed in Table 12.

Table 12 - Quantitative Strategic Planning Matrix template.

		Alternative 1 - Buy from Poland			Alternative 2 - Automated production in Norway		
Internal strengths		Weight	Rating	Weighted score	Weight	Rating	Weighted score
1.	Location of business	9 %		0,00	9 %		0,00
2.	Worker's unique skill set	10 %		0,00	10 %		0,00
3.	Quality of product	16 %		0,00	16 %		0,00
4.	Work productivity	11 %		0,00	11 %		0,00
5.	Unique product	8 %		0,00	8 %		0,00
Internal Weaknesses							
1.	Little early outfitting	10 %		0,00	10 %		0,00
2.	Sensitive to oil prices	10 %		0,00	10 %		0,00
3.	Skill set in-house	13 %		0,00	13 %		0,00
4.	Difficult to lay off labour	8 %		0,00	8 %		0,00
5.	Product logistics	5 %		0,00	5 %		0,00
Rating: major weakness (1), minor weakness (2), minor strength (3), major strength (4)							
TOTAL WEIGHTED SCORE		100 %		**0,00**	100 %		**0,00**
Opportunities		Weight	Rating	Weighted score	Weight	Rating	Weighted score
1.	Industry consolidation	6 %		0,00	6 %		0,00
2.	Increased throughput	14 %		0,00	14 %		0,00
3.	Educate workers	7 %		0,00	7 %		0,00
4.	Construct lighter hulls	11 %		0,00	11 %		0,00
5.	Reduce bottlenecks	5 %		0,00	5 %		0,00
Threats							
1.	Declining margins	12 %		0,00	12 %		0,00
2.	Climbing wages	9 %		0,00	9 %		0,00
3.	Economic downturn	12 %		0,00	12 %		0,00
4.	More competition	9 %		0,00	9 %		0,00
5.	HSE	15 %		0,00	15 %		0,00
Rating: poor (1), below average (2), above average (3), superior (4)							
TOTAL WEIGHTED SCORE		100 %		**0,00**	100 %		**0,00**
Sum Total Attractiveness Score				0,00			0,00

6. Case Study

To test the model developed, it is applied to a case study. The case study must be well-defined with a pre-established framework. The framework for this case study is as follows:

A shipyard with high-cost labour will make a strategic move from buying the hulls from other yards, to making them in-house. This scenario is highly relevant for Norwegian yards, but can also be representative for any yard with only high-cost labour available. In order to make this transition as profitable as possible, the situation must be investigated thoroughly. Every investment scenario is measured in their potential profitability, as will this.

The hypothesis is that it will be too expensive to hire manual labour to perform the vast amount of construction work needed to complete a hull. It is a very labour-heavy task, and getting a large enough qualified workforce can prove difficult. The aim is to investigate if modern automation technology can be a viable investment to reach the goal of taking back more steel work of the hull production.

Step 1: Establishing case data

This study will focus on the building of a semi-advanced Platform Supply Vessel, with a typical length of 75-90 meters, breadth of 17-20 meters and 3500 tons of steel.

Through conversations with A. Hagen (2015), the following numbers are established as working estimates:

- A PSV hull takes 100 000 hours to complete.
- A completed PSV costs 300 MNOK.
- Steel cost is 3300 NOK/ton.
- The wage in Poland is 100 PLN/hour.
- Including contribution margin, an industry worker in Poland can be presumed to cost 250 PLN/hour.
- The currency exchange rate is 2 NOK/PLN.
- Work distribution for the different stages of hull construction are as shown in Table 13.

Table 13 - Work distribution for each stage of hull construction.

Distribution	Stage 1 - Burning and cutting	Stage 2 – Part production and prefab.	Stage 3 - Section and block building	Stage 4 - Surface treatment	Stage 5 - Section and block assembly
Work distribution [%]	20	30	30	- [3]	20
Manhours	20 000	30 000	30 000	-	20 000

[3] Not a part of the steel work calculations.

The bigger blocks the given yard is able to construct, the bigger part of the work will be in that stage, and subsequently smaller part on hull erection. The block size restrictions are usually given by the yards crane capacity and height, as well as hall sizes and horizontal transportation capacity.

In (Shetelig, 2013), a coarse estimate of cost distribution for a completed PSV can be found:

Table 14 - Distribution of costs for PSVs.

Technological group	Portion of total cost
Hull	20-30%
Machinery and Propulsion	25%
Cargo containment and handling	20-25%
Ship common systems/Ship assembly and systems integration (for outfitting yard)	20%
Hotel and accommodation	5%
+ Financial costs	+ Financial costs

The hull cost includes the manhours and the material needed to complete the hull, and is representative when built in a low-cost country like Poland. For high-cost countries like Norway, the cost would be much higher, mainly due to the high labour-cost. The hull price from Poland can be calculated as:

$$\begin{aligned} Hull\ cost, Poland &= steel\ cost + manhour\ cost \\ &= 3500\ tons\ \times 3300\ \frac{NOK}{ton} + 100\ 000\ hours\ \times 500\ \frac{NOK}{hour} \\ &= 61\ 550\ 000\ NOK \end{aligned} \tag{9}$$

With a PSV total cost of 300 MNOK, we can compare the hull cost to the cost distribution in Table 14. The hull cost adds up to 20.5 % of the total 300 MNOK, matching with results from (Shetelig, 2013).

Step 2: Mapping Process time consumption

With the case data in Table 13, and the key figures developed in the case study, the workload distribution table template in Table 4 can be completed. The result is displayed in Table 15. The tasks included in each stage ties back to the description in chapter 2.3.

With the entire process mapped out, the results are used to test the impact of efficiency change through automation. The template in Table 5 is used, and case data estimated for each of the relevant tasks is inserted. The results are shown in Table 16.

Table 15 - Workload distribution table.

Portion of total amount hull related steel work:	20 %	30 %	30 %	0 %	20 %
	Stage 1 Burning and cutting	Stage 2 Part prod. And prefab	Stage 3 Section building	Stage 4 Surface t	Stage 5 Section assembly
Tasks:					
Burning	30 %				
Cutting	20 %				
Edge preparation	15 %				
Grinding	20 %	10 %	10 %		10 %
Bending of plates, profiles and pipes	15 %				
Assembly		20 %	25 %		30 %
Control		5 %	5 %		
Rectification		20 %	20 %		
Welding		45 %	40 %		20 %
Lift/placement					10 %
Alignment/rectification					10 %
Tagging and adapting					5 %
Prepare for surface treatment in joining area					5 %
Surface treatment of joining area					10 %
SUM	100 %	100 %	100 %		100 %

Table 16 - Estimated task rate of automation, and associated efficiency change.

	Assumed rate of work that can be automated	Assumed increased efficiency where robots are operating:
Tasks:		
Burning	90 %	5 %
Cutting	90 %	10 %
Grouting	70 %	10 %
Grinding	65 %	20 %
Bending of plates, profiles and pipes	40 %	0 %
Assembly	25 %	0 %
Control	0 %	0 %
Rectification	95 %	50 %
Welding	90 %	30 %
Lift/placement	60 %	10 %
Alignment/rectification	50 %	0 %
Tagging and adapting	50 %	10 %
Prepare for surface treatment in joining area	50 %	10 %
Surface treatment of joining area	70 %	20 %

By combining the data in Table 15 and Table 16, and equation 3 in chapter 5.2, calculations for potential time saved through automation is performed. A detailed calculation for stage 1 of the process is shown in Table 17. For detailed calculations of all stages, see appendix A.

Table 17 - Calculations for potential savings through automation of stage 1.

Example of potential savings in stage 1:		
Original time cost stage 1:		
Burning	6 000	hours
Cutting	4 000	hours
Edge preparation	3 000	hours
Grinding	4 000	hours
Bending of plates, profiles and pipes	3 000	hours
TOTAL	20 000	hours
Potential time saved with robots utilized:		
Burning	270	hours
Cutting	360	hours
Edge preparation	210	hours
Grinding	520	hours
Bending of plates, profiles and pipes	-	hours
TOTAL TIME SAVED	1 360	hours
Potential savings	680 000	NOK

Step 3: Maximum investment cost to break even

By applying equation 4 from chapter 5.2, the potential cost savings are used to find an investment limit, defined by equation 5. That is, the maximum investment to break even over a given time period. For calculation purposes, some case study assumptions are made:

- The yard can manage a throughput of four PSV vessels per year.
- The depreciation period for the capital costs is set to 5 years.
- The capital interest is set to 8 % p.a.

The results are displayed in Table 18.

Table 18 - Max investment cost.

Stage	Savings/year [MNOK]	Max investment cost to break even [MNOK]
1	2,7	9,3
2	13,8	46,9
3	13,0	44,1
5	3,7	12,5
TOTAL	**33,2**	**112,7**

Step 4: Net Present Value and Payback Period

The Net Present Value can be calculated using equation 6 from chapter 5.2. The equation requires some case data present to be calculated. The investment cost and annual cash flow is based on the results from the “Maximum investment cost” calculation. Discount rate is chosen based in shipping industry average (KPMG, 2010). The time period is set equal to the depreciation period for the capital cost displayed in step 3.

- The investment total cost is set to 112 MNOK, just below the maximum investment cost limit calculated in step 3.
- The annual cash flow is set equal to 33 MNOK, just below the calculated savings/year in step 3.
- The discount rate, r= 8%
- The time period, T = 5 years

Following the template in chapter 5.2, provides the following results:

Table 19 - Net Present Value calculations.

Year	Cash Flow	Present Value
i=0	$-112\ MNOK$	$-112\ MNOK$
i=1	$33\ MNOK$	$30{,}6\ MNOK$
i=2	$33\ MNOK$	$28{,}3\ MNOK$
i=3	$33\ MNOK$	$26{,}2\ MNOK$
i=4	$33\ MNOK$	$24{,}3\ MNOK$
i=5	$33\ MNOK$	$22{,}5\ MNOK$
Total		$\mathbf{19,9\ MNOK}$

As described in chapter 5.2, this is what the resulting NPV tells us about the investment decision:

- If NPV > 0, the investment will add value to the company, and the investment should be accepted.
- If NPV < 0, the investment will subtract value from the company, and the investment should be rejected.
- If NPV = 0, the investment will neither add value or subtract value, and the investment should be based on other criteria than financial.

This means that based on the case data present, the introduction of automation technology has the potential to add ≈20 million NOK to the company's value over a five-year period.

The Payback Period is calculated by applying equation 7 from chapter 5.2. The initial investment and annual cash flow used in the NPV method is applied again.

$$Payback\ Period = \frac{Initial\ investment}{Annual\ cash\ flow} = \frac{112\ MNOK}{33\ MNOK} = 3.4\ years$$

A Payback Period of 3.4 years is accepted if the management's maximum desired payback period is less than, or equal to 3.4 years. If else, it is rejected.

Step 5: Developing sensitivity analysis

With the calculations made in the previous steps, the financial side of the investment is known for a particular set of parameter values. The values for the parameters used are not established constants, but estimates. The data for one company may not be identical to the next company or the next project. It is therefore desirable to uncover the sensitivities of different key parameters, to find the impact it has on the outcome.

Four key parameters are chosen for this analysis. They are studied to see what impact a 10% increase in the value has on the outcome. The parameters studied are:

- Robot efficiency
- Polish currency rate
- Throughput
- Polish wages

Table 20 - Ranked Sensitivity Table.

Input parameter	Change in max investment sum [MNOK]	Parameter impact ranking	%outcome change
Robot task efficiency +10%	46,0	1	+40,8 %
Polish currency rate +10%	11,3	2	+10,0 %
Throughput +10%	11,3	2	+10,0 %
Polish wages +10%	4,5	4	+4,0 %

As the results in Table 20 displays, a 10% increase in the robot task efficiency has the largest impact on the max investment sum. With its 40.8% increase in the outcome, it is by far the most influencing parameter. This parameter should be studied further, to investigate where the specific change comes from. Since each stage of the hull building process contains different tasks, it is desirable to investigate the sensitivity to change in robot task efficiency for each particular stage. The result is displayed in Table 21 and Figure 25.

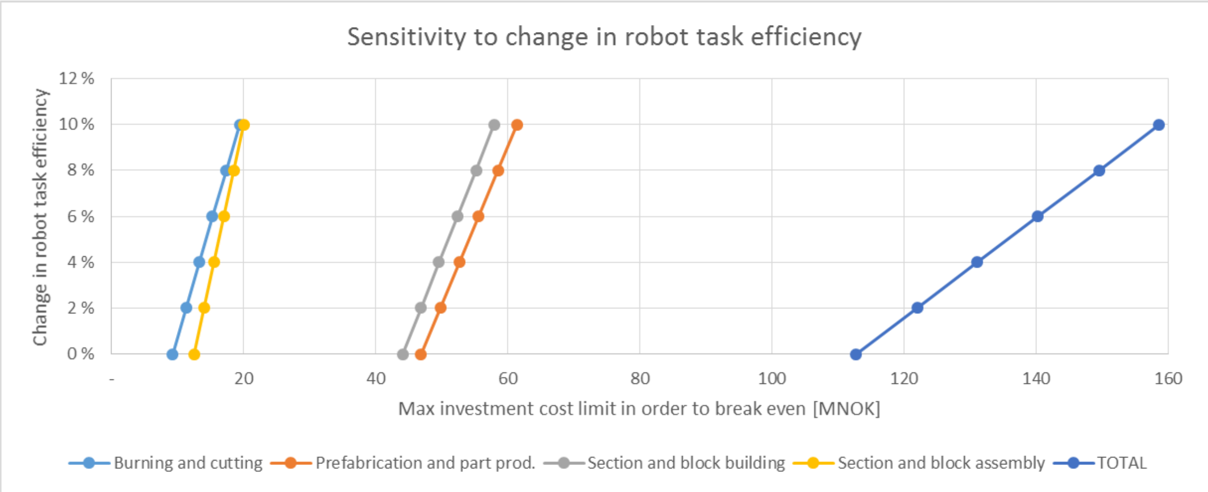

Figure 25 - Sensitivity to change in robot task efficiency.

As both Figure 25 and Table 21 display, stage 1 – burning and cutting, is by far the most sensitive to change in robot task efficiency. A 10% increase in all task efficiencies result in a 110% increase in the maximum investment cost limit to break even.

Both stage 1 and 5 experience a considerately larger impact than stage 2 and 3. This seems to be because the tasks associated with stage 1 and 5 has a rather low efficiency defined to begin with. A 10% increase in the efficiency will represent a larger relative change when the starting point is low.

Table 21 - Each stage's sensitivity to change in robot task efficiency.

Stage	% change in max invest cost
Burning and cutting	110 %
Prefabrication and part prod.	31 %
Section and block building	31 %
Section and block assembly	60 %
TOTAL	**41 %**

Another interesting study, is the mapping of the combined impact two parameters have on the total maximum investment cost limit. This is performed in a 3D-contour plot, and gives answers to questions like "What happens to the total maximum investment cost limit if parameter 1 is increased X%, and parameter 2 is increased Y%?" This is performed for different pairs of the four different parameters listed in Table 20. Figure 26 displays the combined impact of robot task efficiency and yard throughput on the maximum investment total cost, while Figure 27 displays the combined impact of Polish wages and robot task efficiency. Together, they are useful for assessing the sensitivity of the parameters.

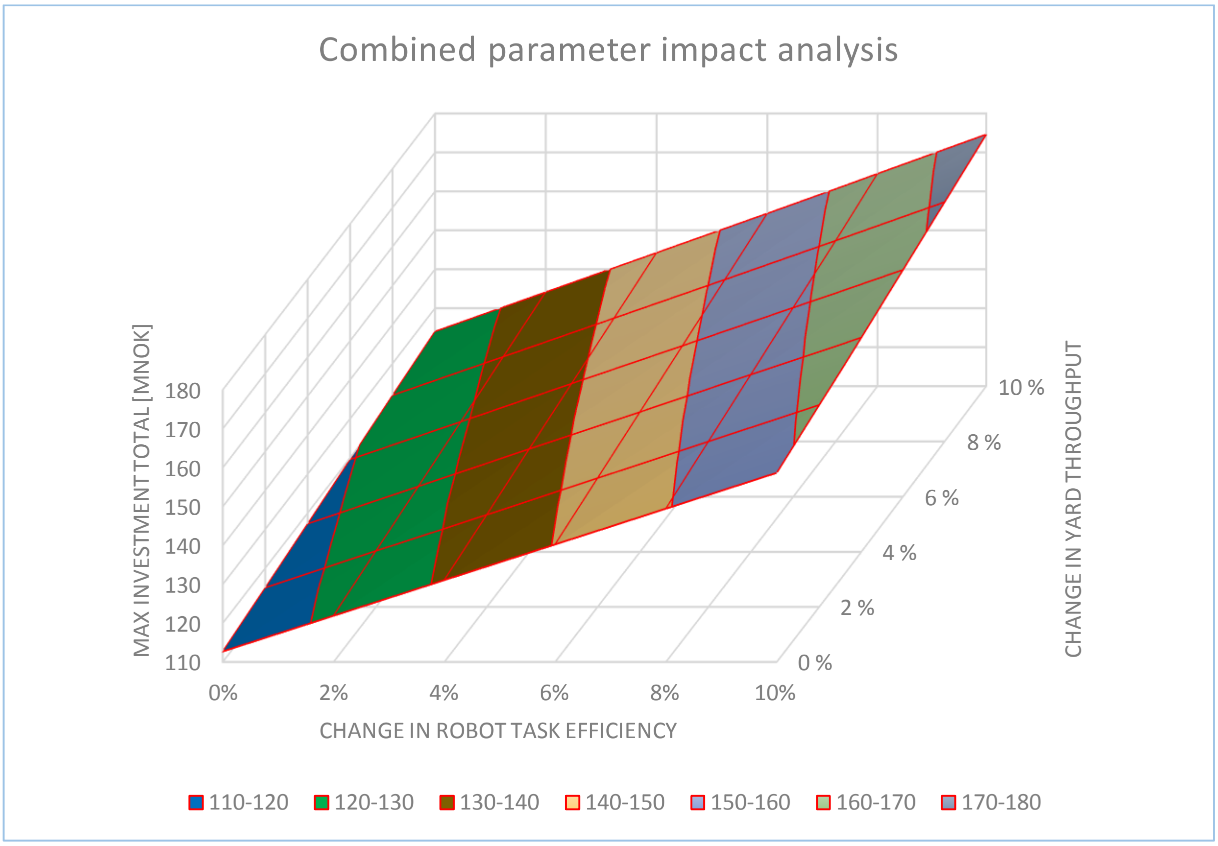

Figure 26 - Combined parameter impact analysis #1.

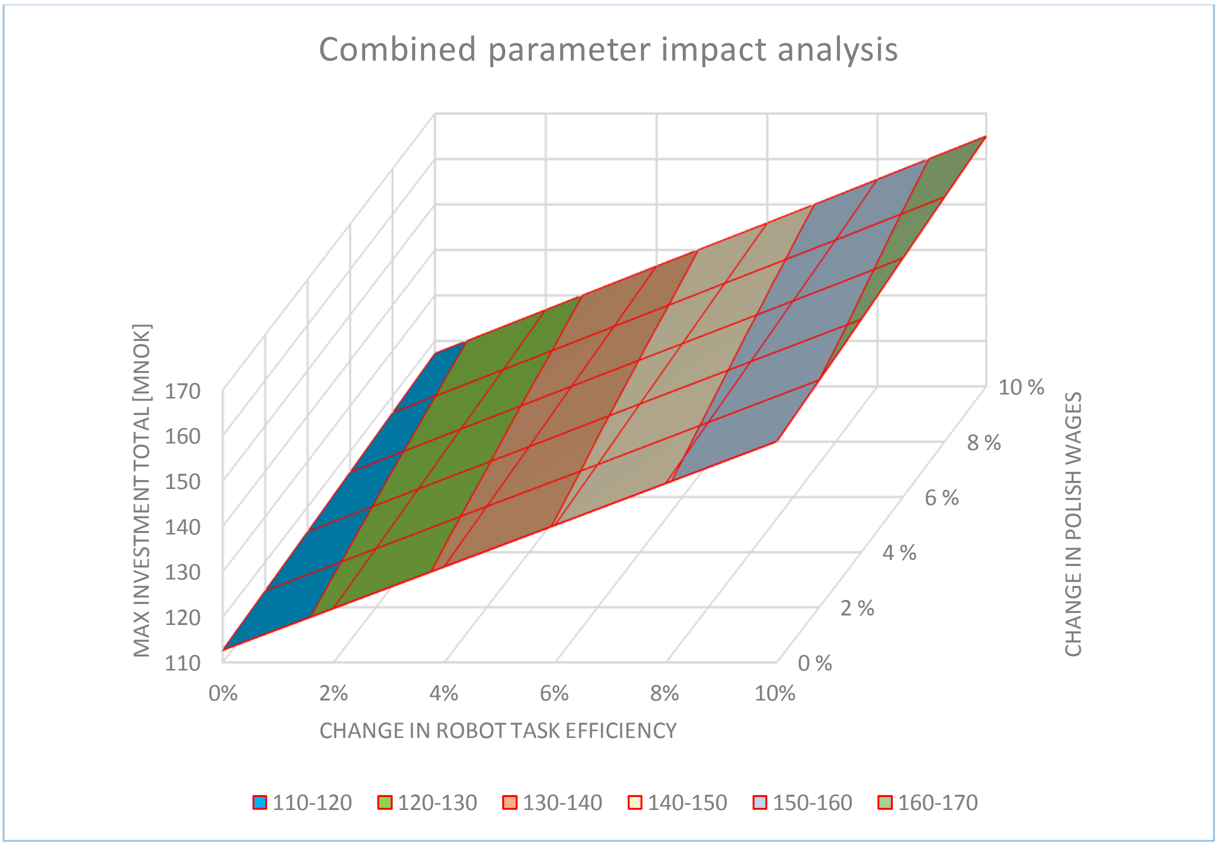

Figure 27 - Combined parameter impact analysis #2.

Step 6: Scenario weighting with Quantitative Strategic Planning Matrix

The template in Table 12 is completed, and the total attractiveness score for each scenario is displayed at the bottom of Table 22. Alternative 2 scores 5.93, thus clearly being favourable to alternative 1 with its score of 4.13. The distance between each score also says something about the relative attractiveness of one option over the other. In other words, alternative 2 is almost 50% more attractive than alternative 1.

Table 22 - QSPM analysis of case study.

		Alternative 1 - Buy from Poland			Alternative 2 - Automated production in Norway		
	Internal strengths	Weight	Rating	Weighted score	Weight	Rating	Weighted score
1.	Location of business	9 %	2,00	0,18	9 %	3,00	0,27
2.	Worker's unique skill set	10 %	3,00	0,30	10 %	0,00	0,00
3.	Quality of product	16 %	3,00	0,48	16 %	4,00	0,64
4.	Work productivity	11 %	2,00	0,22	11 %	4,00	0,44
5.	Unique product	8 %	3,00	0,24	8 %	3,00	0,24
	Internal Weaknesses						
1.	Little early outfitting	10 %	1,00	0,10	10 %	3,00	0,30
2.	Sensitive to oil prices	10 %	2,00	0,20	10 %	2,00	0,20
3.	Skill set in-house	13 %	2,00	0,26	13 %	4,00	0,52
4.	Difficult to lay off labour	8 %	2,00	0,16	8 %	3,00	0,24
5.	Product logistics	5 %	1,00	0,05	5 %	3,00	0,15
	major weakness (1), minor weakness (2), minor strength (3), major strength (4)						
	TOTAL WEIGHTED SCORE	100 %		**2,19**	100 %		**3,00**
	External opportunities	Weight	Rating	Weighted score	Weight	Rating	Weighted score
1.	Industry consolidation	6 %	3,00	0,18	6 %	0,00	0,00
2.	Increased throughput	14 %	2,00	0,28	14 %	4,00	0,56
3.	Educate workers	7 %	1,00	0,07	7 %	3,00	0,21
4.	Construct lighter hulls	11 %	2,00	0,22	11 %	3,00	0,33
5.	Reduce bottlenecks	5 %	2,00	0,10	5 %	3,00	0,15
	External threats						
1.	Declining margins	12 %	2,00	0,24	12 %	3,00	0,36
2.	Climbing wages	9 %	2,00	0,18	9 %	4,00	0,36
3.	Economic downturn	12 %	2,00	0,24	12 %	2,00	0,24
4.	More competition	9 %	2,00	0,18	9 %	3,00	0,27
5.	HSE	15 %	2,00	0,30	15 %	4,00	0,60
	poor (1), below average (2), above average (3), superior (4)						
	TOTAL WEIGHTED SCORE	100 %		**1,99**	100 %		**3,08**
	Sum Total Attractiveness Score			4,13			5,93

For the IFE matrix section of the table, a total weighted score below the average 2.5 indicates a weak internal business. Scores above 2.5 indicate a strong internal position. Based on the results, alternative 1 with its score of 2.19 will give the company a weak internal business. Alternative 2, on the other hand, scores 3.00 and will give the company a strong internal position.

For the EFE matrix section of the table, scores below the average 2.5 indicates a weak external business, while scores above 2.5 indicates a strong external business. Based on the results, alternative 1, with its score of 1.99 will give the company a weak external business. Alternative 2, on the other hand, scores 3.08 and will give the company a strong external business.

This says something about the company's ability to respond to internal and external changes. A higher score reflects a solution that gives the company a better ability to respond to internal and external changes.

7. Discussion

This chapter will discuss the results reached in the preceding chapters. It will comment on choices and assumptions made, and what the result of these were. In particular, the discussion will focus on the research method, the investment decision criteria and the results from the model and case study. How the results from the qualitative elements and the case study should be combined to reach some conclusions will be discussed.

7.1 Discussion of the Research Method

This chapter will go through some of the reflections regarding the research method applied in the early stages of this thesis. The research method in its entirety is described in chapter 1.5.

The research objective was to find background data describing the shipbuilding process in a detailed manner, and based on the tasks described in each stage, research the possibilities to automate the tasks. Due to previous knowledge about the general shipbuilding process, this topic was easier to research. The search phrases resulted in well-written books for educational purposes, and several old reports aiming to streamline the shipbuilding process. A selection of these are presented in the literature review in chapter 1.4.

Automation technology proved more challenging to research. In the beginning, most findings revolved around the automotive industry being as it was one of the first industries to truly utilize robots. Much time and effort went in finding the relevant technology that could be applied to task defined in the shipbuilding process. Based on input from the supervisor, previous studies on automation were discovered. This particularly referred to automation attempts at Odense shipyard, and Meyer shipyard. Findings from these yards resulted in new search phrases, and little by little, the search engines returned relevant reports on automation in shipbuilding. The “IHIMU-alpha” automated steel plate bending from (Yoshihiko, 2011) is a good example of a report that emerged after developing the search phrases further. Other examples are discussed in chapter 4 and in the literature review.

There is no doubt that welding robots are the configuration that has developed most during the last couple of years. The advanced optical sensors and laser measuring systems they apply, enable them to perform welding tasks that was simply impossible before. The development within censoring technology and user interface can only be expected to continue, making it easier to use for a variety of tasks. The research discovered multiple prototypical robots for application on the slipway. They showed promising test results, and robots for this field of work is expected to emerge once the technology continue its development.

Overall, the research is considered satisfactory. It covers the relevant subjects in a good, structured way, and provides angles from different sources. The research also confirmed that the scope of the thesis covers a hole in the relevant body of knowledge, thus making the thesis a meaningful addition to previous research. Different reports brag about impressive results for a given robot in a given test phase, but no studies has been performed to identify the profitability of a complete automation project of the hull building phase.

7.2 Discussion of the Investment Decision Criteria

This chapter will discuss the different criteria chosen for assessing the investment decision of automation technology in the hull building process. Reasons for the choices made will be discussed, as well as how the criteria chosen should be assessed.

When investigating the relevant investment decision criteria, it was important to not make it a pure financial decision. The automation technology affects the company in many ways that cannot be directly measured in monetary values. Several factors discussed in chapter 5.1 are beneficial for the company without directly impacting the financials.

Other elements could have been mentioned, but the ones discussed in chapter 5.1 are considered to be of highest importance. Several of the factors will not provide a direct result on the accounting, but could be the competitive advantage that tip the scales in favour of the company in future tender processes.

Much effort was put in identifying all the benefits automation technology could provide. Many of the benefits mentioned are factors that few take into consideration when discussing automation. It is easier for companies to measure strictly the economic impact an investment has. If enlightened with some of the qualitative factors discussed in chapter 5.1, it is likely that more companies would consider automation to increase their competitiveness and attractiveness as an employer.

The oil and gas sector constitutes one of the largest markets for shipbuilders. Being so, they have some influence on how shipbuilders operate. The oil and gas sector has a high priority of health and safety in the workplace. Not only internally, but from all actors that supply their industry with equipment. This means that shipbuilders also have to prioritize health and safety in their yards. Several of the shipbuilding related tasks represent some hazard to the workforce performing it. One of the most proclaimed benefits of automation technology is the health and safety effects. Automating tasks performed in hazardous environments can improve the overall safety, and the working environment at the yard.

Only a decision including both the qualitative and quantitative effects of automation technology can give the full investment decision overview.

7.3 Discussion of the Model

The model developed in the thesis play an important role in the investment decision. It should act as a framework for the quantitative analysis. When case study data is applied the model can, based on the input, display whether or not the investment in automation technology is profitable for that given case. During the development of the model, the focus was on utilizing several different methods that could provide concluding answers to the investment decision.

The essence of the model lies in the mapping of process time consumption. In order to say anything about the future potential, it has to be compared to a reference point. All the other methods utilized in the model depend on input from the mapping of process time consumption. The idea was to collect this data from collaborating yards, but as the interest from relevant yards was absent, the process time consumption was estimated. This represents a potential margin for error, as the estimations are not necessarily representative for all cases. However, this would still be the case if the data had been collected from relevant yards. The data would then only be representative for yards with similar build strategies as the yard providing the data.

Because of the aforementioned issues regarding process time mapping, it is more important to pay attention to the methods applied instead of the specific numbers they result in. The goal is to create a model that can be adapted to several different cases.

Specific procurement price for robots are difficult to assess. Most producers require a detailed tender to give realistic price estimates. Since the exact number of robots needed for the scenario discussed in this thesis is difficult to assess, it is more suitable to calculate the maximum investment cost to break even. With this upper limit established, the conclusion becomes that any investment cost below is profitable.

To develop the model further, it could have included an assessment of necessary hall area needed to automate the different stages. For a yard that needs to build new halls in order to introduce automation technology, the halls themselves could turn out to represent the majority of the investment. In order to assess necessary hall areas, one should first consider how many robots are needed to automate each stage, given a preset workload or throughput. Based on this assessment, data could have been collected from robot manufacturers on spacial requirements and been compared to special requirements for manual operation.

7.4 Discussion of the Case Study

The case study was developed to have a framework the model could be tested on. The aim was for it to be representative for a typical Norwegian yard, and for it to display credible parameters.

The medium-sized Platform Supply Vessel is considered as highly representative for a typical Norwegian build. The dimensions and steel weight are estimated based on representative vessels. Ideally, the model was to be tested on real case data from a Norwegian yard, but circumstances forced the case data to be estimated instead.

Process time mapping

The process time mapping is completed based on the predefined tasks in each stage of the hull building process. The resulting distribution may be deviating from the distribution at certain yards, but for this case study it is considered satisfactory. The model is flexible, and the case can easily be adjusted to display distributions for yards with other workloads.

As each task was associated with an assumed rate of automation, as well as increased efficiency through automation, it introduces some uncertainties in the case data. The rate of automation possible for each task is very difficult to assess, as different yards have different designs and different ways of performing each task, and therefore can utilize the technology differently. The increased efficiency through automating is also uncertain. It depends largely on the willingness to facilitate for automation in the complete production line. If the automation is done halfway, the efficiency is not likely to increase. By facilitating the automation technology, and by finetuning the automation to fit each individual yards' production schedule, the efficiency should increase and gradually creep towards a maximum utilization level.

Maximum investment to break even

When discussing maximum investment cost, Table 18 shows that stage 2 and 3 has the largest potential to save cost, and can therefore justify a larger investment. This is naturally expected as the two stages defines the largest portions of the total manhours needed, thus larger potential time saved. However, a closer look shows that the initial size of the stage is not the primary reason for the difference. With its 30% of total manhours, stage 2 and 3 consumes 50 % more manhours than stage 1 and 5. The potential time saved, however, is 3-5 times larger in stage 2 and 3. A look at the complete spreadsheet in appendix A reveals that a dominant reason is the expected time saved on welding and rectification. Even though welding is also represented in stage 5 – Section assembly, it is not considered to be as efficient as in the prefabrication and building stage, due to inferior working environment for the robots on the slipway. The robots specialized for slipway assembly is, as mentioned in chapter 3 and 4, still prototypical in its design and not yet optimized.

The reason for the good score on rectification is that the reduction of heat distortions and the ability to produce a consistent quality over time close to eliminates the need for rectifying work, as described in chapter 5.1.

Net Present Value and Payback Period

The discount rate is a key variable in the calculation of the NPV. A company's cost of capital is often used, but many believe that a higher discount rate should be used to adjust for risk, opportunity cost or other factors. A different way of establishing an appropriate discount rate is to decide the rate that the capital could return if invested in a different project. This enables the possibility to compare different projects directly, based on the rate of return. The calculation in the case study has based the discount rate on the latter. It could have been set higher, but being an industrial company, they are assumed to not take the biggest risks with their assets.

As the results in the case study show, investing in automation technology has a potential to add ≈20 MNOK to the company value over a five-year period. This depends on cash flows being exactly as the case study depicts. It is interesting to see what impact it would have on the result if the annual cash flow were to drop by 10%.

Table 23 - Net Present Value, 10% reduced cash flow.

Year	**Cash Flow**	**Present Value**
i=0	-112	-112
i=1	29,7	27,5
i=2	29,7	25,5
i=3	29,7	23,6
i=4	29,7	21,8
i=5	29,7	20,2
Total		**6, 6**

Table 23 shows the NPV with the same investment sum, but a 10% reduction in the annual cash flow. The change resulted in over 13 MNOK reduction in the economic benefit from the investment. This shows how important it is to give accurate predictions of the future cash flows. For this case, if the cash flow estimations are off by 15%, the investment is suddenly subtracting value from the company instead of adding value. This could be a fatal error for a company in a highly competitive market.

The Payback Period was calculated using the same cash flows as in the NPV. Resulting in a Payback Period of 3.4 years, it is assessed as a short period for this type of investment. Such equipment is expected to last for a much longer period the the Payback Period.

The method greatly depends on the annual cash flows used in the calculation. In a bad market, the annual cash flows will be lower, thus increasing the Payback Period. They are linearly dependent, so a 10% reduction in the estimated annual cash flow result in a 10% increase in the Payback Period.

Sensitivity analysis

The sensitivity analysis was carried out to identify important parameters, and their respective impact on the outcome. As results from the previous calculations are only valid for a given case data, sensitivity analysis are useful for analysing cases that deviate from the original case data. By looking at the sensitivity analysis, one can immediately spot if the deviations will have a big impact on the conclusion.

The 3D-contour plots displaying the combined impact of two parameters on the maximum investment limit adds an interesting dimension to the analysis. It maps out a large area of variations, and easily displays the impact when two parameters change simultaneously. This information is useful when assessing the sensitivity of the outcome.

The sensitivity analysis performed in this case study is very simplistic. Many of the parameters correlate linearly with the output, thus making the analysis of these parameters redundant. For further work, the model should be developed into a more sophisticated revision. Further studies should be made on different models of uncovering and displaying sensitivities in investment decision scenarios. The 3D-contour plots should be based on a larger set of data, in order to increase the resolution of the plot.

Overall, the outcome of the case study provides satisfying results. By applying the methods from the model on this particular case study, the results show that the increased efficiency through automation justifies a substantial investment. This is supported by the many qualitative elements discussed that favours automation technology.

8. Conclusion and Further Work

Norwegian shipbuilding are typically known for their complex vessels and prototypical one-off designs. Compared with other global competitors, they produce on a small-scale basis. This has long been considered as features that makes it difficult to apply automation technology in a cost-efficient way. Robots are excellent for repetitive operations, and have proven success in the automotive industry. Large-scale yards have also increased their focus on automation, with Geoje yard being a good example. However, in later years sensor technology has enabled robots as an option for industries without a large-scale production. Improved user interface reduces the human interaction needed to run operations, and the robot task flexibility has launched it as a possibly viable option for small-scale production.

This thesis have investigated if the introduction of automation technology can be beneficial for a semi-integrated yard in a high labour-cost country who wants to take steps towards becoming a fully integrated yard, making their own hulls. The investigation included discussing investment decision criteria, creating a model and testing the model on a case study.

The main conclusion of this thesis is that automation technology can in fact perform several of the tasks needed in a hull building process. The calculations performed in the case study show that robots can make the tasks more efficient than manual labour, and justifies a substantial investment in the technology. Whether the total investment reduce cost or not depends on the actual number of robots required to perform the tasks with a satisfactory rate of automation.

In addition to justifying a substantial investment, the automation technology introduces several qualitative factors highly beneficial for the company. Qualitative elements bring value to the company in form of greater competitiveness, better working environment for employees, increased safety and better production reputation due to increased quality and consistency.

Without specific hull building data it is difficult to assess the validity of the estimations made in this thesis. The thesis have partly taken this into account by looking at sensitivities, but testing against a real case would be interesting.

By expanding the model to account for floor area required for the different solutions, it would be easier to assess a total cost picture. Hall structures with sufficient ventilation and infrastructure is costly, and the investment total cost will depend on the amount of infrastructure available for automation technology. If a company has to build new expensive halls, it could change the outcome of the investment decision.

Further work should also include a detailed analysis of the exact type and number of robots needed for each given task and workload. By building a cost model that includes specific robot cost it will uncover directly whether the investment is viable or not for each given case.

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Appendices

Appendix A - Potential savings in all stages of the hull building process.

Example of potential savings in stage 1:		
Original time cost stage 1:		
Burning	6 000	hours
Cutting	4 000	hours
Edge preparation	3 000	hours
Grinding	4 000	hours
Bending of plates, profiles and pipes	3 000	hours
TOTAL	20 000	hours
Potential time saved with robots utilized:		
Burning	270	hours
Cutting	360	hours
Edge preparation	210	hours
Grinding	520	hours
Bending of plates, profiles and pipes	-	hours
TOTAL TIME SAVED	1 360	hours
Potential savings	680 000	NOK

Example of potential savings in stage 2:		
Original time cost stage 2:		
Grinding	3 000	hours
Assembly	6 000	hours
Control	1 500	hours
Rectification	6 000	hours
Welding	13 500	hours
TOTAL	30 000	hours
Potential time saved with robots utilized:		
Grinding	390	hours
Assembly	-	hours
Control	-	hours
Rectification	2 850	hours
Welding	3 645	hours
TOTAL TIME SAVED	6 885	hours
Potential savings	3 442 500	NOK

Example of potential savings in stage 3:			Example of potential savings in stage 5:		
Original time cost stage 3:			Original time cost stage 5:		
Grinding	3 000	hours	Grinding	2 000	hours
Assembly	7 500	hours	Assembly	6 000	hours
Control	1 500	hours	Welding	4 000	hours
Rectification	6 000	hours	Lift/placement	2 000	hours
Welding	12 000	hours	Alignment/rectification	2 000	hours
			Tagging and adapting	1 000	hours
			Prepare for surface treatment in joining a	1 000	hours
			Surface treatment of joining area	2 000	hours
TOTAL	30 000	hours	TOTAL	20 000	hours
Potential time saved with robots utilized:			Potential time saved with robots utilized:		
Grinding	390	hours	Grinding	260	hours
Assembly	-	hours	Assembly	0	hours
Control	-	hours	Welding	1 080	hours
Rectification	2 850	hours	Lift/placement	120	hours
Welding	3 240	hours	Alignment/rectification	0	hours
			Tagging and adapting	50	hours
			Prepare for surface treatment in joining a	50	hours
			Surface treatment of joining area	280	hours
TOTAL TIME SAVED	6 480	hours	TOTAL TIME SAVED	1 840	hours
Potential savings	3 240 000	NOK	Potential savings	920 000	NOK

Appendix B - Complete process time mapping

Portion of total amount hull related steel work:	20 %	30 %	30 %	0 %	20 %			
	Stage 1 Burning and cutting	Stage 2 Part prod. And prefab	Stage 3 Section building	Stage 4 Surface	Stage 5 Section assembly	% of total work	Assumed rate of work that can be automated	Assumed increased efficiency where robots are
Tasks:								
Burning	30 %					6 %	90 %	5 %
Cutting	20 %					4 %	90 %	10 %
Edge preparation	15 %					3 %	70 %	10 %
Grinding	20 %	10 %	10 %		10 %	12 %	65 %	20 %
Bending of plates, profiles and pipes	15 %					3 %	40 %	0 %
Assembly		20 %	25 %		30 %	20 %	25 %	0 %
Control		5 %	5 %			3 %	0 %	0 %
Rectification		20 %	20 %			12 %	95 %	50 %
Welding		45 %	40 %		20 %	30 %	90 %	30 %
Lift/placement					10 %	2 %	60 %	10 %
Alignment/rectification					10 %	2 %	50 %	0 %
Tagging and adapting					5 %	1 %	50 %	10 %
Prepare for surface treatment in joining area					5 %	1 %	50 %	10 %
Surface treatment of joining area					10 %	2 %	70 %	20 %
SUM	100 %	100 %	100 %		100 %	100 %		

Appendix C - Sensitivity to change in robot task efficiency