NTNU
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Mobile Drilling Robot

A Case Study Of The Effects On The
Construction Site

Ole Hovland Rosenlund

Civil and Environmental Engineering
Submission date: June 2017
Supervisor: Frode Olav Drevland, IBM
Co-supervisor: Kjetil Anfinnsen, nLink AS

Norwegian University of Science and Technology
Department of Civil and Environmental Engineering

NTNU
Faculty of Engineering
Department of Civil and
Environmental Engineering

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Name: Ole Hovland Rosenlund				
Professor in charge/Supervisor: Frode Drevland				
Other external professional contacts/supervisors: Kjetil Anfinnsen				

Abstract:

Several studies have shown that there is an improvement potential in the construction industry. It is argued that while the construction industry has gone through a steady and gradual increase in turnover, the productivity has declined compared to other industries.

A white paper, drawn up for the Norwegian Government, states that two of the reasons for the decline in the construction industry productivity is the absence of major technological innovations and the lack of attention around productivity and the future development of the industry. It is specified that the construction industry has not sufficiently harvested benefits and gains of modern technology.

This master thesis concerns and analyzes the mobile drilling robot developed by nLink As. The main objective of the master thesis is to evaluate the effects of using the drilling robot on a construction site.

The drilling robot is analyzed in six main areas within cost, time and quality; the robot, time study, logistics, safety, extra design and future potential.

Keywords:

1. Robot Analysis
2. Mobile Drilling Robot
3. Construction
4. nLink As

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I want to thank all the people I have interviewed for their insight and perseverance. I also want to thank my supervisor Frode Drevland for his guidance and feedback during the project period. I owe an equal thanks to my external supervisor Kjetil Anfinnsen for his great cooperation, support and interesting input. The research and insight in the construction industry has been made possible by nLink As.

Trondheim, 7 June 2017

Ole Rosenlund

SUMMARY

Several studies have shown that there is an improvement potential in the construction industry. It is argued that while the construction industry has gone through a steady and gradual increase in turnover, the productivity has declined compared to other industries.

A white paper, drawn up for the Norwegian Government, states that two of the reasons for the decline in the construction industry productivity is the absence of major technological innovations and the lack of attention around productivity and the future development of the industry. It is specified that the construction industry has not sufficiently harvested benefits and gains of modern technology.

This master thesis concerns and analyzes the mobile drilling robot developed by nLink AS. The main objective is to evaluate the effects of using the drilling robot on a construction site. Six main topics within cost, time and quality have been analyzed and discussed; the robot, time study, logistics, safety, extra design and future potential. Throughout the thesis different advantages and disadvantages have appeared within these topics. Figure 1 illustrates the most important benefits (green) and the weaknesses (red) found in this thesis.

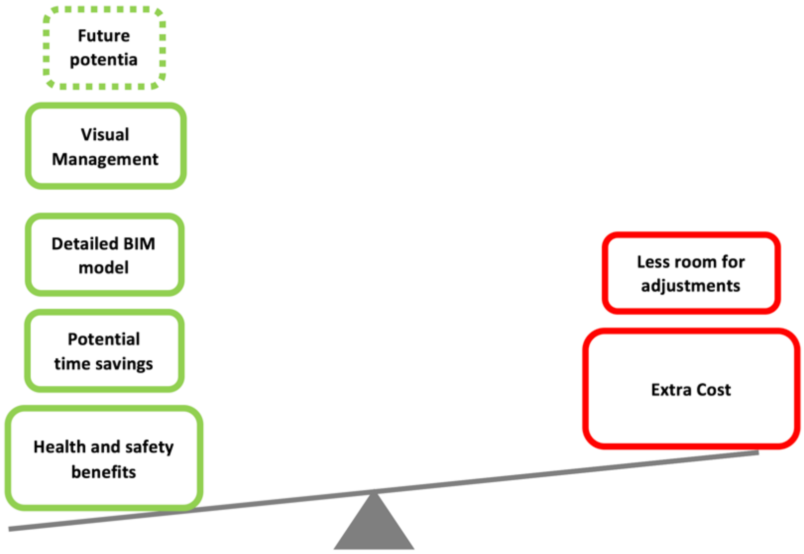


FIGURE 1 SUMMARY FIGURE

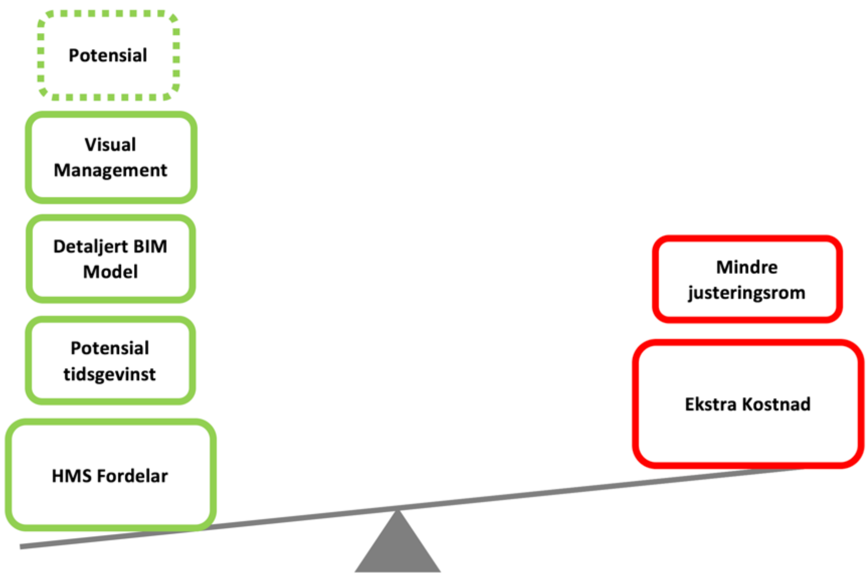
As the figure states, the total advantages of using the robot is considered to weigh heavier than the few disadvantages. The conclusion is therefore that the use of the robot is advantageous compared with the conventional method. The conclusion relies only on the advantages and disadvantages found and discussed in this thesis, and assumes that all the potential benefits are utilized of the project team.

SAMANDRAG (NORWEGIAN)

Fleire studie har vist at det finns eit forbetringspotensiale innan dagens byggebransje. Det kjem fram at medan byggebransjen har hatt ei stabil og gradvis auke i omsetning, har produktiviteten gått ned i forhold til andre industriar.

I Stortingsmelding 28 blir den negative produktivitetsutviklinga mellom anna forklart ved fråværet av store teknologiske nyvinningar, og for lita merksemd rundt produktiviteten i næringa. Det blir og presisert at byggenæringa har i for liten grad teke i bruk og hausta gevinstar av moderne teknologi.

Denne prosjektoppgåva omtalar verknaden og potensialet boreroboten frå nLink kan ha i byggebransjen. Hovudmålet med oppgåva er å kartleggja verknadane av å nytta drillrobot på dagens byggeplassar. Innan kvalitets parameterane kost, tid og kvalitet har seks områder blitt analysert og diskutert; roboten, tidsstudie, logistikk, helse miljø og sikkerheit, ekstra prosjektering og framtidig potensial. Gjennom oppgåva har fordelar og ulemper blitt belyst og diskutert. Figur 2 illustrerer relevante funn av fordelar og bakdelar roboten medfører i respektive grøne og raude rektangel.



FIGUR 2 OPPSUMMERINGS FIGUR

Som figuren viser, er fordelane vurdert til å vekta tyngre enn ulempene roboten medfører. Konklusjonen er dermed at installasjon med bruk av takboringsroboten er fordelaktig i forhold til den konvensjonelle installasjonsmetoden. Konklusjonen er basert på funna i denne oppgåva og er avhengig av at alle fordelane og ulempene er utnytta av prosjektleiinga.


WALL

CONTENTS

LIST OF FIGURES

List of Tables

1. Introduction

1.1 Brief Introduction to the Norwegian Construction Industry

In this chapter the main goal is to inform the reader on some basic numbers and developments in the Norwegian industry. Information about the industry is gathered from Statistics Norway, and a white paper (Stortingsmelding 28) from the Ministry of Trade and Industry. Statistics Norway has the overall responsibility for official statistics in Norway, and the white paper is drawn up when the Government wishes to present matters to the Norwegian legislative power, Stortinget, that do not require a decision.

From 1998, there has been a stable and gradual turnover among the construction enterprises in Norway (SSB, 2017). In 2014 the total turnover of construction enterprises was 462 billion NOK, an increase of 6,3 percent from 2013. Figure 1.1 shows the turnover in the construction industry from 1998 to 2016. The dashed red line illustrates the general development of turnover.

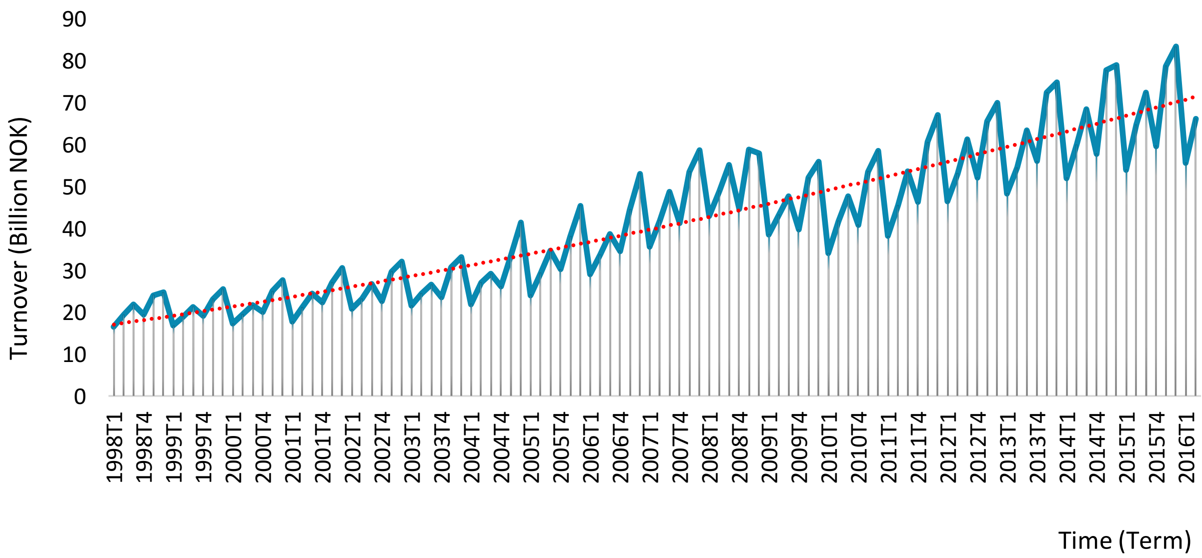


FIGURE 1.1 TURNOVER IN THE NORWEGIAN CONSTRUCTION INDUSTRY

While the construction industry has gone through a steady and gradual increase in turnover, the White Paper 28 confirms that the productivity has declined compared to other industries. Figure 1.2 is taken from the White Paper and shows the development in man-hour productivity from 2000 to 2011 for construction activities, industry and collected sets from industry. The purple line represents a total of all industries; the black line represents the manufacturing industry and the light blue line represents the construction industry.

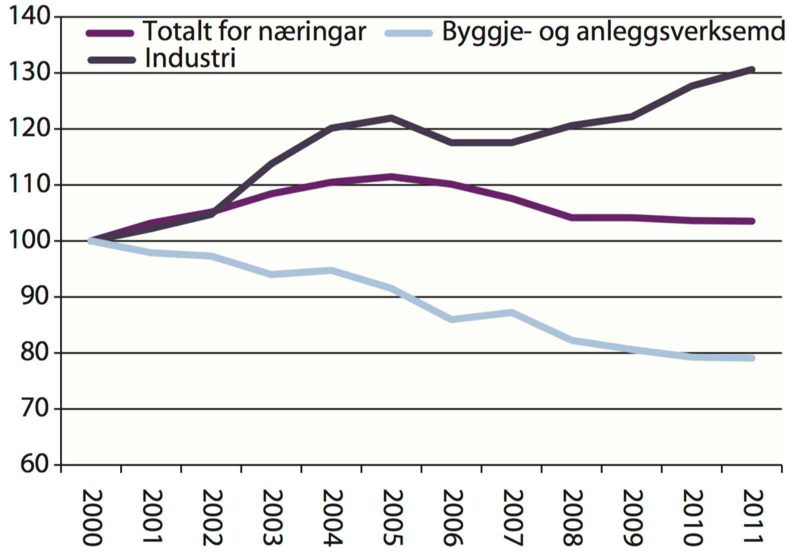


FIGURE 1.2 OVERVIEW OF PRODUCTIVITY (KOMMUNAL OG MODERNISERINGSDEPARTEMENTET, 2012)

While other industries have experienced an increase in productivity, the construction industry has declined since the 1990s. Figure 1.2 shows that the manufacturing industry has had a productivity increase of 30 percent the last twelve years, whereas the construction industry has fallen about 20 percent in the same time interval.

The white paper states that one reason for the decline in the construction industry is the absence of major technological innovations and the lack of attention around productivity and the future development of the industry. It is specified that the construction industry has not sufficiently harvested benefits and gains of modern technology. A comparison between car technology and construction sites are given in the white paper:

> "When we buy a new car, we naturally expect state of the art advanced technology. Technology that tells us to fasten your seat belt, gives directions and alternative routes and turn on and off the headlights. The car has support tools such as GPS, cruise control and different alert systems to help us navigate the car. There has been a major technological development the last few years. This development has contributed to increase the comfort, increase the security and reduce the energy consumption. An equivalent technological development has not taken place in building or construction sites. It is obvious that the technology also has potential when it regards protection against fire, warning of various kinds, prevention of injuries, remote functions, automatic lighting, ventilation and heating in buildings. " (Kommunal og Moderniseringsdepartementet, 2012)

A stable increase in turnover combined with a stable decrease in productivity can point to a large improvement potential in the Norwegian construction industry. Greater utilization and implementation of robotics on construction sites can contribute positively in this potential.

1.2 Previous Research

World Robotics (2016) states that since 2010, the demand for industrial robots has accelerated considerably due to the ongoing trend toward automation and the continued innovating technical improvements in industrial robots. Between 2010 and 2015, the average annual supply rose to about 183,000 units. This is an increase of approximately 59 percent, and a clear sign of the significant rise in demand for industrial robots worldwide.

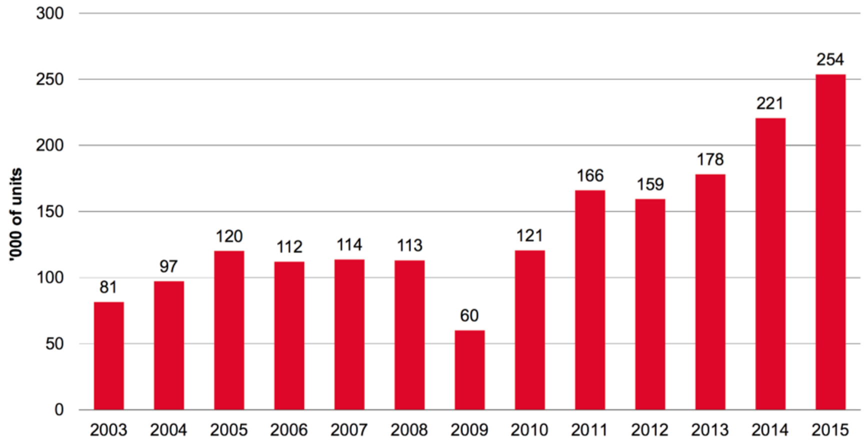


FIGURE 1.3 ESTIMATED WORLDWIDE ANNUAL SUPPLY OF INDUSTRIAL ROBOTS (WORLD ROBOTICS, 2016)

In 2015 the overall robotic sale increased by 15 percent. Approximately 254.000 robotic units were sold. This lead to the highest volume of robotic units ever recorded by far. World Robotics states that the main driver of the growth was the general industry, in particular the electronics industry, metal industry, chemical industry, plastics industry and rubber industry. The robot sales in the automotive industry only moderately increased in 2015 after a five-year period of continued considerable increase. That being said, compared to all other sectors the automotive industry has a considerable high rate of automation.

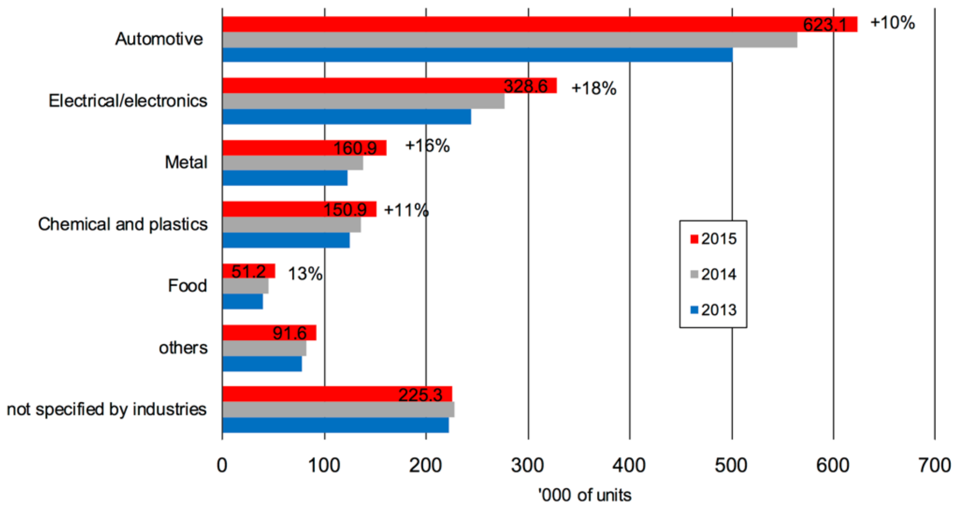


FIGURE 1.4 ESTIMATED WORLDWIDE ANNUAL SUPPLY OF INDUSTRIAL ROBOTS BY INDUSTRIES (WORLD ROBOTICS, 2016)

The International Federation of Robotics (2016) state that many countries in Europe have a high potential for robot installations. In Europe 2015, the average robot density of multipurpose industrial robots per 10.000 employees in the manufacturing industry was 92, a high density compared with the average world density of 69.

When comparing the distribution of multipurpose industrial robots in various countries, the robot stock, expressed in the total number of units, can sometimes be a misleading measure. The International Federation of Robotics have taken this into account by calculating the robot density, see Figure 1.5. This method takes the differences in the size of the manufacturing industry in various countries into account.

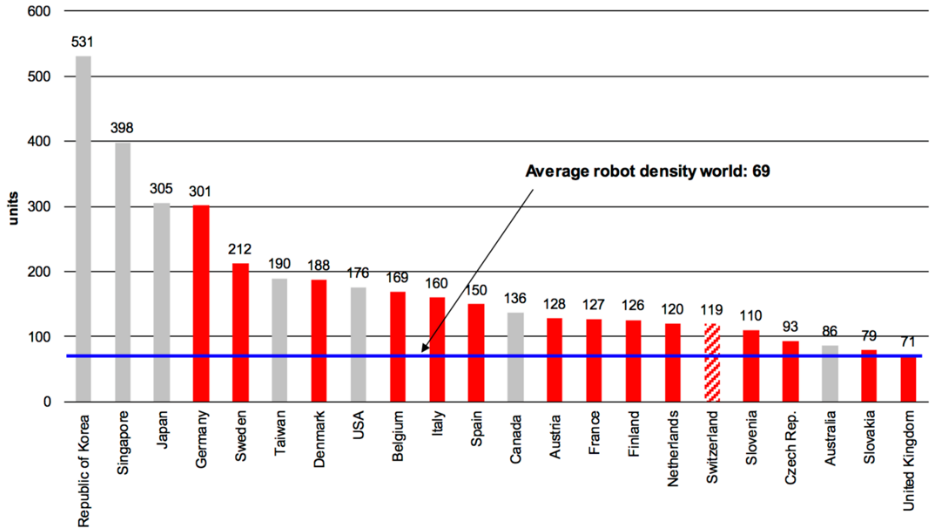


FIGURE 1.5 ROBOT DENSITY IN EU COUNTRIES (INTERNATIONAL FEDERATION OF ROBOTICS, 2016)

World Robotics (2016) claims that robots and automation will increasingly shape the way we work in the future, with enormous potential for improvements in productivity and quality. It turns out that there has not been much research on implementing robotics in Norwegian construction sites.

We know that robotics has had a positive impact on production in other industries, especially the automotive industry (World Robotics, 2016). Compared to this industry, we know relatively little about robotic effects in the construction industry. This thesis aims to find out more about one new drilling robot that contributes to bring robotics forward in the construction industry. The thesis also aims to inform and enlighten the construction industry of the possibilities and effects of implementing a drilling robot on construction sites.

This master thesis is developed from an initiative from nLink As. nLink is a high-tech startup firm, that develops robotic solutions for the construction industry. The firm was founded in 2012 with a goal of revolutionizing the construction industry. nLink are now introducing the first commercial mobile drilling robot to the global construction industry. The firm claim that their robots are efficient, customized for working on construction sites, they increase worker safety and ensure a faster project completion. Their main goal is to develop robots that solve problems identified by the construction business, and they have already received several awards for their innovative robot. The drilling robot aims to reduce time consumption and relieve the construction workers from heavy, repetitive and hazardous work.

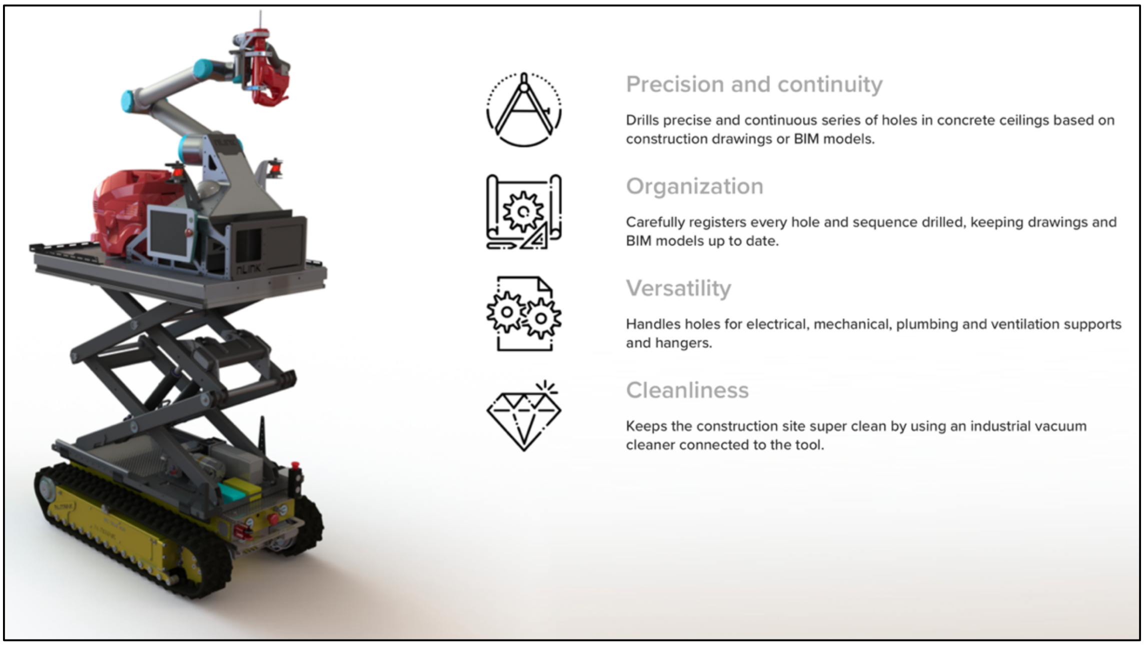


FIGURE 1.6 THE CEILING DRILLING ROBOT (NLINK, 2017)

1.3 GOALS AND RESEARCH QUESTIONS

The main objective of the master thesis is to evaluate the effects of using the drilling robot on a construction site. To guide and center the thesis five research questions are developed.

1. How does the drilling robot influence the installation time and scheduling planning?
2. How is the logistics related to the robot?
3. What are the effects of using the robot in a health, safety and environment perspective?
4. How much more time and money does the project need to invest in the design phase to use the drilling robot? Which other benefits does the early and detailed design lead to?
5. What is the future potential of the robot?

1.4 THESIS STRUCTURE

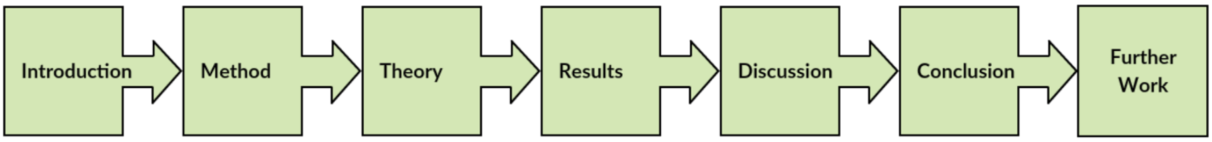


FIGURE 1.7 THESIS STRUCTURE

The thesis structure is formed as a reader guidance. Figure 1.7 shows the seven different chapters and the structure of the thesis. In addition to the seven main chapters the bibliography and appendix is located at the end of the thesis.

Chapter 1 Introduction. This chapter starts by giving the reader a brief introduction to the Norwegian construction industry and nLink AS. At the end of the chapter the goals and research questions are stated.

Chapter 2 Method. In this chapter the method and methodology is presented to the reader. This includes when, where, how and why the result of this thesis is compiled. The strength and weaknesses of the selected methodology is also presented.

Chapter 3 Theory. This chapter goes through previous research and relevant literature tied to the thesis. The chapter is theoretical and contains no new interpretations or statements.

Chapter 4 Results. In this chapter, all results will be presented. A clean and comprehensive presentation will give the reader an opportunity to study the results without the author's own interpretations and statements.

Chapter 5 Discussion. In the discussion section of the thesis, comments and different interpretations on the results will be given and discussed. It is important that the different advantages and disadvantages of using the drilling robot is evaluated in a clear and concise manner.

Chapter 6 Conclusion. Before the final conclusion and statements this chapter gives a summary of the main topics that are covered in the thesis.

Chapter 7 Further work. Based on the results and conclusions, this chapter will list up proposals for new issues and how future work can be defined and done.

2 METHOD

In this chapter the methodology of the thesis is presented. This includes when, where, how and why the result of this thesis is compiled. The strength and weaknesses of the selected methodology is also presented.

2.1 APPROACH

Together with a presentation of previous work, this subsection explains how and where the information is gathered form.

In the previous semester, autumn 2016, a relevant literature review and a semester rapport that discussed robotics linked to construction sites, was conducted at NTNU. Both the literature study and semester project has been useful support for the design of this thesis. The work informed, and gave examples, of future and already existing robots at different construction sites. It gave an updated picture of the current situation regarding robotics and productivity in the construction industry.

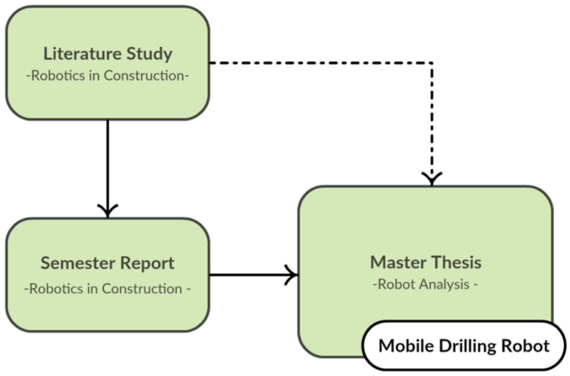


FIGURE 2.1 PREVIOUS WORK

The new information gathered in this thesis is mostly from an anonymous project, nLink AS and reports and articles that where not mentioned in the literature study or semester report. Figure 2.2 shows all the different information sources which forms the foundations and data of the thesis. The guidance and help from both my supervisors Frode and Kjetil is also worth mentioning.

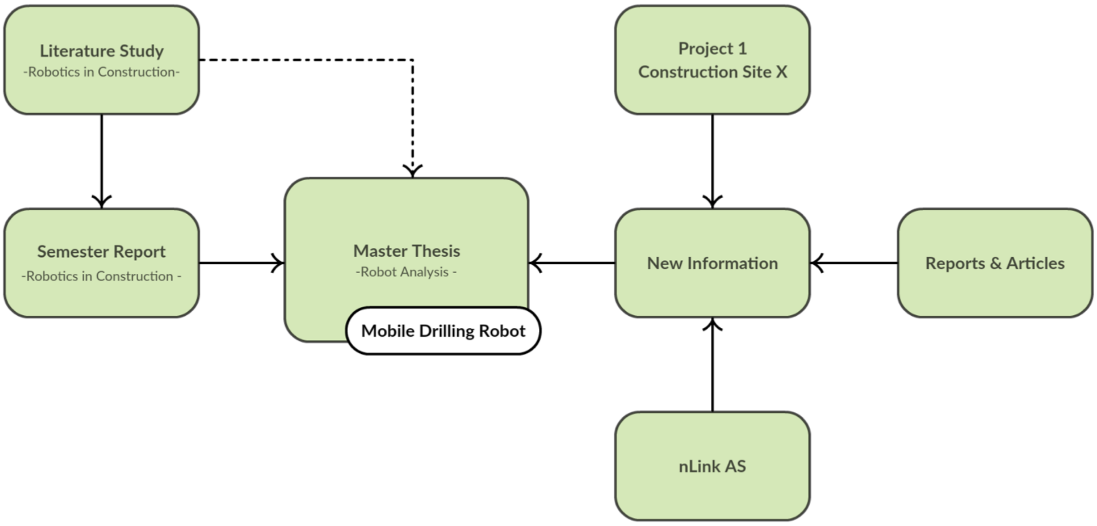


FIGURE 2.2 INFORMATION SOURCES

The anonymous project, project 1, is a new primary school that at the time of writing is under construction. The school will accommodate approximately 650 students. The project is divided into two subsections or buildings. Subsection one is located in the main building. This subsection is a three-story building that mainly consists of classrooms and offices. All the technical installations in this subsection follows the usual and conventional method of installation.

Subsection two is a three-story building that has both conventional installation and installation assisted with pre-drilled holes from nLinks robot. In floor two and three the robot from nLink has approximately drilled 2800 holes divided over an area of 1600 m^2. The execution time was ten days, two days to set up preparations and to disassembly, and eight days to conduct the drilling.

A lot of information is gathered from nLink as, both the firm and their sister firm Rocketfarm AS has supplied the thesis with good contents and data. Through the work with the thesis, reports and articles have been recommended from supervisors, interviews, students and teachers. All the articles and reports have been reviewed before they have been used in the thesis.

2.2 QUANTITATIVE AND QUALITATIVE METHODS

Olsson (2011) claims that research methods can be divided into two categories; Quantitative and qualitative methods. Even though they often are combined, it is usual to distinguish them from each other.

Quantitative methods are research methods that are based on numbers and what is measurable or quantifiable. Quantitative studies emphasize objective measurements and precision. These methods can often be verified later.

Qualitative methods are based on oral or textual information. Often these methods concentrate on fewer objects, in return they collect more direct and concrete information. The main focus of qualitative methods is to achieve a comprehensive understanding of the subject matter, and how big of a relevance it has to the study.

TABLE 2-1 QUANTITATIVE AND QUALITATIVE METHODS

Quantitative methods	Qualitative methods
Surveys	Qualitative interviews
Computer analysis	Literature Study
Observations	Observations
Statistical calculations	Lectures and conferences
Case study	

Olsson (2011) also stats that in a case study, the goal is to describe and explain what is happening in a special situation. Often several of the methods are used, particularly qualitative methods, but a lot of quantitative methods may be relevant to use or can be combined with the other qualitative methods. The study should not be representative or generalized, because the results are always time and place dependent.

2.3 QUALITY OF INFORMATION AND METHODOLOGY

Olsson (2011) mentions that it is important to assess the quality of the different information that is gathered in the thesis. In this assessment, it is useful to use the two main parameters, reliability and validity to evaluate the quality of information.

The reliability parameter is to evaluate if the measuring is done correctly. A measure has good reliability if it produces similar results under consistent conditions multiple times. Samset

(2010) claims that reliability is a measurement on whether the information is dependable. And that it can in principle be tested or re-examined.

To minimize and avoid doubt, it is important to decide and use clear and fixed parameters. The reliability of information from reports, articles and books is dependent on how reliable the source is.

Samset (2010) states that the term validity is used to characterize the degree to which information reflects the phenomenon being studied. In other words, the validity indicates how well the measurement measures what we attended to measure. How precise does the measurements hit the "target", herein the goal and research questions of the thesis. To achieve a high level of validity, it is important to strive to measure directly on the target conditions.

2.4 Selected Methods

In this subchapter the different selected methods of the thesis are presented and discussed. Together with an overview, table 2-2 gives information and guidance on where to find the different attachments in the appendix.

TABLE 2-2 SELECTED METHODS

<table>
<tr><th colspan="2">Method</th><th>Information</th><th>Appendix</th></tr>
<tr><td rowspan="3">CASE STUDY</td><td>Observation (Quantitative)</td><td>Several time observations from project 1 is gathered in a time study.</td><td>Appendix B shows the used time study form, and results.</td></tr>
<tr><td>Observations (Qualitative)</td><td>Direct observations from the construction site is also implemented and discussed in the thesis.</td><td>Pictures and tables in the thesis</td></tr>
<tr><td>Qualitative interviews</td><td>A total of twelve interviews is concluded in the case study. All completed with a semi – structured interview guide</td><td>Appendix A shows the used interview guide.</td></tr>
</table>

Combined the three selected methods forms the foundation to answer the research questions. As an example, research question one "How does the drilling robot influence the installation time and scheduling planning?", needs both empirical time observations gathered from the construction site, and qualitative information gathered from interviews, to provide a good response. A more detailed explanation of the choice of methods are given in the representative subchapters.

2.4.1 OPERATIONAL TIME STUDY

This chapter concerns the method of the time study that has been concluded at Project 1. The different amount of time used on every construction site is always an important factor to systematically plan and perform the development on the site. The different time study can be used to estimate and adjust both the productivity and the profitability, and is often a significant factor to decisions regarding delivery, use of recourses and material.

Yin (2013) states that because a case study should take place in the real-world setting of the case, the opportunity for direct observations are created. Assuming that the phenomena of interest has not been purely historical, some relevant social or environmental conditions will be available for observation.

A time study of the operational installation of fire sprinkles is developed based on direct observations from the construction site. The purpose of the time study is to compare the time usage of the conventional installation with the time usage of installation with robot assistance.

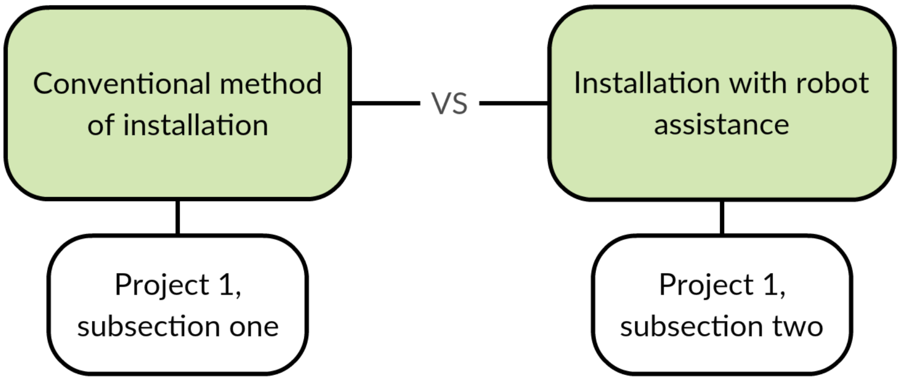


FIGURE 2.3 TIME STUDY OVERVIEW

At the operational level, three scenarios have been analyzed. All scenarios have the same conditions and restrictions. The installation firm is the same, the pipes have the same dimension and the roof mounts are the same, see figure 2.4 and 2.5. The difference is that scenario one is conducted at subsection one, and scenario two and three has been conducted at subsection two. The first scenario is the conventional installation of fire sprinklers. The second is the scenario when a hole has been drilled by the robot, but for different reasons the installer cannot use the predrilled hole, and must drill an extra. The third scenario is when the installer uses the predrilled holes as planned.

At subsection one conventional installation method was used. But in subsection two the installation of fire sprinkles was assisted with predrilled holes from the drilling robot. In addition to the predrilled holes, the operator from nLink has color-coded the holes based on the different technical installations. The sprinkle installer can now locate his/her holes and start installing the expansion bolts straight away.

FIGURE 2.4 SUBSECTION ONE (OLE ROSENLUND, 2017)

FIGURE 2.5 SUBSECTION TWO (OLE ROSENLUND, 2017)

The operational time study is conducted in spring 2017. The underlying data has personally been timed with a stopwatch spread over four construction site visits. The time study template is developed and based on a template used in a production field study of concrete works. See appendix B and reference list. Appendix B includes the used template and all the time observations from all the three scenarios.

All observations are randomly selected in the installation process, and is carried out by four different installers. The cycle time and activities of the three different scenarios have been measured twelve times each. In other words, all average numbers are based on twelve random observations of the isolated activity. Microsoft Excel is used to gather, process and illustrate the results.

Based on the fact that a measurement has good reliability if it produces similar results under consistent conditions, the result of the time study conducted in this thesis is considered to have a high reliability. The validity indicates how well the measurement measures what we attended to measure. In this thesis it was intended to measure the time of installing with and without pre-drilled holes. These measures have been conducted directly on target, resulting in a high validity.

2.4.2 Time Study On Project Level

The time study project level looks at different possibilities of planning and reorganizes the project time table. Floor 2 and 3 of the previous mentioned subsection two has been analyzed and discussed in this thesis. First, the original time table of the main contractor is introduced. Then the robot´s impact on the original plan is presented. Finally, a new method of planning is introduced and analyzed together with the possible robotic impact.

Compared to the directly measured operational level, the project levels contain uncertainties, assumptions and simplifications that lead to a lower reliability and validity. This is as expected when the situation is more complex with many factors to take into account. The time study on project level is developed to give the reader an insight of the possibility of schedule planning regardless of the relatively low reliability and validity.

2.4.3 Qualitative interviews

Yin (2013) claims that interviews are an essential source of case study evidence because most case studies are about affairs or actions. Well-informed interviewees can provide important insight into such affairs or actions. At the same time Yin states that when your interviews focus on actions because they are a key ingredient in your case, the interviews should always be considered verbal reports only. As, such, even in reporting about such events or explaining how they occurred, the interviewees responses are subject to the common problems of bias, poor recall, and poor or inaccurate articulation.

In this thesis the method of qualitative interviews is complemented with a semi-structured interview guide. The interview guide describes the main questions together with some relevant key words. It is developed to guide the interview objects into the right topic, without being to specific. With this method the responding interview objects can emphasize and elaborate what they consider relevant, without too much interference and guidance from the interviewer. The interview guide turned out helpful in all interviews, and can be located as appendix A at the end of the thesis.

Qualitative interviews are used as a method as it often provides a comprehensive understanding and concrete answers (Yin, 2013). Interviews performed in this thesis gave good answers, and information related to research questions. Together with tips and opinions of the robot, several relevant sources and articles were discussed during the different interviews. Based on the quality and preciseness of the interviews a high validity was achieved.

Before the interview all interviewees were informed of the thesis goal and research questions. A list of all the interview objects together with the date of interview, type of interview and the objects different backgrounds are listed in Table 2-3.

TABLE 2-3 INTERVIEWS INFORMATION

Interview objects	Date	Type of interview	Firm
CFO	10.11.2016	Skype	nLink AS
CTO	10.11.2016	Skype	nLink AS
CEO	21.11.2016	Skype	nLink AS
BIM developer	14.11.2016	Phone	Kruse Smith AS
Project manager	14.02.2017	Face to face	Main Contractor, Firm B
Construction manager	15.02.2017	Face to Face	Main Contractor, Firm B
Design manager	15.02.2017	Face to face	Main Contractor, Firm B
Sub-contractor plumbing	14.02.2017	Face to face - Group Interview	Firm D
Field engineer and operator	27.02.2017	Face to face	nLink AS
Sub-contractor electrician	28.02.2017	Face to face - Group Interview	Firm E
Field engineer and operator	27.02.2017	Face to face	nLink AS
Consultant Design Engineer	15.05.2017	Phone	Firm C

2.4.4 Group Interview Using a SWOT Analysis

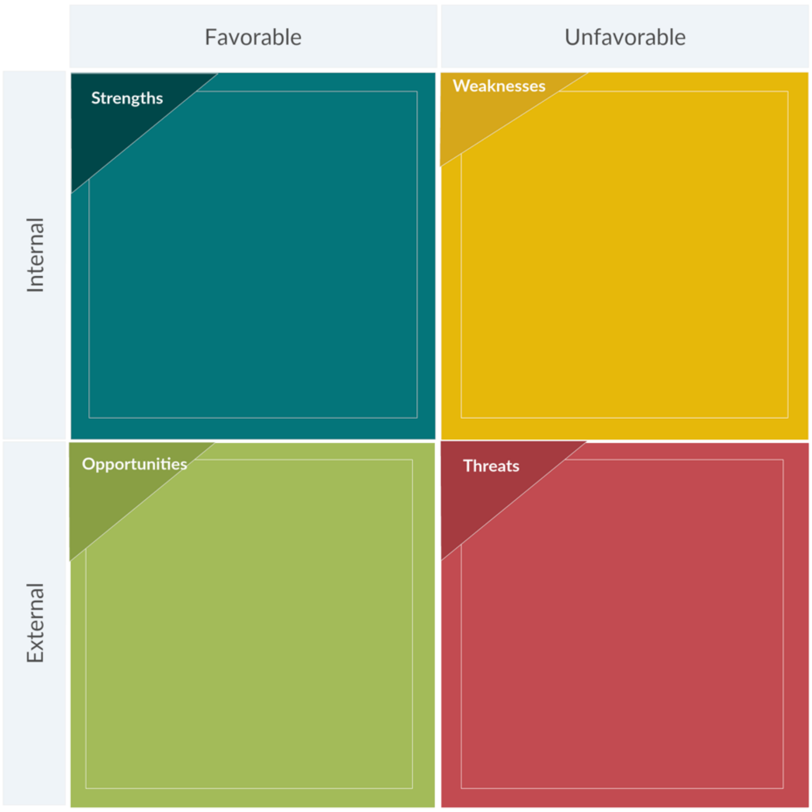
A group interview that eventually resulted in a SWOT analysis is conducted in the thesis. Valentin (2015) states that a SWOT analysis can be carried out for a company, product, place, industry or person. The SWOT abbreviation represents strength, weaknesses, opportunities and threats. It´s a simple qualitative method with an essence to describe the reality within the outcome spaces divided into the four categories. As table 2-4 shows, internal and external attributes are listed in rows while favorable and unfavorable aspects in columns.

Samset (2010) states that SWOT analyses are often conducted as expert groups reviews or brainstorming sessions in which informed experts jointly bring forth a description of status quo in the form of key conditions or elements, sorted into the four categories. Briefly, the procedure has three steps:

1. Establish a group of analysts, whose expertise and backgrounds differ.
2. Identify strengths, weaknesses, opportunities and threats related to the alternative decision at hand, based on the brainstorming.
3. Summarize the results for each alternative in a four-cell table.

A SWOT analysis is conducted of the robots effects on the construction site. The participations of the group analysis where four competent technical installers. The result is a highlighted overview of their thoughts of positive and negative consequences the robot implementation brings. This method is chosen to present the direct feedback form the installers to the reader. A clean presentation of the installers feedback, without any interpretations could give the reader an opportunity to understand the installers perspective.

TABLE 2-4 SWOT MATRIX TEMPLATE



The strength of the method is that it is methodically consistent, that it operates with an outcome space that is all inclusive, so systematic bias is avoided and that it operates with mutually exclusive categories so there are no indistinct grey zones. These strengths suit and support group-based brainstorming, because to a great extent it rules out discussion of choice of categories as well as vagueness concerning their interpretation. The method is also straightforward and inexpensive.

The weaknesses of this method are that its simple descriptions of reality in categories cannot contribute to illustrating the interactions between and dynamics in the processes studied. Consequently, it can only be used as a first approximation to an analysis. Its results depend on the insight and understanding of the participants in the analysis and on their composition. If the key interest groups are not represented, the result is likely to have limited value and validity. If the result builds on a consensus-based dialogue between informed parties, the result of a SWOT analysis may be extremely valuable.

2.5 Restrictions

The contractor in the analyzed project divides the different technical installations into four main groups; pipe and fire sprinkle, electrical installation, ventilation and ceiling panels. Project timetable together with the thesis delivery date, restricts which technical installation that can be analyzed. In the time period of the thesis, the only technical installation that worked with both conventional and with assistance of the robot, was the installation of the fire sprinkler system.

Both the installer and management stated that the different measurements and customization of the fire sprinkle installation causes it to be the most advanced installation. To measure the installation proses on site, some restrictions and demands was defined:

- Calculate and measure the net time. It is too complicated to measure gross time.
- Measure time of installation of one pipe, independent on length and only pipes that have one roof mount.
- The two subsections are similar in complexity. The same firm installs the same type of sprinkle system, with the same type of expansion bolts, roof mounts and pipes.
- A minimum of ten random time measurements shall be the basis of the average activity calculation within the two subsections.
- The average of the random selected measurements reflects and represents the normal and standard installation.

All constraints are developed in cooperation between the student and the supervisors.

3 THEORY

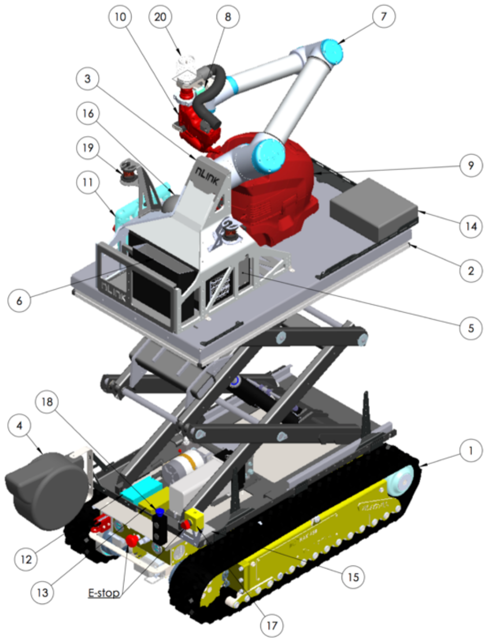
This chapter represents the theoretical framework of the thesis. It only contains previous research, no new interpretations or statements are made. The chapter covers theory of nLink as, the implementation phase, uncertainty and information, production philosophy, the health and safety aspect, location based planning and visual management. These themes are included because the theory is further discussed and highlighted in the discussion chapter.

3.1 NLINK AS

nLink As is a high-tech startup, developing robotic solutions for the construction industry. The firm was funded in 2012 with a goal of revolutionizing the construction industry. Since then they have received several awards for their ceiling drilling robot. Their headquarter is in Sogndal, on the West Coast of Norway, but they also have a commercial office located in Oslo Science Park. Today nLink and their partner company, Rocketfarm, has 15 full-time engineers, business developers and sales employees.

nLink are introducing the first commercial mobile drilling robot to the global industry. The firm claims that their robots are efficient, customized for working on construction sites, increases worker safety and ensures a faster project completion. By integrating BIM, Building Information Models, with robotics, nLink will contribute to accelerate the use of BIM beyond planning purposes.

The ceiling drilling robot drives on battery, and drills with electricity from a power cable. A vacuum cleaner is installed to collect dust and protect the camera. The robot weighs 850 kg when it is fully uploaded for set-up. When the robot operates, the weight is approximately 800 kg. The robot uses two prisms to communicate with the total station. Figure 3.1 is a technical drawing from nLink that contains further information about the robot.



ITEM NO.	DESCRIPTION	TYPE
1	TRACKS	ALITRAK, DCT-450
2	SCISSOR LIFT	EDMOLIFT, TLD-1000
3	TOP FRAME	NLINK
4	CABLE REEL	
5	ROBOT CONTROL BOX	UNIVERSAL ROBOTS / NLINK
6	3D CAMERA SYSTEM	SCORPION, 3D STINGER
7	ROBOT ARM	UNIVERSAL ROBOTS, UR10
8	HOLE DEPTH MEASURING	PEPPERL-FUCHS, VDM18-300/32/105/122
9	VACUUM CLEANER	HILTI, VC20-U
10	ROTARY HAMMER	HILTI, TE7
11	ROBOT ARM CONTROL PENDANT	UNIVERSAL ROBOTS
12	TOTAL STATION CHARGER	LEICA
13	TRACK CONTROLLER CHARGER	ALITRAK
14	IPAD CHARGE BOX	NLINK
15	JUNCTION BOX	NLINK
16	WIFI, 4G, GPS ANTENNA	TAOGLAS LIMITED, PANTHEON 3 IN 1 GPS LTE
17	EMERGENCY STOP BUTTON	BACO
18	SCISSOR LIFT CONTROLLER	DEMOLIFT
19	PRISME	LEICA
20	VACUUM CUP	
	STEEL BRACKETS	NLINK

FIGURE 3.1 TECHNICAL INFORMATION (NLINK, 2016)

The ceiling drilling robot has been designed and developed closely together with contractors, to ensure that the robotic solution actually solves their problems and needs. nLink´s main goal is to develop robots that solve problems identified by the construction business. The drilling robot aims to reduce time consumption and relieve the construction workers from heavy, repetitive and hazardous work. Based on data from nLink AS a timeline of the robotic development is made.

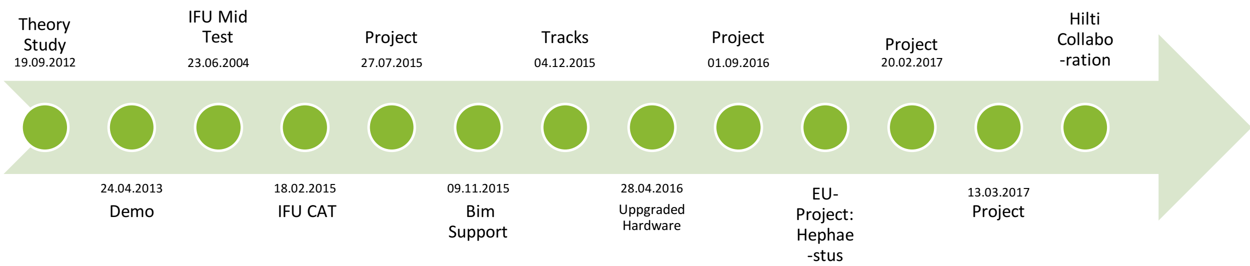


FIGURE 3.2 ROBOT DEVELOPMENT

The main and simplified idea of the robot is that after the prefabricated concrete elements are assembled at a construction site, the robot locates and drills all the holes to the technical installations. While the robot is drilling, an operator observes the robot and color –codes the different holes to the different technical installations. This provides an easier basis for installation while it also eliminates heavy workloads above shoulder height.

3.2 IMPLEMENTATION PHASE

It is important for the reader to understand the situation and the conditions the robot is analyzed in. A brief presentation of a projects life cycle is therefore presented and narrowed down to the level where the analysis, and master thesis, takes place in the project cycle.

Samset (2010) states that a project´s life cycle may be split into separate phases. Whatever characterizes the different phases may be more or less clearly defined. Phases are defined according to what appears useful, commonly by process, ownership or responsibilities. One common way to split the life cycle of a project is to distinguish between the identification phase, the definition phase, the pre-appraisal phase, the planning phase, the implementation phase, the operational phase and the termination phase. Since these phases will overlap, the distinction between them may seem unclear. Accordingly, Samset simplifies the picture by splitting the cycle into just three phases: the front-end phase, implementation phase and operational phase. In this thesis, the effects of the robot are analyzed in one specific project that has reached the implementation phase.

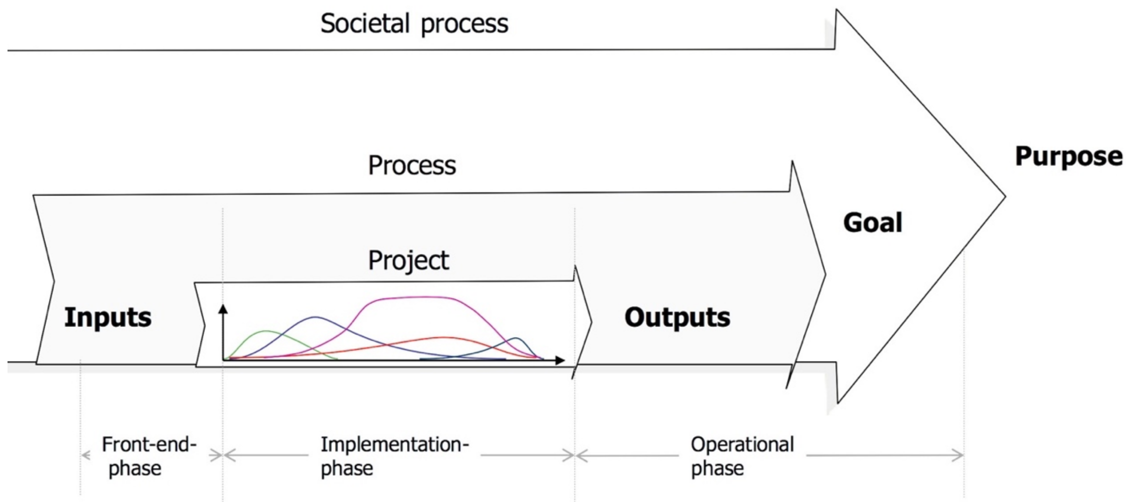


FIGURE 3.3 THE PROJECT AS A PART OF A LARGER PROCESS (SAMSET, 2015)

Seen in a project management perspective, the project is a sequential series of overlapping processes, from the time it is commissioned until its output have been delivered. The planning and execution processes dominate. The project starts when funding is secured and the decision to go-ahead is finalized. It starts with initiating processes that essentially are concerned with committing the various parties to planning and execution. It proceeds with planning and detailed engineering, while at the same time the execution processes are phased in. The project will be finalized in a short but intense phase of closing processes involving approval, accounting, documentation training etc. (Samset, 2010).

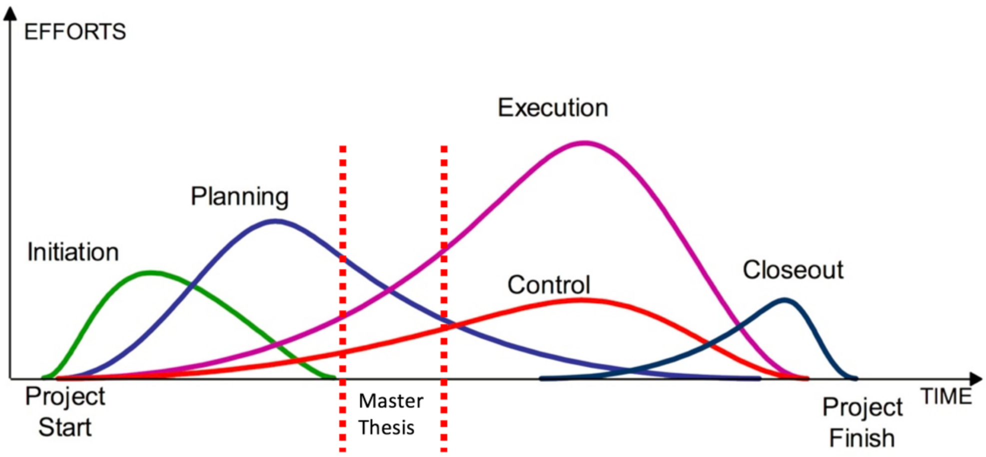


FIGURE 3.4 THE PROJECT MANAGEMENT VIEW (SAMSET, 2015)

This master thesis was conducted within the time frame illustrated with the red dotted lines in Figure 3.4. The limited time causes natural restrictions of the thesis' content and analyzes. Most of the planning had been done, and limitations regarding installations progress was a factor. Fortunately, one technical installer performed work with, and without, the robot in the limited time period; the fire sprinkler installers. For this reason, the fire sprinkler installation forms the basis of the comparison between the conventional installation method and the new installation method in this master thesis.

3.3 Uncertainty and Information

Samset (2015) states that uncertainty is customarily defined as a lack of relevant information for valid decision making. This definition is useful but has its limits. Clearly, uncertainty cannot be eliminated merely by acquiring information. Information is necessary but insufficient means for mastering and reducing uncertainty. Later in the thesis both uncertainty and information are discussed. And since these discussions are revolving the fact that the implementation of the robot requires new information and brings forth new uncertainties, this subchapter is included in the theory.

Uncertainty associated with a course of events implies that the actual output probably will deviate from those anticipated. Uncertainty manifests itself in the combined impact of all events and processes that cause and influence the output of a project. Each of these events and processes may be predictable. To degree, uncertainty is determined by the type and scope of such processes and events. In turn, this makes decision making more difficult with increasing uncertainty. But it also causes the predictability to rise with the increasing inflow of relevant information, the uncertainty is reduced from the viewpoint of the decision maker. (Samset, 2010)

One interpretation Samset explains is that the term uncertainty reflects the extent of the lack of information required to reach a decision that ensures that the anticipated output is realized.

One interpretation would then be that if all relevant information is at hand, there is no uncertainty. If the information base is poor, uncertainty is great.

Samset (2015) states that in principle, the lather substantial changes are made in the course of a project, the greater excess costs they incur, as that may involve changes in plans, work progress or contractual commitments. Such changes introduced in the implementation phase can considerably affect cost. In general, it is increasingly difficult to introduce change as a project nears completion, and the effects of changes diminish as work draws to a close. This underscores the importance of a total picture of a project's uncertainty with possibilities and risks, as failing to handle uncertainty early in a project may trigger inconvenient changes later on.

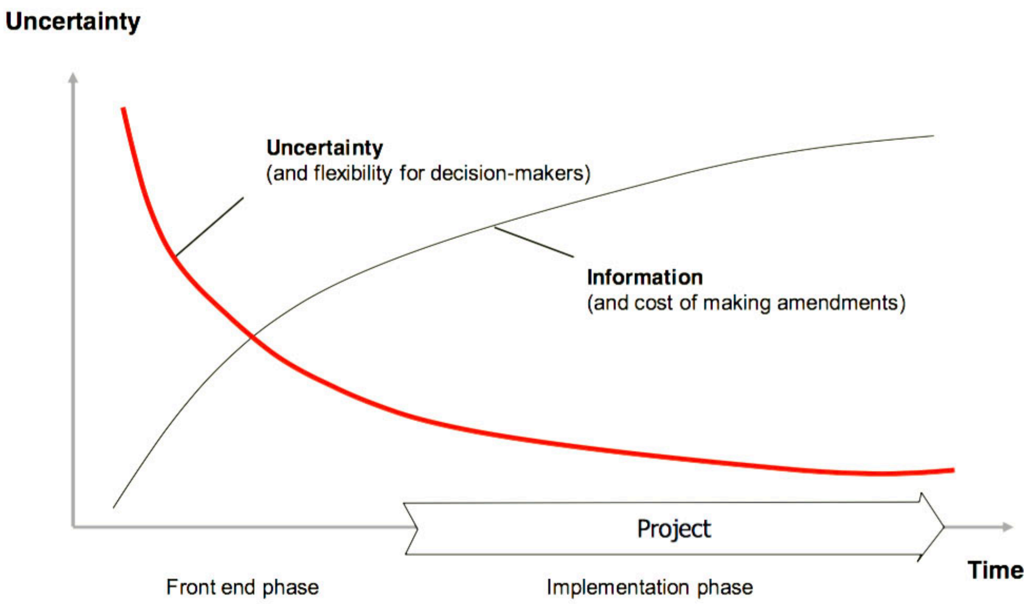


FIGURE 3.5 UNCERTAINTY AND AVAILABLE INFORMATION (SAMSET, 2015)

Samset´s principle is illustrated in figure 3.5 in which uncertainty and the complication of information vary with elapsed time in a project. Uncertainty is greatest at the starting point and thereafter diminishes as a consequence of gradual acquisition of more information. At this stage, the possibilities to influence are greatest and the knowledge of what lies ahead is least. The influence possibilities diminish little by little as decisions are made, alternatives chosen, strategies determined, contracts entered and work begun and they finish out in the project phase.

Accessible information is most minimal at the start. The graph suggests that the potential to reduce uncertainty and risk is largest up front, and decreases substantially when the project is implemented. Samset (2010) claims that this illustrates part of a paradox in project studies. The discipline of project management is principally concerned with handling uncertainty in the implementation phase when the possibilities for reducing uncertainty are marginal compared with those in the front-end phase. Most textbooks and teaching in project management focus attention on the implementation phase, while assessment of the front-end phase is cursorily covered in a few pages as if it were an unexplored region on a map.

However, Samset (2010) also states that there are limits on how much an increase in information in the front-end phase may reduce project uncertainty. Clearly, uncertainty cannot be eliminated merely by acquiring more information. Equally obvious, not all necessary information will be available early on. This is because projects are dynamic processes that are implemented in societal context, in which the natural dynamics of the process and the influence of the surroundings dictate that much of what happens cannot be foreseen. A good deal of information surfaces on the way. In other words, this means that you must always live with uncertainty in a project.

Projects are exposed to surroundings wherein complexity and dynamics are great, which in turn induces considerable uncertainty in implementation. According to Samset (2010) in project analysis, it is customary to distinguish between operational and contextual uncertainty.

Operational uncertainty is associated principally with the organization and implementation of projects and is regarded to be relatively independent of the context within witch the project operates. Operational uncertainty exists both in innovative research and development projects and in routine projects that it declines with time as a project evolves. This happens both because the compilation of information increases and because the project managers acquire a better grasp of the processes they manage. Operational uncertainty in a project can be reduced to some extent through systematic, realistic planning that leads to achievable goals by increasing access to relevant information and by improving project management.

Contextual uncertainty is associated with the surroundings of a project. It is high in innovate projects implemented in unknown conditions. The possibilities of acquiring knowledge of and influencing contextual uncertainty are often limited. This is because contextual uncertainty is associated with aspects outside the projects mandate and sphere of authority, such as political processes or decisions, cooperation with affected institutions, needs and demands in the market, technological development, etc. The possibilities for reducing contextual uncertainty are correspondingly limited. Moreover, in many cases, uncertainty may be understood only in retrospective, after the consequences have become apparent. Contextual uncertainty is often brought about by complex processes, so the information gap persists, despite attempts to acquire relevant information. This is illustrated in figure 3.6.

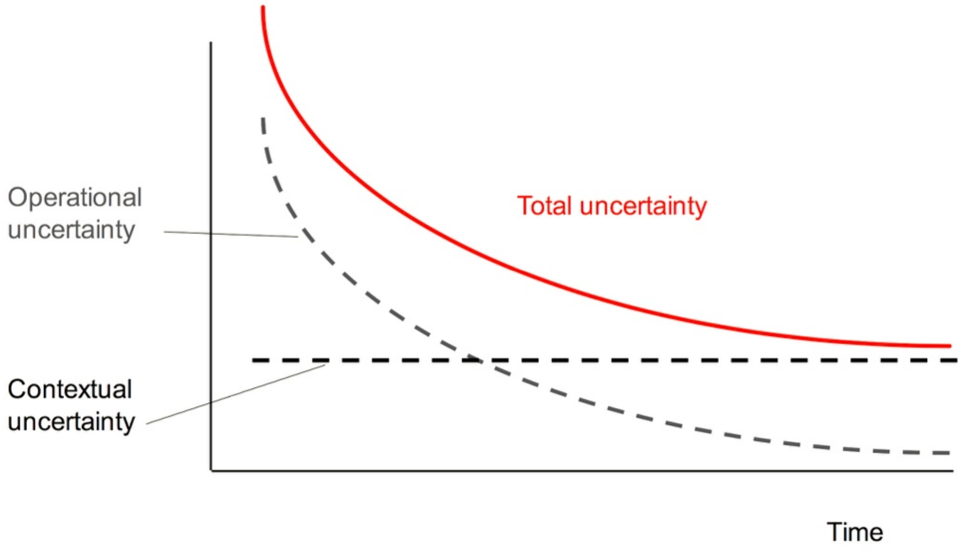


FIGURE 3.6 OPERATIONAL AND CONTEXTUAL UNCERTAINTY THROUGH THE PROJECTS PHASES (SAMSET, 2015)

Samset (2010) states that traditionally, attention has focused on the internal, operational aspects of projects. Uncertainty associated with the surroundings of projects has drawn less attention, both theoretical and practical. The challenge here lies first and foremost in understanding the complexity in a project and its interaction with its surroundings.

To date, uncertainty has usually not been treated systematically as a steering parameter in projects. This inattention needs to be changed, as consideration of uncertainty in the front-end phase and the implementation phase is essential to improving the results and effects of projects. (Samset, 2010)

Jessen (2005) states that it is reasonable to assume that the utility of additional data declines as the cost of acquiring it increases. Hence, the amount of information must be limited to a reasonable level. In principle, in the start-up phase, the benefits of collecting information are great in relation to the cost of acquisition. With time, the cost of collecting additional information increases while the benefits of it becomes marginal. This is illustrated in figure 3.7. Consequently, in the front-end phase the challenge is to limit the complications of information to a level that gives the best possible relationship between benefits and costs. Obviously, it is not the amount of information that is decisive, but rather the degree to which the information is relevant.

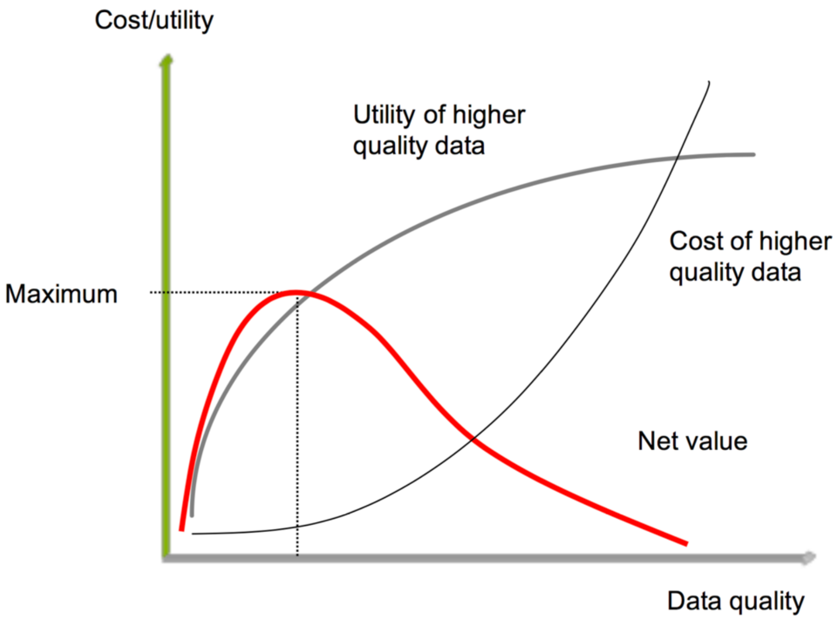


FIGURE 3.7 COST/INFORMATION RATIO AND QUALITY OF INFORMATION IN A PROJECT (SAMSET, 2015)

Samset (2010) explains that from the viewpoint of cost versus benefits, the costs of an initial concept development are often small while the potential reward is large. After the process or project starts, the situation is often the opposite. The reward attained does not always reflect the cost of steering the process.

3.4 PRODUCTION PHILOSOPHY

In 1992 Koskela described a new conceptual basis for a new production philosophy. Koskelas model was a synthesis and generalization of different models suggested in various fields. Koskela (1992) defined the new production model as follows:

> "Production is a flow of material and/or information from raw material to the end product. In this flow, the material is processed (converted), it is inspected, it is waiting or it is moving. These activities are inherently different. Processing represents the conversion aspect of production; inspecting, moving and waiting represents the flow aspect of production.
>
> Flow processes can be characterized by time, cost and value. Value refers to the fulfillment of costumer requirements. In most cases, only processing activities are value-adding activities. For material flows, Koskela stated that processing activities are alternations of shape or substance, assembly and disassembly. "– Koskela (1992)

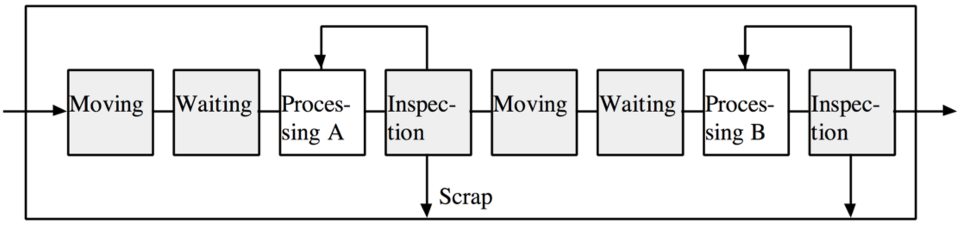


FIGURE 3.8 PRODUCTION AS A FLOW PROCESS

Koskela (1992) stated that in essence, the new model implied a dual view of production; it consists of conversions and flows. The overall efficiency of production is attributable to both the efficiency (level of technology, skill, motivation, etc.) of the conversion activities performed, as well as the amount and efficiency of the flow activities through which the conversion activities are bound together.

While all activities expend cost and consume time, only conversion activities add value to the material or piece of information being transformed to a product. Thus, the improvement of flow activities should primarily be focused on their reduction or elimination, whereas conversion activities should be made more efficient. Koskelas core idea of the new production philosophy is illustrated in Figure 3.9.

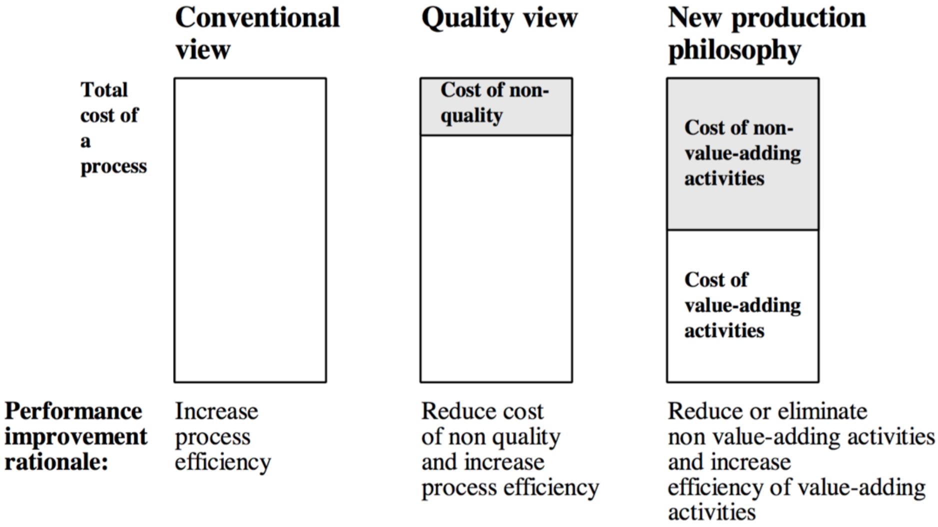


FIGURE 3.9 PERFORMANCE IMPROVEMENT IN CONVENTIONAL, QUALITY AND NEW PRODUCTION PHILOSOPHY APPROACHES (KOSKELA, 1992)

To define how the processes should be designed, Koskela (1992) defined 11 principles that would contribute to a positive workflow and eliminate waste:

1. Reduce the share of non value-adding activities.
2. Increase output value through systematic consideration of customer requirements.
3. Reduce variability.
4. Reduce the cycle time.
5. Simplify by minimizing the number of steps, parts and linkages.
6. Increase output flexibility.
7. Increase process transparency.
8. Focus control on the complete process.
9. Build continuous improvement into the process.
10. Balance flow improvement with conversion improvement.
11. Benchmark.

Koskela (1992) stated that in general, the principles apply both to the total flow process and to its sub processes. A selection of these 11 principles are compared and discussed with the findings of the robotic impacts on the construction site. Especially principle number 4, reduction of cycle time, and principle number 7, increase process transparency is highlighted in the discussion chapter.

3.5 HEALTH AND SAFETY

Samset (2010) claims that all projects involve risk in the sense that the result is not exactly as expected. Many aspects affect risk. Some of them cannot be foreseen. Risk is associated with the degree of uncertainty associated with a project. The degree of certainty that contributes to reducing risk is based either on knowledge of and experience with other projects or on the ability of project management to handle uncertainty. This means that risk may be regarded to be a function of the uniqueness of the project and the experience of the project organization.

According to Haugen (2015) risk management is a continuous management process with the object to identify, analyze, and assess potential hazards in a system or related to an activity, and to identify and introduce risk control measures to eliminate or reduce potential harm to people, the environment, or other assets.

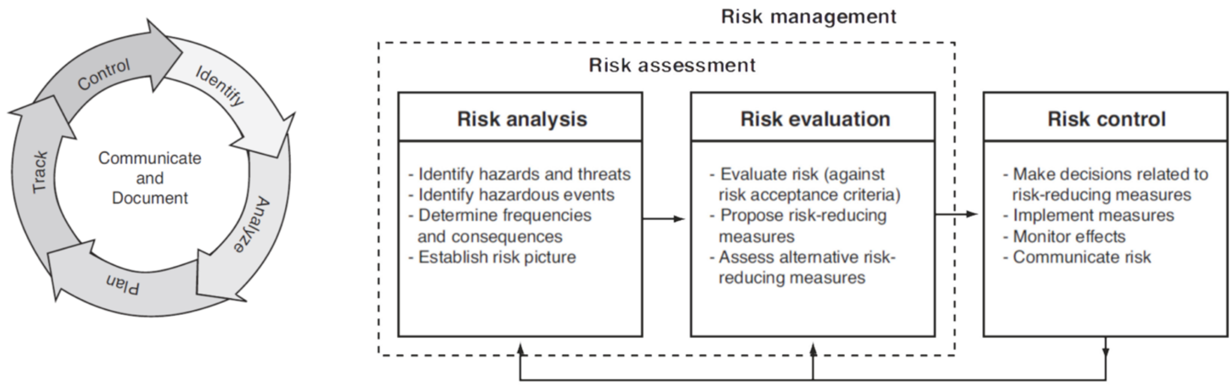


FIGURE 3.10 RISK MANAGEMENT (HAUGEN, 2015)

The risk assessment is defined by Haugen (2015) as the overall processor of risk analysis and risk evaluation. Risk analysis is the systematic use of available information to identify hazards and to estimate the risk to individuals, property, and the environment. The three main steps in an analysis is hazard identification, frequency analysis and consequences analysis. Risk evaluation is defined as the process in which judgment is made on the tolerability of the risk on the basis of a risk analysis and taking into account factors such as socioeconomic and environmental aspects. Haugen also points out that sometimes risk evaluation is comparing results from risk analysis with risk acceptance criteria.

According to Samset (2010) risk is in general defined as a function of two parameters, the probability of an event happening and the consequence of the event should it happen, that is:

Risk = f(probability, consequence)

Once the magnitudes of the two parameters are known, the risk function gives the degree of risk. These expected values can be ranked and put in a risk matrix. Since this provides a twodimensional view of consequence and probability where these are ranked. The matrix provides a picture of the nuances of risk relative to each other and independent of the risk calculation based on the above equation. It also depicts the risk profile of a project subjected to several risks and may also be used to spell out whether risks are acceptable or unacceptable.

Consequence / Probability	Unlikely 1	Some chance 2	Possible 3	Probable 4	Very likely 5
Disastrous 5					
Serious 4					
Considerable 3					
Limited 2					
Insignificant 1					

FIGURE 3.11 RISK MATRIX EXAMPLE

Samset (2010) claims that the drawback of using expected value alone is that a risk with a low probability of occurrence may be ignored, even though its consequence may be extensive, because the product of the two parameters is small. Samset mentions a nuclear reactor as an example. If anything goes wrong with the reactor, the impact may have fatal consequences for thousands. So even if the probability of an accident is very small, its risk cannot be ignored. In comparison to a nuclear reactor we look at a different case in this thesis. A shoulder injury, hearing damage or dust pollution are most likely to have a lower consequence but a higher probability of occurring.

According to Samset (2010) a risk policy is necessary to provide rules or guidelines for deciding what to do when faced with risk. Samset explains three different types of risk policies. The simplest risk policy might be to rank risk elements according to their calculated expected values and set an upper limit for acceptable risk. A more advanced policy might be to aggregate the effects of risk elements, such as by using influence diagrams or Monte Carlo simulations. This permits simulating the effects of various risk within the overall picture. A third variant, between these two extremes, may be to make do with simple classifications of risk elements and then compare it with a risk policy that differentiates between various types of risk and states what should be done with each of them.

The risk matrix is a simple, useful tool for such an approach. For example, the differentiation may be according to the degree of risk, as illustrated in figure 3.12, which distinguishes between unacceptable, tolerable and negligible risk. As indicated in the figure a tolerable risk is associated with an assessment of cost by reducing the risk relative to benefit gained. Acceptable risk is partly associated with the expected value and partly with the consequence of given event.

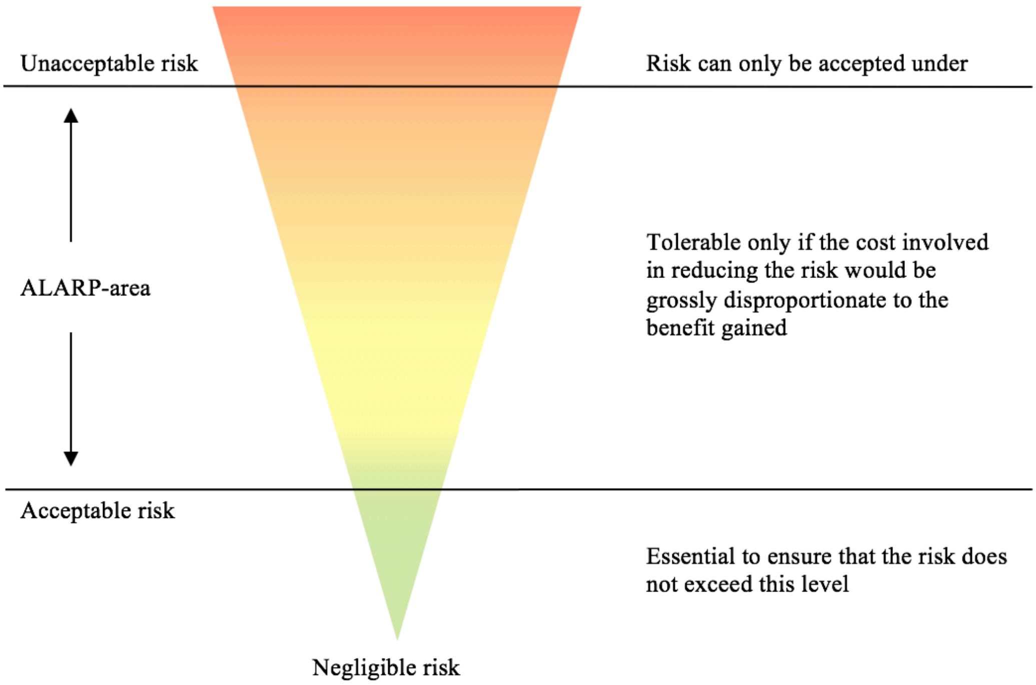


FIGURE 3.12 AS LOW AS REASONABLE POSSIBLE (ALARP) PRINCIPLE AS A BASIS FOR RISK POLICY

But the differentiation may also be associated to a particular risk, such as by having criteria for tolerance of financial risk, environmental risk and institutional risk. As an example, Samset (2010) claims that an unacceptable risk could be defined as one that might result in financial overruns, creates politically difficult situations or injures people. One might accept that a risk that results in lesser damages could be tolerated, provided that the cost of reducing the risk are much higher than the loss incurred when the damage occurred. For example, risk up to a certain level may be deemed acceptable in a project implemented jointly with reputable institutions. Or one might elect to ignore risks associated with lesser pilot projects, because the consequences are curtailed or because it is inherently valuable as a small-scale test of the uncertainty and consequence of a full-scale project implemented later.

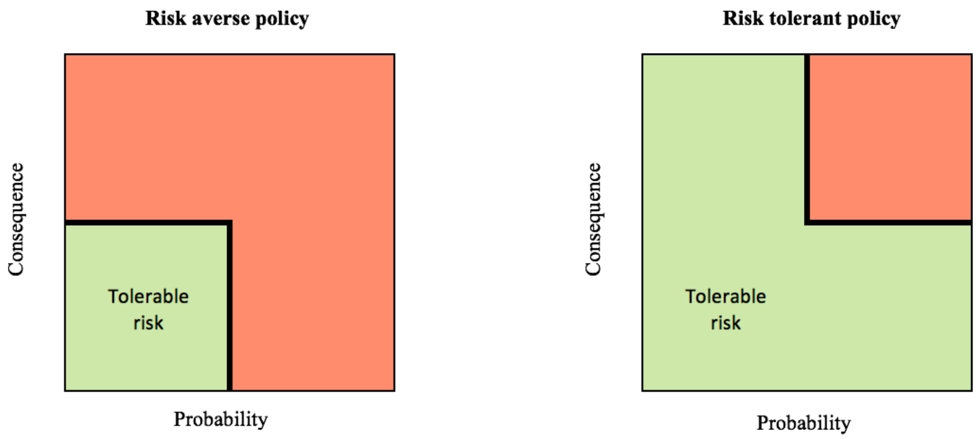


FIGURE 3.13 THE RISK MATRIX AS USED TO PROVIDE AN OVERVIEW OF THE RISK PROFILE OF A PROJECT

Samset (2010) mentioned that risk policy may also be determined by the division of the risk matrix outcome space. This is illustrated in Figure 3.13, in which a risk adverse policy sets upper limits to acceptable consequence and probability, and a risk tolerant policy accepts outcomes when one of the parameters is high but the other stays within a given limit.

Regardless of whether you use the risk matrix or some other illustration tool to visualize the risk, the different risk events can be reduced, or better eliminated by providing another way of doing the activity. In this master thesis, a focus on locating different activities related to the drilling robot is implemented. It will be interesting to see if any activities could be reduced or eliminated from the risk picture, and see what the cost of reducing or eliminating these risks are.

3.6 Location Based Planning

This chapter presents a way to manage construction projects: the location-based management. Kenly (2010) states that the new system is designed to reduce risk, reduce production cost, increase site harmony, improve subcontractors performance, reduce material waste, improve the quality of constructions and deliver more certain outcomes. The location-based management system for constructions is a comprehensive new production control system for construction, with an emphasis on the planning, scheduling and control of projects and including, in its implementation, time, cost and quality. Essentially, it is an integrated system designed to improve the probability for all participants from clients to subcontractors. The system does, however, require a new way of thinking.

Kenly (2010) explains that there are two main methodologies for scheduling work: activity-based scheduling and location-based scheduling. These two methodologies in turn have many methods and techniques, but are principally associated with two principal scheduling methods, each designed to achieve the same purpose in different ways: Critical Path Method and either line of balance or flow line.

Activity-based scheduling is the current dominant scheduling technique and was first developed in the 1950s (Kenly, 2010). Common to all activity-based methods is the underlying logical structure of the models. Each individual activity is considered free to move in time as long as it maintains its logical relationship with its predecessors and successors. Such a model suits very well any project where activities are completely discrete and have no correlation. Kenly (2010) described six characteristics of an ideal activity-based schedule for projects:

- Dominant by discrete locations
- Involving much prefabrication of components
- Complex assembly of prefabricated components, involving discrete activities
- Highly sequential, in that long-duration activities are not running simultaneously
- One of many critical paths may be identified
- Resource management is a time/resource optimization problem

Unfortunately, this list does not describe much commercial construction at all well. This suggests that activity-based scheduling does not well match the character of construction projects, which consist of large amounts of on-site fabrication involving continuous or repetitive work.

Kenly (2010) states that some of the characteristics of commercial constructions align more closely with an alternative methodology; location based planning. This methodology is based on tracking the continuity of crews working through a building and was originally based on graphical techniques, used as early as 1929 on such innovative projects as the Empire State Building. Kenly claims that this older suite of techniques found strong support in continuous general production systems (and is more typical in engineering construction) but has only found limited support in commercial construction. The characteristics of an ideal location-based schedule for projects is described as:

- Multiple locations (or more accurately, multiple work places)
- On-site and continuous assembly of components (including prefabricated work)
- Complex assembly involving repetitive but variable activities (work which repeats in different locations, but in which the amount or context changes)
- Equally parallel and sequential paths
- Resource management is a flow-optimization problem, designed to achieve smooth flow and continuity in the use of resources.

The flow line is a location based planning method to represent the flow of work through locations. Kenly (2010) explains that the flow line representation is designed to handle normal constructions projects rather than the repetitive production of completed units such as housing. To do this, the project is broken down into sections of roughly equal size and content. However, instead of the horizontal line representing the production of a unit the space occupied between the lines now represents the location. The lines passes from the left corner (start of location, start of duration) to the upper right corner (end of location, end of duration), so its depth has meaning. In detailed form, the flow line representation uses the same basic components, but represents a crew passing through a location. In figure 3.14, the tasks 1-5 are shown passing through locations A-D. It is also easy to see that there is a logical relationship between tasks within locations.

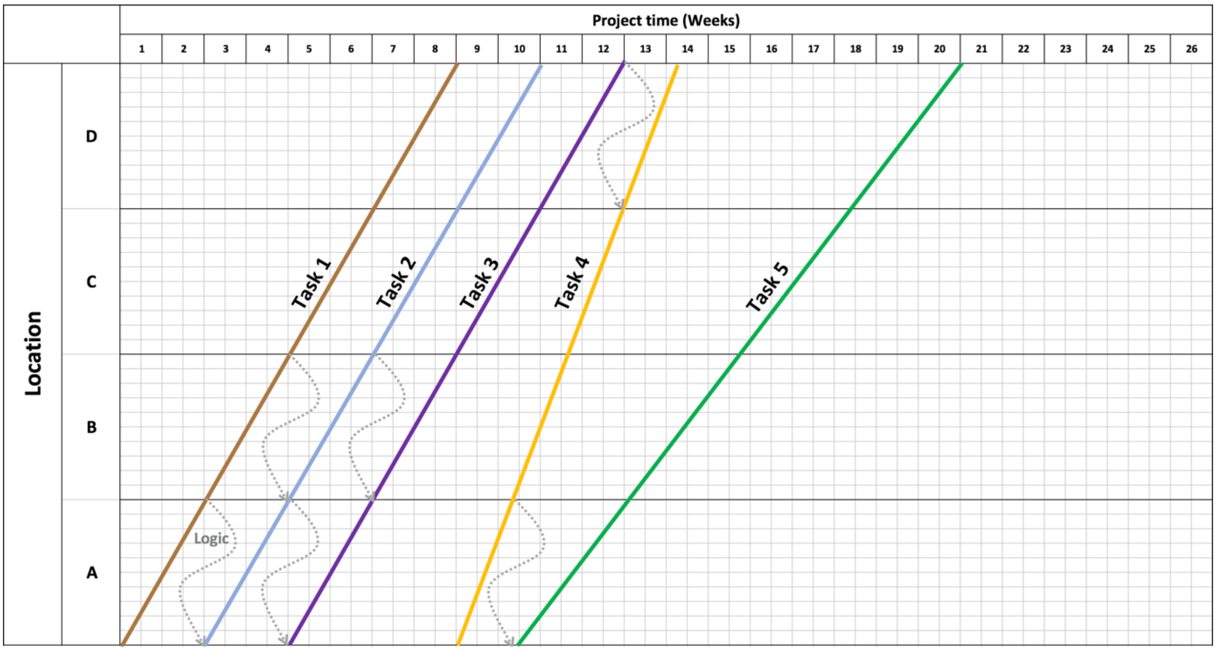


FIGURE 3.14 FLOWLINES FOR TASK 1-5 IN LOCATIONS A-D

In a flow line, continuity is an essential component of the criticality assumption. When production is balanced to the extreme, as in the flow line production in figure 3.15, most of the work is critical. (Kenly, 2010)

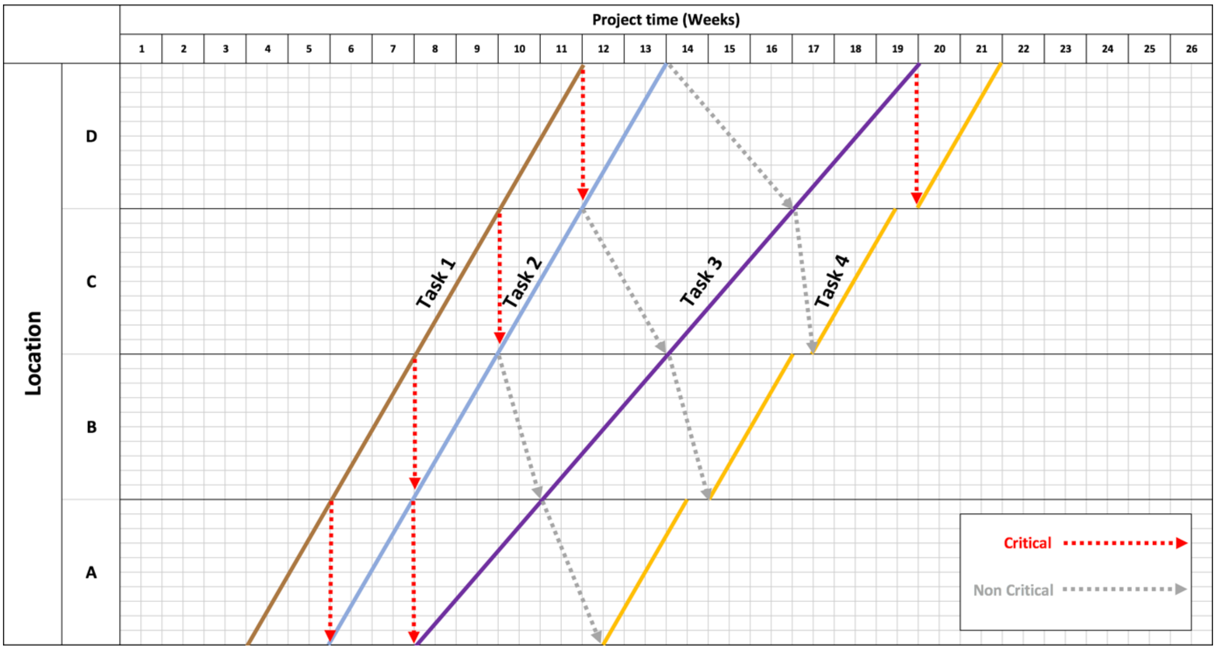


FIGURE 3.15 CRITICALITY IN FLOWLINE

The final task is only critical in the final location due to the float which allows the activity to start earlier than optimal (for continuity) with no effect on the project duration. The criticality can be illustrated in a Gantt chart, as in figure 3.16, which shows the activities clearly in each location together with the logical relationships.

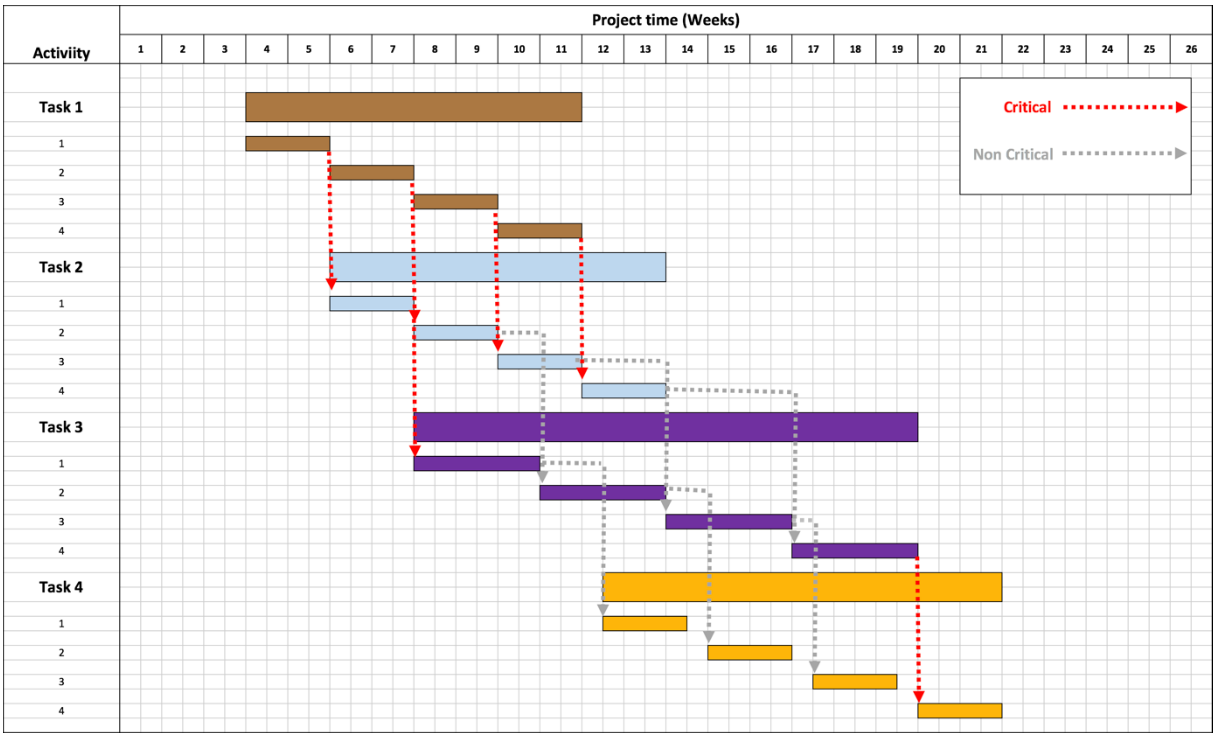


FIGURE 3.16 FLOWLINE CRITICALITY IN A GANTT REPRESENTATION

Mohr (1979) explored the relationship between time and production alignment. In the process he developed two fundamental operations to deal with tasks with non-aligned production, for

faster or slower production. Non-aligned production causes interference with the following activities, thus delaying the project. The method for improving the project plan involves breaking the work into sections for both cases. In the case of slower production, the work is broken to allow multiple gangs to work simultaneously. In location-based management, this is called splitting. In the case of faster production, the work is broken into sections with a delay in between. In location-based management this is called non-paced or non-continuous.
The third option, the default in LBMS, to increase the number of gangs in each location, was not specifically mentioned by Mohr.

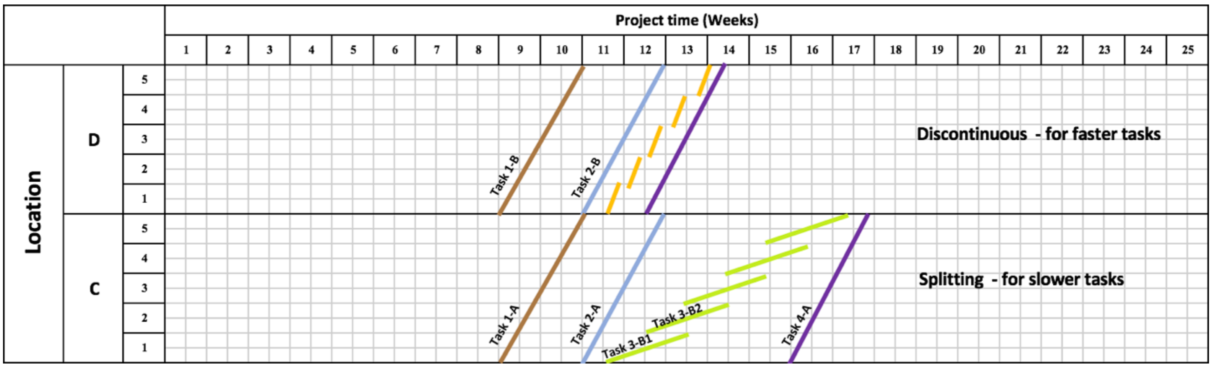


FIGURE 3.17 BREAKING THE WORK INTO SECTIONS TO IMPROVE PRODUCTION

There are two causes of non-rhythmic construction. Work may be planned to be non-rhythmic, or it may become so during construction. Our concern is with the former. Mohr´s use of the latter provides the first example of flow line being used as a control system. Mohr recognized that not all production is rhythmic.

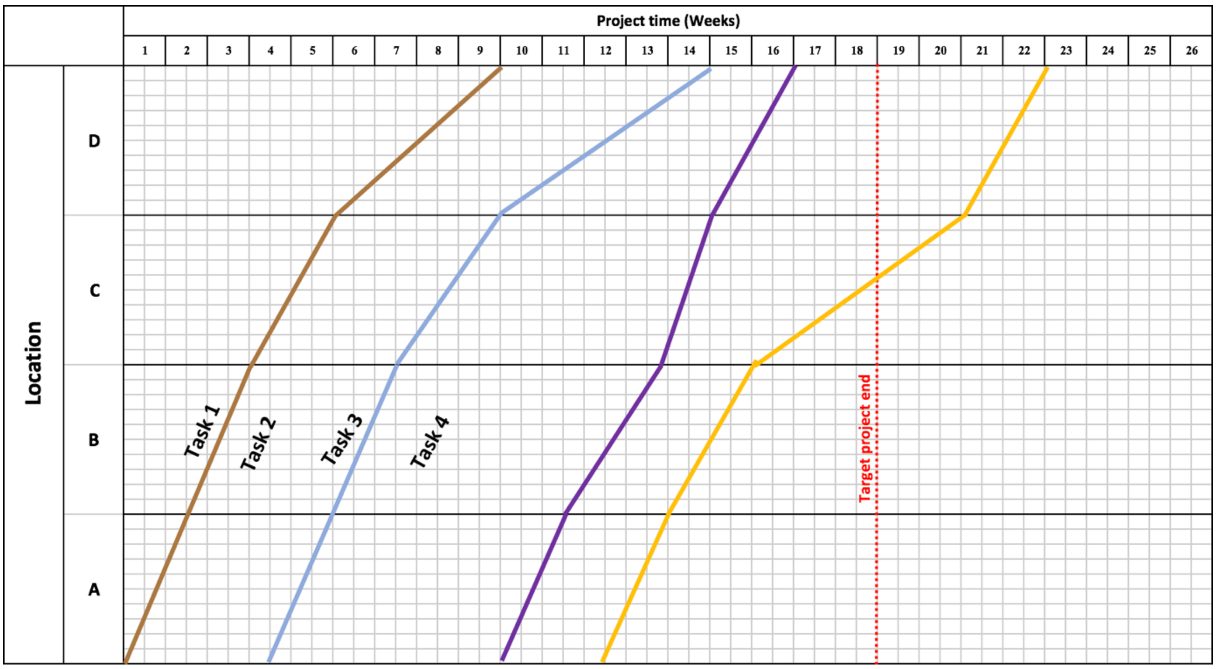


FIGURE 3.18 CONTINUOUS PRODUCTION - OPTIMUM DURATION

He argued that a simple bar chart could lead to assuming the project could be completed earlier than possible, if only the first activities for a task in the first location were sequenced, with each location then proceeding without regards for other locations. The precedence diagram most clearly shows the logical construction of a network which forces sequence in both locations and trades. This is a heavily constrained network and is laborious to build. The flow line equivalent is shown in Figure 3.19. However, achieving continuous production (as is accepted by Mohr as basic criterion of the flow line approach) requires a duration of 22 days, figure 3.18. Mohr (1979) states that using this form of presentation it is easily shown where the work groups are disconnected to fit in with the work of other activities.

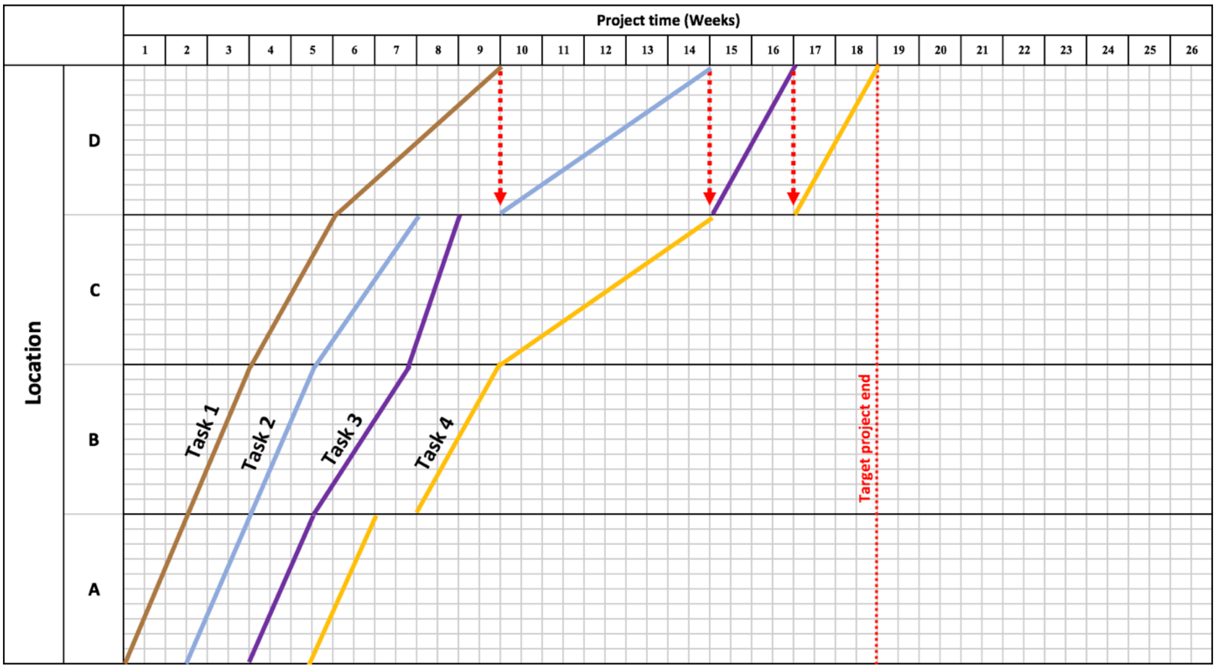


FIGURE 3.19 DISCONTINUOUS PRODUCTION - MINIMUM DURATION

Kenly and Seppänen (2010) claim that actual production is likely to vary and buffers are required to reduce the incidence of negative criticality. The client change has great impact on a project schedule and may be handled in two ways in location-based management. A buffer can be used to allow for uncertainty where this is expected. This shields the production from design variability. Buffers can provide room to re-sequence the work, for changes in quantities or for control mechanisms. In conjunction with the buffers, the data available in location-based management allows for detailed documentation of the cause and effect of variation, particularly when compared with the baseline plan. It is very easy to demonstrate the effect of client changes on the production efficiency of the project, and thus to establish the cost of lost efficiency if required.

3.7 VISUAL MANAGEMENT

According to Tezel (2010) people are exposed to various information transactions in their work environments. Information overloads or deficiencies may lead to undesirable consequences. Some organizations utilize simple, yet cognitively effective visual tools, particularly for operational purposes, to manage different aspects of work, to organize their workplace, to facilitate human effort and to distribute system wide information. This conscious effort of managing information in daily transactions, using visual tools, is called visual management. The work setting, in which visual management is realized and different visual tools/systems exist is a visual workplace. Visual management can serve different functions depending on the extent it has been used, the most important one for an organization is perhaps increased transparency.

Tezel (2010) claims there are parameters affecting the use of visual management in construction, such as construction technology, contractual relations and project specific variables (e.g. construction site topography). For some tools, repetitive standard construction (e.g. multi-story building with a standard number of brick types) can be necessary for an effective implementation. Tezel states that usually the companies collaborate with each other and academia to develop their operational practices, which provides them with different modes of learning.

Visual management is realized in visual workplaces, which are structured with information giving, signaling, limiting or guaranteeing visual devices to communicate with "doers", so that places become self-explanatory, self-ordering, self-regulating and self-improving. Visual elements create an information field for people to pull the necessary information from and help people make sense of the organizational context at a glance by merely looking around.

Tezel (2010) claims that visual management serves different functions within an organization, namely transparency, discipline, continuous improvement, job facilitation, on the job-training, creating shared ownership, management by facts, simplification and unification.

Transparency is defined by Tezel as "the ability of a production process (or its parts) to communicate with people". Transparency involves a separation of the network of information and the hierarchical structure of order giving, in other words, an increase in self-control, which in classical organization theory are identical. The goal is thus to substitute self-control for formal control and related information gathering.

Visual Management reflects people's adherence to the expectations of processes by transforming the abstract concept of discipline into directly observable concrete practices. Anyone, even a newly hired, inexperienced employee, should be able to distinguish between normal and abnormal conditions at a glance and start taking the correct steps, developing an intuitive, habitual correctness, without being dependent on another entity. Discipline is explained by Tezel as "following standardized procedures ", and defined as "making a habit of properly maintaining correct procedures".

Tezel (2010) states that continuous improvement, or kaizen in the lean terminology, is a highly dynamic capability and can be defined as “an organization-wide process of focused and sustained incremental innovation”. Visual management serves as a base for continuous improvement, and perhaps more importantly stimulates employee involvement to manage and improve quality.

Job facilitation is defined by Tezel (2010) as a conscious attempt to physically and/or mentally ease people’s efforts in routine, already known tasks by offering various visual aids. Visual management facilitates routine job tasks for people by offering a quick, correct and holistic understanding of their job requirements. When the amount of information required to complete a task pushes the capacity of working memory, it must be made available in the physical world through visual displays.

On-the-Job training includes learning from experience. Integrating working with learning is a competitive imperative for organizations. Information in the environment enables on the job training, which is an effective way of learning, as it is integrated in actual work and helps employees learn by practical experience. It is a cost effective, less work disruptive, encouraging, and easy to assess (for supervisors) organizational learning practice that employs visual management.

Tezel (2010) defines psychological ownership as a feeling of possessiveness and being psychologically tied to an object (material or immaterial). Visual Management is used to create and designate territories and work teams. One other function of Visual Management is image creation for stakeholders. It is particularly effective in creating a desirable organizational impression on potential/existing employees, customers and other shareholders. Visual elements are extensively used for internal marketing efforts and change management practices to convey a desired message, to persuade people and to alter the perception for creating ownerships.

Management by facts is based on the use of facts and data based on statistics. Visual management is partially about opening the objective organizational reality to the relevant people through the flow of information. This reality is free from personal bias and/or subjective experience or understanding of individuals. Openness, or willingness to share ideas and information willingly, frankly and accurately, is a condition for obtaining employees trust in management.

The management of information in dynamic and complex environments sometimes goes beyond the efforts and abilities of individuals. Organizations mainly use strategic information to make decisions, to make sense of changes and developments in their external environments and to generate new knowledge through organizational learning. In cascading strategic information from the upper organizational levels to lower levels, some mechanism is necessary for monitoring, processing and presenting the vast amount of information for people to make sense of.

According to Tezel (2010) organizations are constituted of interconnected socio-technical departments, with various layers. One of the managerial issues is to establish synchronization and harmony between these layers. People may illusively think that they work in an isolated manner solely according to the departmental values and conditions to which they belong. In an organization, the vertical boundaries (the boundaries between layers), the horizontal boundaries (the boundaries between functional units), the external boundaries (the boundaries between the organization and the outside world) and the geographic boundaries (the boundaries between different organizational units located in different geographic areas) can partly diminish with information sharing and dialogue creation. Creating a "boundary-less" organization, where people act openly without status or functional loyalty and look for ideas from anywhere or anyone, is a major concern, especially in knowledge management efforts.

4 RESULTS

In this chapter, all results will be presented. The result chapter is divided into five subchapters. First information, development and result of the robot is presented. Second the robotic impact on both operational and project level scheduling is presented. Third the logistics related to the robot is given. Second to last the health and safety result is presented before the last subchapter presents future potentials.

4.1 SCHEDULE IMPACTS

Completing a major construction project on time, cannot be taken for granted. Two time studies are developed to detect potential time savings by implementing the drilling robot to the installation processes. One time study looks at the potential time savings at operational level, and the other study looks at the potential time savings at project level. It is important to separate between the robot´s impact on operational- and project level as they have two different perspectives and detail levels. The operational time study looks at a specific installation while the project time study looks at the overall project planning.

To give the reader a continuous reading experience, a description and a further explanation of the time studies are presented before the results.

4.1.1 DESCRIPTION OF TIME STUDY - OPERATIONAL LEVEL

A time study of the operational installation of fire sprinkles has been conducted. The purpose of the time study was to compare the time usage of the conventional installation with the time usage of installation combined with robot drilled hole in advance.

As previously mentioned three scenarios have been analyzed at the operational level. The first is the scenario of the conventional installation of fire sprinklers. One cycle consists of six activities, see figure 4.1. The first activity is the drawing measurement, the installer measures the printed drawing and scales it up to get the specific roof-distances. Common practice is to use a multi-scale ruler and a paper drawing in a 1:50 scale. The second activity is the roof measurement; the installer uses a folding ruler and a pencil to mark where the different holes should be placed. In both the first and second activity, human error and precision may affect the accuracy of the measurements. The third activity is the physical drilling of the holes. The fourth activity is the installation of the expansion bolt, followed by the fifth activity; installation of the roof attachment installation. The sixth and final activity of the cycle is the pipe installation, which is conducted with hand power and two pipe wrenches. In the time study both the average activity time and the average cycle time is measured.

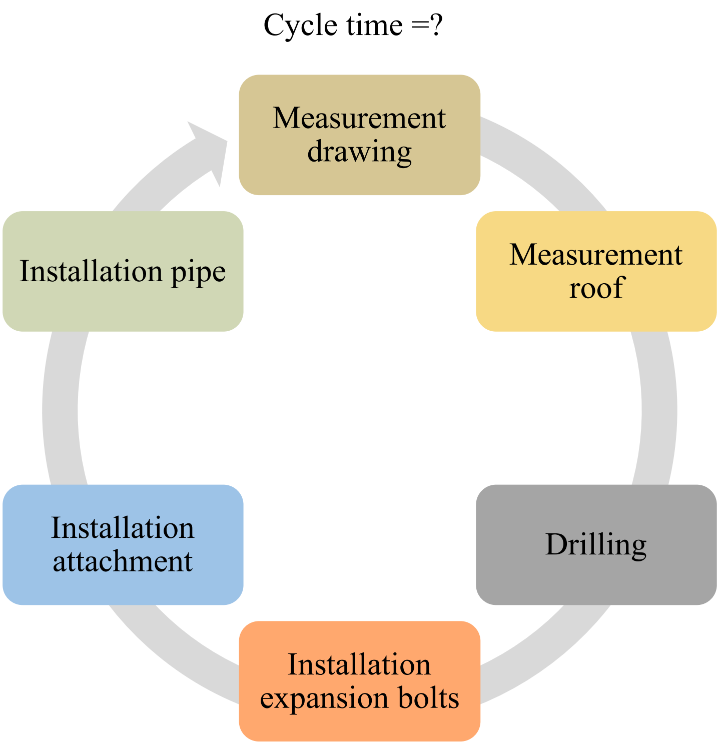


FIGURE 4.1 SCENARIO ONE CYCLE

FIGURE 4.2 SCENARIO ONE PICTURES (OLE ROSENLUND, 2017)

The second scenario is when a hole has been drilled in the robot, but for different reasons the installer cannot use the predrilled hole, and must drill an extra. Since the robot has conducted work, this scenario takes place at subsection two. It is interesting to see if the cycle time can be reduced in this scenario. The installer can potentially save the time he normally would spend on measurements on the paper drawings, and maybe save some time related to the roof measurements. The eventual time saved will probably lead to a lower cycle time of the fire sprinklers.

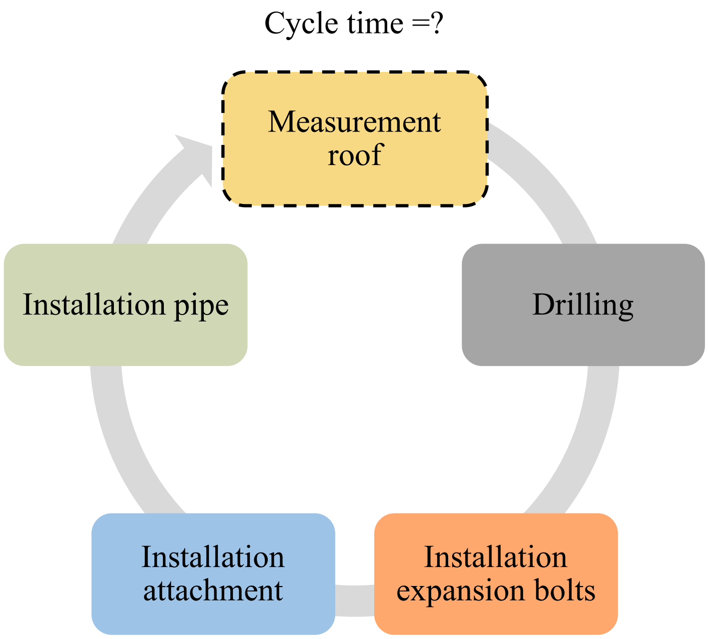


FIGURE 4.3 SCENARIO TWO CYCLE

FIGURE 4.4 SCENARIO TWO (OLE ROSENLUND, 2017)

The third scenario is when the installer uses the predrilled holes as planned. This scenario takes place in subsection two. The installation firm is the same, the pipes have the same dimension and the roof mounts are the same. The remaining activities are the same as well, but with two modifications; the robot from nLink has predrilled the holes and the operator from nLink has color-coded the holes based on the different technical installations. The installer can now locate his/her holes and start installing the expansion bolts straight away.

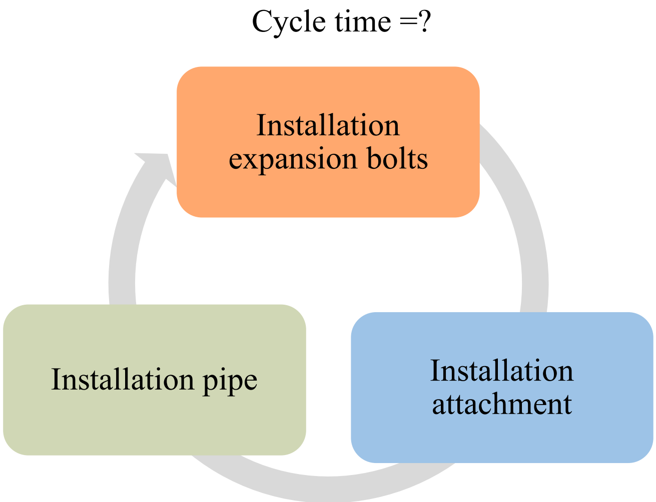


FIGURE 4.5 SCENARIO THREE CYCLE

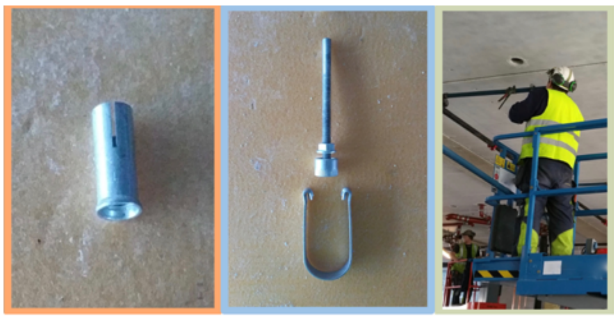


FIGURE 4.6 SCENARIO THREE (OLE ROSENLUND, 2017)

Throughout the time study gross- and net time have been separated. In installation, the gross time includes all extra time that is necessary for the installation process to go as normal. An example is the time the construction worker uses to steer the lift he dismounts from, or the time it takes to gather equipment and different installation parts. In this thesis, the net time is defined as the time the worker does physical work. Physical work is here further defined as the specific time the installer uses on example drilling a hole in the concrete roof. Start and finish time is whenever he or she hits and releases the drill button. Another example is the time the installer uses to measure the different distances and tolerances on the drawings. A synonym to the net installation time is the phrase "Tool-time".

By using cycle time of one specific pipe installation, with only one roof mount, we narrow down the complicated installation process and eliminate a number of error sources. Due to the limited time, logistics and the thesis execution, these restrictions and simplifications are made. The restrictions may result in precise numbers with low deviations, that being said, the time study is precisely executed and all the data of the time study is attached to the thesis for validation. And when the time study regards only net time of single and isolated pipe installation with one roof mount, precise average numbers can reasonably be expected.

4.1.2 Results - Operational Level

A time overview of the first scenario, conventional installation time of the fire sprinklers, is shown in figure 4.7. The results are three folded; the first result is a percentage overview of the different activities done in the cycle. The second is the average total cycle time of one pipe installation. And the third result is the potential time that can be reduced or saved by using a drill robot in advance of the installation.

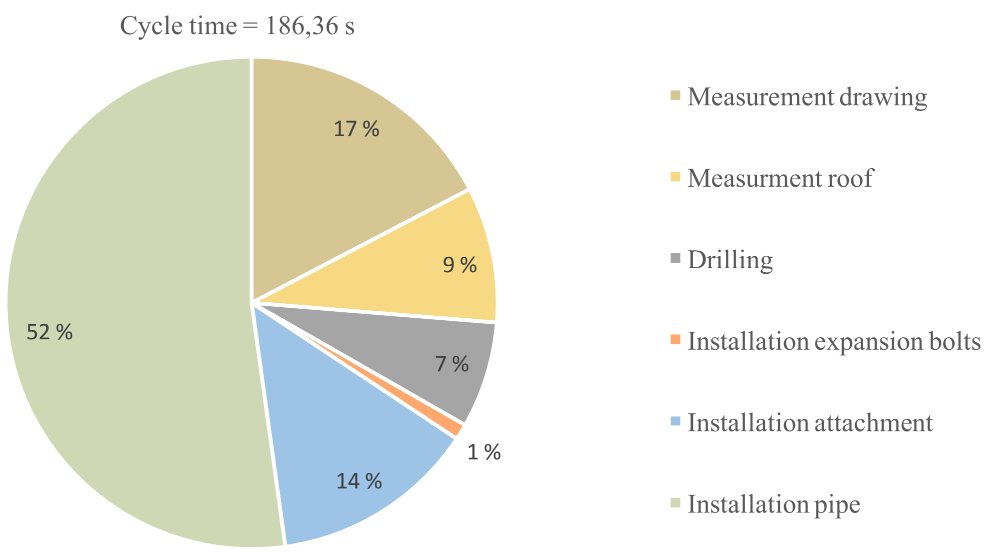


FIGURE 4.7 CONVENTIONAL INSTALLATION OF FIRE SPRINKLES

The pie diagram shows that 17 percent of the net time goes to measurements on the drawing. nine percent goes to roof measurements and markings, and seven percent is the physical drilling. The installation of the expansion bolts covers approximately one percent, while the installation of the attachment and pipe takes 14 and 52 percent.

Figure 4.7 shows that the average cycle time of one conventional pipe installation is calculated to be 186,36 seconds. The potential of time savings by implementing a drill robot is the time usage of the three activities of measurements and drilling, figure 4.8. If we remove the tree slices that aggregate 33,27 percent combined, the new theoretical and potential cycle time is calculated to be 124,36 seconds. It must be mentioned that the robot in this case works at an earlier stage on the construction site, so it doesn't interfere or push the startup time of the pipe installation.

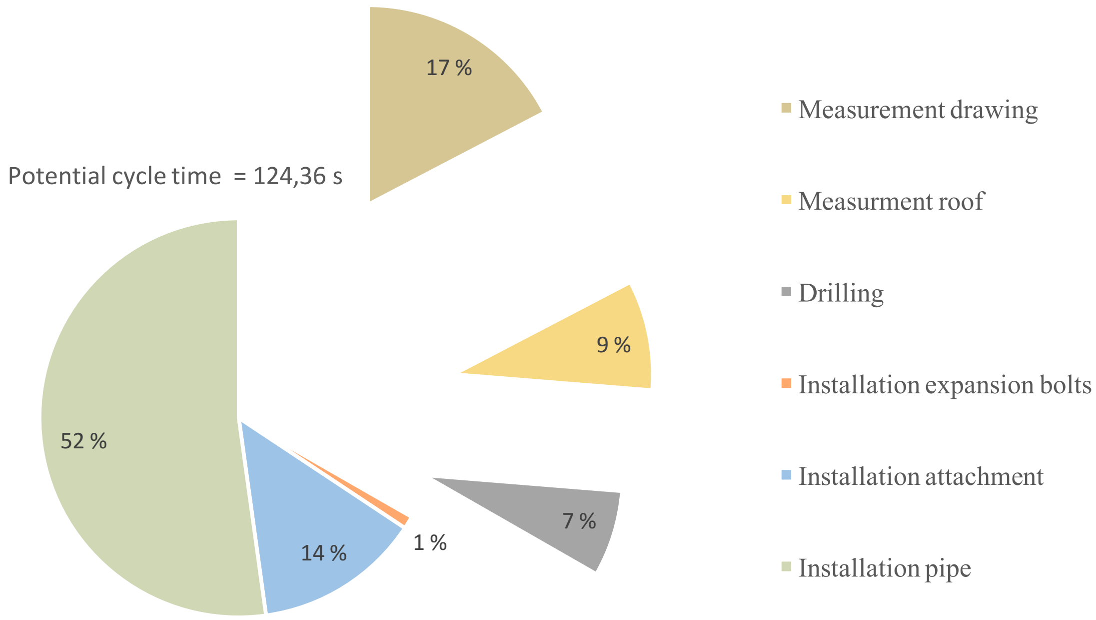


FIGURE 4.8 POTENTIAL CYCLE TIME

As previously mentioned, as a verification and control of the possible theoretical cycle time, the second and third scenario is analyzed at the same construction site, at a separate subsection, with the same conditions and restrictions as the first scenario. The installer can locate his or her holes and start installing the expansion bolts straight away. As figure 4.9 shows, the sprinkler installation has pink holes on the observed construction site.

The observations and time study of the second scenario shows that the installer saves the time he normally uses on measurement on the drawings and reduces the measurements and marking in the roof by 11 percent. The average cycle time of scenario two is calculated to 149,42 seconds. It is important to mention that according to the installers roughly 40 present of all pre-drilled holes were not used.

The consultant designer explains the deviation with the fact that the extra redundant holes was expected due to that the robotic pre-drilling is a new test project. The designer had dialog with the installers about the practical execution and assembly of the fire sprinklers. It turned out that the main pipes are delivered in 6 meters lengths. The conventional installation method is to install a roof mount one meter from the endings, and with a c/c of 2 meters at the middle part. In the drafting of the design the consultant engineer did not have the information about the location of the extensions, it was therefore decided that roof mounts should be drawn with a c/c of one meter. Leading to extra redundant holes in the installation proses. Extra redundant holes that are aligned and not used due to sufficient attachment are not counted in the category “holes not used”.

FIGURE 4.9 EXAMPLE SCENARIO TWO (OLE ROSENLUND, 2017)

As figure 4.12 shows an example of scenario two, we can see that none of the three predrilled holes are used. But as we see in the middle, a new hole is drilled manually right next to the predrilled hole. The reason for this can be that the predrilled hole does not lie on a straight line or the red side inlet is in the physical way. Another reason that was discovered at the construction site is that the installation of the shiny metal roof mounts has a certain maximum and minimum distance from the side inlet. If the BIM designer does not take this into account in the design scenario two, the drilling of an extra hole, will occur. The different technical installers use different standards. On the studied construction site the standard “NS-EN 12845:2004 +A2:2009 Fixed firefighting systems” was used.

Figure 4.10 illustrates the results of the measured average cycle times of the three scenarios. The average cycle time of the third scenario, when the installer uses the predrilled holes as planned, is calculated to 127,70 seconds. A cycle time that verifies and confirms the theoretical potential of a cycle time of 124,36 seconds.

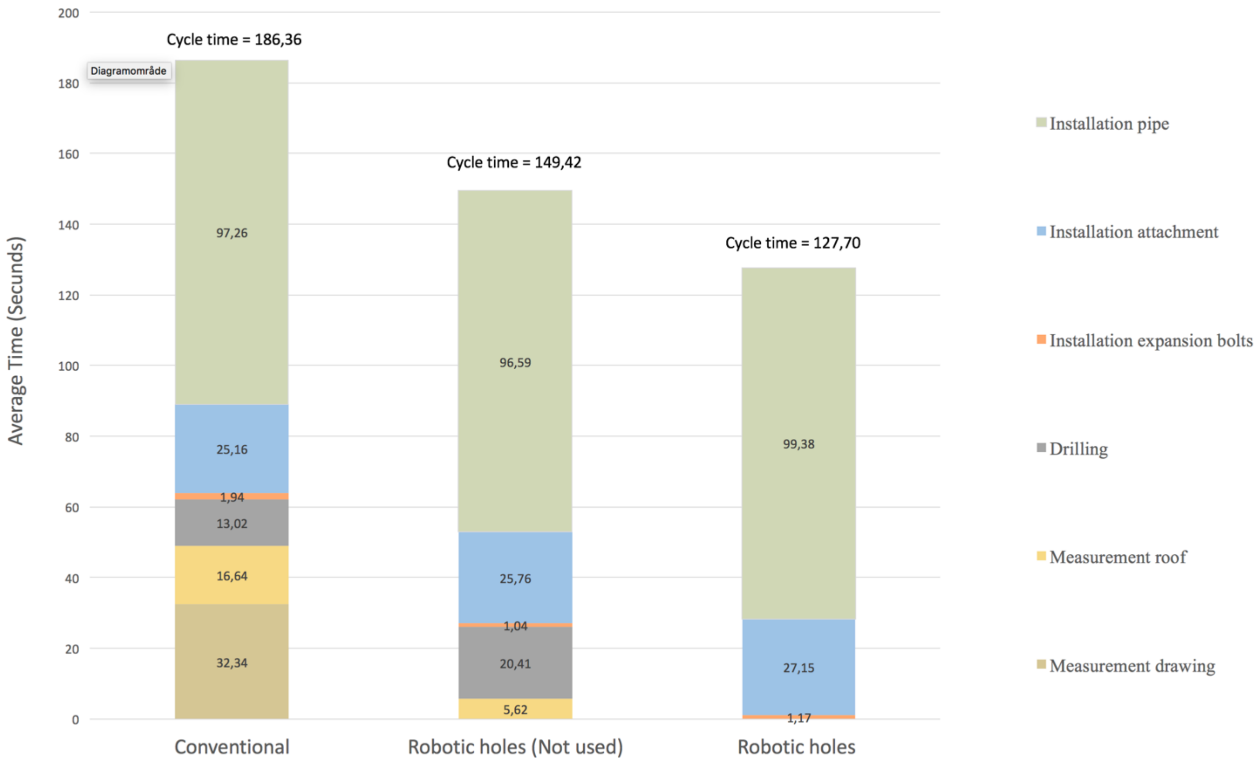


FIGURE 4.10 COMPARISON OF AVERAGE CYCLE TIME

To measure the variation of the time observation, the standard deviation is calculated. Scenario one, two and three is calculated to have respectively 43.19s, 20.49s and 28.23s. All three numbers are considered low related to the input time observations. This confirms that the data points are close and not spared out over a range of values. In other words, the normal distribution of the time observations would have a relatively narrow bell shaped curve.

In the operational time study, the process of installing fire sprinkles has been the focus. The results indicate that the installer can save about 33 percent of his net cycle time of the installation of one water pipe with one roof attachment. To verify and confirm the theoretical timesaving potential, time observations of the actual installation are conducted and analyzed after the robot has predrilled the holes. The average cycle time went from 186,36 seconds to 127,70 seconds, leading to a 31,5 percent time saving. This confirms the potential time reduction of 33 percent. The next step in the thesis was to see how this potential can be exploited at the project scheduling level.

TABLE 4-1 OPERATIONAL TIME STUDY

	Scenario One	Scenario Three
Observed average time	186,36 seconds	127,70
Potential time reduction	33,3 % (Theoretical)	31,5 % (Observed practice)

4.1.3 DESCRIPTION OF TIME STUDY – PROJECT LEVEL

This subchapter looks at different possibilities of planning and reorganizes the project timetable. Only Floor 2 and 3 of subsection two has been analyzed and further discussed. First, the original time table of the main contractor is introduced. Then the robot´s impact on the original plan is presented. Finally, a new method of scheduling is introduced.

Figure 4.11 is a rough copy of project one´s activity based time table. The Gantt diagram is based and shaped on the expected duration of each relevant sub-contractor in floor 2 and 3. The dotted red line represent the theoretical finish, leading to a total duration of 50 weeks. It can be hard to see if the schedule is well planned with the traditional Gantt chart. The size of the bars indicates that work has been, or shall be conducted, but it does not represent the amount of work being done. The chart cannot become complex, they need to be constantly updated and is often difficult to review on one sheet of paper. Location collisions, confusion and the consequences of these, are often discovered when the work has started at the construction site. The result can lead to unstructured work, where some workers may start working in random locations wherever there is room for it. This could again cause days where the construction site is too crowded, and days when the locations are partly empty. In a worst case scenario, the conflicts and discontinuous working could cause waste, delays and additional costs to the project.

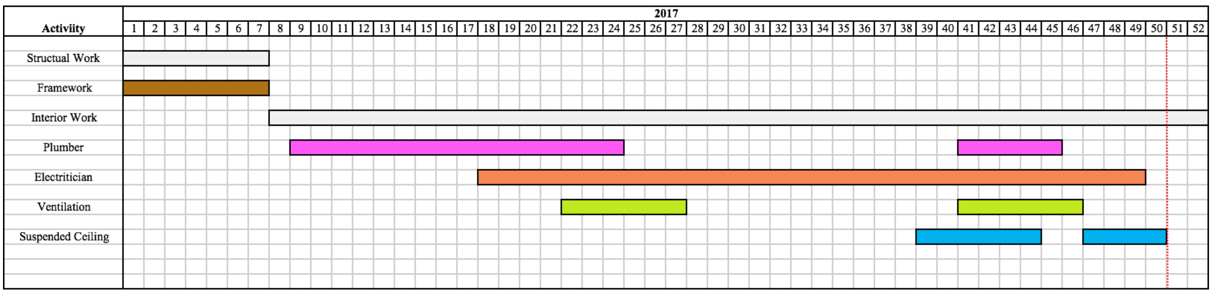


FIGURE 4.11 PROJECT ONE´S ORIGINAL GANTT CHART

As discovered in previous chapters the net cycle time can be reduced up to 30 percent. As an underestimation, we could assume the operational net reduction of 30 percent could lead to a gross activity reduction of 10 percent. Figure 4.12 illustrates the new Gantt chart of the technical roof installations at floor 2 and 3. The activities are reduced by 10 percent, leading to a time saving of approximately half a week. The rigging of the framework is not reduced when it is not impacted by the robot.

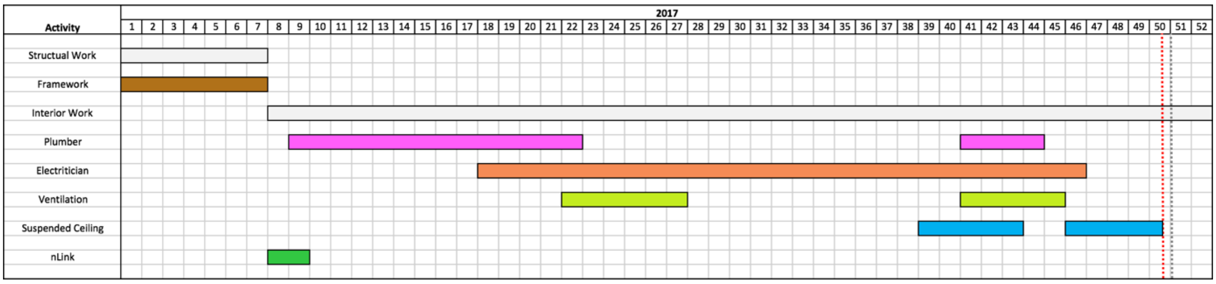


FIGURE 4.12 PROJECT ONE´S GANTT CHARD INCLUDING ROBOT DRILLING AND 10% TIME REDUCTION ON ACTIVITIES

The reduction of half a week is a relatively small reduction. The utilization of the robotic drilling is not optimal with this scheduling method. Mostly due to the fact that the total time reduction is only based on the last activity and not the whole planning picture. In addition to this small time reduction, the buffer between activities has become larger. Later it is pointed out that this extra time buffer is just a way of increasing the waste time, or the time that the locations are partly empty with no one working there.

From the timetable of the project analyzed in this thesis it was not possible to adjust any activities without too many assumptions and speculations. As a result of this the robot was claimed to fall in to the category “nice to have”. This was stated by several sources at the construction site, from both the project administration and installation workers. A typical statement was: “The way the robot operates today, it does not do enough to be worth the money.”

As the theory chapter states the flow line is a way to represent the flow of work through locations. The representation is designed to handle normal constructions projects rather than the repetitive production of completed units such as housing. To do this, the project is broken down into sections of roughly equal size and content. All information of start and stop dates in the transformation figure 4.13, is gathered from the original project time table.

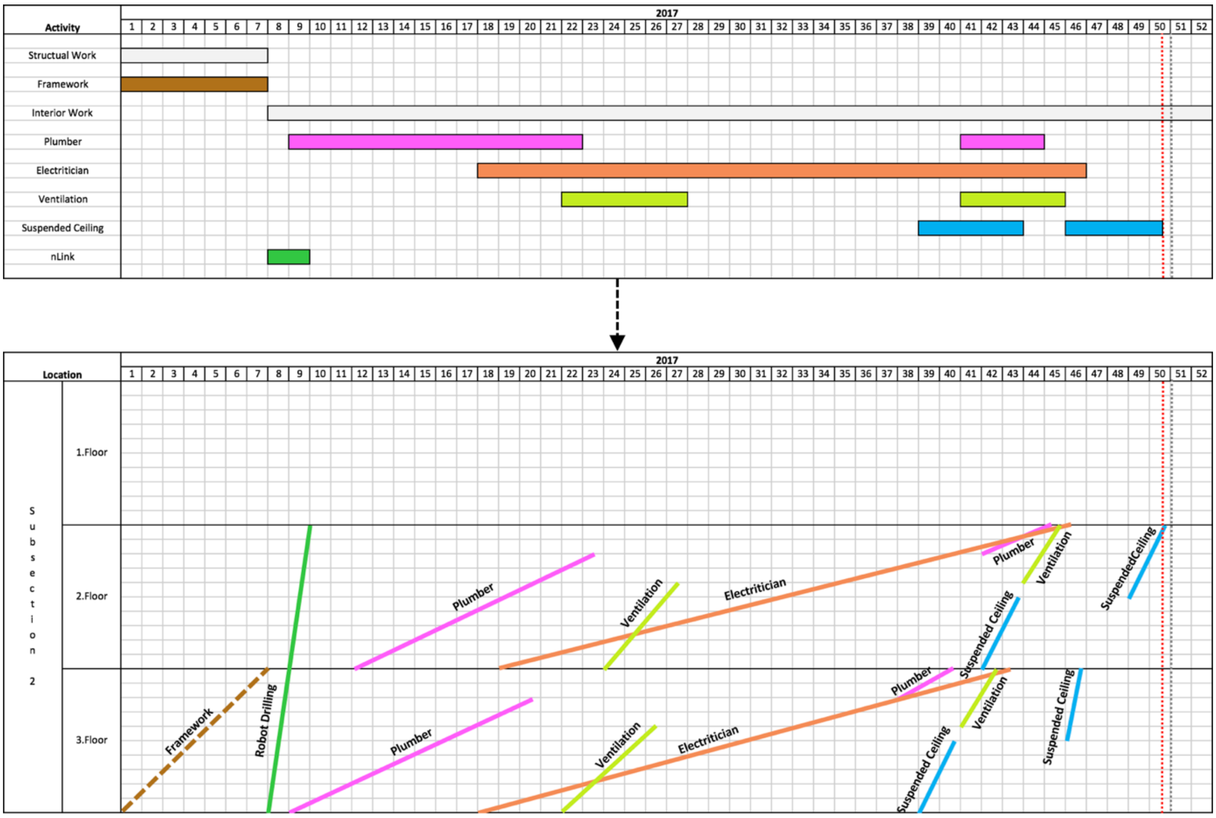


FIGURE 4.13 TRANSFORMATION FROM ACTIVITY BASED GANTT SCHEDULING TO LOCATION BASED FLOWLINE SCHEDULING

With location based planning, here represented with flow line diagram, all activities and locations are clearly displayed at the same time. The lines which cross each other reveal where and when the workers would be in the same location. As an example figure 4.13 shows that both ventilation workers and electricians works at the third floor in week 22 to mid-week 26. One of the main objectives with location based planning is that only one technical installer works at one location at the time. The locations could be divided into smaller areas than floor level, to achieve a more advanced optimization, but in this thesis we analyze at the floor level as to clearly bring forth the main point. It must be mentioned that all methods of planning in this thesis is simplified to underline the main points.

The location schedule can be improved by creating a continuous work flow and balancing the amount of planned recourses. By doing this a uniform and clear overview plan is created. Figure 4.14 shows the first step to achieve the theoretical continuous work flow. The logical relation between the task and location is visualized, and potential ineffective use of project location and resources could be discovered.

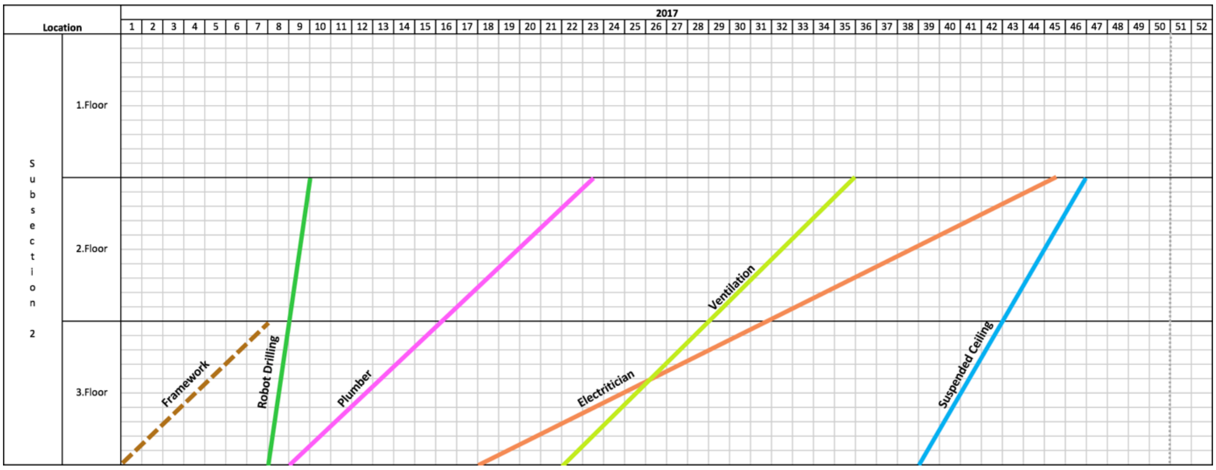
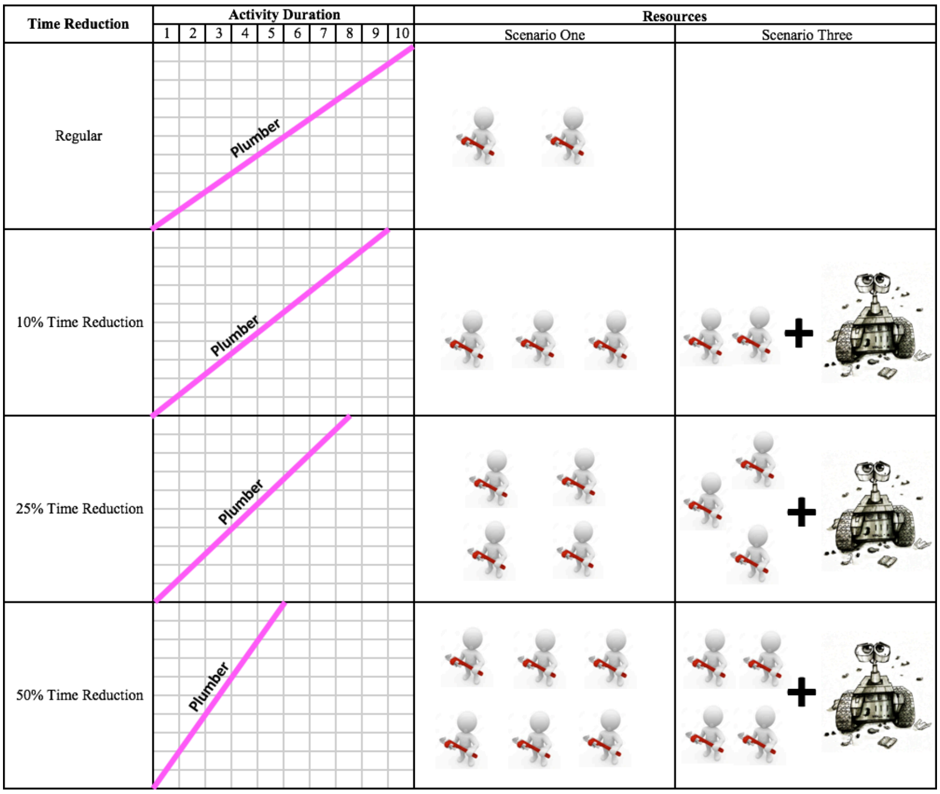


FIGURE 4.14 FLOWLINE DIAGRAM: CONTINUOUS WORKFLOW

By balancing the amount of planned recourses, the different work-speed or duration can be adjusted. A time reduction often demands extra cost, while a time increase is generally seen as an advantageous time buffer. As table 4-2 illustrates the different time reduction demands different resources. The table is developed to illustrate the possible resources needed to reduce the activity duration by 10, 25 and 50 percent. The table is mostly assumptions due to the difficulty of calculating the amount of recourses and the cost that comes with it. The different contractors contain the information to do so, this thesis use assumptions and approximations to make the point easy to understand. As previously mentioned we could assume the implementation of the drilling robot on the operational level, 30 percent reduction, could lead to a gross activity reduction of 10 percent.

TABLE 4-2 FLOWLINE: TIME REDUCTION BY BALANCING RECOURSES



It is important to note that the use of the robot will influence all the technical installations and not only the plumber as shown in table 4-2. As an allegation we could say that the more technical installations use the robot combined with the recourses planning, the more time and money could potentially be saved.

4.1.4 Results – Project Level

By exploiting the tradeoff between time duration and resources multiple plans can be created. To illustrate the potential time saving the robot could achieve combined with the right planning system, three different flow charts is presented in this subchapter.

In example plan 1, figure 4.15, all the activities have been reduced by 10 percent and restructured. Leading to a one week's earlier finish.

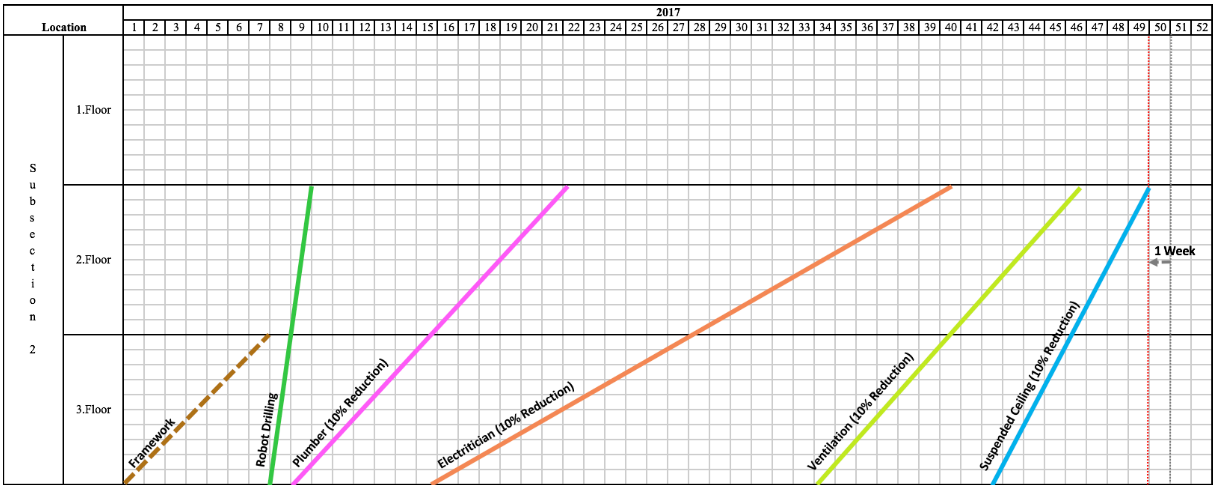


FIGURE 4.15 FLOW LINE DIAGRAM: EXAMPLE PLAN 1 (ALL ACTIVITIES REDUCED BY 10 PERCENT AND RESTRUCTURED)

Note that only one activity at a time operates at one location, defined here as one floor. The ventilation installation cannot start earlier because it would collide with the electrician work in floor two. This is because the electrician has a slower working pace, or gentler working slope compared with the ventilation.

In figure 4.16, the red square marks the potential parallel work of the electrician and ventilation. By allowing this 6 weeks are added to the total time saving, resulting in a seven-week earlier finish.

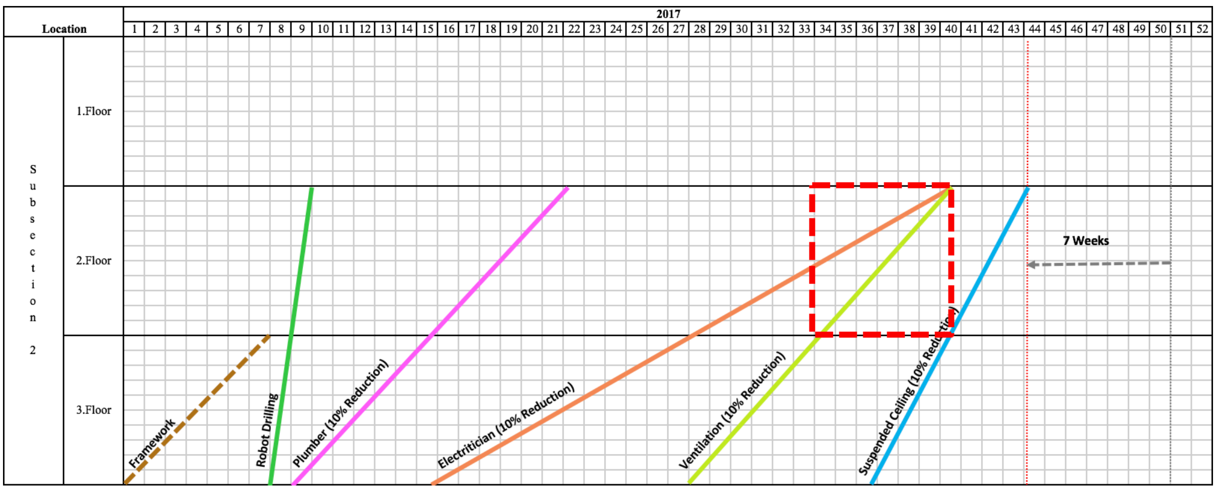


FIGURE 4.16 FLOW LINE DIAGRAM: EXAMPLE PLAN 1 (ALL ACTIVITIES REDUCED BY 10 PERCENT AND RESTRUCTURED WITH TWO PARALLEL ACTIVITIES IN WEEK 39 TO MID-WEEK 40)

In the second plan, figure 4.17, all the activities have been reduced at different levels and changed to 14 week durations, also leading to a seven-week earlier finish.

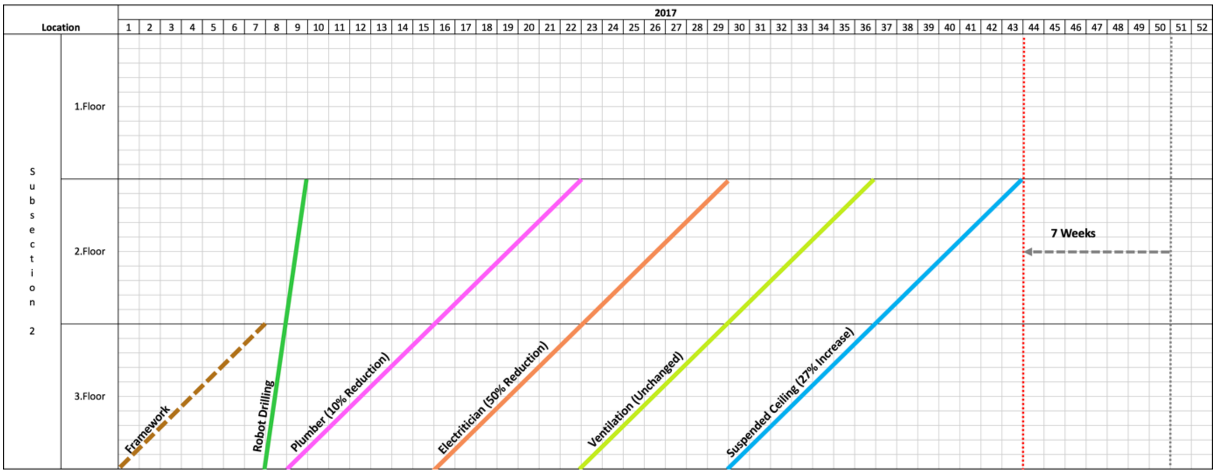


FIGURE 4.17 FLOW LINE DIAGRAM: EXAMPLE PLAN 2 (ALL ACTIVITIES CHANGED TO 14 WEEK DURATIONS AND OPTIMALLY STRUCTURED)

In the third plan, figure 4.18, all activities have been evenly reduced by 25 percent and optimally structured. This could result in a potential eight weeks earlier finish on floor two and three.

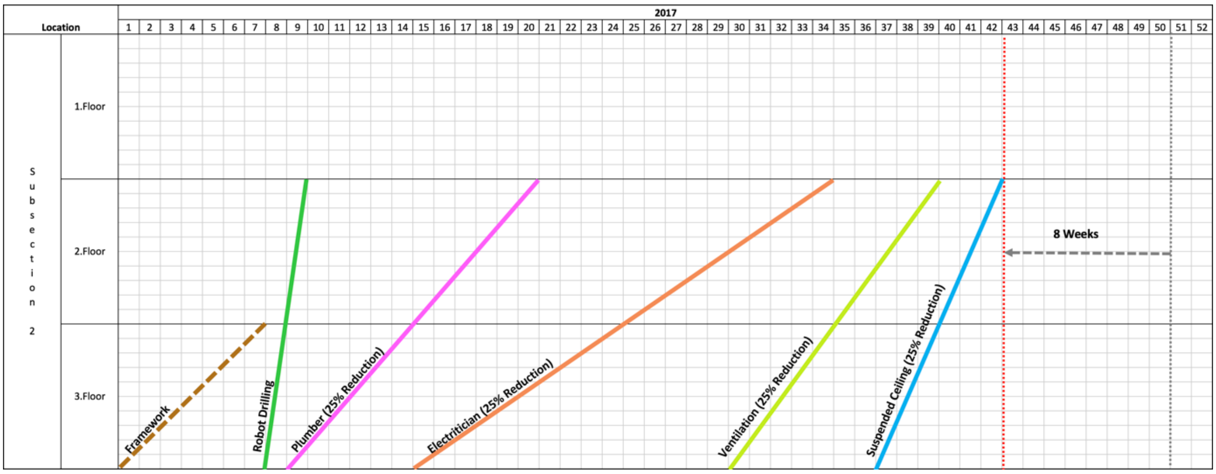


FIGURE 4.18 FLOW LINE DIAGRAM: EXAMPLE PLAN 3 (ALL ACTIVITY REDUCED BY 25 PERCENT AND OPTIMALLY STRUCTURED)

All the example planes are developed by balancing the recourses and restructure the original timetable of the analyzed project. This restructure depends on several factors such as the recourses versus money trade off, logistics and flexibility in the project. Implementing the drilling robot in this form of planning could contribute to reduce the activity duration as illustrated in Table 4-4.

It turned out that using the location based planning system could give a better overview of the project. The purpose of the method is to make sure the different trades aren’t working in the same location at the same time. This is to ensure continuous flow of the planned activities and to exploit the construction work area effectively. Kenly and Seppänen (2010) claims that with location based scheduling you could get a clearer project overview, continuous optimized workflow and faster and more efficient execution.

4.2 Field Study Results

Based on the direct observations, collected data and interviews conducted on the construction site, all the field study result is presented in this subchapter.

4.2.1 Robot Data

Data collected from nLink AS shows that the robot has drilled 2823 holes over an area of 1600 m^2 at the construction site. The execution time was calculated to be ten days, two days to set up preparations and disassembly and eight days to conduct the drilling. The results presented by nLink are listed in table 4-3. As the table shows the actual drilling took nine days, but the table also shows that on day five, zero holes were drilled.

TABLE 4-3 STATED PROGRESSION FROM NLINK AS

Day	Goal	Achieved	Progression
1	303	510	510
2	303	207	717
3	440	400	1117
4	440	371	1488
5	309	0	1488
6	309	453	1941
7	309	270	2211
8	306	306	2517
9	306	306	2823

Time observations conducted at the construction site gives an average overview of the time usage of the robot. As figure 4.19 shows, 65 percent of the time the robot is operating, drilling is conducted. Nine percent of the time goes to the robotic movement inside the drilling area, ten percent goes to move the robotic arm to the right locations and sixteen percent of the time goes to calibrate the robot with the total station.

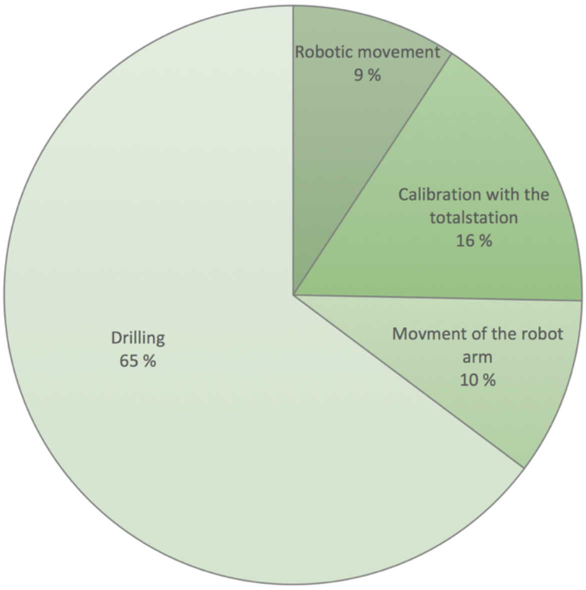


FIGURE 4.19 AVERAGE TIME SPENT BASED ON OBSERVATIONS

A SWOT analysis was conducted of the robots effects on the construction site. The participations of the group analysis where four competent technical installers. The result, illustrated in table 4-4. The SWOT-matrix reflects the feedback form the installers, and what they highlighted to be the positive and negative consequences of the robot implementation.

TABLE 4-4 SWOT-MATRIX

	Favorable	Unfavorable
Internal	**Strengths** • Potential time and money gain • Detailed design • Improved safety and health • Good visual effects	**Weaknesses** • Gives less room for adjustments in the installation phase • Difficult to use pre-drilled holes in tight areas with many holes • Detailed design sometimes impossible to install due to the fixed center to center ratio
External	**Opportunities** • Use of BIM stations • Extra quality control of design in BIM • Good future potential	**Threats** • Extra cost • Dependent on lift • Bigger consequences of wrong design • Could potentially take the job from the installers

4.2.2 Robotic Logistics

The logistics tied to the robot could be divided into six main points; The set-up and rigging of the robot, the storage logistics, the power supply, weather conditions, visual management and the operator.

4.2.2.1 The set-up and rigging of the robot

From the nLink storage the robot is transferred by car to the different project's locations, the car is equipped with a ramp and the robot can easily be driven to the location of potential drilling. If the robot is going to operate higher than floor 1, an elevator or lift is being used to transfer the robot. The robot weighs 850 kg, so the eventual elevator must endure this weight. If a lift is being used, the robot is strapped to a pallet and lifted to the relevant floor.

Both interview and time observation confirms that the set-up time from the robot is at the physical place to it is ready to drill the first hole is between 30 and 45 minutes. The set-up time include activities as:

- Set up a total station
- Calibrate the total station with the fixed zero-point on the construction site
- Adjust the light opening on the total station to the natural daylight
- Drain and replace the vacuum dust-bag
- Function test of robot
- Boot the computers

FIGURE 4.20 FUNCTION TEST OF ROBOT (OLE ROSENLUND, 2017)

4.2.2.2 STORAGE LOGISTICS

On the observed project, no problems or major challenges linked to storage logistics were discovered. The robot demands no storage of any kind in the area the robot is going to operate. This was avoided when activity of predrilling of the holes was planned directly after the framework.

In several interviews it was stated that it quickly becomes problematic for the robot to complete the drilling if there is a lot of temporary and permanent storage at the relevant location. The robot arm is flexible and the robot can maneuver and adapt to a situation like a big hole in the floor. But unnecessary obstacles will increase the time duration, and complicate the drilling pattern.

FIGURE 4.21 ROBOT IN ACTION, ONE UNNECESSARY OBSTACLE TO THE LEFT (OLE ROSENLUND, 2017)

4.2.2.3 Power Supply

The robot is currently dependent on electricity by power cords. A problem at construction sites is that unsystematically, power failures occurs. These failures cause an automatically shut down of the robot and its computers. This was solved by giving the robot an own electrical circuit. But it turned out that other workers were not informed to use a separate circuit, so different electrical machines were plugged in and led to some power failures anyway.

FIGURE 4.22 ELECTRICAL CHISELING WORK CAUSING POWER FAILURE (OLE ROSENLUND, 2017)

4.2.2.4 Weather Conditions

Field observations on the construction site revealed that much rain and snow over prolonged periods may result in drainage through the various floors. If water settles in the concrete elements, the robot drill may hit the water pocket which causes the water, mixed with concrete, to be sucked up by the vacuum cleaner. This would lead to often and repetitive replacement of the dust-bag. Another issue is when the water is constantly dripping from the ceiling and down on the expansive robotic. Long exposure may damage the hardware on the robot. This can be solved by using a waterproof shield.

When the robot is not operating, the temperature could cool down the computers, causing a longer start-up time. To avoid this issue, nLink uses a tent with electrical heating, see figure 4.20.

4.2.2.5 Visual Management At Assembly

nLink operates with a color code system that helps the installers to separate and see which holes that are pre-drilled to each technical installer. In the kick-off meeting with the main contractor and nLink, the different colors were explained and divided between the different technical installers. As we can see from figure 4.23, the fire sprinkle installation has pink holes. If a hole is drilled at the wrong location, the hole is marked with grey or black color to avoid misunderstandings.

FIGURE 4.23 VISUAL MANAGEMENT (OLE ROSENLUND, 2017)

4.2.2.6 The operator

Today the robot is operated by one field engineer. The operator is responsible and performs the set up and the rigging of the robot. During the drilling, the operator controls that the process goes smoothly, calibrates the robot with the total stations if necessary and informs/confirms the next location the robot should drill at. As per today the operator also marks the holes with different colors, figure 4.24.

FIGURE 4.24 FIELD ENGINEER (OLE ROSENLUND, 2017)

4.2.3 Health and safety

The interviews conducted gave the best and concise information linked to the result regarding health and safety. Several sources had statements and good information connected to the implementation of the drilling robot.

Information from nLink As states that the robot is developed on a request from a contractor in Norway, Vintervoll AS, to improve over-head installation and reduce shoulder damages. The robot has been design and developed closely together with contractors to ensure that the robotic solution actually solves their problems and needs. The robot aims to reduce time consumption and relieve the construction workers from heavy, repetitive and hazardous work. In interviews with both nLink and the workers it is mentioned that the robot should work with, and not instead of, the installers.

4.2.3.1 REDUCTION OF HEAVY WORKLOADS ABOVE SHOULDER HEIGHT

In many risk management situations, time, money and recourses is used to reduce the probability and consequences. An example from one interview is illustrated in figure 4.25. Activity one, here manually drilling above shoulder height, is at the starting point at a high risk marked with a dotted rectangular. With different measures, and a trade between cost and risk, the risk could be lowered to a satisfactory level.

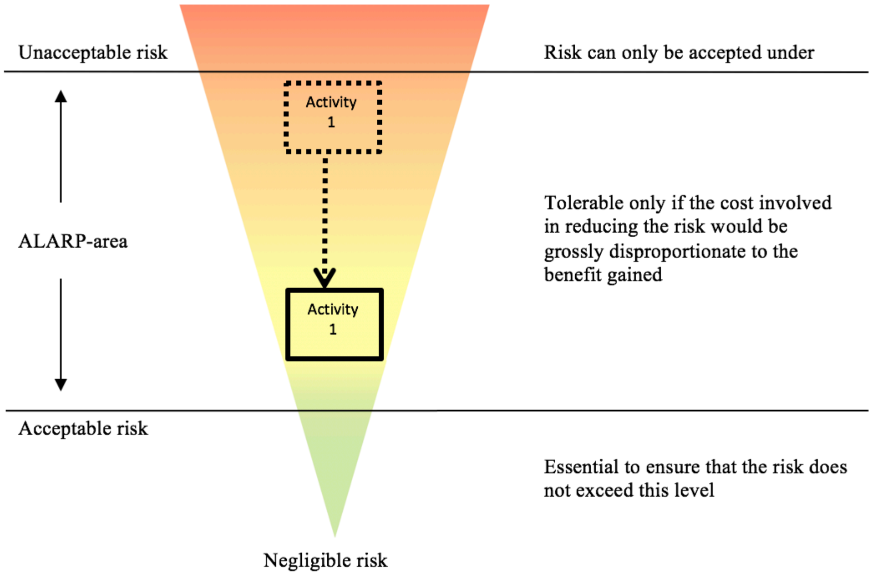


FIGURE 4.25 TYPICAL RISK HANDLING

By using the robot, activity one is not only reduced to a satisfactory level, it is eliminated as a negligible risk. The activity in not performed anymore, and is no longer a concern of the risk management. See figure 4.26. Now another tradeoff is introduced; the money worth spending on implementing the robot versus the benefits gained of implementing the robot.

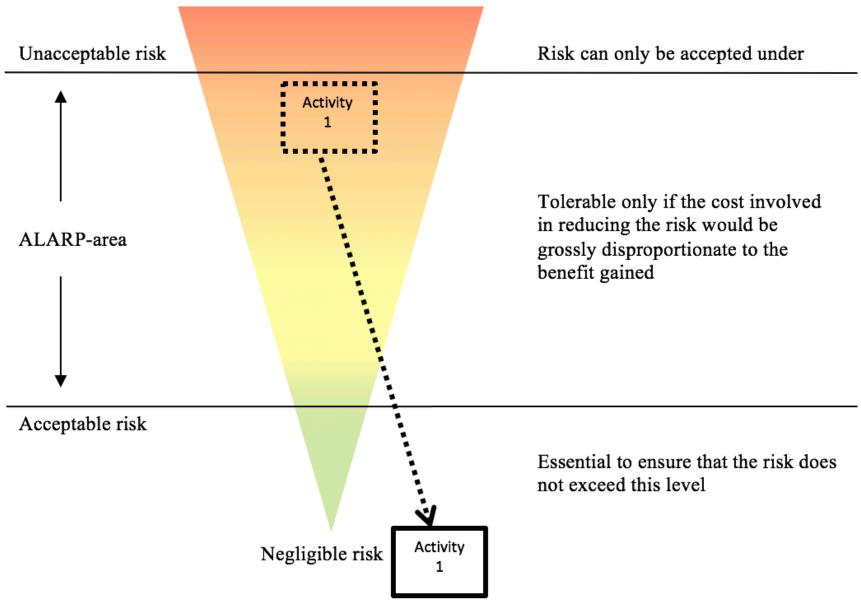


FIGURE 4.26 NEGLIGIBLE RISK

One of the main arguments discovered in the interviews is that the use of robotics can lead to a competence change. The feedback from the analyzed construction site, was that the predrilling simplifies the installation work and relief the workers of major parts of the shoulder strain. The robot can execute the repetitive heavy work, while the operator could contribute with knowledge and logistics skills instead of raw power. This combination could result in longer, safer work hours for the installers.

4.2.3.2 Dust

One interview respondent claims that using nLinks drilling robot gives benefits within noise, dust and clean workplaces. He stated that for optimal use of the robot, the workplace must be clean and easy to get a good overview of. By "demanding" this the robot contributes to the mindset and implementation of a "pure and dry building mentality" (Reint tørt bygg). One purpose of using this mentality is to achieve a good indoor climate in the finished buildings. By preventing the spreading of dust and fiber particles the robot contributes positively to this mentality. Another interview respondent stated that traditionally the installation, including the manual drilling of the suspended ceiling is conducted at a late stage of the building process. This leads to spreading of dust in a location that is almost finished, resulting in a cleaning process before the air quality reaches a satisfactory level. By drilling all the holes in advance, this scenario is avoided when the robot drills and collects all the dust at an earlier stage. nLink AS states that the robot collects about ten kilos of dust per thousand drilled holes. From one interview, it was also stated that it will nevertheless give a positive effect by having a neat and clean workplace, regardless of robotic use.

As the location based planning system shows, the main contractor of the studied construction site, works with a top-down procedure. When the framework is finished, the workers start at the top of the building and work their way down. This is done to avoid unnecessary dust, damages and dirt when the workers and materials are passing by the finished location.

4.2.3.3 Noise

According to nLink the robot reaches an 80 dB while drilling. Dalehaug (2014) states that a normal conversation is commonly around 70 dB, a car on a highway 90 dB and a shouting voice on 100 dB. As a comparison Dalehaug claims that machines on a construction site approximately reach 120 dB. In areas the robot is operating in, hearing protection is a requirement.

Several respondents mentioned the potential use of the robot by night. It was argued that noise, safety and neighbor-demands are the main boundaries for working at night. It was further stated that if these boundaries are satisfied the autonomously work throughout the night has a huge potential. If one robot were to encounter a problem, the robot could stop and wait for the operator the following morning. In addition to improving the productivity, discussed in time studies, the robot will appear less in the way, and be less of a concern for the workers at night. One respondent pointed out that if the robot is working in an area with a lot of offices around the construction site, the noise demands and adjustments would probably be easier to handle as it is commonly known that there is not a lot of people in the office by night.

nLinks confirms that the work with the robot is most productive past 6 am. One explanation and reason for this is that the robot is relatively new in the construction industry, and a lot of people are interested and it requires time to explain and show these people how the robot is operating.

4.2.3.4 Avoid New Hazardous events and Injuries

It is important to avoid new hazardous events and injuries when the robot is implemented at the construction site. As an example there will always be risk attached to crush injuries. It was stated in an interview that with relatively simple technology like audio and motion sensors, hazardous situations can be avoided. As it is today, the robot has installed a working light at the rear to alert the workers that work is in the area around the robot. It is also a safety that a competent field engineer follows and control the robot. The robot is also equipped with an emergency stop at the lover right corner.

FIGURE 4.27 EMERGENCY STOP AND WARNING LIGHT (OLE ROSENLUND, 2017)

4.2.4 Extra BIM-Design

A BIM model is easily explained as a digital representation of a physical and functional building drawn in a 3D program. The model is used to plan, design, construct, operate and maintain physical infrastructures such as water pipes, electricity, and ventilation. To use the robot, the design team that provides the technical specifications in BIM must deliver models on a higher detail level compared to the conventional method and use of BIM. This leads to extra cost, some advantages and some disadvantages.

4.2.4.1 Cost of extra design

From one interview it was stated that, the project designer is paid both to teach how to achieve the detailed level, and to actually design the BIM model at this level. In the interview, it was also stated that in the studied project the owner pays for both the extra design and nLinks contract. The contracts are confidential, but the extra design of approximately $1600m^2$ was stated to be 100 additional hours of teaching and designing. With an hourly rate of 1000 NOK, the extra design cost roughly 100.000 NOK.

One source claims that one reason for the interest of the robot is the main contractor local building price; “The building of the year 2018”. One criteria to achieve this praise, is to facilitate and implement new thinking and innovation. And without further explanation the firm aims for this stamp by including the robot drilling and other measures.

The construction manager states that one of the most difficult tasks is to convince the sub-contractors that using the robot drilling leads to time and money saved for the different sub-contractors. He further explains that this pursuance will demand a lot of time and convincing evidence. This is due to the lack of knowledge and experience of using the robot in the construction industry. On the bright side, he could also inform that one sub-contractor, the suspended ceiling contractor, was willing to cut the square meter cost by 5 NOK/m^2 in the areas where there has been robotic drilling. On the analyzed construction site the area of robot drilling ($1600m^2$) is relatively small, but the reduction in price is definitely a step in the right direction and a proof that the robotic drilling clearly could be utilized. It was stated that the sub-contractor would probably not reduce the price if they were not convinced that the working conditions and time of installation is improved by using the robot.

4.2.4.2 Advantages and disadvantages of extra design

Several interviews states that the biggest advantage of the extra design is that the method automatically leads to an extra collision test in BIM. Major and minor problems could be discovered at an earlier stage than normal. The design also demands additional information, for example the center to center (c/c) measurements.

Another mentioned advantage is that the project develops a detailed BIM model. If the workers and project managers uses this model actively, with for example BIM stations this would be an advantage. Observations from the construction site shows that this possibility has not been done or utilized optimally.

The consultant designer engineer stated that the use of the robot in the analyzed project is a test for both the designers and installers. It was mentioned that it would have been beneficial if the decision of using the robot at the two floors had been made on an earlier date. In the analyzed project this decision was made after the main work with the design had been conducted. The consultant claimed that they could adapt and adjusted the pre-drilling and the effects in to the design. It was argued that it would be an advantage to become more aware of the places the robot is used. Areas with straight lines and open spaces should be prioritized above complex areas with a lot of technical installations. The designer stated that this would also lead to a higher utility and probably lead to a more beneficial economic situation.

From the interviews it was mentioned that the biggest disadvantage by spending the extra time and effort in the design phase is that the consultant designer is expensive. As previously mentioned the extra design of 1600 m^2 is estimated to be approximately 100.000 NOK. Several interviewees also mentioned that any wrong design would have a higher consequence. By increasing the detail level, the risk and margins at installations drops. Discussions, problems and demands could occur at the construction site leading to cost, time and money waste. In other words, more responsibility regarding installation is handed to the designers in return for more money.

FIGURE 4.28 EXAMPLE OF WRONG DESIGN, THE VENTILATION PIPES DOES NOT SLIP INTO EACH OTHER (OLE ROSENLUND, 2017)

The consultant designer mentioned that use of pre-drilled holes does restrict the adjustment room. The designer stated that when the robot is used, the design does "locks itself a bit".

One installer from the construction site experience that the designer designed a solution that is not permitted to install, as figure 4.29 shows, a "double t-cross" is drawn in the design, but due to a restriction in the Norwegian standard, this is not permitted to install. A fire sprinkle is not allowed to have a cross section with four outgoing pipes. The drawn cross section part is also not a regular installation piece of a fire sprinkler stock.

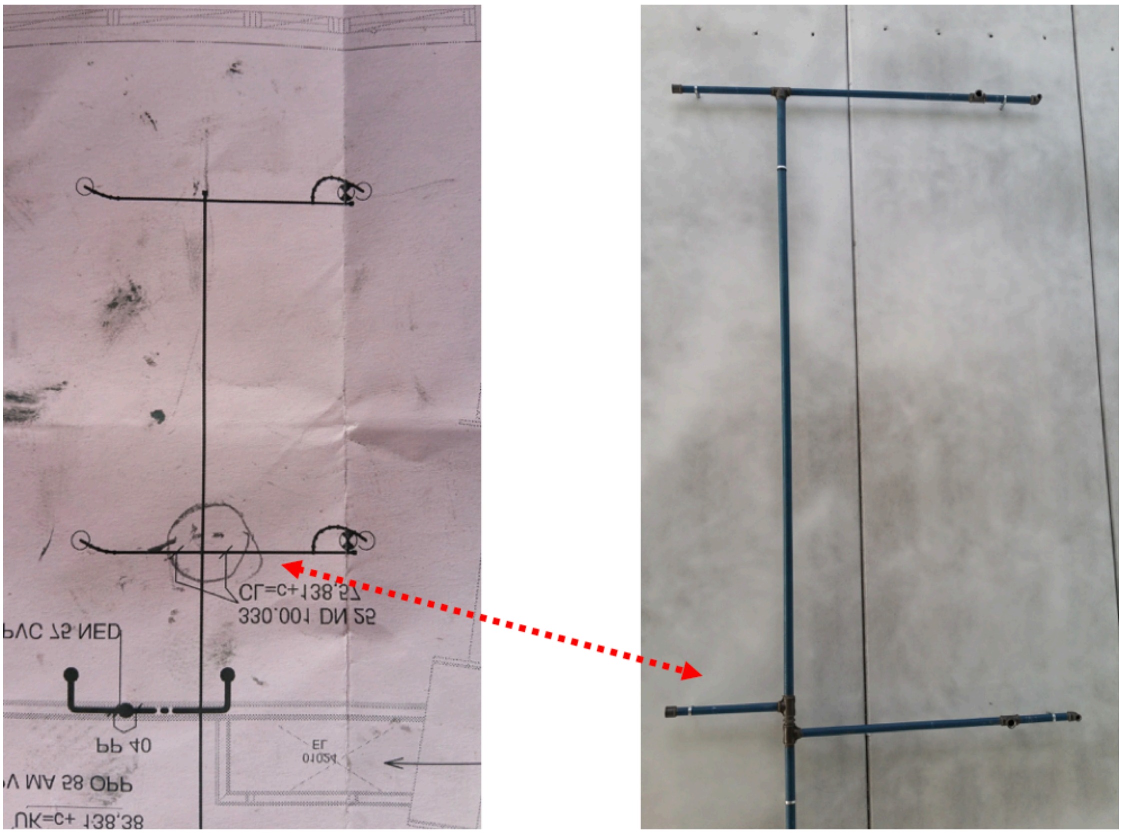


FIGURE 4.29 EXAMPLE OF WRONG DESIGN, CROSS SECTION WITH FOUR PIPES (OLE ROSENLUND, 2017)

In the interviews with the installers it was also mentioned that the robot causes limited room for adjustments and modifications in confined areas with many technical installations. In the tight areas with a lot of technical installations the pre-drilled holes would have to be extremely accurate and rely on lots of information and planning. As an example the technical rooms was mentioned.

4.2.4.3 Future Design And Algorithms

By integrating BIM directly with robotics, nLink accelerates and improves the use of BIM. In an interview with one of nLinks founders, it was stated that the "thing" that communicates best with a computer and BIM is another computer, or robot. In the future, if the modeling is done right, it may not need any more input, configuration or feedback from human beings and can go straight from modeling to actual building. This is one thought in a long-term perspective. In a short-term perspective, today's technology, computers and algorithms is constantly improving. Programs and computer power could contribute to make the design easier. As an example when the project designer draws a simple line, let's say a fire sprinkler system, the center to center measurements, maximum and minimum distance between joints and roof mounts could be directly implemented in the BIM model.

The consultant designer was positive to the idea, and stated that a new software could improve the design work. The design connected to the pre-drilling was in this project conducted manually. As an example of the potential computer development the designer informed that for each roof attachment he plotted, he had to wait approximately 3 seconds for the computer to respond and implement the attachment in the design. In this relatively small project about 2800 holes were drawn in the model, leading to an approximately extra time of 140 minutes or 2.3 hours just to wait for the computer to respond.

4.2.5 Future potential

From several interviews, with both the management and working staff, it was mentioned that the drilling robot as it is today does not do enough to be worth the price and potential time savings. A typical statement was: "The way the robot operates today, it does not do enough to be worth the money". The potential improvements that are listed in this chapter is based on interviews with the working staff, the construction management and nLink AS. The potential descriptions are brief, and they are designed to give the reader a picture of the potential development and potential.

4.2.5.1 Mark and Highlight Inner wall production

The robot can potentially improve the productivity and optimize the production system of installation of inner walls. A test is conducted at the studied construction site, see figure 4.30. The orange color holes mark where the inner wall corner is placed in the BIM model. This thesis is delivered before the inner wall installation, so there is no information or data to back up a result.

FIGURE 4.30 TEST OF INNER WALL PLACEMENT (OLE ROSENLUND, 2017)

4.2.5.2 Core drilling

From both the installers and project management it was stated that including core drilling as a part of the robots functions would increase the usage of the robot. A core drill is a drill designed to remove a cylinder of material. The material inside the drill is referred to as the core. A number of different core drills exist; concrete, metal and clay are three examples of core drills. At a construction site drilling, concrete is most relevant. In addition to relieving the workers of the heavy work, a robotic core drill would be precise and based on a total-station.

4.2.5.3 Autonomous

Today the robot is semi-autonomous and depends on one operator to fully function and deliver the predrilled holes according to the BIM model. A future potential is fore the robot to become autonomous. This implies that the robot could move around and synchronize with both the total station and workers on the construction site. The responsibility of safety and quality control is transferred from the operator to the robot. The robot could also mark the different colors in the ceiling and locate if any holes have the wrong placement, dimension or depth. It will most likely take time to develop a fully autonomous robot, but the potential exists.

4.2.5.4 3D SCANNER

Implement and use a 3D scanner to control and create an “as built” documentation already exists at some construction sites. This technology could be combined and compared to the “as design” documents of a BIM model. It would be interesting to see how well the two models match. The 3D scanning would also be a good tool for developing the BIM models, and step by step improving the models to be more similar to “as built”-scanning.

4.2.5.5 STAIRS MOBILITY

If the robot is going to operate higher than floor 1, an elevator or lift is being used to transfer the robot. The robot weighs 850 kg, so the eventual elevator must endure this weight. If a lift is being used, the robot is strapped to a pallet and lifted to the relevant floor.

If the robot works at a construction site, without an elevator, it is dependent on the lift. As it turned out at the studied construction site, the lift is busy with many work tasks so the lift must be planned. At the construction site, it was experienced that the lift had a malfunction, leading to a one day delay. If the robot had been independent from both elevator and lift this could be avoided. It is probably difficult and unlikely that the robot could handle stairs in the future, as an example it was stated that it could be possible by using a winch.

5 Discussion

In this part of the thesis, comments and different interpretations of the results will be given and discussed. As an introduction to the discussion, the result matrix of the SWOT analysis is presented. The discussion is further divided and structured around the three important components in project management; cost, time and quality.

The SWOT analysis is used in this thesis for acquiring information directly from the four competent technical installers. Samset (2010) claims that the quality of a SWOT analysis result depends on the insight and understanding of the participants. If the key interest groups are not represented, the result is likely to have limited value and validity. In this thesis the result was based on a consensus-based dialogue between the four informed and competent technical installers. This led to a result with high validity that gave a good first impression of the robot's effects on the construction site.

TABLE 5-1 SWOT MATRIX

	Favorable	Unfavorable
Internal	**Strengths** • Potential time and money gain • Detailed design • Improved safety and health • Good visual effects	**Weaknesses** • Gives less room for adjustments in the installation phase • Difficult to use pre-drilled holes in tight areas with many holes • Detailed design sometimes impossible to install due to the fixed center to center ratio
External	**Opportunities** • Use of BIM stations • Extra quality control of design in BIM • Good future potential	**Threats** • Extra cost • Dependent on lift • Bigger consequences of wrong design • Could potentially take the job from the installers

The analysis is subjective and relies on the groups experience and judgement. There is therefore a possibility that not all factors have been mentioned. In addition, there is no weighting of the different factors, so it is difficult to compare the pros and cons directly in the matrix. That being said, the analysis gives a good first impression of the consequences robot drilling leads to. The content of the analysis is further discussed below.

Cost

From the interviews it has been pointed out that the robot is currently too expensive compared to the benefits it leads to. The construction manager states that one of the most difficult tasks is to convince the sub-contractors that using the robot drilling leads to time and money saved for the different sub-contractors. He further explains that this pursuance will demand a lot of time and convincing evidence. This is due to the lack of knowledge and experience of using the robot in the construction industry. On the bright side, he could also inform that one sub-contractor, the suspended ceiling contractor, was willing to cut the square meter cost by 5 NOK/m^2 in the areas where there has been robotic drilling. On the analyzed construction site, with an area of 1600m^2, the total reduction is relatively small, but the reduction in price is definitely a step in the right direction and a proof that the robotic drilling clearly could be utilized.

A major part of the total cost of implementing the robot is the extra design the robot demands. In the interviews, it was stated that in this project the owner pays for both the extra design and nLinks contract. The contracts are confidential, but the extra design of approximately 1600m^2 was stated to be 100 additional hours of teaching and designing. With an hourly rate of 1000 NOK, the extra design cost roughly 100.000 NOK. In the future when for example the extra BIM-design has become cheaper due to algorithm development, the price of the extra design is most likely reduced. But as the price is relatively high today, it becomes natural to discuss if the extra design and information, is worth the extra cost. Jessen (2005) states that it is reasonable to assume that the utility of additional data declines as the cost of acquiring it increases. Hence, the amount of information must be limited to a reasonable level.

The result states that the biggest advantage of the extra design is that the method automatically leads to an extra collision test in BIM. Major and minor problems could be discovered at an earlier stage than usual. The design also demands, and thus provides, additional information. As an example, the placement and center to center ratio of the fire sprinklers could contribute to the discovery of major and minor problems at an earlier stage than usual. This could lead to a lower operational uncertainty which in turn would lead to a lower total uncertainty.

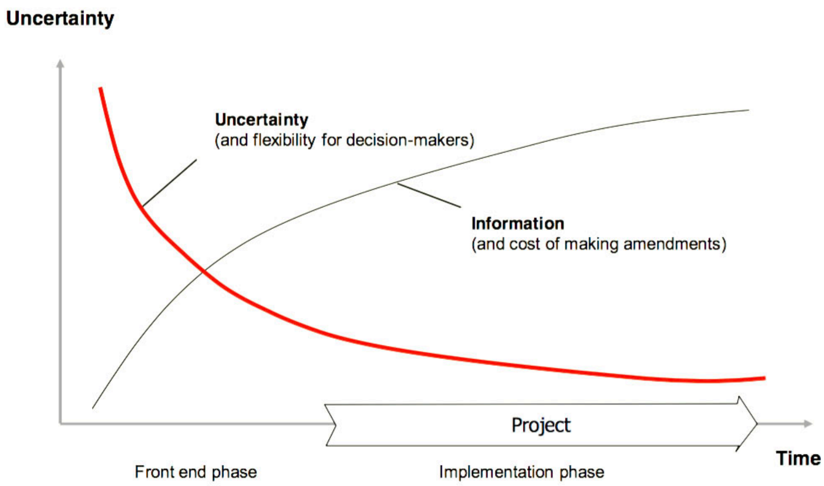


FIGURE 5.1 INFLUENCE POSSIBILITY (SAMSET, 2015)

From the viewpoint of cost versus benefits, the cost of an initial concept development is often small while the potential reward is large. After the process or project starts, the situation is often the opposite. The reward attained does not always reflect the cost of steering the process. As figure 5.2 illustrates, the decision of including the robot and additional information to the analyzed project was made after the main work with the design had been conducted. According to Samset (2010), if this information had been developed on an earlier project stage, this could have lead to a lower level of uncertainty. This is based on the fact that in the start-up phase, the benefits of collecting information are great compared to the cost of acquisition. With time, the costs of collecting additional information increase while the benefits decrease.

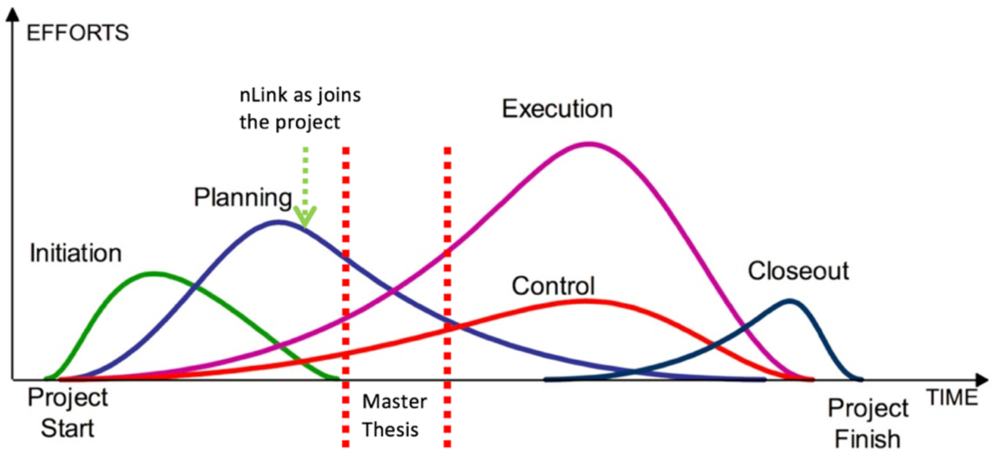


FIGURE 5.2 PROJECT OVERVIEW

The consultant designer engineer stated in an interview that it would have been beneficial if the decision of using the robot at the two analyzed floors had been made on an earlier date. He explained that they could have adapted and adjusted the pre-drilling and the effects in to the design. It was argued that it would be an advantage to become familiar with the places the robot is used. Areas with straight lines and open spaces should be prioritized above complex areas with a lot of technical installations. This would also probably lead to a higher utility and a more beneficial economic situation. Due to the relatively high cost and the observed cost/utility ratio, the cost parameter is considered a negative parameter in the analyzed case study, and thus in the thesis.

TIME

Completing a major construction project on time cannot be taken for granted. Two time studies are conducted to detect if potential time savings by implementing the drilling robot to the installation processes do occur. The operational time study conducted in this thesis regards if the installer could save time, and thus reduce the cycle time of one fire sprinkler installation, by using the pre-drilled holes from the robot. One of Koskelas (1992) principles for flow process design and improvement, is to reduce the cycle time. Koskela states that the production flow can be characterized by the cycle time, which refers to the time required for a particular piece of material to traverse the flow. Koskela also states that the cycle time can be progressively compressed through elimination of non value-adding activities. The progression of cycle time reduction through successive process improvement is illustrated in figure 5.3.

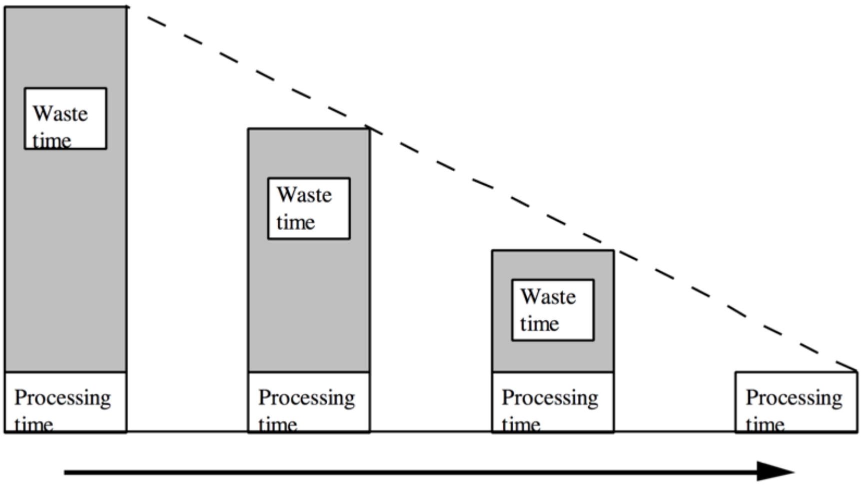


FIGURE 5.3 CYCLE TIME REDUCTION (KOSKELA, 1992)

Koskela defines a cycle time as summation of processing time, inspection time, wait time and move time. Due to the limited time, logistics and the thesis execution, the cycle time in this thesis is defined as the net time of installing one specific fire sprinkler pipe.

The operational time study claims that the installer can theoretically save up to 33 percent of his net cycle time by using the pre-drilled holes from the robot. The observed practice showed that the average cycle time went from 186,36 seconds to 127,70 seconds, leading to a 31,5 percent time saving. The observed practice confirms the potential time reduction of approximately 33 percent, and clearly indicates that there is a potential to reduce the cycle time of the technical installation in the roof.

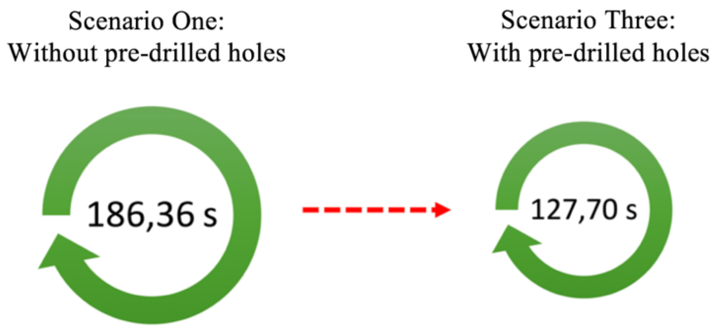


FIGURE 5.4 MEASURED CYCLE TIME REDUCTION

By using the cycle time definition, the complicated installation process has been simplified and narrowed down. This leads to, and eliminates, different error sources. Due to the simplification of the installation process, one error may be that the results show too precise numbers, with low deviations. With that being said, the time study has been precisely executed and all the data of the time study is attached to the thesis for validation. When the time study regards net time of one single and isolated pipe installation, precise average numbers can reasonably be expected. The installation work of four installers was randomly observed in the installation process. Appendix B shows that the activities have been measured twelve times each. The cycle times are the average times of these twelve random observations of the isolated activity.

At the project scheduling level, it turned out that the robot alone had a minimal impact on the Gantt schedule used at the analyzed project. The relative low impact was mostly due to the fact that the total time reduction is only based on the last activity in the schedule, and not the whole planning picture. In addition to the small time reduction, the results show that the buffer between activities became larger. To reach a higher time reduction, the different activities and planning system must be more dependent of each other. From the timetable of the project analyzed it was not possible to adjust any activities without too many assumptions and speculations. As a result of this the robot was claimed to fall in to the category “nice to have”.

To illustrate the potential time saving the robot could achieve combined with the right planning system, the Gantt chart of the studied project was replaced with a location based planning system. Using the location based planning system gave a better overview of the project. One of the main purposes of this method is to make sure that the different trades are not working within the same location at the same time. Three different plans where created in the result chapter. The plans depended on several factors like the recourses versus money trade off and logistics and flexibility in the project. It turned out that using location based planning together with the robot, could potentially lead to a higher time savings, and better utilization of the robot. If the robot is not combined with the right planning tool, the total time savings could be minimal. It must be mentioned that using a traditional Gantt schedule would most likely lead to bigger time buffers, but not lead to an earlier project delivery.

QUALITY

Within the quality parameter, logistics, virtual management and safety are analyzed. Time observations conducted of the robot’s activity is illustrated in figure 5.5. As the figure shows, 65 percent of the time that the robot is operating, drilling is conducted. Nine percent of the time is taken up by the robotic movement inside the drilling area, ten percent goes to move the robotic arm to the right locations and 16 percent of the time is used to calibrate the robot with the total station.

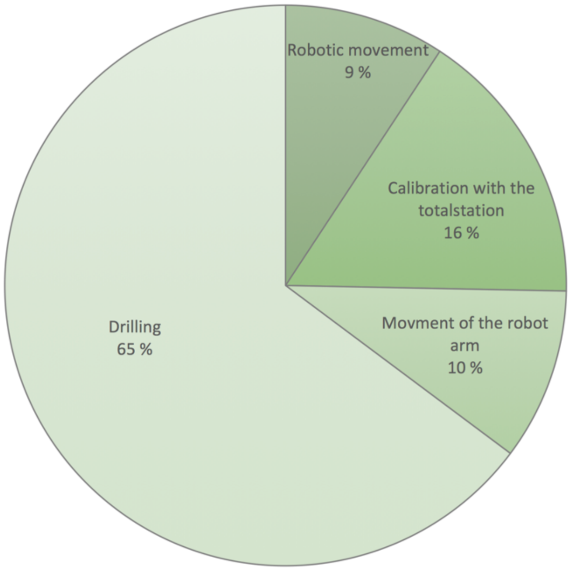


FIGURE 5.5 ROBOT OPERATING TIME OVERVIEW

Both interviews and time observation confirm that the set-up time, from the robot is at the physical place to it is ready to drill the first hole, is between 30 and 45 minutes. It would be an advantage if the set-up time would be reduced, but if an improvement was to be made on the robotic operating time, the time wasted on the periodical calibration with the total station should be prioritized. The other potential time savings are not considered to be significant in comparison to the time wasted on waiting for the calibration.

It quickly becomes problematic for the robot to complete the drilling if there is a lot of temporary and permanent storage at the relevant location. On the observed project, no major problems or challenges linked to storage logistics were discovered. To avoid this eventual problem, nLink AS demands that no storage of any kind is stored in the area the robot is operating.

Field observations on the construction site revealed that much rain and snow over prolonged periods may result in drainage through the various floors. If water settles in the concrete elements, the robot drill may hit the water pocket which causes the water, mixed with concrete and dust, to be sucked up by the vacuum cleaner. This would lead to often and repetitive replacement of the dust-bag. This eventual problem and the potential power supply challenges mentioned in the result chapter is relatively small and not considered a major disadvantage.

nLink operates with a color code system that helps the installers to separate and see which holes are pre-drilled to each technical installer. By using this system, three visual management topics are discussed: transparency, discipline and complexity.

Transparency is defined by Tezel (2010) as the ability of a production process to communicate with people. One of Koskelas (1992) principles for flow process design and improvement is to increase the process transparency. Two practical approaches Koskelas mentions are to make the process directly observable through appropriate layout and signage and utilizing visual controls to enable any person to immediately recognize standards and deviations from them. Observations from the construction site show that by using pre-drilled holes and a color-code system, the transparency will improve. The goal of increasing the transparency is to substitute self-control for formal control and related information gathering. This goal fits well with nLinks AS' way of thinking of the color-codes; Information is gathered in the BIM model, used by the robot and displayed in colors to the installer.

Using the robot does slightly improve the discipline related to visual management. Anyone using pre-drilled holes should be able to distinguish between the different colors of the pre-drilled holes resulting in a more disciplined and forced installation process. By using this system, the organization also contributes to a continuous improvement, and could stimulate employee improvement to manage and improve quality.

Tezel (2010) claims that the management of information in dynamic and complex environments sometimes goes beyond the efforts and abilities of individuals. By eliminating and simplifying some steps of the installation process, the complexity goes down.

The robot is developed on a request from a contractor in Norway, Vintervoll AS, to improve over-head installation and reduce shoulder damages. The main arguments in the interviews are that the use of robotics can lead to a competence change. The feedback from the analyzed construction site, was that the predrilling simplifies the installation work and relieve the workers of major parts of their shoulder strain. The robot can execute the repetitive heavy work, while the operator could contribute with knowledge and logistics skills instead of raw power.

By using the robot, the risk connected to the drilling activity is not only reduced to a satisfactory level, but eliminated as a negligible risk. The activity is not performed anymore, and is no longer a concern of the risk management. Benefits within noise, dust and clean workplaces are also positive outcomes of implementing the robot. From multiple interviews, it was also stated that the robot should work with and not instead of the installers. This combination could result in longer, safer work hours for the installers.

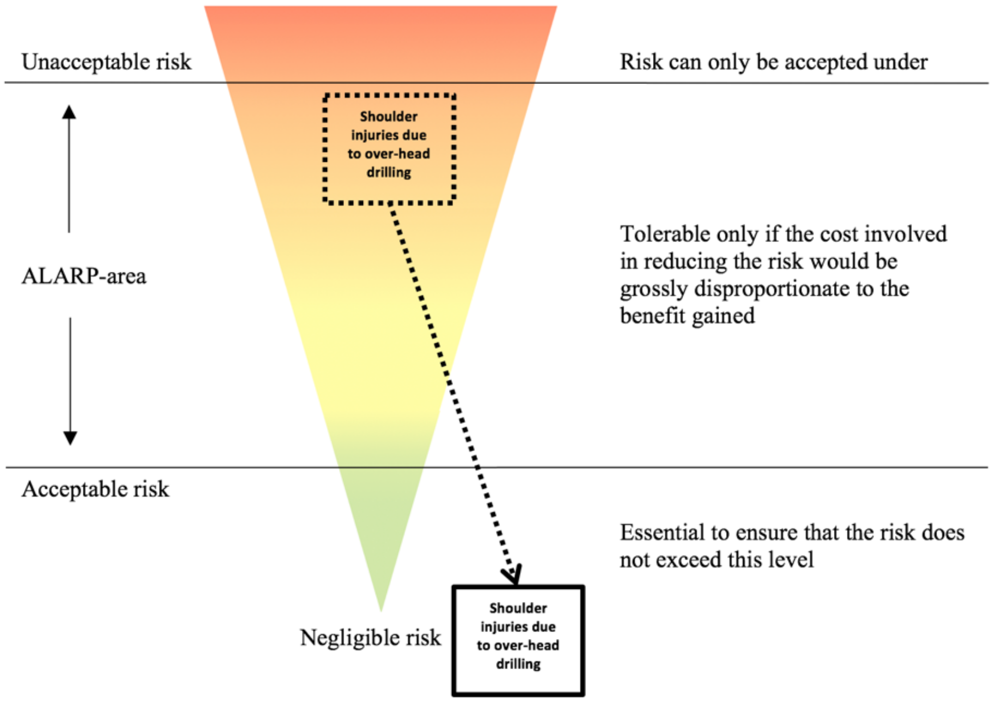


FIGURE 5.6 NEGLIGIBLE RISK

Throughout the interviews conducted in this thesis a typical statement was: "The way the robot operates today, it does not do enough to be worth the money." The potential improvements are listed to give the reader a picture of the potential developments of the robot. The potentials descriptions are brief, and are based on input from the working staff, the construction management and nLink AS.

6 Conclusion

Several studies have shown that there is an improvement potential in the construction industry. It is argued that while the construction industry has gone through a steady and gradual increase in turnover, the productivity has declined compared to other industries.

A white paper, drawn up for the Norwegian Government, states that two of the reasons for the decline in the construction industry productivity is the absence of major technological innovations and the lack of attention around productivity and the future development of the industry. It is specified that the construction industry has not sufficiently harvested benefits and gains of modern technology.

One robot that can contribute to reverse the descending productivity trend is the drilling robot developed by nLink AS. The robot operates on data from a BIM model, it is customized for working on construction sites, contributes to simplify installations and reduces the risk of shoulder injuries.

The main objective of this thesis was to evaluate the effects of using the drilling robot on construction sites. The operational time study shows that the installer can theoretically save up to 33 percent of his net cycle time by using the pre-drilled holes from the robot. The project time study shows that the potential time savings by using the robot could possibly be more effective with a location based schedule compared to an activity based schedule.

Regarding logistics, the most important issue is that it becomes problematic for the robot to complete the drilling in areas with a lot of temporary or permanent storage.

The feedback from the analyzed construction site, was that the predrilling simplifies the installation work and relieve the workers of major parts of their shoulder strain. Benefits within noise, dust and clean workplaces were also mentioned as positive outcomes of implementing the robot.

In the interviews, it was stated that in this project the owner pays for both the extra design and nLinks contract. The contracts are confidential, but the extra design of approximately $1600m^2$ was stated to be 100 additional hours of teaching and designing. With an hourly rate of 1000 NOK, the extra design cost roughly 100.000 NOK.

From several interviews, with both the management and working staff, it was mentioned that the drilling robot, as it operates today, does not do enough to be worth the price and potential time savings. Based on feedback from both the working staff, the construction management and nLink AS, a list of improvements is provided to give the reader a picture of potential and future developments.

Throughout the thesis, different advantages and disadvantages have appeared. Figure 6.1 illustrates the most important benefits (green) and the weaknesses (red) found in this thesis.

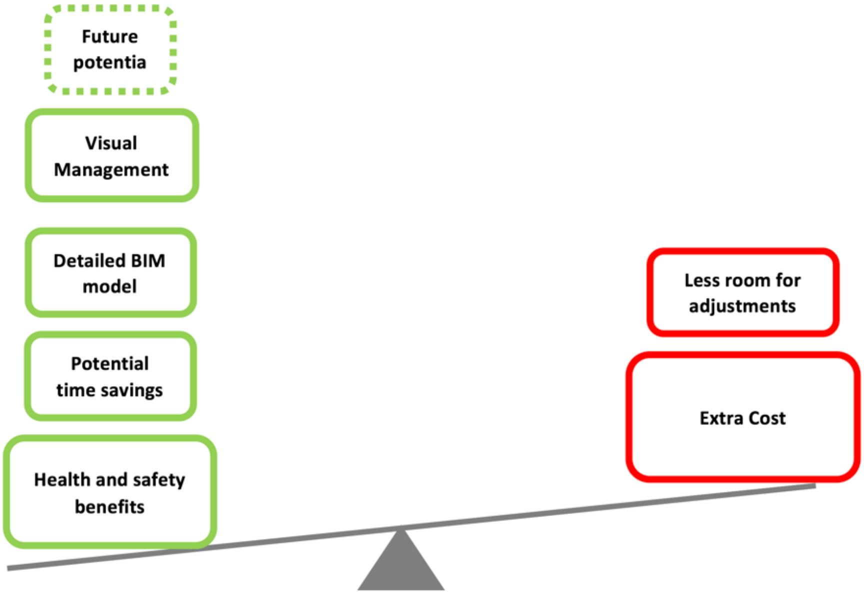


FIGURE 6.1 CONCLUSION

As the conclusion figure states, the biggest advantages lie within health and safety, potential time savings, detailed BIM models, visual management and future potential. The two biggest and essential disadvantages are the extra costs and the limited adjustment room.

The total advantages of using the robot are considered to weigh heavier than the few disadvantages. The conclusion is therefore that the use of the robot is advantageous compared to the conventional method. The conclusion relies on the advantages and disadvantages found and discussed in this thesis, and assumes that all the potential benefits are utilized of the project team.

7 FUTURE WORK

This chapter lists up proposals for new issues and how future work can be defined and done.

While this master thesis is an introduction thesis discussing five main topics, future work could review and discuss more specific topics more thoroughly. It would for example be interesting to follow up the potential time savings and location based management.

In the operational time study, only the process of installing fire sprinkles has been the focus. The results indicate that the installer can save about 33 percent of his net cycle time of the installation of one water pipe with one roof attachment. It would be interesting to conduct a similar time study of the whole installation process, both fire sprinkle, electrical installation, ventilation and ceiling panels.

Another interesting case is to conduct a time study of the gross time of the technical installations. Due to limited time and resources, this has not been completed in this master thesis. But in interviews with the electricians, it was stated from several sources that the isolated amount of time they use on drawing measurements and roof marking is approximately 40 percent of the total gross time. On the down side, it was also mentioned, as in this thesis, that the robot causes limited room for adjustments and modifications in confined areas with many technical installations.

It could be useful to evaluate and control the data in this thesis to decide if the thesis is reliable, if the measuring is done correctly and to determine if the information is dependable. It would also be possible to supply this thesis with new data from new construction sites, interviews and articles.

The industry is constantly evolving. Today nLink AS are working on some specific developments. These developments in addition to the more abstract future potentials mentioned in this thesis could be interesting to conduct a follow up study on.

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APPENDICES

Appendix A: Interview guide (Norwegian)

nLink As
Korleis kom du ikontakt med nLink As? Kvifor var dette av interesse?
Produktivitet og LBMC
Korleis kan robotten bidra positivt inn i produktiviteten på byggeplassar? • BIM • Bemanningsproblematikk • Nattarbeid • Tekniske entreprenørar & fagpersonar • Samhandling Korleis kan roboten bidra positivt inn i den planlagde framdrifta? • Tid • Lokalbasert • Samarbeid • BIM
HMS
På kva måte kan roboten verka inn på HMS arbeidet dykkar ute på byggeplassar ? • Reint tørt bygg dagleg • Sikker bygging med god kvalitet • Skapa godt arbeidsmiljø • Sikkerheitsområder På kva måte kan roboten forhindra skadar og helseproblem? • Støy • Smuss • Lyd • Klemskadar • Handtering av byggavfall
Framtidig bruk av robotikk på arbeidsplassar
Korleis ser du for deg framtidig utvikling? Kva er viktig å tenkje på når det gjeld implementering av robotar i framtida? Kva er dei største utfordringane knytt til framtidig bruk og utvikling av robotikk?
Prosjektering
Kor mykje ekstra prosjektering må til for å nytta roboten? • Kostnad • Fordeler/bakdeler • Standardisera • Algoritmer i framtida
Logistikk
Utfordringar og fordelar med lagring? • Just in time delivery • Lagring før bruk av robot Utfordringar og fordelar ved montering? • Visual management - Fargekodar Kvifor er det enklare/vanskelegare?

Appendix B: Operational Time Study Observations

Templete

Project:
Construction Site:
Floor: First

Date	**Date**	**Date**						**Notes**
		Measurement Drawing.	Measurement Roof	Drilling	Installation Expansion Bolt	Installation Attachment	Installation Pipe	

Scenario One - Conventional Installation

Project: Project 1 – Conventional Installation
Construction Site: Subsection One
Floor: First

Date	Cycle no.	**Activity** (Seconds)						Notes
		Measurement Drawing.	Measurement Roof	Drilling	Installation Expansion Bolt	Installation Attachment	Installation Pipe	
14.02.17	1	45,2	10	12,3	2,74	10,62	67,43	
14.02.17	2	30,64	9,87	13,9	1,32	43,1	72,52	
14.02.17	3	44,42	8,21	11,34	3,21	14,3	64,28	
14.02.17	4	62,68	10,8	10,78	1,1	20,3	67,86	
15.02.17	5	20,85	24,97	23,5	1,04	20,6	126,62	
15.02.17	6	30,3	60,46	13,21	3,87	38,76	204	
15.02.17	7	43,86	13,4	8,24	1,76	20,8	107,56	
15.02.17	8	10,1	5,27	15,31	1,66	22,6	64,41	
15.02.17	9	25,65	9,73	10,3	2,57	32,84	72,23	
15.02.17	10	14,8	29,2	17,15	0,95	25,8	74,6	
15.02.17	11	23,85	8,2	11,32	1,32	24,6	132,7	
15.02.17	12	35,7	9,54	8,94	1,76	27,6	112,87	

Scenario Two – Robotic holes not used

Project: Project 1 – Robotic holes not used
Construction Site: Subsection Two
Floor: Third

Date	**Cycle no.**	**Activity** (Seconds)						**Notes**
		Measurement Drawing.	Measurement Roof	Drilling	Installation Expansion Bolt	Installation Attachment	Installation Pipe	
13.03.17	1			23,06	1,1	25,5	92,62	
13.03.17	2			19,1	0,91	18,53	83,82	
13.03.17	3			16,64	1,32	13,17	62,35	
13.03.17	4			22,31	1,09	14,17	73,8	
13.03.17	5			18,68	0,98	37,17	84,6	
14.03.17	6			18,4	1,81	17,61	117,63	
14.03.17	7			26,07	0,97	32,85	123,08	
14.03.17	8		67,44	21,89	0,86	27,52	94,17	
14.03.17	9			19,64	0,7	16	103,17	
14.03.17	10			18,82	0,95	34,62	111,8	
14.03.17	11			23,68	1,04	32,76	106,83	
14.03.17	12			16,62	0,73	39,24	105,2	

Scenario Three – Robotic holes used

Project: Project 1 – Robotic holes used
Construction Site: Subsection Two
Floor: Third

Date	**Cycle No.**	**Activity** (Seconds)						**Notes**
		Measurement Drawing.	Measurement Roof	Drilling	Installation "Slaganker"	Installation Attachment	Installation Pipe	
13.03.17	1				1,06	23,06	97,44	
13.03.17	2				1,32	23,06	91,16	
13.03.17	3				1,41	25,63	97,42	
14.03.17	4				0,8	23,1	100,6	
14.03.17	5				1,65	50,01	118,94	
14.03.17	6				1,34	21,91	71,85	
14.03.17	7				0,91	25,6	67,31	
14.03.17	8				1,23	33,74	170,66	
14.03.17	9				0,89	23,18	77,49	
14.03.17	10				1,16	21,34	105,2	
14.03.17	11				1,03	27,64	107,72	
14.03.17	12				1,25	27,54	86,8	