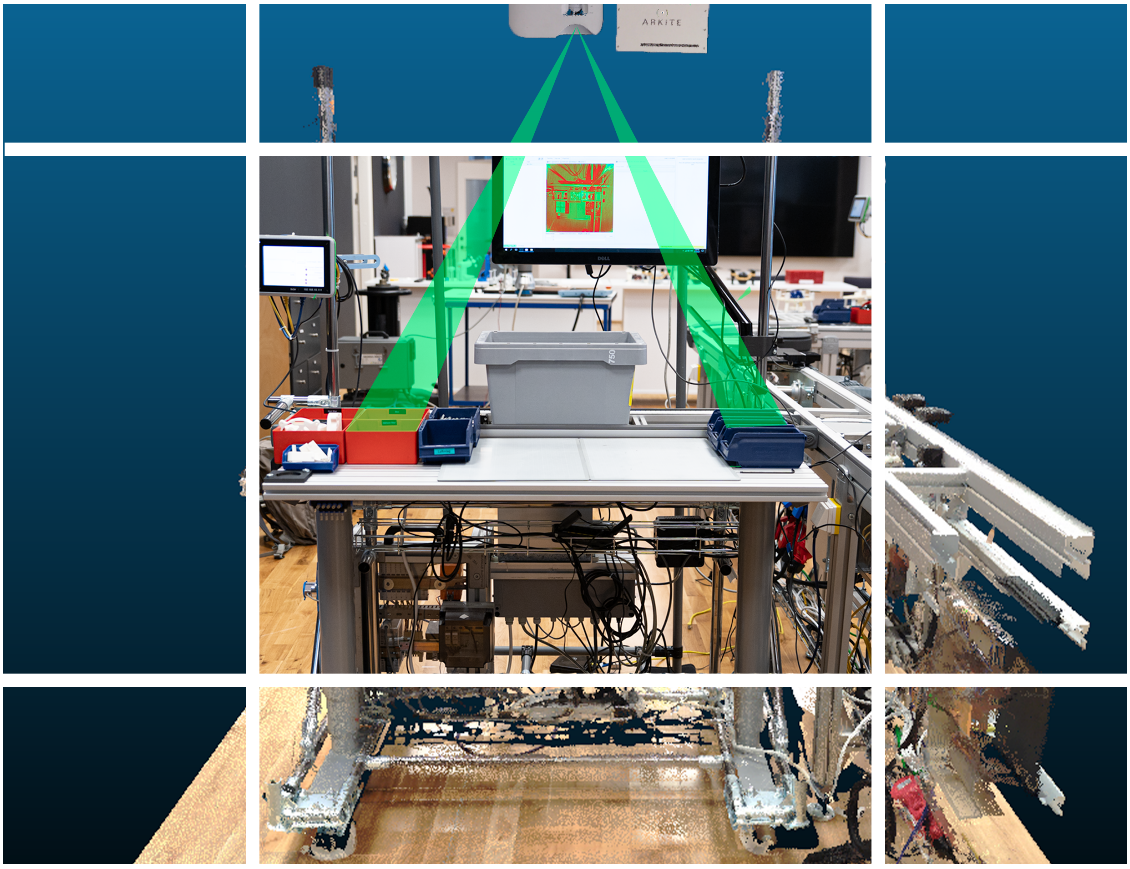

# Virtual Commissioning of a Projection Based Support System

## A Case Study Regarding the Digitized Commissioning of a Manual Assembly Support System

Master's thesis in Master Programme Production Engineering

Erik Lilja, John Magnusson

Department of Industrial and Material science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021

Master's thesis 2021:IMSX30

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Cover: Visualization of the HIM system both from a picture and a 3D scanning combined.

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# Abstract

The purpose of the thesis was to investigate the improvement potential regarding the commissioning process of projection based support systems, which guides operators in manual assembly. A case system was used as a representation of this kind of technology. To improve the commissioning process, a virtual commissioning solution was developed, moving parts of the current commissioning process to a digital preparation stage. The investigation ended in a comparison between the current commissioning and the virtual commissioning. To investigate the commissioning, design science research was mainly used to develop a software solution, called an artifact in the method. In a laboratory experiment, the artifact aided virtual commissioning was compared to the current commissioning to assess its potential improvement of the commissioning process. From the development and experiment, virtual commissioning showed promising potential in parts where the connectivity of the system, in other words interoperability was high. The virtual commissioning did however not reach the full desired level of functionality, due to interoperability isolation of some software parts. The results suggested that using virtual commissioning outside the field of robotics to improve the commissioning of other technologies is viable. Improvement potential in this field is however dependent on software factors and interoperability level in the equipment used.

Keywords: virtual commissioning, projection based support system, digitized commissioning, HIM, interoperability

# Acknowledgements

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We would also like to thank the company Virtual Manufacturing for taking us in and allowing us to use their HIM system for this thesis. Virtual Manufacturing provided a great place to work with creative people from many different fields. Erik Malmström deserves special recognition for his support through this thesis, for all the help, support, and meetings from the start to the end of the project. We would also like to thank the CEO of Virtual Manufacturing, Torbjörn Danielsson for the constructive feedback during the project.

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John Magnusson, Gothenburg, May 2021
Erik Lilja, Gothenburg, May 2021

# Contents

# List of Figures

# List of Tables

# Abbreviations

**API** Application Programming Interface.

**CC** Current Commissioning.
**CPPD** Cost of Planned Production Downtime.

**HIM** Human Interface Mate.

**IR** Infrared Radiation.

**SII-lab** Stena Industry Innovation Laboratory.

**ToF** Time-of-Flight.

**VC** Virtual Commissioning.

# 1

# Introduction

This chapter will first go over the general background of why this thesis is important in today's industry and in what context this thesis should be viewed. Descriptions of the technology investigated in the thesis involving Industry 4.0, information systems, commissioning, and how they relate to each other are described. The aim is then presented followed by the research questions to be answered in the thesis. Lastly the scope is explained with the limitations of the project.

## 1.1 Background

The advancement of the fourth industrial revolution, Industry 4.0, is currently underway. One major focus of Industry 4.0 is the digital transformation of organizations, in order to successfully interconnect them in virtual environments to share information (Savastano et al., 2019). This focus is especially noticeable within the manufacturing industry, which is traditionally based on analog physical processes (Savastano et al., 2019). Manufacturing industries thus need to undergo rapid change, to utilize these newly developed technologies and remain competitive on the market. Undergoing such rapid change is however not easy, especially if the company in question has a low digital maturity level (Kupriyanova et al., 2020). Methods thus need to be developed to ensure that companies can make the shift towards the digital future.

Even with the shift towards Industry 4.0, manual labor is still a key part of many manufacturing environments (Larek et al., 2019). In both the fields of logistics and assembly, manual labor often outperforms automated mechanical solutions (Mishev, 2006). The current demand for higher flexibility in production does however pose a challenge regarding the cognitive load that operators face in their day-to-day operation, which increases the risk of quality issues occurring (Savastano et al., 2019; Fässberg & Fasth, 2011). Operators could thus benefit from smart solutions, which can help to alleviate the cognitive load while also fulfilling the need for connectivity from Industry 4.0.

Several studies have been performed focusing on developing projection based support systems to aid within both logistics and manual assembly (A. Baechler et al., 2016; Rupprecht et al., 2020; Funk et al., 2018; Ojer et al., 2020; Pickl, 2014). This technology uses projections to guide the operator and sensors to confirm the actions made by them. These studies show that compared to traditional methods, projection based technologies greatly reduce the cognitive load and mistakes performed by the operator during their work (A. Baechler et al., 2016; Funk et al., 2018; Pickl, 2014). The studies also showed that the general acceptance of the operators by this technology was high since they aren't physically encumbered by it themselves (Rupprecht et al., 2020; Ojer et al., 2020).

The Belgian company ARKITE has developed a picking solution which they call the Human Interface Mate (HIM) system (ARKITE, 2020). The HIM system mainly uses pick-by-projection technology together with sensors that monitors the movement of the operator for quality control. This combination of technologies gives the HIM system great potential within the field of manual assembly and logistics. When a novel product enters a market, it needs to mature in order to reach a wide customer base (Parment, 2015). This is the current situation regarding the HIM system and projection based support systems in general. Even though the technology has proven to be effective, companies might still be skeptical to invest the time and money needed to implement it within their industries. One way to convince these companies to invest in the technology is to make it easier and quicker to implement within their facilities. One way of doing so is to shift the commissioning of the technology to a virtual environment.

By using virtual commissioning, parts of the commissioning process of technological solutions can be moved from being performed in a factory to instead being done within an office. Virtual commissioning makes it possible to test technologies before implementing them, reducing the total setup lead time (Albo & Falkman, 2020). Furthermore, virtual commissioning gives early insight on the compatibility between different systems, in this case, the HIM system and the customer's system, possibly avoiding time-consuming problems (Albo & Falkman, 2020). Costs incurred in the commissioning phase are reduced by avoiding travel, optimizing each step, and being able to earlier understand the limitation of the technology (Albo & Falkman, 2020). Manufacturing environments often have short opportunities to stop production and introduce new technology in the process, without affecting the overall output (Shahim & Moller, 2016). Therefore, digital preparation before the real commissioning is seen as a strong competitive advantage worth pursuing. Many of the benefits of virtual commissioning are intangible however. These intangible benefits include increased flexibility in commissioning and increased perceived value adding activities while working (Shahim & Moller, 2016). Being able to shift the commissioning work from an often noisy on-site environment to an office is beneficial to the person doing the work (Shahim & Moller, 2016). The environmental impact of commissioning the system onsite is also an overlooked factor. The effects on the production that a disruptive commissioning has, can lead to wasted natural resources and working hours (Vecchi & Vallisi, 2016).

Earlier research on the HIM system suggested that further research on the implementation and competitiveness of the system is needed (Johannisson & Palage, 2020). One way of improving the competitiveness of the HIM system is to decrease the time it takes to commission on-site. Furthermore, this contributes to the core process of the information system commissioning, by exploring improvements in a largely unexplored research area.

## 1.2 Aim

The aim of the thesis is to investigate the improvement potential regarding the commissioning process associated with projection based support systems in the industry. The solutions will be developed and evaluated based on the commissioning time and cost in order to quantitatively compare to the current commissioning method.

## 1.3 Research Question

To improve the commissioning process of the HIM system, one first needs to understand how the current commissioning is performed. This leads to the formulation of the thesis's first research question.

- **Research question 1:** What parts are involved in the current commissioning of the HIM system, and which of these parts has the potential to be digitized for virtual commissioning?

Once the current situation has been thoroughly analyzed, solutions of how to shift parts of the commissioning to a digital environment will be developed. This leads to the second research question.

- **Research question 2:** How can the parts of the commissioning process with potential for digitization be modified to support virtual commissioning?

Finally, the effects of the shift towards virtual commissioning will be evaluated. This will primarily be done by evaluating the time and cost difference of setting up the system through the original methods and the developed method. This results in the third research question to be answered.

- **Research question 3:** What are the effects in terms of time and cost of digitizing the commissioning parts of the HIM system?

## 1.4 Scope

The HIM system will be considered as a final physical product. Hardware changes to the HIM system will not be considered in this thesis. The thesis will only focus on the major, already existing uses of the device in manufacturing environments. The intended use specified by ARKITE of the HIM system is as an aid with manual assembly. No new or niche uses will be considered regarding the commissioning. Using additional equipment alongside the HIM system will still be considered in this thesis.

No changes can be made to the direct software running on the HIM unit. Technical solutions and methods will therefore be adapted to fit the existing interface and software features of the HIM unit. It is however expensive and technically challenging to build a complete digital model, which is often used in virtual commissioning, of the HIM system. (Shahim & Moller, 2016). Thus, this thesis will focus on performing the parts of the commissioning digitally, without building a complete digital twin.

The effect on the user from a work environment perspective will not be considered when conducting the thesis. The system is purely viewed from an economical and time saving perspective.

The sustainability aspects of this thesis will be reflected upon during the conduction of the thesis, and discussed further in section 5.4.

The thesis will also take the current Covid-19 pandemic into consideration. Throughout the thesis, the safety of the people involved will be of great concern, even though it may affect the results of the thesis negatively. Interviews for gaining knowledge will be performed over digital platforms and no company visits will be performed. In order to evaluate the result, laboratory experiments will be performed instead of doing field experiments.

# 2

# Theory

The theory chapter will focus on the knowledge needed to understand the concepts relating to the thesis. This chapter first theoretically explains the digital transformation and which context the thesis is related to it. After the theoretical context, the information system called the HIM system used in the thesis is explained with a detailed summary of how the hardware and the software works. Additionally, other picking systems are explained in order to understand the market context the HIM system is in.

In the subsequent part of the theory, the important concepts of virtual commissioning which is central to understand the thesis is explained. Following this concept, the theory details interoperability which relates to the systems communications and the communication of the HIM system. A brief explanation of 3D point cloud scans is then presented. Lastly, theory to support cost estimation of the effects from digitizing the commissioning process is presented.

## 2.1 Digital Transformation and Maturity

Industry 4.0 focuses on combining the physical manufacturing world with the digital IT world (Tie, 2020). In order to do so, businesses need to adapt and digitally transform multiple sections of their enterprises (Vogelsang et al., 2019). With the rapid development of digital technologies, such as AI, businesses will need to adapt in order to embrace these technologies and remain competitive on the market (Savastano et al., 2019).

Many manufacturing environments are however very rigid and small disturbances can cause huge effects on their profitability (Vogelsang et al., 2019). Implementing new digital solutions in these environments can thus be challenging, and even detrimental to the business overall. In order to assess if a company is able to take the step towards digital transformation, various digital maturity models have been developed (Kupriyanova et al., 2020) (VanBoskirk & Shar, 2016). Different models measure different aspects of digital transformation. Some focus more on the strategic business-oriented sides, while other focus directly on the implementation of digitized solutions. Companies need to assure that they reach a sufficient digital maturity level in the relevant areas before beginning their digital transformation (Kane et al., 2017). A company's digital maturity can be increased in several ways. One way is the development of a talented IT department, while another is to rethink the entire business model for the company (Kane et al., 2017). Another way to increase the digital maturity is by using tools or softwares which can help with the digital transformation of general business practices (Kane et al., 2017).

One part of the digital transformation is the digitization of information systems which informs the operator on what and how to perform assembly (Kane et al., 2017). Ensuring that all operators within a manufacturing environment are supplied with the right information has been a key issue since the early days of manufacturing. This is usually done through various information systems. With the current shift towards industry 4.0, manual assembly is still a key component of many manufacturing environments. However, with the need to produce in smaller batches and higher variety of products, assembly workers needs to keep track of multiple sets of information (Sochor et al., 2019). This can cause a high cognitive load on the workers, which in turn leads to frustration and quality issues when assembling products (Claeys et al., 2019; Fässberg & Fasth, 2011). A need thus emerged for newer and smarter ways of aiding workers during manual assembly. An issue within the industry today is that even though the assembly information exists, the method used does not convey complex information in a efficient way (Sochor et al., 2019). Another issue is the risk of providing too much information so the worker needs to spend their time sifting through it to find what's relevant (Sochor et al., 2019).

## 2.2 The HIM System

One of the information systems that exist is the projection based support system (A. Baechler et al., 2016). Projection based support systems uses a projector to highlight areas to the operator (A. Baechler et al., 2016). They often use a software system to keep track of the operator's movements in and out of defined locations (A. Baechler et al., 2016). The HIM system is a projection based support system. The purpose of the HIM system is to provide manual assembly workers with real time assembly instructions which automatically updates as the work progresses. The system is able to provide the worker with instructions in form of projections, on-screen instructions and sounds. The system is also able to sense how the operator works and provide feedback in case of error if the operator follows the instruction incorrectly, for example, picking from the wrong container.

The HIM system consists of the HIM unit, a projector and a computer display. The projector in this specific case is a Casio XJ-F211WN, but the system can utilize multiple kinds of projectors to project instructions. The communication between the system components is done through a combination of HDMI, VGA and display port outputs.

### 2.2.1 The HIM Unit - Hardware

The HIM unit, seen in Figure 2.1, consists of a computer running Windows 10, an Infrared Radiation (IR) blaster and sensors. In order to make detections, the HIM unit sends out IR beams and uses two sensors to detect the world around it (Schildt, 2000). The first sensor is a depth sensor which measures the Time-of-Flight (ToF) for the IR beams, while the second sensor measures the energy values of the reflected beams to determine how much has been absorbed (Schildt, 2000). The first sensor will be referred to as the ToF sensor, while the second will be referred to as the IR sensor. The theory behind these sensors will be further explained in section 2.2.1.1 and 2.2.1.2.

**Figure 2.1:** Image of hardware used, the HIM unit.

#### 2.2.1.1 Inferred Radiation Sensor

The IR sensor uses light with a wavelength of 700 nm to 1 mm which makes it possible to distinguish details that the human eye can't see (Van Den Berg & Tan, 1994). IR sensors emit light, which is reflected on the object and then returns to the sensor, this light is used to interpret information about the object (Benet et al., 2002). Bright and shiny materials reflect a higher amount of radiation when compared to dark and matte materials (Benet et al., 2002). By measuring the received radiation, the sensor is thus able to detect shifts in material and contrast.

#### 2.2.1.2 Depth Sensor

The depth sensor uses ToF, which is a way of using the IR light to make it possible to determine the distance to objects (Kolb et al., 2009). ToF mechanics includes the possibility to paint a 3D cloud of measurements with distances to the points (Kolb et al., 2009). This technology makes it possible to accurately detect multiple objects and their change in distance to the sensor. It does however have a minimal threshold for which it is able to detect differences in depth.

### 2.2.2 The HIM Unit - Software

The HIM unit comes with a built in software used to operate the HIM unit. It's through this software that the current commissioning of the HIM system takes place. The HIM system consists of different interconnected parts that together form the finished supporting experience for the operator. These interconnected parts are divided into various tabs within the software.

Within the detection's tab it is possible to create and adjust what and where the unit should detect physical objects. Through the use of the sensors the unit is able to create a point cloud environment of what it's able to see. Inside this environment it is possible to create three dimensional virtual boxes in space. By using the depth sensor, the software is able to determine how much of this virtual box is filled by a physical object. This is called the fill rate of the virtual box and is used to assess when someone is working within the box or not. The software also uses before and after images to determine when the detections should trigger. This is needed if the detection has low variety on depth, such as if a thin metal plate is added to an object. In those cases the IR sensors is used for determining when the detection should be active or not.

Another important tab is the processes tab. This is where the information regarding the picking order is processed. The steps within these processes are linked to the detection's created previously. The structure of these process steps are similar to industry standard instruction such as MTM-SAM for assembly work. Images can also be added and are closely connected to process.

The final tab of note is the local variable manager. Within this tab it is possible to perform more advanced programming of the HIM unit. This is done through visualized programming language, and the use of internal variables. Visual programming enables users without experience in textual programming to still work with the HIM unit, but it also sets a lot of constraints of what can be done with it.

## 2.3 Picking Information Systems

Generally other picking information systems than projection based support systems are more common within the industry. Common picking information systems that exists today are pick-by-paper, pick-by-light, pick-by-voice, (Fager et al., 2019) with newer systems including pick-by-vision (Pickl, 2014).

Pick-by-paper is the traditional picking information system where the operator uses a paper list and follows a sequence (L. Baechler et al., 2016). Pick-by-light uses a light as a signal to indicate were to pick the item, a button is pressed as confirmation leading to a new light signal where the item should be placed (L. Baechler et al., 2016). Pick-by-voice uses a headset with voice commands to guide the operator and can be interacted with by simple voice commands (Pickl, 2014). Pick-by-vision uses augmented reality glasses or headgear to guide the operator to the picking item in the augmented overlay (Pickl, 2014). The picking information system research is scarce and different terminology is often used for the same system. This scarcity of research leads to less references and validation possibilities, while providing a generally unexplored field to develop.

## 2.4 Virtual Commissioning

The concept of virtual commissioning is generally used within the field of automation assembly, and focuses on virtually testing and implementing physical equipment (Shahim & Moller, 2016). This can be done either by using fully simulated environments or by connecting the physical equipment to the digital model (Reinhart & Wünsch, 2007). Virtual commissioning allows for the testing of physical hardware in a simulated digital environment in order to ease its implementation within the industry (Shahim & Moller, 2016). Some of the focuses of virtual commissioning is to remove time and resource consuming physical tasks, give earlier validation of processes and shorten the setup lead time (Shahim & Moller, 2016; Albo & Falkman, 2020). Some form of virtual representation of the physical environment is needed in order to perform virtual commissioning (Albo & Falkman, 2020). This could be built from layout plans, 3D-scanned models, or any other representation of the environment. Constructing these representations can be both time consuming and costly (Shahim & Moller, 2016). It's therefore important to know when virtual commissioning should be used, and where traditional commissioning is better before beginning the project. Figure 2.2 displays the virtual commissioning concept used in the project and the current commissioning.

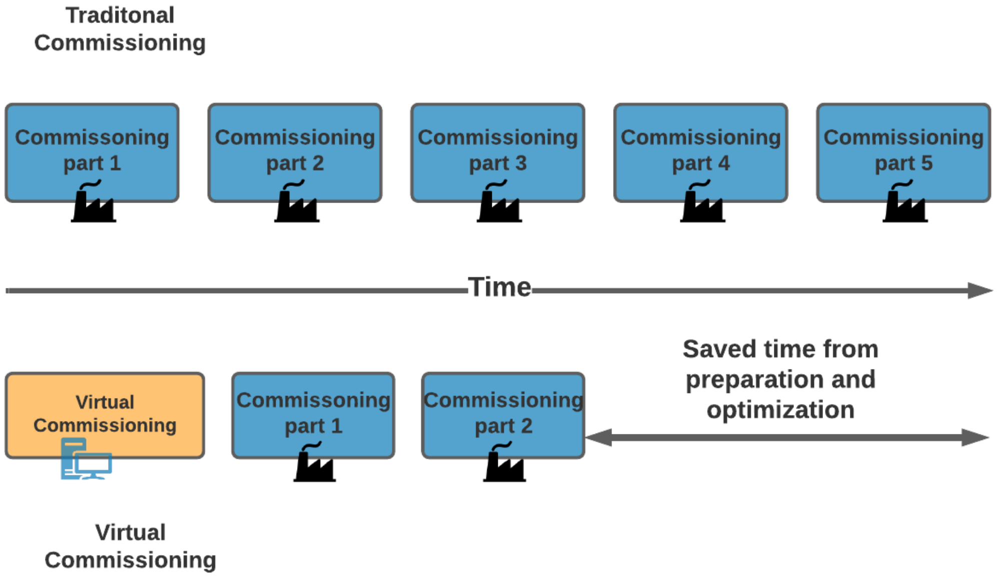


**Figure 2.2:** Explanation of Virtual Commissioning concept, illustration based on source (visualcomponents, 2016).

In many production environments however, disruptions are costly enough to merit that time should be spent on building the virtual representations (Albo & Falkman, 2020). Figure 2.2 demonstrates the move from a traditional commissioning in the factory, to a partial virtual commissioning, not disrupting production to the same extent (Albo & Falkman, 2020).

## 2.5 Interoperability

Industry 4.0 also includes the ability to connect and transfer large amount of data in a interconnected way between different systems (Burns et al., 2019). The ability to connect the system to different devices and send data to and from these devices is defined as the interoperability of the systems (Burns et al., 2019). Interoperability in a individual device is determined by the ability to input and output data in a standardized way (Burns et al., 2019). Overall interoperability in industry is a problem that has remained unsolved since the 1970s (Liao et al., 2017). The constant development of technology leads to mismatches in the standards used, and therefore interoperability problems still exist (Liao et al., 2017).

A common way to make different software able to communicate with each other is through an Application Programming Interface (API) (Patni, 2017). There are various forms of APIs, with one of the more common being REST-APIs (Patni, 2017). The benefit of using REST-API is that you can retrieve and store data in another software through standardized API-calls sent to the software through HTTP communication (Patni, 2017). There's thus no need to understand or directly manage the software of which is being interacted with. The REST-API uses Json format to store the data being transferred and uses HTTP commands containing specific keywords to let the software know how to use the data (Patni, 2017). The most common keywords and their functions are seen in Table 2.1.

**Table 2.1:** Common API calls, based on table from source (Patni, 2017).

| **Keyword** | **Function** |
|---|---|
| Get | Retrieve data from software |
| Post | Update data on software |
| Patch | Change partial data on software |
| Put | Create new data on software |
| Delete | Remove data from software |

Since this project only dealt with REST-APIs, this is what will be referred to when mentioning APIs further in this thesis. One way of seeing how efficient APIs are at connecting with other systems is by evaluating their interoperability level (McLean et al., 2007). Table 2.2 show a way of ranking the level of interoperability of a system, developed by McLean et al. (2007).

**Table 2.2:** Level of interoperability using API, from the source (McLean et al., 2007).

| Rank | Interoperability level | Requirement |
|---|---|---|
| 4 | Total control | Take over power |
| 3 | Action and information sharing | Calls and information sharing |
| 2 | Information sharing | Readable information sharing |
| 1 | Data transfer | Raw data transfer |
| 0 | Isolated | No connection with API |

In Table 2.2 the level of interoperability based on a ranking system from 0-4 can be seen (McLean et al., 2007). A low rank of 0-1 means the interoperability is low and there is little or no connection using API (McLean et al., 2007). A high rank of 3-4 means that most things can be performed using the API and a high level of interoperability (McLean et al., 2007). The level needed to perform a task can vary depending on the nature of the task. The highest rank of four mean the system can be operated with total control with an external software. Level three can reach a high level of information sharing, but is restricted from total control. The second level can only send and receive readable information. Level one is able to send raw data that is limited in its use for the system and restricted. The lowest level zero means the system is isolated and can not communicate with external programs.

## 2.6 3D Point Cloud Scanning

3D Point Cloud scanning data has many use cases and the technology is more and more widely used in industry (Wang & Kim, 2019). Often this data consists of scans from a factory to use in measuring or to later adjust equipment. 3D point cloud data consist of X, Y and Z coordinates combined to represent the surface of an object (Wang & Kim, 2019). The 3D point cloud data can often hold a high quality and can be used in detailed measurements of various points from a real life work spaces (Wang & Kim, 2019).

Today the emergence of the 3D point cloud data in factories is used for drawing and simulating the factory. Another use case for the data could be the integration in the preparation of virtual commissioning of new technology in the same factory. Today the use of virtual models in robotic commissioning has been successful in utilizing rich data to save time in the commissioning (Shahim & Moller, 2016). The growing number of factories being 3D scanned offers new potential information sources for use future commissioning work.

## 2.7 Cost of Planned Production Downtime

When implementing technological changes in production environments, there is a risk that it will create disturbances in the production system. A survey performed by Tabikh (2014) investigated the cost of downtime in several Swedish manufacturing organizations. In this survey the Cost of Planned Production Downtime (CPPD) varied between 175 SEK/hr to 500 000 SEK/hr, with a median of 1 000 SEK/hr (Tabikh, 2014). One of the defining features affecting the cost of downtime is the size of the manufacturing organization. The cost of downtime is, among other things, measured as to loss of potential value from production as well as the cost of fixing the stoppage (Salonen & Tabikh, 2016). Larger manufacturing companies, which generally produce more per minute than smaller companies, thus lose more potential profit per minute than smaller ones (Atlassian, 2021). By segmenting the data gathered by Tabikh (2014) it's possible to make an estimation of CPPD for small, medium and large manufacturing companies, seen in Table 2.3.

**Table 2.3:** Cost of planned production downtime, based on the number from source (Tabikh, 2014).

| Size of company | Small | Medium | Large |
|---|---|---|---|
| CPPD | 406 SEK/hr | 1 354 SEK/hr | 69 090 SEK/hr |

CPPD will be used in order to assess the potential cost reduction of virtual commissioning of the HIM system for companies of various sizes.

# 3

# Methods

The method chapter firstly describes the general methodology used, which includes the type of research methods used and why they were used. Each of the methods are then described with an explanation on how they were used to answer the research questions. After that it presents an explanation on how the methods were combined. The method of validating the results from this thesis is then presented, both with general validation methodology alongside the design of the conducted experiments.

## 3.1 General Research Design

The methods used in the thesis were selected with the aim of virtually commissioning a projection based manual assembly support systems in the industry. An artifact solution was developed, which was adapted to the environment and with the support of a knowledge base, see Figure 3.1. Due to the current lack of similar scientific projects or research, design science methodology was mainly used to develop the artifact, see the middle of Figure 3.1. Elements of case study and action research methodology were also used to asses and build the knowledge base. The methodology of this thesis began with laying the foundation for the knowledge gathering with case study and action research methodology. Figure 3.1 visualizes that through the knowledge gathering, an artifact was developed using an iterative method with feedback to the design science methodology. Finally the results using all three methods were validated through an experiment, with complimentary literature validation where it was possible. The full iteration of the thesis methodology is seen in Figure 3.1.

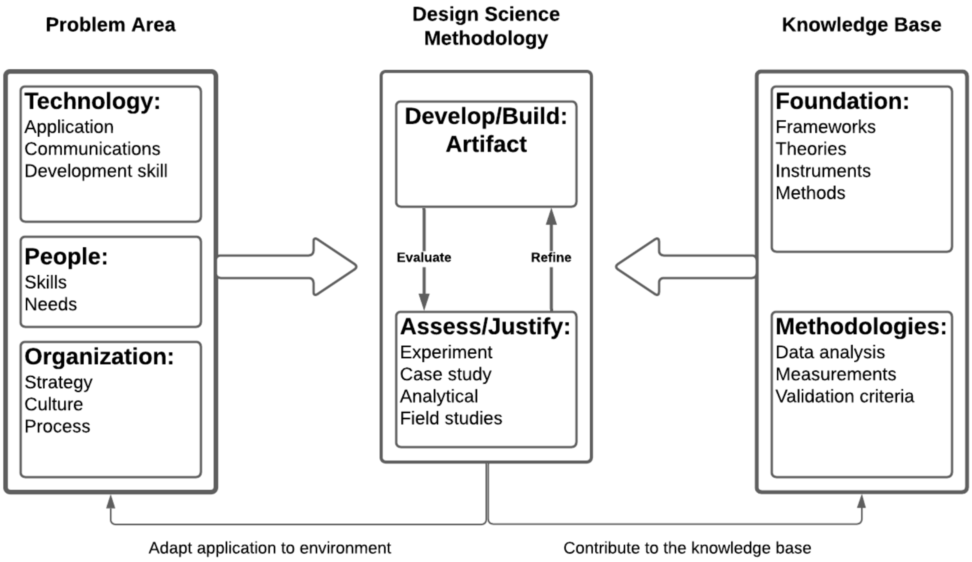


**Figure 3.1:** The methodological model for the building of the artifact. Adapted from literature (Dresch et al., 2015).

Figure 3.1 demonstrates the input from both the problem area and the knowledge base into the final development of the artifact. At the same time, assessments of the usability and validation of the artifact was performed to refine the final solution.

### 3.1.1 Literature Review

The first step in many research projects is to gather knowledge in the field being researched and possible other relevant fields (Bryman & Bell, 2011). Therefore, this thesis was initiated with a literature review. The literature review was then conducted throughout the entire thesis in order to gain knowledge in the needed fields. Using relevant theoretical and case specific literature provided insight both to the possible solutions to be used, and challenges in the field (Al-Tabbaa et al., 2019). Primarily using databases such as *Google Scholar* and discovery systems such as *Chalmers Library Service*, relevant articles were found and analyzed. For the technical areas, such as projection based technology, digital maturity etc, newer literature was prioritized. For more traditional subjects, such as the field of manufacturing support systems, much older publications were considered as well. The literature review gave valuable insights into the theoretical aspects of this thesis. In these areas search terms were used to find the most relevant information (Al-Tabbaa et al., 2019). The following list is some of the most used keywords when searching for literature:

- "Virtual commissioning" AND "Digitizing" AND "Experiment";
- "Interoperability" AND "API";
- "Downtime" AND "Cost";
- "Digital" AND "Transformation" AND "Industry 4.0";

- "Projection" AND "Manual Assembly"

It was however not enough relevant literature available to draw a conclusion regarding the commissioning of projection based support systems. In order to fill this knowledge gap, more practical methodologies were considered. Design science methodology was therefore used to build a novel artifact through an iterative method.

### 3.1.2 Design Science

The main objective of design science is the design of an artifact solution to solve a problem (Dresch et al., 2015). Design science methodology was created to be used in modern settings where an artifact is developed, tested and analysed (Dresch et al., 2015). An artifact can for example be a novel software, a new hardware or some other solution which needs to be developed in order to solve a problem (Dresch et al., 2015). In other words, design science research is a method to creates artifact solutions to real life problems (Dresch et al., 2015). This artifact is the focus of the conducted research, and the methodology is therefore well adapted to creating a solution which is then quantitatively analysed. While the methodological objective of other research methods is also well adapted to the aims of the thesis, the lacking theory in the novel area being researched makes the validation method difficult. In addition, the novel technology used in the HIM unit creates a need to gain understanding early in the thesis as a part of the method. This is also an important aspect of design science methodology.

The focus of the design science methodology is prescriptive instead of descriptive which is well adapted to this thesis (Dresch et al., 2015). While descriptive research tries to only observe, prescriptive research goes beyond trying to describe what happens, and involves coming up with solutions or new ideas (Wollman, 2018). This research is not problem focused either, but solution focused (Dresch et al., 2015). These solutions should be focused on being able to be implemented in reality, and not just tested in laboratory settings. The process in the knowledge gathering builds on a pragmatic view that each situation is unique and that there is a lack of theoretical information of how to solve it (Dresch et al., 2015). In addition, the nature of the artifact being developed and researched has undefined properties which requires non standardized approaches to create the solution (Dresch et al., 2015). In this regard the design methodology is well suited. Design science methodology has historically mainly been used on information systems, with for example IT or interfaces (Dresch et al., 2015). This makes it well suited for this thesis.

There are several ways of carrying out design science methodology, but some general steps are accepted as standard in research (Dresch et al., 2015) (Peffers et al., 2007). Being aware of the problem and the technology being used is generally the first step. There is however no clear framework regarding finding information in design science methodology. It can thus be combined with other methodologies to fill this gap (Dresch et al., 2015). After that, early designs of the artifact are developed and tested in an iterative process (Dresch et al., 2015). The artifacts functionality is tested with validation in the design science method, see chapter 3.2.1. This testing is done through a experiment to gain quantitative measures, see chapter 3.2.2. These measures are then evaluated to determine the result together with the other information gathered during development. In order to gain additional structure where design science was lacking, it was decided that it should be combined with other methodologies for the advancement of this thesis.

### 3.1.3 Case Study

In research, different methodologies exists in how to conduct the studies, among them is case studies (Bryman & Bell, 2011). Case studies is a way of applying the research to a specific case, with a limited scope, in a detailed way (Voss et al., 2002). Case studies also has the benefit of being adaptable to technical subjects (Voss et al., 2002). This means that the research was aimed more towards the specific topic, and less general in nature. Case studies are however time consuming and relies on a high data quality from a multitude of sources (Voss et al., 2002). Data quality is hence a critical element of this research method. Data from similar research was therefore used in the early stages and the evaluation of the thesis (Voss et al., 2002). In novel technologies, case studies provide a way of gaining valuable insights despite these challenges (Voss et al., 2002). Case studies make it possible to map the relationships between process and essential factors in detail through data gathering (Rashid et al., 2019).

Case studies included multiple ways data can be gathered such as through interviews, direct observation or literature (Voss et al., 2002). Interview in case study methodology varied depending on the specifics of the research that was conducted. Interviews could be both formal or informal, long or short depending on the conditions on the ground. Direct observations included open iterative testing with the technology. The iterative testing could include methods to practically create solutions that technologically fulfilled certain premises. The data for developing the technical solutions were found by using this case study methodology.

### 3.1.4 Action Research

This thesis also uses components of action research methodology (Dresch et al., 2015) (Avison et al., 2018). Action research is a methodology that is similar to case studies but the researcher takes a more active role in the implementation process of a solution, while at the same time evaluating the result scientifically (Dresch et al., 2015). The center point of action research is the implementation, study and analysis of an action that is taken (Dresch et al., 2015). Furthermore, in action research methodology the monitoring of the progress is a continuous process that is performed, in the background, throughout the research (Dresch et al., 2015). Because an action is performed during the research, the implementation of the action should be shown in the results, and be analysed as a comparison to the system before the solution is implemented (Dresch et al., 2015).

### 3.1.5 Combining the Methodologies

The methodology that was most adaptable to the thesis objectives was design science methodology. However, in the building of an artifact, including evaluation support from the case study and action research methodologies was beneficial (Dresch et al., 2015). Both case study and action research methodology can be used to scientifically build the foundations for the knowledge base in the design science research. This knowledge base will be used to improve and refine the artifact (Dresch et al., 2015). These methods add to the research rigor of the design science method that mainly rely on pragmatic iterative technology development. The descriptive nature of case studies and action methodology complements the prescriptive design science method. In instances were there is previous knowledge, case studies and action methodology is better suited to find, gather and use the information. However in the iterative building of the artifact, design science methodology provides a practical method for the aim of this thesis. A combination of the methods were therefore used, see Figure 3.2, to achieve an efficient way of conducting this kind of research. Combinations of the research methods were also found to be common and supported in several studies (Dresch et al., 2015)(Peffers et al., 2007).

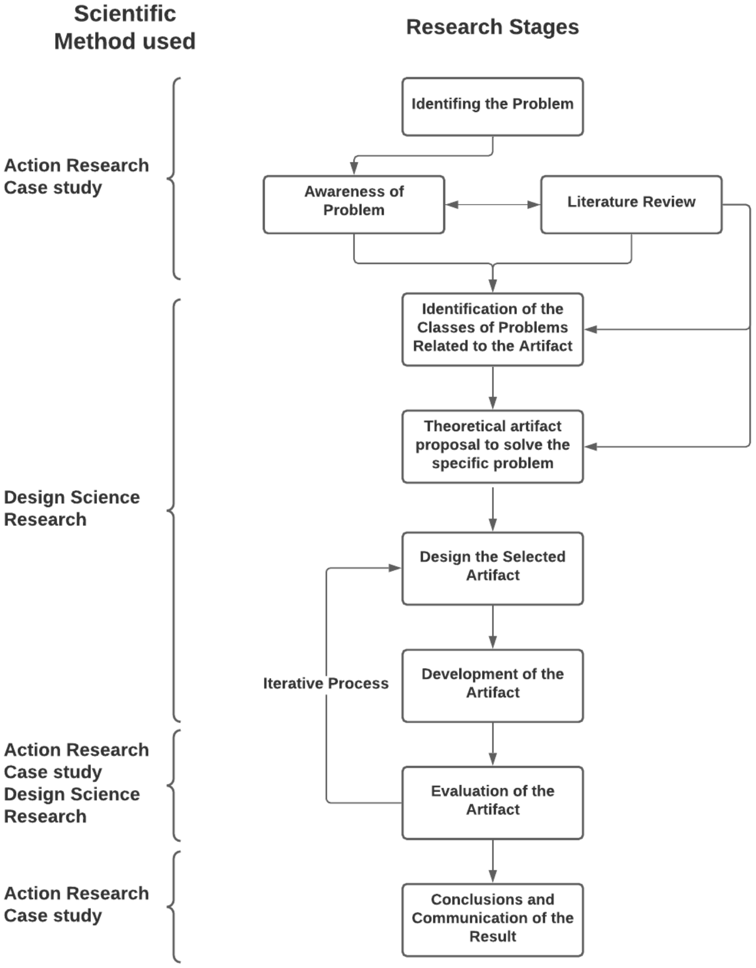


**Figure 3.2:** Each of the method parts with the corresponding scientific method that was used. Adapted from literature (Dresch et al., 2015).

Figure 3.2 systematically displays the research stages and their corresponding scientific method. Action research and case study methodology was used mainly in the start and end of the thesis, while design science research is used in the building of the artifact, seen in the middle of Figure 3.2.

## 3.2 Validation

When conducting research, it's important to examine the validity of the results gained. This section will cover general validation methodology and the specific experimental methodology used in the thesis to validate the results.

### 3.2.1 Validation methodology

Validation can be divided into different types of validity. Internal validation is if there seems to be a strong cause-effect correlation in the study, with the specifics of the environment, setup and framework used in the research (Voss et al., 2002). If this can be applied in a real life scenario, it's externally validated in that scenario (Voss et al., 2002). At which level the results from the research can be externally applied, depends on the validation strength and the specific case. The case study depends on collecting raw field data (Voss et al., 2002). To validate data in such a study it's important to use multiple sources and to consult experts working in the field (Voss et al., 2002). It's also important not to leap into conclusions with a small data set (Voss et al., 2002). To achieve this with quantitative data, other methods than case studies can be used. This creates a multitude of sources, which together can validate data better than one source.

Validation of design science is mainly done through successful application of the artifact, performing experiments and simulations (Dresch et al., 2015). Simulations have the disadvantage of being complex and hard to apply to certain novel artifacts. Actually testing the solution was more adaptable to the novel nature of the technology used in the thesis. Experiments give a quantitative and clear answer if the solution was better or not, which can be widely applied. Therefore both the functionality of the artifact and the experiments of applying it was used to validate the result.

Both case study and action research methodology used comparison against literature to validate the result (Dresch et al., 2015). This was used in the economic evaluation of the results. The literature is combined with the result from the experiment to use both validation methods together.

### 3.2.2 Experimental Validation

One way of validating design science methodology was through industrial experiments, comparing before and after implementation of the artifact (Dresch et al., 2015). Experimental research is often considered trustworthy in terms of internal validity, and is thus highly regarded within academia (Bryman & Bell, 2011). The downsides of experimental designs is that it requires a high level of planning and manipulation in order to be properly executed (Coleman & Montgomery, 1993). Experiments are often split into field experiments and laboratory experiments (Bryman & Bell, 2011). Field experiments are conducted on an already existing location, in order to observe how the experiments affects the present conditions (Bryman & Bell, 2011). The downsides of field experiments is that they need to be adapted to the specific field, which might put limitations on the outcome of the experiment. In laboratory experiments, on the other hand, the researchers have more control over the parameters of the experiment, which reduces the risk for disturbances (Bryman & Bell, 2011). The scale of an experiment is determined on the results needed, the resources that it takes to perform the experiment and the level of planning. An experiment on a greater scale needs the equivalent planning scale (Coleman et al., 1993). Constraints were important to find early, so the design of the experiment could be adapted. Otherwise constraints could lead to experiment designs that was overly complex, nonfunctional or not yielding the desired result (Coleman et al., 1993).

In order to assess the potential of the developed artifact, experiments were performed. In the situation of a case study, both laboratory and field experiments are viable options. Field experiments are a viable if the field is related to the specific case (Bryman & Bell, 2011). In the thesis it was not viable to implement the technical solution in an actual industrial environment, due to Covid-19. Laboratory experiments were thus opted for.

Earlier experiment in a thesis at Chalmers University of Technology using the HIM unit performed by Johannisson & Palage (2020) was based on an experiment design created by Coleman & Montgomery (1993). Therefore, the same method was used to have a continuation in experimentation methodology, in this thesis. The parts of the experiment were divided into seven areas described below:

1. Problem formulation
2. Factor and level choice
3. Selecting the response variables
4. Designing the experiment
5. Performing the experiment
6. Analysing the data
7. Conclusion

The first part consists of clarifying the problem statement which the experiment wishes to evaluate (Coleman & Montgomery, 1993). In this case it is related to the third research question and was thus formulated as: *What are the effects of digitizing the commissioning process of the HIM system?*

The second part involves choosing the factors and levels of the experiment (Coleman & Montgomery, 1993). This was chosen as the two commissioning methods, the *current commissioning* and the *virtual commissioning.*

In order to know what to measure in the experiments, a response variable must be selected, which is the third part of the experimental design process (Coleman & Montgomery, 1993). Based on the selected factors, *time* was chosen as the response variable for these experiments. By measuring and categorizing the time needed to commission the HIM system during the experiments, quantitative data could be extracted.

The next part in this experiment design methodology is to design the experiment (Coleman & Montgomery, 1993). The experiments were designed to emulate an actual commissioning of the HIM system. In order to achieve this an existing workstation in the Stena Industry Innovation Laboratory (SII-lab) at Chalmers University of Technology was used. The data related to this workstation was gathered and the needed preparatory work for the experiments was performed. A trial experiment was also performed before the actual experiment in order to ensure that the design would work (Coleman & Montgomery, 1993).

The experiments were then performed, according to the fifth part of the experimental design (Coleman & Montgomery, 1993). The HIM system was commissioned at the workstation using both the current commissioning and the virtual commissioning several times. All commissions were filmed in order to extract times accurately. A detailed description of the conduction of the experiments are found in Appendix A.

In part six of the experimental design, the data from the experiment was evaluated mainly from a time and economical perspective. Pragmatic validity seeks to ensure the usefulness of the artifact and the economic benefit of the solution (Dresch et al., 2015). The analysis was done through analysis of the extensive footage from the experiment. The footage of each experiment iteration was analysed and data was summarized into graphs and tables. From these graphs and tables, conclusions were drawn which became the results for research question three. This final part was also the seventh step in the experimental methodology.

# 4

# Results and Analysis

The results and analysis chapter presents the results in terms of answers to the research questions. Each research question will be answered separately, alongside a description of how the results were achieved. The first research question will present the analysis and digitizing potential of the current commissioning. The second research explains the results of building the artifact software to digitize the commissioning parts. This sub-chapter involves how it was done and what the outcome was. The third research question evaluated the artifact with an experiment. The results from the experiment is explained in this sub-chapter with a further economic evaluation of the result.

## 4.1 Answering Research Question 1

**What parts are involved in the current commissioning of the HIM system, and which of these parts has the potential to be digitized for virtual commissioning?**

To find the answer to research question 1, the current commissioning process was studied to understand the process and system. This was done through design science research investigation regarding the functionality of the system. The commissioning process could thus be divided into commissioning parts that could be assessed individually with respect to their potential of being digitized (Dresch et al., 2015). These commissioning parts were analysed one by one in order to find the potential for virtual commissioning through a interoperability analysis of the parts.

A full description of the commissioning parts and their sequence is displayed in Figure 4.1.

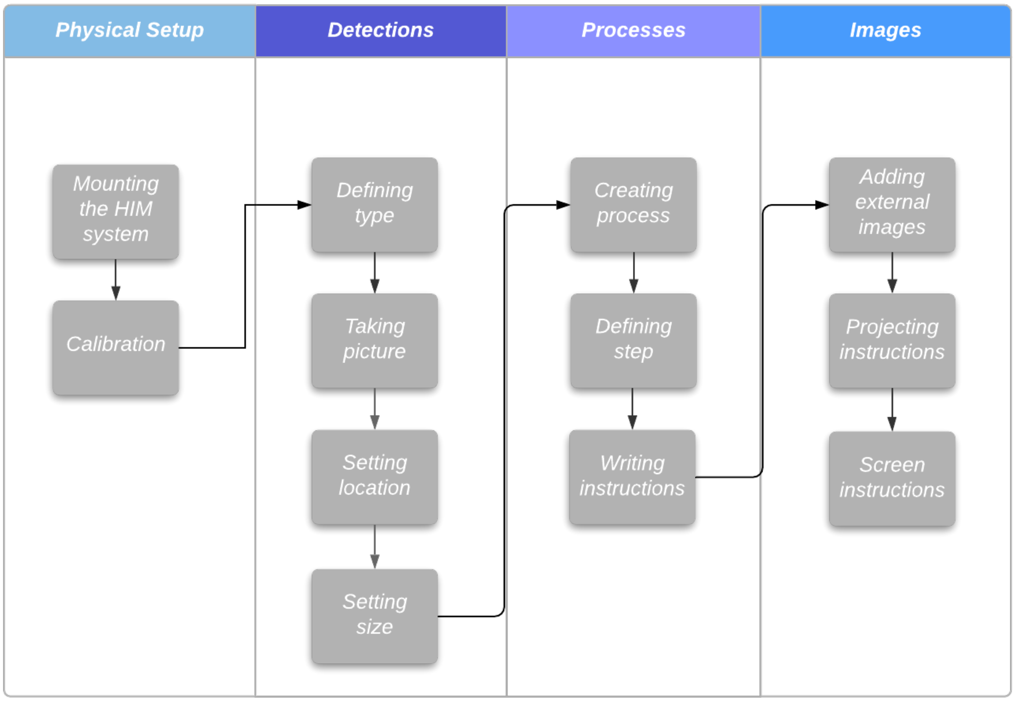


**Figure 4.1:** Flowchart of the current commissioning methods of the HIM system.

### 4.1.1 Current Commissioning of the HIM System

The setup of the HIM system requires several steps to be complete, some relating to the physical aspects of the unit and some relating to its software.
Currently the first step involved in the setup is to physically mount the HIM unit and the projector at their set location above the work space. Both the HIM unit and projector are screw mounted from the back and needs to be mounted perpendicular to the work table of which they will provide assistance. Other than these aspects, the physical mounting is made on a case-by-case basis which could be more or less complex. Once the physical mounting is completed the needed power and communication cables are connected.

Once these physical steps are completed, the setup shifts to the software of the HIM unit. To align the projector with the HIM unit and compensate for minor angular deviations from desired perpendicular angle, an initial calibration is performed. This is done by projecting a few boxes onto the work surface and then interacting with them through the software of the HIM unit. This step can also be performed at later stages but it's important to do it accurately to ensure that the HIM unit understands the environment and its relation to the projector. In order

to set up the internal coordinate system of the HIM unit, an origin point is also defined of which all other coordinates relates to. This origin point is often defined in relation to a static physical point, such as the corner of the work station.
The first software part is to define the detections needed. In order to do this, the type of detection is initially selected among the following alternatives:

- Container
- Activity
- Object
- Tool
- Virtual button

The detection type "Container" refers to the containers where the material for the assembly is located. "Activity" refers to an activity which the operator needs to perform, such as screwing or using a tool. "Object" refers to the object being assembled. Once a material has been removed from its container it is considered as an object part of the assembly process. "Tool" refers to the location of specific tools when they're not used for the assembly process. "Virtual button" refers to a projected virtual button which the operator can interact with to confirm or influence the process.

Once the right detection category is selected, the size and location of the detection is defined by moving a geometric figure to the desired location and resizing it to fit the specific item being detected. Afterwards the detection needs to be taught of when it should be considered active and not. Depending on which kind of detection is being created, the teaching process varies slightly. For activities, a recording is made of when the operator performs the activity in question. For containers, tools, objects and virtual buttons, two pictures are taken. Regarding tools and containers, one of the pictures is taken when the container or tool is present, and the other when it's missing. For objects, one picture is taken of how the assembly looks before the object is added, and the other of when the object is added. For virtual buttons, the first picture is taken of the surface where the button should be projected, and the other of a hand above that surface, symbolizing a button press. When these images and recordings are captured, the ToF or IR sensors on the HIM unit also read the specific values in order to set accurate thresholds of when the detections should be active or not. This process is currently being done directly in the software, where the detections are added one at a time.

When all relevant detections have been added and taught, the processes steps needs to be created. These process steps are also created manually on-site. The processes steps follows a MTM-SAM work instruction structure where steps are defined in sequence (Karger & Bayha, 1987). These process steps are reliant on that the related detections already exist. For example, if an instruction is added to use a certain tool, the detection for the tool must already exist in the software.

Finally, the relevant instruction being shown to the operator are created. Projections are created which include general location boxes showing which detection is active, image instructions and text instructions. Instructions which are shown on the computer display of the HIM system are also created. These instructions are linked to each process step previously created. This is the visible part for the operator using the system.

### 4.1.2 Evaluating the Current Commissioning Steps

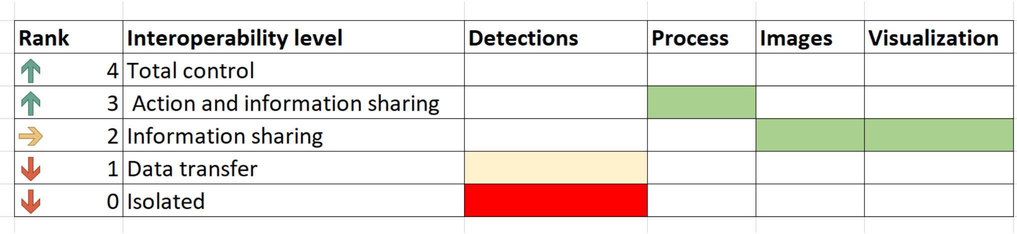
In order to move parts of the commissioning to a virtual environment, the data needed for these parts had to be able to be manipulated without physically interacting with the HIM unit. The required data needed for the various parts of the commissioning process differed from each other. In order to digitize a specific part of the commissioning, the data had to be collectable through means which didn't hinge on the HIM system being present. This data then had to be transformed in order for the HIM unit to understand it. The level at which this data could be transformed is reflected as the level of interoperability in the system (Liao et al., 2017). To achieve a high level of interoperability, the system was dependent on the use of standardised file formats, file structure and the HIM units input possibilities (Patni, 2017). High interoperability therefore needed digital solutions which uses a standardized way of transferring data upstream to the HIM unit (Burns et al., 2019). By analysing the transferable freedoms in the original downstream software from the HIM unit, solutions with limitation in output-data variation had to be set.

The HIM system was originally created to be set up and run on-site. This affected the possibility of transferring data between the HIM unit and an external software. The following criteria was therefore set up to determine which steps that could be integrated into an external software artifact, aiding in streamlining the information sent to the HIM unit (Di Martino et al., 2017):

- The step were not affected by on-site conditions altering the outcome of the step.
- The overall operational quality of the HIM system shouldn't be affected by moving the step to a virtual environment
- There must be seamless transfer of data between the HIM unit and an external program.
- The data required for the steps could be gathered externally.

An API test described in Table 2.2 was performed to find out if the step could be integrated with an external software artifact. The rankings used can be seen in Table 2.2 in the same chapter. The test went through each part of the commissioning, previously described, and tested the API capability according to Table 2.2. A high ranking meant that there was a high capability, while a low ranking meant there was little to none. This level of interoperability with API can be seen in Table 4.1. The test was performed by using a iterative process of all API calls on each one of the commissioning parts and reading the API documentation.

**Table 4.1:** Analysis of the API capability of the commissioning steps.



| Rank | | Interoperability level | Detections | Process | Images | Visualization |
|---|---|---|---|---|---|---|
| ↑ | 4 | Total control | | | | |
| ↑ | 3 | Action and information sharing | | 🟩 | | |
| → | 2 | Information sharing | | | 🟩 | 🟩 |
| ↓ | 1 | Data transfer | 🟨 | | | |
| ↓ | 0 | Isolated | 🟥 | | | |

In Table 4.1, detections were classified as being isolated, with some simple data transfer API capability. This capability was however not useful regarding the commissioning of the detections. Detections were marked as red because they could not be used when interacting with the API. Table 4.1 shows that the process column had a high interoperational capacity with API and had the ability to both communicate and perform actions. They could perform the actions necessary for the commissioning and was therefore marked as green. Images and visualizations had the possibility to be altered using API but was limited in their abilities. Both were able to reach the level of interoperability to be used for commissioning purposes, and was marked as green. A full description of the commissioning parts API capability is displayed in Figure 4.2.

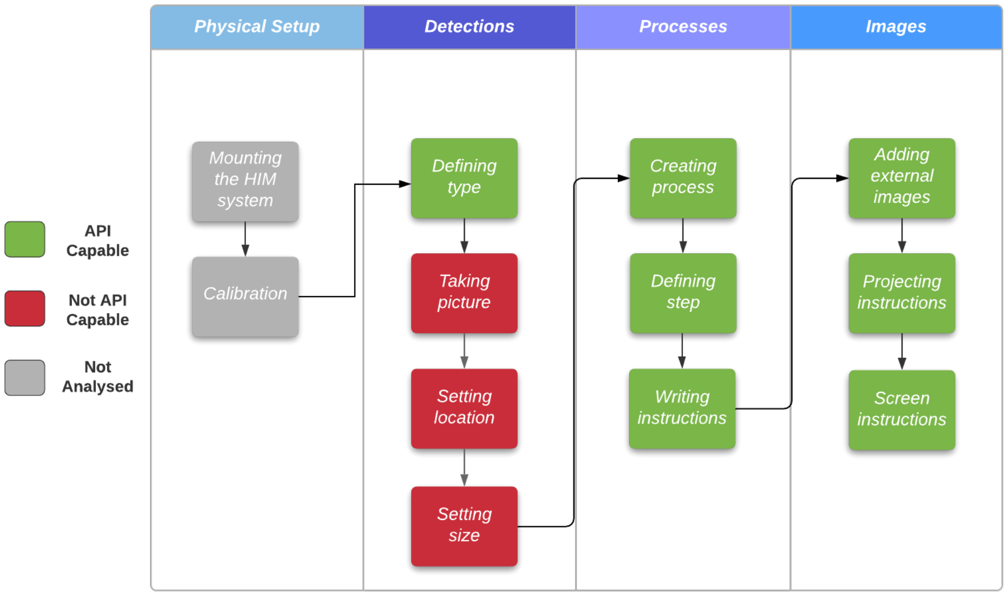


**Figure 4.2:** Flowchart of the commissioning parts of the HIM system, classified as API capable, not API capable or not analysed.

The commissioning parts that lacked API capability were further analysed to find out if the they still could be digitized. Not all steps could be accessed from the API, because of limitations in the interoperability of the software. Data needed in the commissioning steps was set either by manual input, such as a picture taken with the ToF sensor, or by the API depending on the limitations of the specific step. If the step uses the ToF or IR sensor, which is the case in detections, the API lacks the right capabilities to effect the data. These interactions were mapped in detail, to find the limitations when digitizing the steps. Interviews and further discussions with the developers of the HIM unit were held to find out to which extent this could be influenced. From these interviews it was made clear that setting this data through the API wouldn't be possible. In order to still integrate the detections in the virtual commissioning to some extent, a workaround solution had to be developed. Integration was necessary because of the inherent connection between detections and process.

## 4.2 Answering Research Question 2

**How can the parts of the commissioning process with potential for digitization be modified to support virtual commissioning?**

To answer research question 2, an artifact was built to act as the interface between the HIM unit and external software. This artifact solution was divided into three parts, one for detections, one for the process and one for the images. Each part needed separate solutions to handle the data gathered from external software, while at some parts being interconnected with each other. Firstly the development of the artifact is explained and the problem faced. In this explanation the workaround solution for the problem faced is also presented. Secondly the artifact solution is presented and explained.

### 4.2.1 Developing the Artifact

In order to digitize the parts of the current commissioning process, a software was constructed using the high level programming language Python. This software represents the artifact described in chapter 3.1.2, and will henceforth be referred to as the artifact. Python was chosen due to it's versatility and high level of interoperability with other technical solutions. The developed software was able to process data gathered from external programs, transform this data into the right Json protocols and send it to the HIM unit through the API. Figure 4.3 shows conceptual image of how the developed artifact functions. In this chapter each part of the virtual commissioning solutions development is explained, and what what role the development steps played in the final artifact.

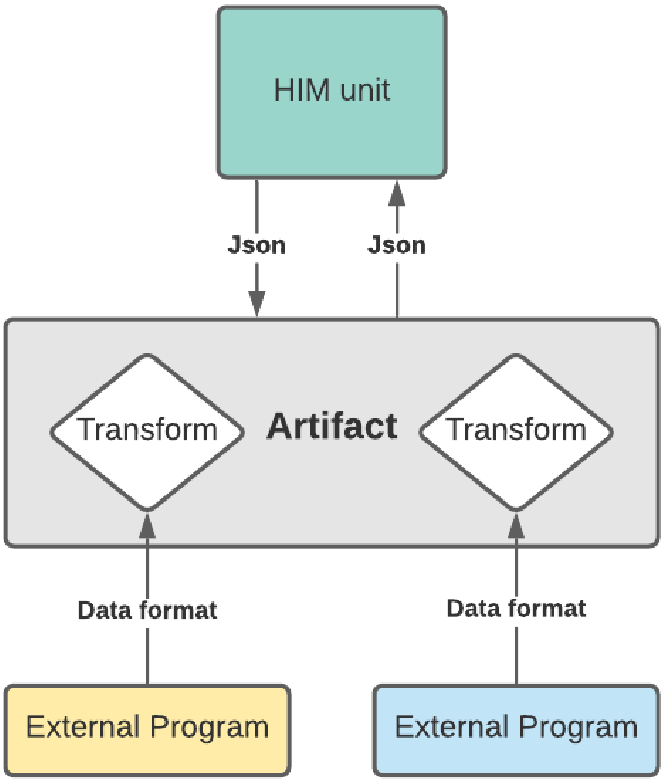


**Figure 4.3:** Data flow of the artifact, based on framework in research (Di Martino et al., 2017).

#### 4.2.1.1 Detections

The first part that was digitized was the setup of the detections. This step relied heavily on the physical environment of which the HIM unit is mounted. In order to get an accurate digital representation of the physical environment, a point cloud scanner was used. Many industries utilize point cloud data to build digital representations of their physical environments. Especially with the advancement to Industry 4.0, digital representation of physical environments are becoming more commonplace (Ahmed & Nargund, 2018). Utilizing these already existing digital models gives a great view of where detections will be needed in the HIM unit (Ahmed & Nargund, 2018). Key coordinates from the point cloud model could be highlighted for the needed detections. These coordinates were extracted using the software Cloud Compare (Girardeau-Montaut, 2021), and were sent to the developed artifact through CSV files. This gave the detections an exact location where the boxes should be located and what they contained, see Figure 4.4, but not all this information could be utilized due to the lacking API capability previously mentioned.

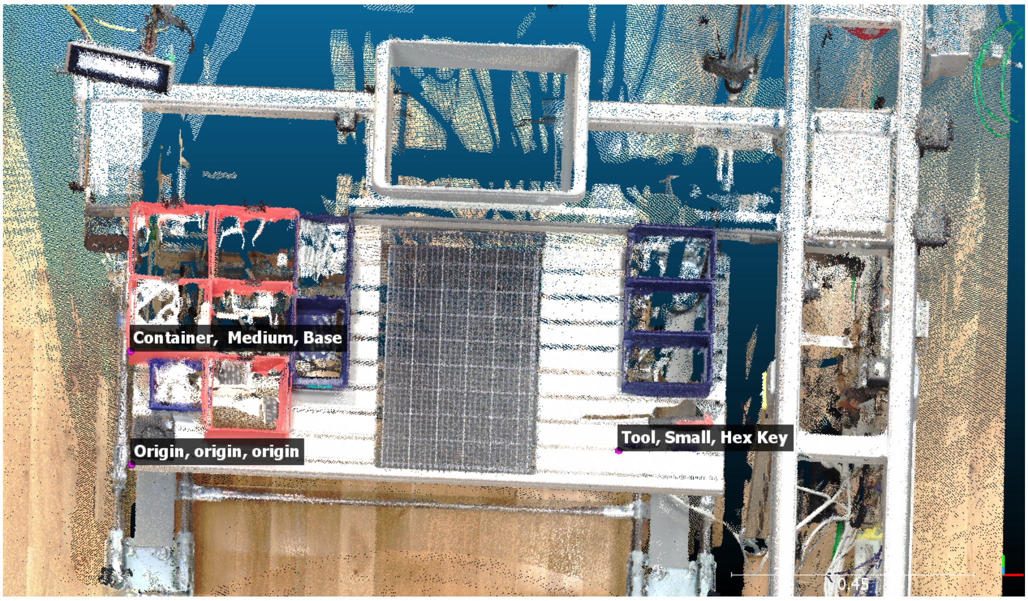
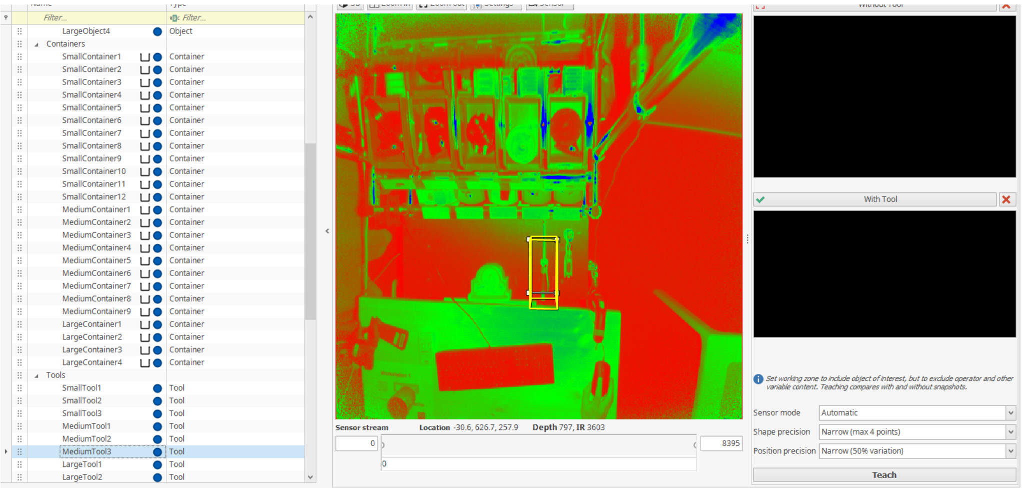


**Figure 4.4:** Visualization of the 3D point cloud program Cloud Compare to mark the coordinates for detections.

Through the API of the HIM unit it was possible to rename detections and change variables connected to the teaching mechanism. It wasn't however possible to place these detections into the virtual space of the HIM. Therefore, the artifact software could not manipulate that part of the commissioning, meaning it still had to be done manually. In order to work around this issue, it was decided to instead build a template project with several dummy detections already included. These dummy detections could through pre-made internal settings be manipulated with internal variables, which could be changed through the API. A limitation of this process was that the size of the virtual boxes only could be altered manually afterwards. In order to compensate for the difference in height that the HIM unit could be mounted at, virtual boxes in multiple standard sizes were created, seen in Figure 4.5. This would allow for the user to generally specify the size of requested box, and the software will connect it to an existing virtual box of appropriate size.

This workaround was necessary in order to still integrate detections into an API solution. Using a template project meant that the detections could be created beforehand and be renamed and placed by the API. This made it possible to still integrate detections into the virtual commissioning to some extent. The naming of the detections was necessary in order for the processes and images to work properly. The placing of the detections through the API was also found to be only half functional because of the way the teaching of detections worked. This meant that a workaround to send the coordinates of each detection to the HIM unit also had to be created. This was done through the local variable manager inside the HIM units software.



| | |
|---|---|
| *Filter...* | *Filter...* |
| LargeObject4 | Object |
| Containers | |
| SmallContainer1 | Container |
| SmallContainer2 | Container |
| SmallContainer3 | Container |
| SmallContainer4 | Container |
| SmallContainer5 | Container |
| SmallContainer6 | Container |
| SmallContainer7 | Container |
| SmallContainer8 | Container |
| SmallContainer9 | Container |
| SmallContainer10 | Container |
| SmallContainer11 | Container |
| SmallContainer12 | Container |
| MediumContainer1 | Container |
| MediumContainer2 | Container |
| MediumContainer3 | Container |
| MediumContainer4 | Container |
| MediumContainer5 | Container |
| MediumContainer6 | Container |
| MediumContainer7 | Container |
| MediumContainer8 | Container |
| MediumContainer9 | Container |
| LargeContainer1 | Container |
| LargeContainer2 | Container |
| LargeContainer3 | Container |
| LargeContainer4 | Container |
| Tools | |
| SmallTool1 | Tool |
| SmallTool2 | Tool |
| SmallTool3 | Tool |
| MediumTool1 | Tool |
| MediumTool2 | Tool |
| MediumTool3 | Tool |
| LargeTool1 | Tool |
| LargeTool2 | Tool |

**Sensor stream** **Location** -30.6, 626.7, 257.9 **Depth** 797, **IR** 3603

0 8395

0

*Set working zone to include object of interest, but to exclude operator and other variable content. Teaching compares with and without snapshots.*

Sensor mode: Automatic
Shape precision: Narrow (max 4 points)
Position precision: Narrow (50% variation)

**Figure 4.5:** Template project containing dummy detections.

The HIM unit bases the coordinates of all detections on the origin point set during the initial calibration of the system. The artifact uses the same logic when assigning the coordinates to the variables. The origin point thus needs to be selected already during the point cloud coordinate selection phase in order to ensure that the detections end up where they should. The system also needs to ensure that the cartesian coordinates of the point cloud and the HIM system align. To set the coordinates for the detections sent to the HIM system, three variables for each detection had to be assigned through the API via the local variable manager of the HIM unit, seen in Figure 4.6. These three variables represents the x, y and z coordinates of the detection. The local variable manager allowed the coordinates of the dummy detections to be altered through variables, that in turn were altered through the API.

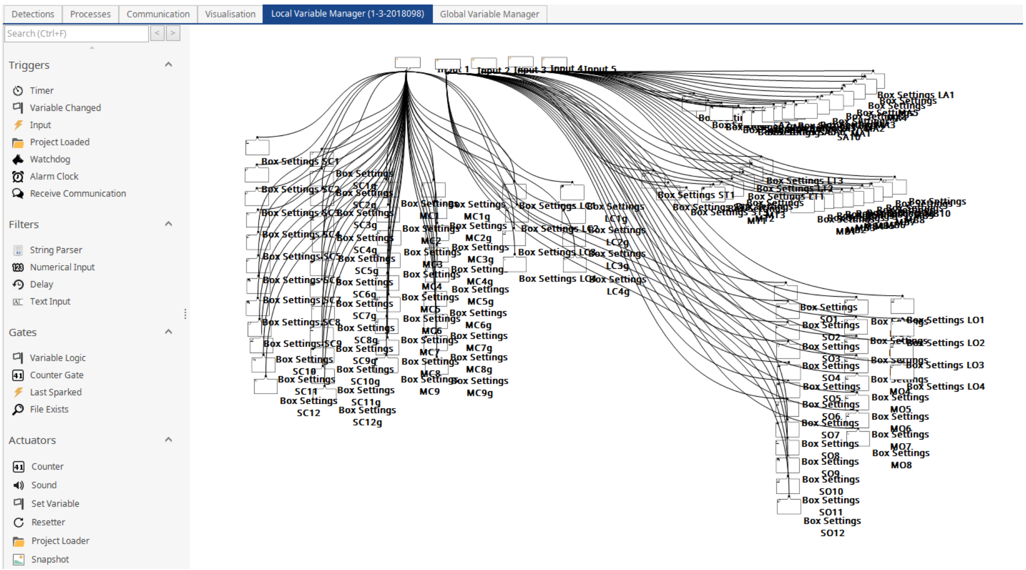


**Figure 4.6:** Local variable manager, a part of the workaround solution for the detection part, shown in the HIM software.

The local variable manager is then activated and the name and the coordinates for the detection are sent to the HIM unit from the artifact. This then changes the position of the detection teaching boxes, to the correct position of the corresponding detection. The operator still needs to manually teach the detection through the steps described in section 4.1.1, but the naming and location of the detection has already been set. A downside to this template project workaround is that the unused dummy detections needs to be manually removed from the project once the commissioning is complete. This is a simple task to complete, but it adds another step to the commissioning.

#### 4.2.1.2 Processes and Images

The next step that was digitized was the creation of processes and process steps. Through the API of the HIM unit it was possible to add multiple kinds of process steps to a process, where each step required various information. In order to focus on the set up of MTM-SAM related instructions, the steps shown in Table 4.2 were used. The top row of the table explains the process steps while the three rows below that displays the associated action of the process step. In Table 4.2, Virtual buttons are pressed and activities, such as threading a screw are performed.

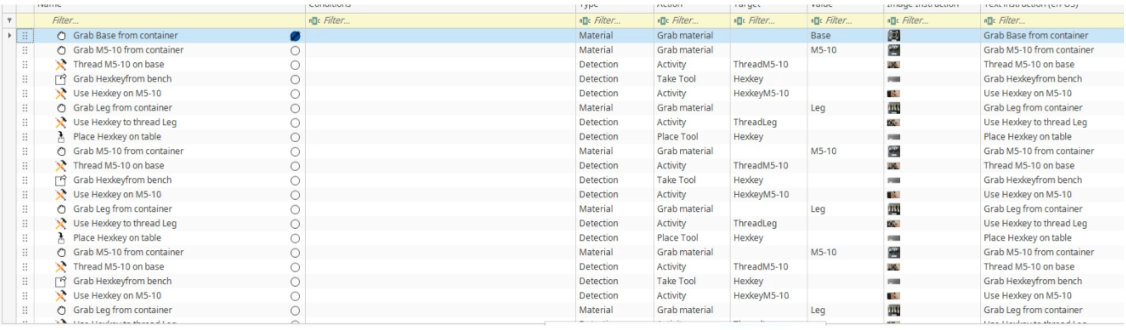
**Table 4.2:** Table of added process steps through the artifact.

| Container | Tool | Object | Material | Virtual Button | Activity |
|---|---|---|---|---|---|
| Take | Take | Take | Take | Press | Perform |
| Place | Place | Place | | | |
| Take From | | | | | |

There are many industry standards of how to create work instructions. Even though

MTM offers a framework for developing work instructions, many companies change them to better suit their own specific case. This posed an issue when trying to automate the addition of process steps to the HIM unit, due to the dynamic code needed to cover all possible cases. In order to get a solution that would be able to be used in multiple cases, a standardized excel spreadsheet was developed. The spreadsheet worked as a template, where the work instructions related to the assembly station could be translated in a standardized way. This excel spreadsheet is presented in in Appendix B.

The artifact was then able to process the spreadsheet and make the right API calls in order to create the right processes and process steps. The software also linked the process steps to the right detection previously created. Therefore the chronological order of first creating the detections were essential in the artifact. When the process steps has been sent they are also connected to the correct image from the artifact, and are ready to be used, seen in Figure 4.7.



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Filter... | | Filter... | Filter... | Filter... | Filter... | Filter... | Filter... |
| Grab Base from container | ● | | Material | Grab material | | Base | | Grab Base from container |
| Grab M5-10 from container | ○ | | Material | Grab material | | M5-10 | | Grab M5-10 from container |
| Thread M5-10 on base | ○ | | Detection | Activity | ThreadM5-10 | | | Thread M5-10 on base |
| Grab Hexkeyfrom bench | ○ | | Detection | Take Tool | Hexkey | | | Grab Hexkeyfrom bench |
| Use Hexkey on M5-10 | ○ | | Detection | Activity | HexkeyM5-10 | | | Use Hexkey on M5-10 |
| Grab Leg from container | ○ | | Material | Grab material | | Leg | | Grab Leg from container |
| Use Hexkey to thread Leg | ○ | | Detection | Activity | ThreadLeg | | | Use Hexkey to thread Leg |
| Place Hexkey on table | ○ | | Detection | Place Tool | Hexkey | | | Place Hexkey on table |
| Grab M5-10 from container | ○ | | Material | Grab material | | M5-10 | | Grab M5-10 from container |
| Thread M5-10 on base | ○ | | Detection | Activity | ThreadM5-10 | | | Thread M5-10 on base |
| Grab Hexkeyfrom bench | ○ | | Detection | Take Tool | Hexkey | | | Grab Hexkeyfrom bench |
| Use Hexkey on M5-10 | ○ | | Detection | Activity | HexkeyM5-10 | | | Use Hexkey on M5-10 |
| Grab Leg from container | ○ | | Material | Grab material | | Leg | | Grab Leg from container |
| Use Hexkey to thread Leg | ○ | | Detection | Activity | ThreadLeg | | | Use Hexkey to thread Leg |
| Place Hexkey on table | ○ | | Detection | Place Tool | Hexkey | | | Place Hexkey on table |
| Grab M5-10 from container | ○ | | Material | Grab material | | M5-10 | | Grab M5-10 from container |
| Thread M5-10 on base | ○ | | Detection | Activity | ThreadM5-10 | | | Thread M5-10 on base |
| Grab Hexkeyfrom bench | ○ | | Detection | Take Tool | Hexkey | | | Grab Hexkeyfrom bench |
| Use Hexkey on M5-10 | ○ | | Detection | Activity | HexkeyM5-10 | | | Use Hexkey on M5-10 |
| Grab Leg from container | ○ | | Material | Grab material | | Leg | | Grab Leg from container |

**Figure 4.7:** Process sent form API that are ready to use, shown in HIM software.

In the artifact, the user was able to select images to be used in the visualization of the instructions. These images were selected and linked with the work process steps to automatically be shown together with the work instruction through either projection or on the screen. The linking of the image and the process step was done through the name of the image, and the name of the object in the step.

### 4.2.2 The Artifact

In this section, the software that was developed as an artifact is presented and explained in detail. First an initialization window was necessary to connect the artifact to the HIM unit, seen in Figure 4.8. Here the IP address of the HIM unit, project and unit was selected in order to connect the artifact to the correct technical address.

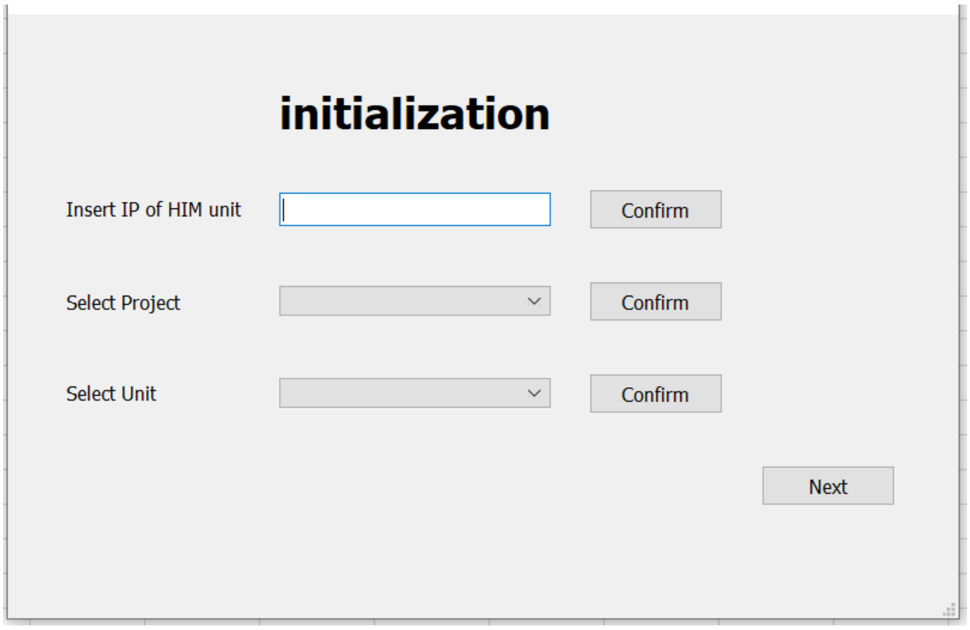
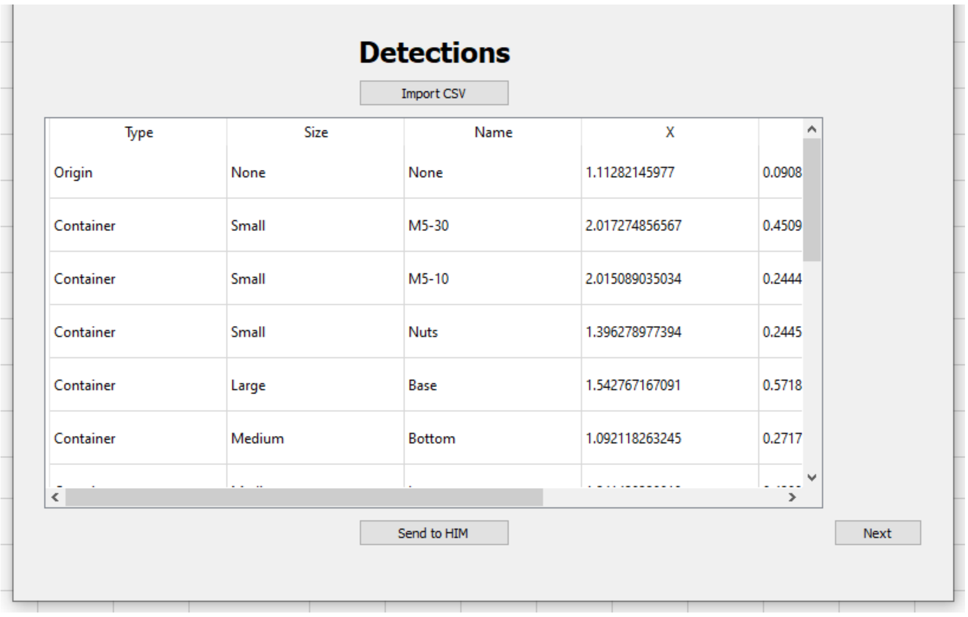


**Figure 4.8:** Initialization screen of the artifact, setting up the connection.

After the connection has been established between the artifact and the HIM unit, the detection information is sent from the artifact to the HIM unit. Detection data is sent first because this information is the basis for later information in both process and images. After the Cloud Compare preparation has been made, this data is sent as a CSV file to the artifact to be sent on to the HIM unit. This can be seen in Figure 4.9.

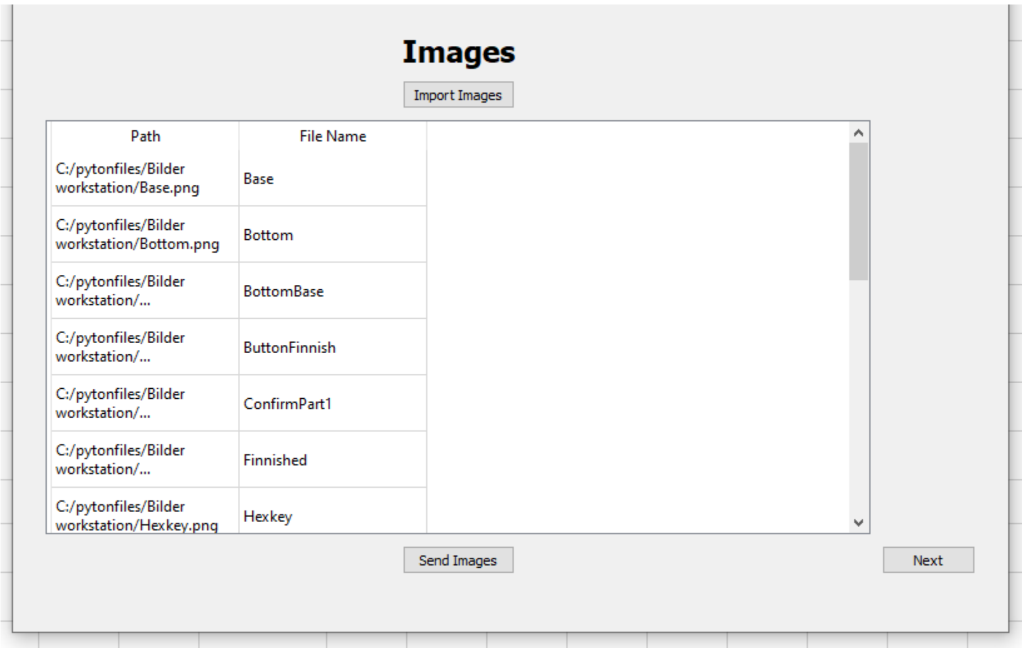


| Type | Size | Name | X | |
|---|---|---|---|---|
| Origin | None | None | 1.11282145977 | 0.0908 |
| Container | Small | M5-30 | 2.017274856567 | 0.4509 |
| Container | Small | M5-10 | 2.015089035034 | 0.2444 |
| Container | Small | Nuts | 1.396278977394 | 0.2445 |
| Container | Large | Base | 1.542767167091 | 0.5718 |
| Container | Medium | Bottom | 1.092118263245 | 0.2717 |

**Figure 4.9:** Detection screen of the artifact, importing CSV files from Cloud Compare.

The detections page in the artifact imports information about type, size, name and coordinates from Cloud Compare seen in the columns in Figure 4.9. The coordinate information for x, y and z is sent to variables in the HIM systems local variable manager to partially change the position of teaching boxes. After the information has been sent to the HIM unit, commissioning work is still needed in the detections, because of the low level of interoperability with API.

When the detections have been created, images are sent to the HIM unit from the artifact. Figure 4.10 show the artifact parts that relates to this.

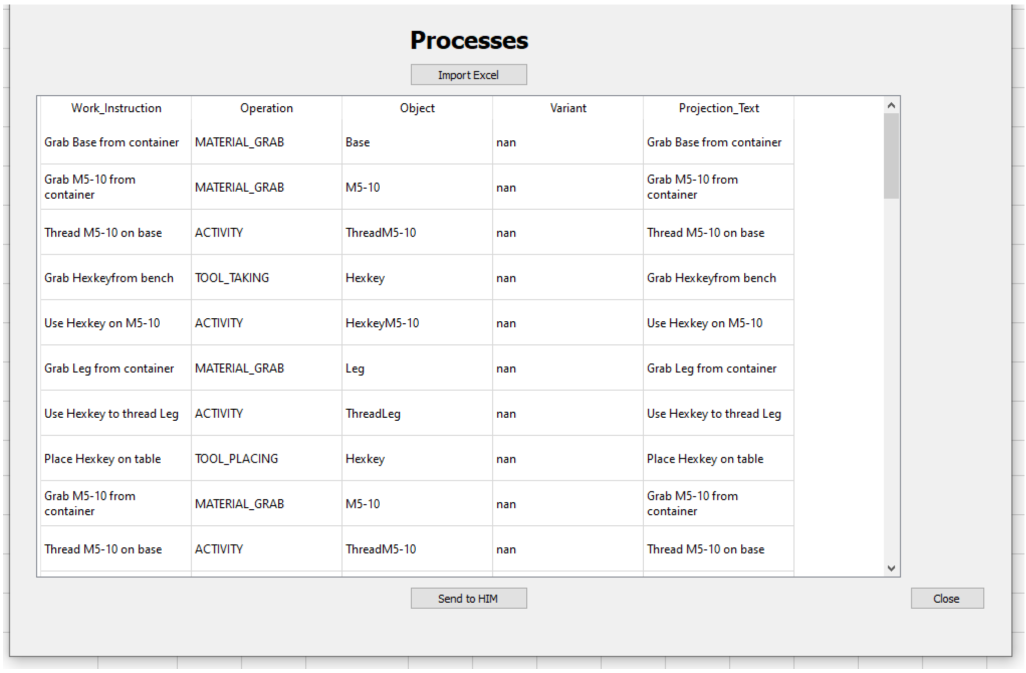


| Path | File Name |
|---|---|
| C:/pytonfiles/Bilder workstation/Base.png | Base |
| C:/pytonfiles/Bilder workstation/Bottom.png | Bottom |
| C:/pytonfiles/Bilder workstation/... | BottomBase |
| C:/pytonfiles/Bilder workstation/... | ButtonFinnish |
| C:/pytonfiles/Bilder workstation/... | ConfirmPart1 |
| C:/pytonfiles/Bilder workstation/... | Finnished |
| C:/pytonfiles/Bilder workstation/Hexkey.png | Hexkey |

**Figure 4.10:** Image screen of the artifact, selecting and sending the images to the HIM unit through the API.

Figure 4.10 shows the selected images that are prepared to be sent with the API. The name of these images must be the same as the process they are connected to, which must be done beforehand.

The last commissioning part to be sent are the process steps which are selected from Excel and imported into the artifact. They then matched with the images from earlier and merged when creating the process steps. The way this is done through the artifact is seen in Figure 4.11.



| Work_Instruction | Operation | Object | Variant | Projection_Text |
|---|---|---|---|---|
| Grab Base from container | MATERIAL_GRAB | Base | nan | Grab Base from container |
| Grab M5-10 from container | MATERIAL_GRAB | M5-10 | nan | Grab M5-10 from container |
| Thread M5-10 on base | ACTIVITY | ThreadM5-10 | nan | Thread M5-10 on base |
| Grab Hexkeyfrom bench | TOOL_TAKING | Hexkey | nan | Grab Hexkeyfrom bench |
| Use Hexkey on M5-10 | ACTIVITY | HexkeyM5-10 | nan | Use Hexkey on M5-10 |
| Grab Leg from container | MATERIAL_GRAB | Leg | nan | Grab Leg from container |
| Use Hexkey to thread Leg | ACTIVITY | ThreadLeg | nan | Use Hexkey to thread Leg |
| Place Hexkey on table | TOOL_PLACING | Hexkey | nan | Place Hexkey on table |
| Grab M5-10 from container | MATERIAL_GRAB | M5-10 | nan | Grab M5-10 from container |
| Thread M5-10 on base | ACTIVITY | ThreadM5-10 | nan | Thread M5-10 on base |

**Figure 4.11:** Process screen of the artifact, importing selecting instructions from Excel and sending them to the HIM unit.

Figure 4.11 shows work instruction, operation, object and projection text in each column. Work instructions and projection text is the text that is later shown as instructions for the operator. Operation is set for the program to understand which type of process step is created. Object is the name of the part, tool or activity being performed, which in the system much correspond to the detection and image.

This artifact was put to the test in research question 3 which aimed at comparing it to the current commissioning method.

## 4.3 Answering Research Question 3

### What are the effects in terms of time and cost of digitizing the commissioning parts of the HIM system?

Experiments were performed to answer research question three. This section goes over the results from the experiment that was performed commissioning the HIM system. These results are presented in graphs and tables with a systematic approach, going from top to bottom. It then analyzes the time data from the experiments even further to draw more generalized conclusions regarding the commissioning of the HIM system. Here equations are presented based on the experiment data to further analyse the experiment financially. Finally, The equations are used as a basis for the economic evaluation of the experiment.

### 4.3.1 Experimental Results

In order to evaluate the effects of digitizing the commissioning process of the HIM system, an experimental commissioning of the system was performed. The experimental design was explained in section 3.2.2. In these experiments, the HIM system was commissioned at an existing workstation, using both the current commissioning method, as well as the new virtual commissioning method. Several iterations of the different commissioning methods were performed and filmed. Times stamps were then extracted from these videos and classified in order to determine how much time was spent on each part of the commissioning process. The various parts of the commissioning process were divided into the following categories.

- Active Time
- Loading HIM unit
- Loading Artifact
- Clean Up

The "Active Time" category classifies time when the operator is actively commissioning the HIM system and working with the commissioning steps. The "Loading HIM" unit category consists of time spent waiting on the HIM unit to process information provided through the HIM units own software. The "Loading Artifact" category is when the HIM unit is processing information sent through the developed artifact. Finally, the "Clean Up" category consists of time spent by the operator cleaning up the template project used for the digitized commissioning.

The results from the averaged times of the comparison between Virtual Commissioning (VC) with the artifact and the Current Commissioning (CC) are visualized in Figure 4.12.

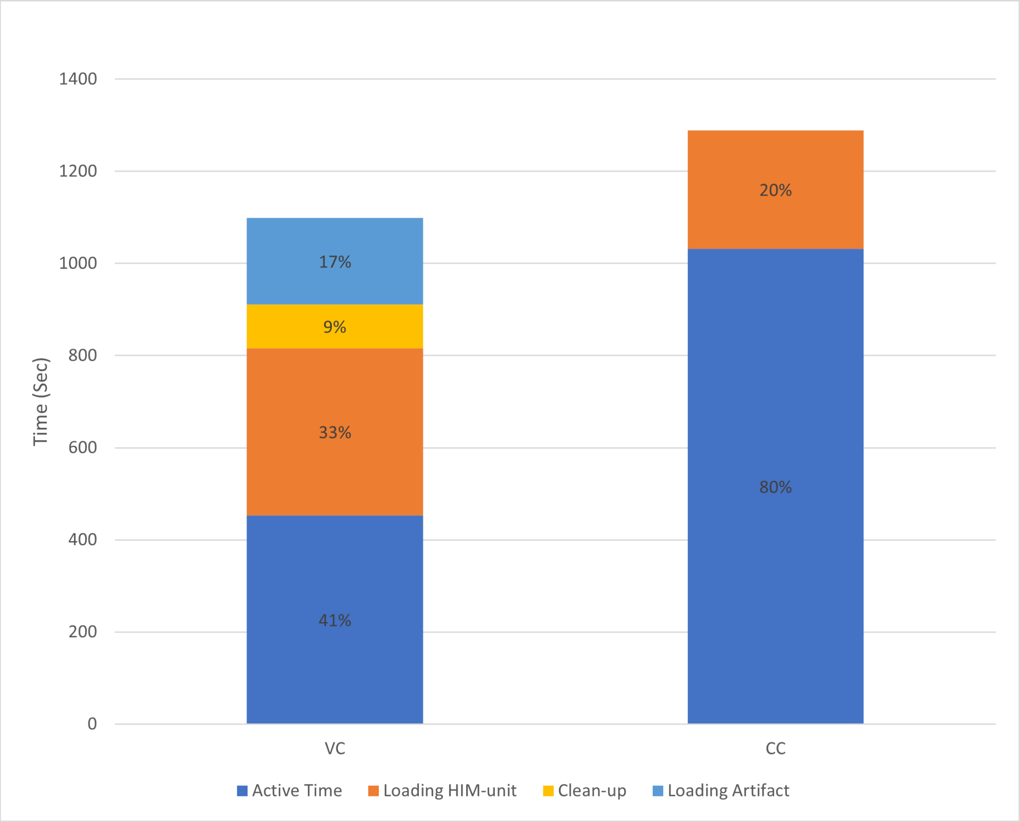


**Figure 4.12:** A visualization of the total commissioning time for virtual commissioning (VC) and the current commissioning (CC).

As seen in Figure 4.12 the virtual commissioning managed to decrease the total time. The largest reduction was achieved in the "Active Time" category. Figure 4.12 also shows that the added "Clean Up" and "Loading Artifact" categories, which are only present in the virtual commissioning however added some time to these experiments. An interesting note was that the loading time for the HIM unit was increased in the virtual commissioning. The percentile time differences between virtual commissioning and current commissioning are presented in Table 4.3.

**Table 4.3:** Percentage time difference between the two commissioning methods per category.

| | Percentile Time Difference |
|---|---|
| Active Time | - 56 % |
| Loading HIM unit | + 41 % |
| Total Time | - 15 % |

The results shows that the total time of commissioning was decreased to 85 % of the current commissioning time, which reflects 3 minutes and 11 seconds. The active time spent on the virtual commissioning was decreased to 44 % of the active time of the current commissioning, which equals a reduction of 9 minutes and 39 seconds. The loading time of the HIM unit was increased to 141 % of the current loading time, which equals 1 minute and 46 seconds. The clean up and loading of the artifact, which were added during the virtual commissioning took 1 minute and 35 seconds, and 3 minutes and 8 seconds respectively.

In order to gain further insights into how the digitized commissioning process differed from the physical one, the time data was further categorized to include time spent on detections, processes, images and miscellaneous activities. These miscellaneous activities include activities which didn't fit into any other category such as adjusting location of projected instructions. The results from this categorization are seen in Figure 4.13

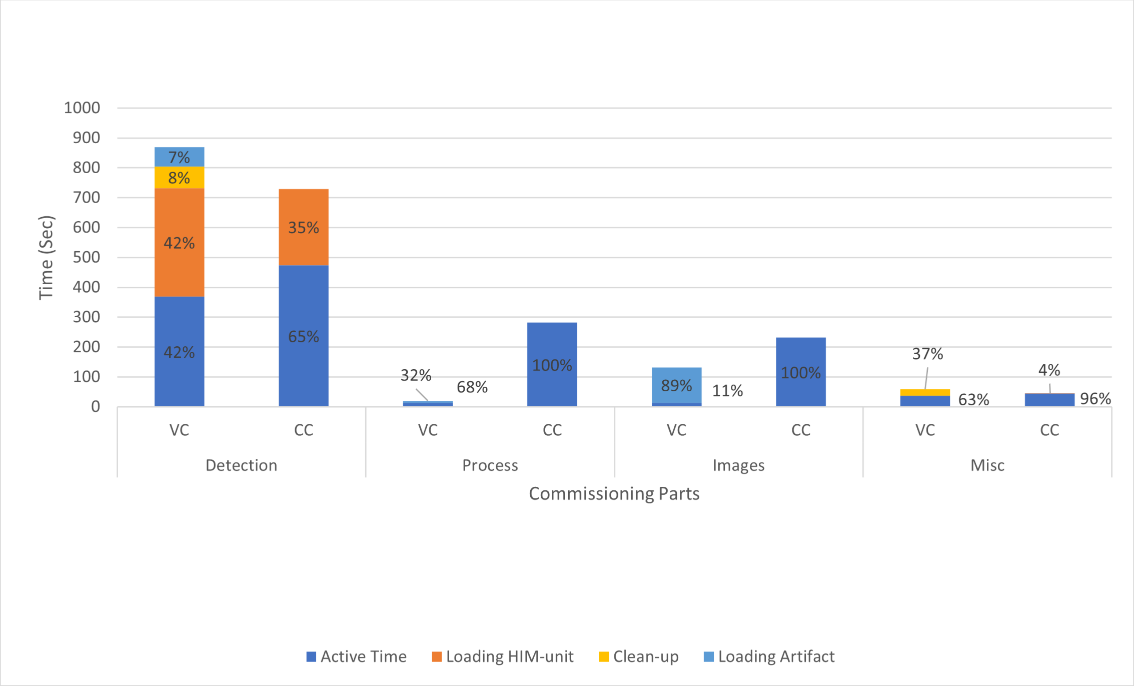


**Figure 4.13:** Average times of the commissioning parts of virtual commissioning (VC) and current commissioning (CC).

Figure 4.13 shows in greater detail how the different parts of the commissioning were affected by the shift to digitized virtual commissioning. It shows that the detections were currently negatively affected by the switch to a virtual commissioning. Even though the active time was decreased, the increased loading times outweighed this gain. A major improvement was however achieved in the processes, where the total time was greatly reduced. The active time in images was also greatly reduced, but a high loading time for the artifact occurred. The specific changes in time for each category are presented in Table 4.4. The times presented in the table are positive if the time was shortened through virtual commissioning, and negative if they were increased.

**Table 4.4:** Time gained or lost by switching to virtual commissioning per category.

| | Detection | Process | Images | Misc |
|---|---|---|---|---|
| Active Time | + 1:45 | + 4:24 | + 3:38 | + 0:07 |
| Loading HIM unit | - 1:47 | 0 | 0 | + 0:02 |
| Clean Up | - 1:13 | 0 | 0 | - 0:22 |
| Loading Artifact | - 1:04 | - 0:06 | - 1:58 | 0:00 |
| Total Time | - 2:19 | + 4:22 | + 1:40 | - 0:14 |

The percentile amount of time gained or lost for active time, loading HIM unit and total time are displayed in Table 4.5

**Table 4.5:** Percentile difference in time between virtual and current commissioning per category.

| | Detection | Process | Images | Misc |
|---|---|---|---|---|
| Active Time | - 22% | - 95% | - 94% | - 15% |
| Loading HIM unit | + 42% | | | 0% |
| Total Time | + 19% | - 93% | - 43% | + 30% |

Table 4.4 and 4.5 shows where the largest gains and losses were in the switch to virtual commissioning. The largest gains were achieved in the processes tab where the virtual commissioning only took 7% of the time compared to the current commissioning. The largest percentile loss was shown in the Misc category, but this still amounted to a small amount in the total commissioning time. As for the detections, the virtual commissioning took 19% longer than the current commissioning, mainly due the the increase in loading times for this category.

In order to better understand how the creation of detections were affected by the switch to virtual commissioning, the time needed to create each type of detection was further analyzed. Figure 4.14 shows the average time shifted for each detection type, between work and loading times when using the current commissioning and virtual commissioning.

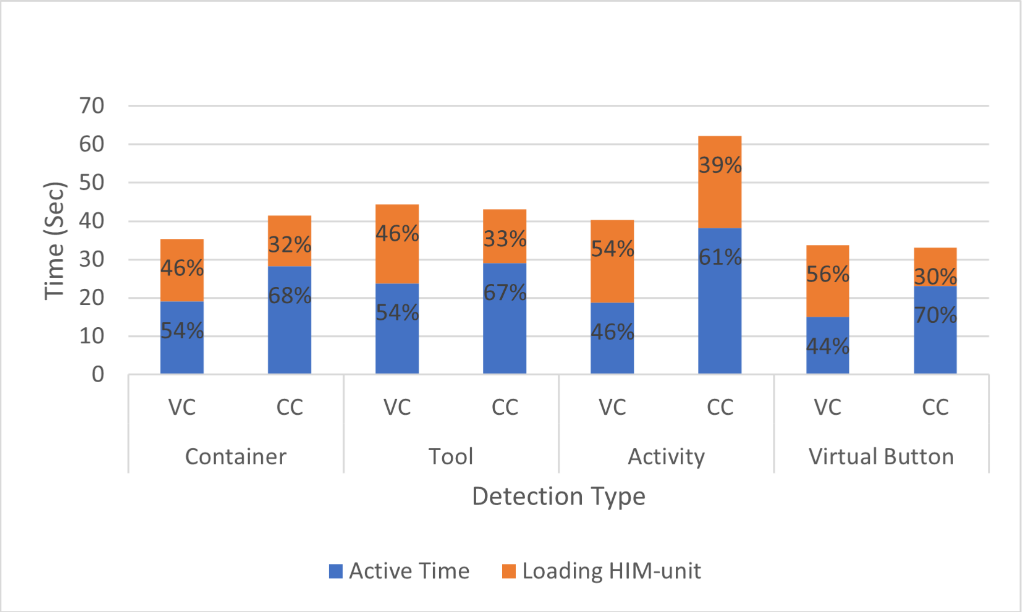


**Figure 4.14:** Time shift for detections between virtual commissioning (VC) and the current commissioning (CC).

As seen in Figure 4.14 the average time for creating tools and virtual buttons are almost unchanged for the switch to virtual commissioning, due to the increase in loading times. The largest difference is noted in the activity category. Table 4.6 shows the percentile difference in both active time and loading time comparing the virtual commissioning to the current commissioning.

**Table 4.6:** Average percentile time difference per type of detections compared to the current commissioning.

| | Active Time | Loading Time |
|---|---|---|
| Container | - 32 % | + 23 % |
| Tool | - 18 % | + 47 % |
| Activity | - 51 % | - 10 % |
| Virtual Button | - 35 % | + 88 % |

Table 4.6 shows that there is a noticeable difference between the different types of detections. All categories had a decrease in active time, but only activities category also had a decrease in loading time. The largest increase in loading time was for virtual buttons, which almost doubled.

Virtual commissioning includes preparation work that is performed in the office before the HIM can be commissioned on location. This work is done in Cloud Compare for detections and Excel for processes. The Images were also organized with the correct name. This preparation work replaces the cognitive work load while commissioning in production. The times from this preparation can be seen in 4.15.

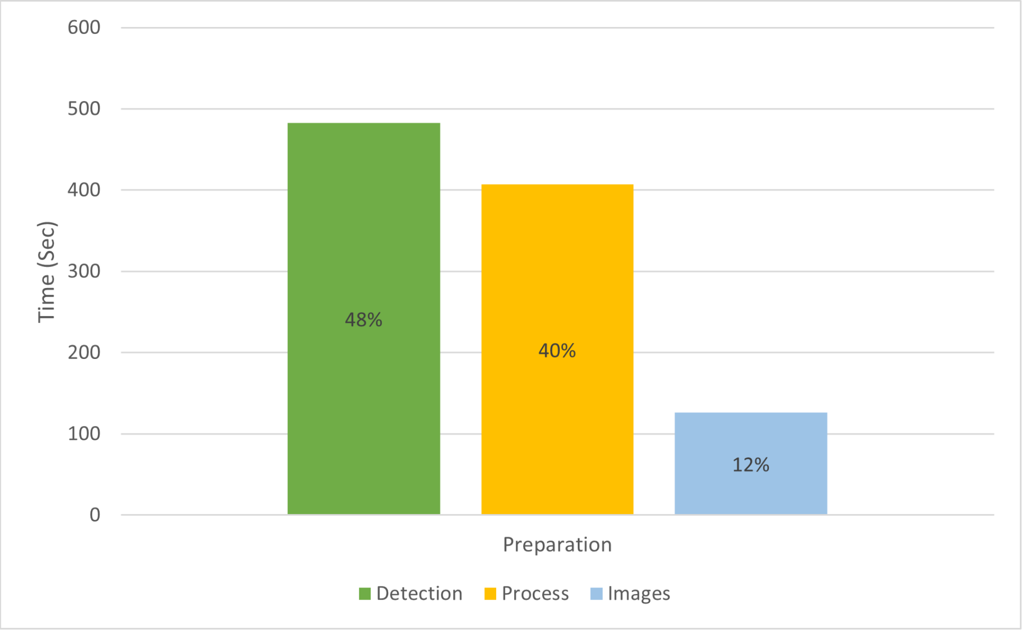


**Figure 4.15:** A visualization of the time spent for preparing the Virtual Commissioning.

As seen in Figure 4.15, almost half of the preparation work is spent on defining the detections in Cloud Compare. For this specific commissioning project, the total time spent on preparation amounted to 16 minutes and 55 seconds.
Each one of these parts were prepared for the artifact from the same general instructions that was used by the Current Commissioning in the experiment at the SII-lab. These instruction were analysed and entered in to Cloud Compare, Excel or as an Image name respectively.

The total comparative times can be seen when the preparation is added to the result from Figure 4.13. This result gives the total time consumed for the Virtual Commissioning and the Current commissioning presented in Figure 4.16.

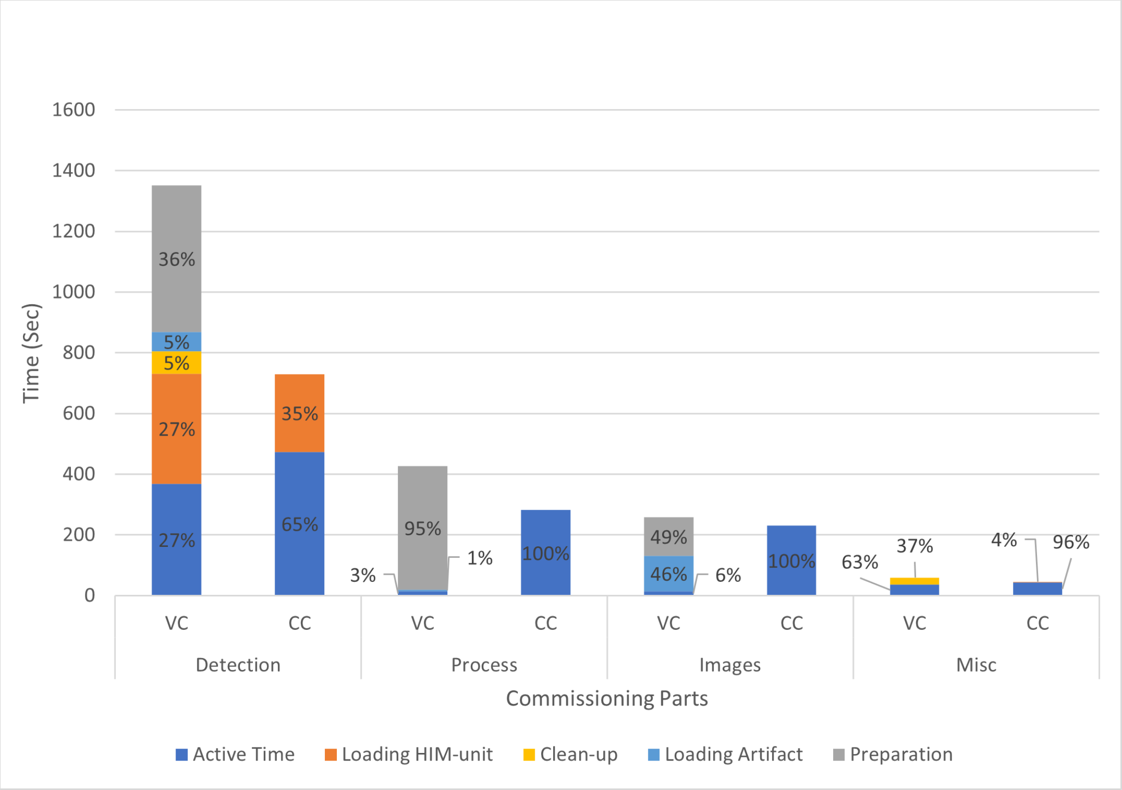


**Figure 4.16:** A visualization of the total commissioning times including preparation for virtual commissioning (VC) and current commissioning (CC).

The time from the preparation increased the total times for detections, process and images respectively. Because of the added times from the preparations the current commissioning was faster in most categories. This can also be seen in Table 4.7 where the preparation times leads to a substantial increase in both detections and processes.

**Table 4.7:** Total time and percentile increase of virtual commissioning when including preparation time.

| | Detection | Process | Images |
|---|---|---|---|
| Preparation Time | + 08:03 | + 6:46 | + 2:06 |
| Percentile Increase | 56% | 2 061% | 96% |

## 4.3.2 Time Evaluation

In order to evaluate the potential for virtual commissioning of the HIM system on workstations other than the one used in this experiment, the times from the experiments were further evaluated. The times derived from this section were all based on the recordings from the experiments and was later used as the basis for the economic evaluation in section 4.3.3. Certain times of the commissioning were dependant on the size of the project being commissioned, while others remained constant regardless of size. The main determining parameters in this regard was the amount of detections and process steps involved in the project. In the virtual commissioning, the amount of images were directly linked to the amount of detections and were thus affected in the same scale. By analyzing the experimental recordings and determining which times could be considered as variable depending on project size, and which were constant, theoretical times for commissioning could be extracted. By dividing the total amount of variable time for detections and images with the amount of detections in the experiment, as well as the variable process times with the amount of process steps, it was possible to get the average time spent on each of these parts. By further dividing these times into times spent on location and time spent preparing, the times shown in Table 4.8 were extracted. This division between time spent on location, and time spent preparing was important for the economic evaluation.

**Table 4.8:** Variable and constant times for the virtual commissioning taken from the experiments.

| | Sec spent on location | Sec spent preparing |
|---|---|---|
| Detection & Image Variable | 52 | 36 |
| Detection & Image Constant | 170 | 30 |
| Processes Variable | 0 | 26 |
| Processes Constant | 20 | 0 |
| Misc Constant | 78 | 0 |

The variable times in Table 4.8 are the average amount of time needed to create one instance of that category. For example, in order to create one detection, 52 seconds needed to be spent on location, and 36 seconds were spent in the office preparing it. Additionally, the constant times were included in the commissioning regardless of project size. For detections this could be reflected in time spent on the artifact loading the CSV file.

In a similar way, the times gathered from the current commissioning could also be broken down. The difference in this case was that the time spent on the images were instead related to the amount of process steps, and not the amount of detections as in the case of virtual commissioning. Similarly in this case the recordings of the current commissioning were analyzed to extract the variable and constant times, seen in Table 4.9

**Table 4.9:** Variable and constant times for the current commissioning taken from the experiments.

| | Seconds spent on location |
|---|---|
| Detection Variable | 46 |
| Processes & Image Variable | 32 |
| Misc Constant | 46 |

The total time spent on-site for a theoretical virtual commissioning could thus be calculated by multiplying the variable times with the number of detections or processes and adding the constant times. These values are found in the first column in Table 4.8. This can be seen in equation

$$T_{location} = 52 * X_{detection} + 268 \tag{4.1}$$

where $T_{location}$ is the time spent on location during the virtual commissioning in seconds and $X_{detection}$ is the number of detections included in the project. The amount of processes were not relevant for the commissioning time on location, since their variable time is 0 in Table 4.8.

Similarly, the time spent on preparing the virtual commissioning could be calculated through the values in the second column in Table 4.8. This equation was formulated as

$$T_{prep} = 36 * X_{detection} + 25 * X_{process} + 30 \tag{4.2}$$

where $T_{prep}$ is the total time preparing the commissioning in seconds and $X_{process}$ is the number of processes. The total time spent on the virtual commissioning could thus be expressed as

$$T_{VC} = T_{Prep} + T_{location} = 88 * X_{detection} + 25 * X_{process} + 298 \tag{4.3}$$

where $T_{VC}$ is the total time spent on virtually commissioning the HIM system at a workstation in seconds.

From the values in Table 4.9 a similar equation regarding the current commissioning was derived. Since there was no preparation work done in the current commissioning, only the time spent on location was relevant. This equation was formulated as

$$T_{CC} = 46 * X_{detection} + 32 * X_{process} + 46 \tag{4.4}$$

where $T_{CC}$ is the total time, in seconds, spent on the current commissioning of the HIM system. Since each process step added in a project was related to an existing detection, the amount of process steps had to be at least equal to the amount of detections. Thus

$$X_{process} \geq X_{detection} \tag{4.5}$$

for all projects being commissioned on the HIM system.

The amount of time spent on location during the commissioning is of great relevance when evaluating the financial impact of the switch to virtual commissioning. The goal of the virtual commissioning is to spend less time on location commissioning the system. Through equation 4.1 and equation 4.4 it's possible to find a minimal project size of when more time is spent on location performing the current commissioning compared to virtually commissioning called the breaking point. In order to achieve this, equation 4.1 needs to be greater than 4.4, which is expressed as

$$46 * X_{detection} + 32 * X_{process} + 46 \geq 52 * X_{detection} + 268 \tag{4.6}$$

which in turn can be expressed as

$$X_{process} \geq \frac{3 * X_{detection} + 111}{16} \tag{4.7}$$

Equation 4.5 and 4.7 gives a breaking point of the size of the project where more time is expected to take place on location during the current commissioning.

### 4.3.3 Economic Evaluation

Research question three aimed to analyze the effect in cost of digitizing the commissioning of the HIM system. This was done by taking the times derived from the experiments in section 4.3.2. Due to the novel nature of this technology, the economic evaluation was performed using the times gathered from the experiments. The economic evaluation was performed using CPPD and wage cost as metrics. These costs were evaluated over 15 theoretical commissioning projects, for companies at various sizes.

As seen in section 4.3.2 the size of the project had a large determining factor regarding the time it takes to commission. Table 2.3 shows the hourly cost of planned production downtime for manufacturing companies of various sizes. At the same time, there was also a cost associated with the wage of the individual performing the commissioning. While the cost associated with planned production downtime only was associated with the time spent on location, the wage cost was associated with both the time spent on location as well as the preparation time.

In order to give an idea of the economic impact of using the different commissioning strategies, hypothetical projects were used. These projects consisted of different amounts of detections and process steps. The projects were created to have a realistic ratio between the amount of detections and process steps. The specifics of these projects are seen in Table 4.10.

**Table 4.10:** Amount of detections and process steps in theoretical projects.

| Project | Detections | Process steps |
|---|---|---|
| 1 | 5 | 5 |
| 2 | 5 | 10 |
| 3 | 10 | 10 |
| 4 | 10 | 15 |
| 5 | 10 | 20 |
| 6 | 15 | 15 |
| 7 | 15 | 30 |
| 8 | 15 | 45 |
| 9 | 20 | 20 |
| 10 | 20 | 40 |
| 11 | 20 | 60 |
| 12 | 30 | 30 |
| 13 | 30 | 60 |
| 14 | 30 | 90 |
| 15 | 30 | 120 |

By applying equations 4.1, 4.2 and 4.4 on the different projects, it's possible to estimate how much time would be spent commissioning each project. The results of these calculations are seen in Figure 4.17

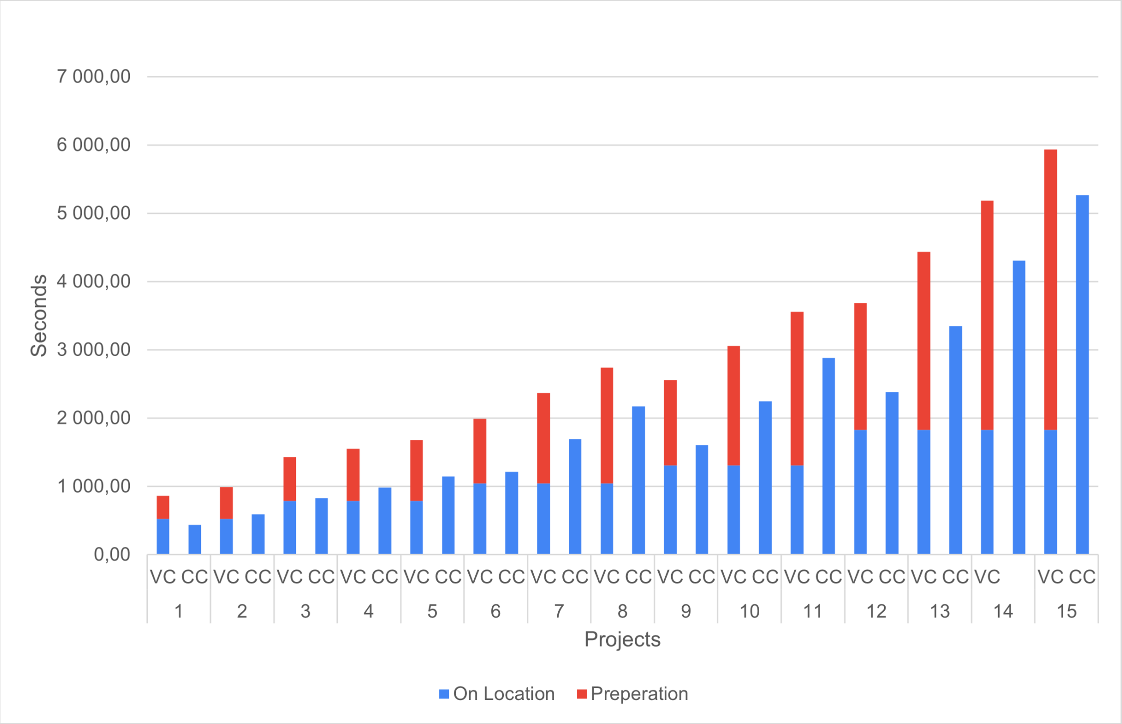
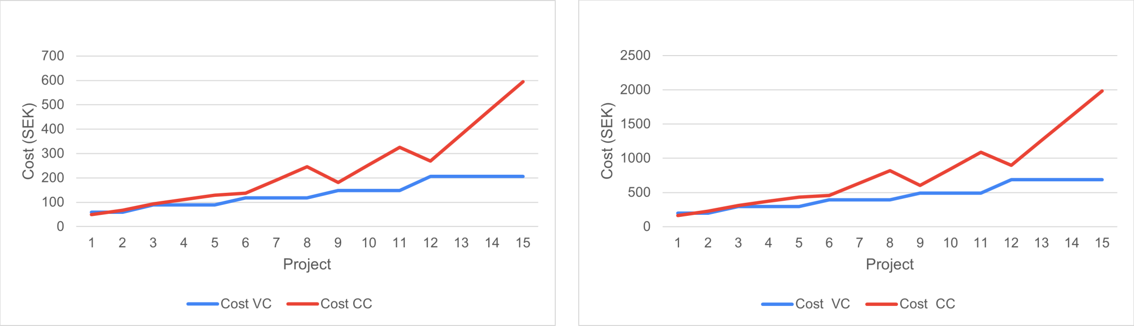


**Figure 4.17:** Time, in seconds, needed to commission theoretical projects using virtual commissioning (VC) and current commissioning (CC).

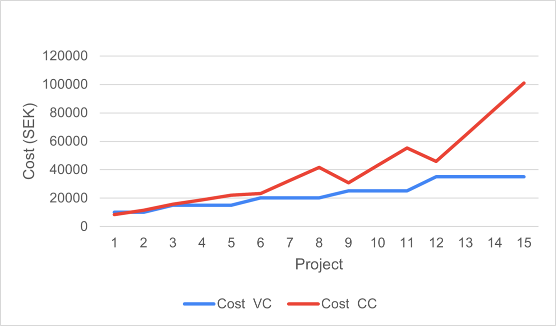
As seen in Figure 4.17 all commissioning projects takes longer time when being virtually commissioned. The time on location is only longer in the first project, where there are few detections and few process steps.

The first economic evaluation that was made was the CPPDof the different projects. By converting the hourly cost presented in Table 2.3 to cost per second and then multiplying with the active time of each project it is possible to see how much they would cost regarding CPPD. These cost are seen in Figure 4.18



**(a)** CPPD small company

**(b)** CPPD medium company

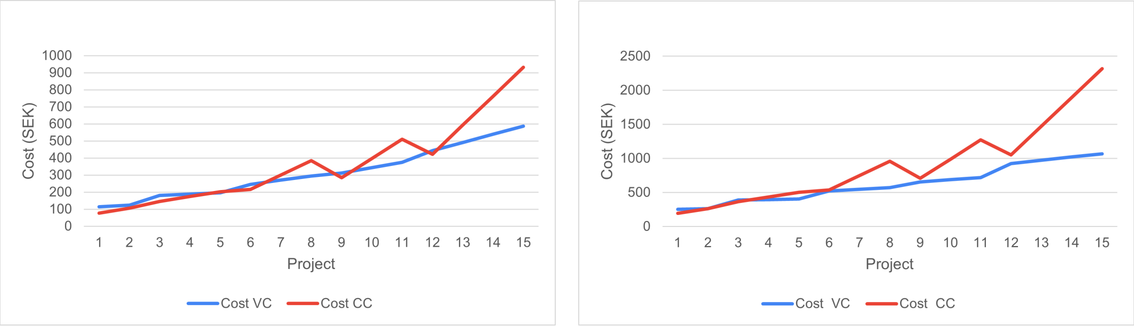


**(c)** CPPD large company

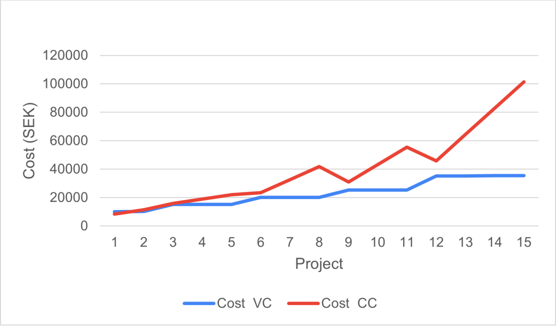
**Figure 4.18:** Cost of Planned Production Downtime (CPPD) when commissioning projects on three companies usin virtual commissioning (VC) and current commissioning (CC).

As seen in Figure 4.18 the CPPDregarding virtual commissioning is almost equal to the CPPD of the current commissioning in projects using few detections, or about equal rate of detections and process steps. There is a substantial difference in the scale of the CPPDfor small, medium and large companies.

In order to further evaluate the economic situation regarding the commissioning, the wage of the person commissioning the HIM system was also taken into account. For this evaluation it was assumed that the person commissioning the HIM system has an engineering background with a few years of experience. According to Sveriges Ingenjörer (2020) an estimated gross wage for this is 40 000 SEK/month, which equals 0.064 SEK/second. By including this cost over the entire commissioning time, further insights were gained regarding the cost of commissioning. This is seen in Figure 4.19.



**(a)** Cost small company **(b)** Cost medium company



**(c)** Cost large company

**Figure 4.19:** Cost for commissioning projects on three companies of different size using virtual commissioning (VC) and current commissioning (CC).

The inclusion of wage cost in the cost evaluations had the most significant effect in the cost for small companies, as seen if Figure 4.19a. In several of the smaller to mid size projects it was often marginally cheaper, or equally costly to use the current commissioning compared to the virtual commissioning. Only when commissioning larger projects with a higher ratio of process steps than detections, there was a financial gain with virtual commissioning.

Regarding medium sized companies, seen if Figure 4.19b, there was a slightly higher financial gain regarding the virtual commissioning especially for the larger projects. For the smaller and medium sized projects it was generally not worth using virtual commissioning. The same was true for projects with equal amount of detections and process steps.

As for the large size companies, seen in Figure 4.19c, virtually commissioning the HIM system had a much higher potential of profitability. In the smallest project it was still cheaper to use the current commissioning method, but for the rest of the projects there was a quite substantial financial gain of the virtual commissioning.

# 5

# Discussion

In this chapter, the general HIM system and the theme for the thesis is discussed to find out how the choice of study affected the results. After that, the methodology is discussed to find aspects that could have affected the results. In this part a critical assessment is also made of the experiment performed. The results are then discussed, starting with research question one and ending with research question three. Each of the research questions are discussed separately. Sustainability is then examined in order to analyze the thesis from a environmental, social, economic and ethical perspective. After that, the contribution to research is then discussed, ending with further research being suggested based on the findings in the thesis.

## 5.1 The HIM System and Digital Transformation

The aim of the thesis is to investigate the improvement potential regarding the commissioning process associated with projection based support systems in the industry. As mentioned in chapter 1, the main benefit of using projection based systems within manual manufacturing is the cognitive support which reduces the risk of errors occurring during assembly. Another reason to implement IT support systems for manual assembly is their possibility to communicate with other systems in the larger scope of the Industry 4.0 landscape. This interoperability is a key factor in the digital transformation of manufacturing environments. When attempting the digital transformation of manual assembly support it's important to know the benefits and downsides of which systems to use.

As mentioned previously there are several benefits to using projection based systems, but there are also downsides to it. One major key component that determines if the system is beneficial or not is the lighting conditions of the assembly station. If the space around the work station is heavily illuminated, the instructions provided by the projections are difficult to discern and could cause a higher cognitive load on the operator. Also, in order for the projections based system to know where projections should be visualized, the workstation needs to remain static and unmoved. Changes to the layout of container and tools would require a new calibration of the system in order to function accurately. For the assembly, the use of fixtures are beneficial as well in order to accurately project onto the assembled part. For workstations where such features wouldn't be optimal, the projection based support systems might not perform as well. Projection based support systems also require a free path from the projector to the workstation in order to accurately show the projections. In assembly stations where this isn't possible, either due to surrounding equipment or due to the operator obstructing the projections when performing the operations, projection based support systems suffer a disadvantage when compared to other assembly support systems. Intractable on-screen instructions might, for example, be a simpler and cheaper way of providing the operator with information. Regardless of which information system ends up being used, it's important to keep in mind that it should have a high degree of interoperability with the already existing systems in order to achieve a high level of digital maturity.

Using the HIM system as a case-study of projection based systems might have influenced the results of this study. If another projection based system would have been opted for instead of the HIM system, there could have been a different outcome. Another projection based support system available on the market is the LightGuide system. The LightGuide system fulfills the same core functions as the HIM system, and would thus also have been eligible for use in this thesis. The developed methods of virtually commissioning the HIM system had a high reliance of the integrated API of the HIM system, and would thus need to be adapted to fit any other system. The software artifact was developed with the goal of increasing the digital maturity of the company commissioning the HIM system by doing so virtually. Depending on what features and API-calls might be available on other systems, a similarly developed artifact might be able to provide a higher or lower level of digital maturity than the current artifact.

## 5.2 Methods

Traditional research methodologies are based on using previous research, often from studies or literature, to build upon to further develop the field. To achieve a development with such a research methodology, data and previous research is therefore necessary. Since the research in this thesis early on became a creative endeavor of finding a technical solution for a novel problem, a methodology which set out a clear procedure for this was selected. The research methodology used to answer the research questions was mainly design science methodology, with support from both action research and case study methodologies. The novel and technical direction of the thesis meant little to no research literature was available on the topic. Therefore the design science methodology was chosen in order to facilitate a clear road map for the project, compared to other more traditional research methods.

Fundamentally, the design science methodology was created for the development of artifacts which was suitable for the thesis to answer research question two. However, the design science methodology did not lay a solid foundation for research question one and three. The methodology leaves room for creating a knowledge base in which other methodologies, such as action research and case study methodology can be used to fill. Both action research and case study methodology had complimenting traits in the gathering of data, which was used in the thesis. Nevertheless, the majority of the work was made using design research methodology, because of the time consuming development of the artifact.

Design science methodology is broad and sometimes hard to define (Buchanan, 2001). The methodology was developed in an age when industry design dealt with physical products but can be adapted to solve technical problems (Buchanan, 2001). To use a product as a center for research can lead to a lacks scientific rigor in the pursuit of a useful artifact (Buchanan, 2001).

To test the functionality and validity of the developed artifact, an experiment was created, executed and analysed. This was used to validate the usability of the artifact, and display a real comparison between the two commissioning methods, with and without the artifact software. The experiment was developed on the basis from established principles of industry experiment methodology (Coleman & Montgomery, 1993). The experiment did however deviate in parts from the methodology in order to adapt to the artifact, the Covid-19 pandemic and the limited time in the SII-lab. One cause for uncertainty in the experiment methodology was the long time for each of the experimental iteration, which meant that the data was based on fewer iterations of the experiment than would have been preferred. This can cause outliers to be over-represented and increases the risk to miss important data points. Another deviation from the methodology was the lack of an outside sourced randomized group that performs the experiment. The justification for this was that the commissioning would be carried out by a professional. The result could still have been affected from the absence of a randomised group performing the experiment. Uncertainty factors mean the experiment may have the wrong result or have a limited applicability in similar research.

A similar test was performed in the office to determine the times of the preparation, for detections, process and images. Each preparation was performed multiple times and the times were measured. This method of testing the preparation was deemed sufficient in comparison to the real experiment at the SII-lab. Although the same criticism could be pointed at this preparation experiment, with no randomized group of outside testers. More experimental iteration was however performed which may increase the quality of the data from the preparation experiment.

Overall the methodology of design research methodology was a applicable match for the technical and novel development of the artifact. With the complimenting knowledge gathering of the other methodologies, a scientific approach which both was adapted to the research question and scientific rigor could be used to answer the research questions.

## 5.3 Results

The results from each of the research questions is discussed in this section with the main findings. The implications of the findings are discussed and how they relate to the broader topic and industry in general. Furthermore, the discussion of the results brings up the limitations of this thesis and how they could have affected the results.

### 5.3.1 Discussing the Implication of Research Question 1

**What parts are involved in the current commissioning of the HIM system, and which of these parts has the potential to be digitized for virtual commissioning?**

In research question one, the commissioning was divided in to parts which were analysed from a virtual commissioning capability perspective. The first research question was also a way of understanding the HIM system. In order to improve it, technical details of the outputs, inputs and functionalities of each parts were essential to understand.

The first software part of the current commissioning that was studied in this way was the detections commissioning part. In detections, the complexity of the software and the way the teaching mechanism works made it difficult for the HIM system to incorporate API interoperability. API analysis found that the detections part was almost isolated. This limit in the interoperability of the detections, allowing it to interact with other software, was unexpected. The finding demonstrated the need to understand the interoperability of the system before starting with an artifact solution. Further analysis found that certain limited capabilities was still possible, but mainly to support the process and images parts of the commissioning.

In contrast, the process and images commissioning parts were capable to send, receive and be used in a smart way with the API. The process part could receive all the necessary information to be virtual commissioned. The images part could also be connected to the process part and be shown in the visualization on the screen and with projection on the work surface. The inherent complexity of the artifact lead to a necessary connection between the detection and process.

The lack of API capability and the interconnections of the commissioning steps meant that a work around solution was necessary for the detection commissioning part. Both workarounds were investigated to be able to integrate some API solutions to the detections. However, the workarounds did not change the fact that the detections part was isolated from a interoperability standpoint.

### 5.3.2 Discussing the Implication of Research Question 2

**How can the parts of the commissioning process with potential for digitization be modified to support virtual commissioning?**

The second research question was the most time consuming and involved the development of the artifact solution. The difficulties of implementing an artifact solution and adapting it to fit the limitations of an end program, not specifically built for that purpose, made the work complicated. In the first part of the development of the artifact, detections presented a challenge in which workarounds were used to overcome their API isolation. The workarounds lead to a higher level of complexity in the artifact. It was nevertheless necessary to integrate the detections part of the commissioning to gain the benefits from the process and image parts, because the way that they were connected. A matching characteristic had to be established to link the detections to the process steps. In this case the name of the process step and detection had to be identical for the artifact to be able to connect them.

If the detection part had a higher API capability, possible integration with 3D-scanned environments and Industry 4.0 technologies could have been feasible. Additionally, the detections development had the potential to improve the most from the current method. Instead of using the created workaround solutions a more straight forward input of locations and variables of the detection boxes, with scanning data would have created a better solution. The way the current system is structured, with time of flight pictures to teach the HIM software, an API solution is not an easy integration for ARKITE.

An important thing to note is that the software of the HIM unit is occasionally being updated as ARKITE develops it further to include new features. This means that an increase of API capabilities in the future isn't impossible. Since the sensor data that builds a detection is based on the physical world where the HIM unit is mounted, there are challenges regarding effective commissioning of the detections even if the API would allow for it. The sensors being used measures the time of flight and energy of the light reflected per detection. If ARKITE would open up the possibility to define the specific sensor values related to each detection through the API, detections could be created and taught through other means. Research has been conducted on the topic of simulating sensors similar to the ones used within the HIM unit (Landau et al., 2016). If these simulations would be able to provide accurate enough data, simulating the entire workstation of which the HIM system is commissioned might be possible. This would open up the possibility of using CAD models of standardized objects that could be detected, such as containers, tools, hands or basic activities such as screwing. Through these models a library could be built where the right simulated detection is chosen and set when needed. If it would be possible to estimate or simulate the lighting conditions of the physical workstation, both sensors would be able to be completely calibrated in the virtual space.

Process and images showed the potential of what the virtual commissioning artifact could achieve with parts that had a high API capability. The input data for the process and image parts could easily be converted into a format which the HIM unit could use. The artifact therefore made it possible to prepare these parts of the commissioning in a digital environment from a different location. The standardized API calls could perform most functions needed for this part of the commissioning.

The process steps added in this thesis followed a simple linear progression. The HIM system is however able to handle more complex processes where multiple variant of the same products are being assembled. It seemed possible to include these more complex process steps through the API, but this wasn't tried out due to time constraints.

The programming of the solution in Python with integration between multiple systems proved to be time consuming. The technical problem of weighing user friendliness in the Excel against the input constraints for the artifact was made many times. The artifact solution needed to understand certain parameters, which limited the freedom in input possibilities. Coding the solution was mainly constrained by the API calls that were possible against the HIM unit. Constraints which in the future could be removed in other projects. Other inputs were first tested in order to determine which to use. The other software inputs similar to Excel had too much input freedom that could not be locked. This meant that it was unpredictable in which way the data would be read and thus leave the artifact unable to read the input data in a standardized way.

To summarize, the results from research question two made it clear that the creation of a virtual commissioning artifact was possible for the HIM system. This could reflect a potential for the virtual commissioning of projection based support systems in general. The process is largely determined by the interoperability of the system to communicate with external programs.

### 5.3.3 Discussing the Implication of Research Question 3

**What are the effects in terms of time and cost of digitizing the commissioning parts of the HIM system?**

The third research questions result was mixed with both improvements and drawbacks in the virtual commissioning compared to the current commissioning. To start, it should be clarified that the commissioning parts detection, process and images did not all reach the same level of digitization. This can be seen in Figure 4.13 where the detection part has increased in time while a clear improvement had been made to the process and image parts. This disparity in the result was caused by the limitation in detections caused by their teaching mechanism. The mechanism was not interoperable with the API use in the artifact solution. Therefore, a complicated workaround increased the time that detection part consumed during the commissioning. The loading time increase in Figure 4.13 also displays the strain that the workaround put on the system. The template project used a total of 252 internal variables in the HIM units local variable manager to work with the detections. By keeping these variables in it's memory, the HIM unit had trouble handling other activities which required a lot of memory and thus slowed down.

Process and images did however show a clear improvement during the test with easy and ready to send commissioning parts. These parts in Figure 4.13 displayed a clear improvement and showed the possibilities with the virtual commissioning. In comparison to detections, both the process and images were interoperable with the API. This meant that no additional work had to be added after sending both parts from the artifact. One less tangible benefit of the virtual commissioning was the cognitive support it gave the operator during the work, even in the detections. The strain of commissioning the different ways was clearly noticeable. All data was already given the correct name beforehand in the virtual commissioning, both process and images were automatically added. This meant no instructions had to be analysed in the commissioning on location.

The experiment only compared the times commissioning on location. Some preparation work was needed for the virtual commissioning, seen in Figure 4.15, which added more time to the total commissioning. Total time, which is seen in Figure 4.16, demonstrates the added time needed to prepare to use the artifact, which was not optimal. The preparation work in both Excel and Cloud Compare did add a layer of quality checks to the preparation work. The preparation made the detections less efficient overall, but made it easier for the operator while performing the last step of the commissioning.

#### 5.3.3.1 Time Evaluation

For the breakdown of commissioning times into variables and constants there are a few interesting things to note. During the experiments, a single HIM unit was used. The times extracted are thus not only related to the HIM system in general, but also this specific HIM unit. Time aversions might thus exist between this unit and other HIM units depending on their age or other factors. Regarding the results of this thesis it was assumed that the HIM unit used was accurately representative of all HIM units, although this wasn't tested. Some implications of this might be that the increase in loading times for the virtual commissioning might not be as severe on another HIM unit, thus making the virtual commissioning even more profitable.

The equations derived from the time measurements gives some interesting insight into the situation regarding the virtual and current commissioning of the HIM system. Equation 4.3 and 4.4 gives the times needed to commission a project using the virtual-, and current commissioning method respectively. By equating the two equation a ratio can be achieved for when an equal amount of time is spent on the virtual commissioning and the current commissioning. This equation is written as

$$X_{process} = 6 * X_{detection} + 36 \tag{5.1}$$

This shows that when having 30 detections, a total of 216 process steps would have been needed in order to have an even commissioning time between the two methods. Since each process step is connected to an existing detection, there would need to be a lot of repetitive work for this project to be able to exist. If the project would include assembling different variants of similar products, there is a possibility for this ratio of detections and process steps to exist. This is since the process steps for each product variant would have to be separate, while still utilizing the same detections for several variants. Since the experiments focused on assembling a single product variant the ratio shown in equation 5.1 was deemed to be unrealistic to achieve in an actual project. If however more product variant would have been included, it might maybe be possible to reach a breaking point in an actual project where the current commissioning was slower in all regards when compared to the virtual commissioning.

#### 5.3.3.2 Economic Evaluation

The economic evaluation of the experiments shows that there is a clear benefit of using virtual commissioning for larger manufacturing companies, even though the total commissioning time becomes longer. For smaller to mid-size companies, there are still several occasions where using the current commissioning is more financially viable. For the smaller companies the cost difference between the current commissioning and the virtual commissioning often doesn't even pass 100 SEK, and at most in the fifteenth project there is only a 345 SEK gain for doing the virtual commissioning. Even though the cost of the HIM system remains undisclosed, the difference in commissioning cost is minuscule when compared to the cost of the HIM system itself. Even though there is a slightly larger possible gain for the medium sized companies, there's still only a gain of 1 250 SEK at most. It's only when advancing to the larger companies that substantial financial gains can be achieved with the virtual commissioning. In this case the largest gain of the theoretical projects becomes 66 000 SEK. Even in certain larger scale manufacturing companies, this gain could be deemed to be negligible on the larger scale of things.

An important note to keep in mind for the economic evaluation is that the values used for the calculations are based on the averaged values of the survey performed by Tabikh (2014). These values provides a good insight into the general financial situation of various manufacturing companies. It's however still important to note that all manufacturing companies function differently, and thus some subjective evaluation will be needed depending on which commissioning method to use. Depending on how well the company can handle planned production disturbances, the cost of commissioning may be varying quite a lot between different companies. Even though many companies try to avoid using storage buffer to avoid unnecessary overhead costs (Bergman & Klefsjö, 2010), some companies still need them as a safety net. With the relatively short time it takes to commission the HIM system on location regardless of method used, the internal buffer systems might be able to keep the rest of production running without disruption. In these cases the only financial impact of the commissioning is related to the person performing it. Thus the current commissioning method is still more economically beneficial, as it often takes a shorter time to perform over all. This doesn't however take into account some of the more intangible benefits of using virtual commissioning.

#### 5.3.3.3 Intangible Benefits of Virtual Commissioning

Shahim & Moller (2016) mentions several benefits to using virtual commissioning in the field of automation. Many of these benefits are defined as intangible, meaning that it's hard to put a monetary value on their impact. Several of these intangible benefits could be achieved by the virtual commissioning of projection based support systems as well. One such benefit is the increased deadline control associated with virtual commissioning (Shahim & Moller, 2016). By using virtual commissioning, it's possible to better prepare for the on-site commissioning and estimate the time needed to perform it. This provides a higher degree of control over the projects and allows for a prepared commissioning with with less cognitive effort.

Another intangible benefit of using virtual commissioning aligning with Shahim & Moller (2016) is the usage of reference model for future changes. Storing the data used from previous commissioning makes it possible to easier make changes to previously commissioned projects through virtual means. If new projects needs to be commissioned which are similar to older ones, it will also be possible to re-use some of the data used in the preparation of the virtual commissioning. In the long run, this makes it possible to save even more time when virtually commissioning the HIM system.

The virtual commissioning also opens the door for changes in the procedure (Shahim & Moller, 2016). The digital preparation makes it possible to gather more information before the commissioning and send the Excel file to the customer that fills in the information for the commissioning themselves, saving time. This also creates a understanding the early part of a project what the system can and cannot do. Part of the process is made user friendly and afterwards the information could be sent directly to the HIM unit, with minimal adjustments. The excel input therefore could make the overall process of commissioning more efficient.

## 5.4 Sustainability

In today's globalized world, it's important to continuously reflect on how the outcome of a project contributes to sustainable world. The concept of sustainability consists of three dimension, which should be fulfilled in order to achieve sustainability (Weinberger et al., 2015). These dimension are environmental, social and economic sustainability (Weinberger et al., 2015). This sections will cover how this project might affect each of the dimensions of sustainability.

### 5.4.1 Environmental Sustainability

By shifting work which needs to be done on location to virtual environments, the need for physical travel will be reduced. In the current commissioning of the HIM system, someone had to physically travel to the location to do the setup of the system. With the possibility to do most of the setup through a virtual environment, it is possible to send the HIM system and prepared files to the customer. This will allow them to perform the final stages of the setup on location with guidance over distance instead of on location. The secondary impacts from the virtual commissioning is the reduction in expected downtime during production. Less downtime leads to less wastes in production while commissioning the HIM unit (Franciosi et al., 2020).

### 5.4.2 Social Sustainability

The shift of task from physical to digital environments also have an impact on the social sustainability of the person performing the task. Manufacturing environments are often noisy and spending a prolonged time in them can cause a high mental strain on a person, and even cause a loss of hearing (McTague et al., 2013). By shifting task to virtual environments which can be performed in offices, the individual performing the task will suffer less of a mental load. In the case of this specific project the overall affect might not be noticeable, but with the digital transformation of several aspects of manufacturing there will be a difference.

The commissioning of the HIM systems within manufacturing environments also have an impact on the social sustainability of the operators working there. The HIM system provides cognitive support to the workers, which alleviates the mental strain they might experience over a workday. Experiencing a high cognitive load over a longer period of time can cause feelings of frustration and anger within the operator (Fässberg & Fasth, 2011). Experiencing these feelings in a workplace will create negative associations to the workplace itself for the operator which will affect their well-being.

### 5.4.3 Economic sustainability

The survey performed by Tabikh (2014), shows the financial costs associated with disturbances within production environments. Many manufacturing environments operate on tight takt times and have strict deadlines. The high implementation of lean practices within manufacturing environments can cause the effects of disturbances to ripple through the entire production flow increasing costs even further. These unforeseen costs can make it hard to calculate the profitability of production, which makes it harder to become economically sustainable (Liebaug & Hartmann, 2013). Reducing the risk of creating disturbances within production is thus financially beneficial. Ensuring that manufacturing companies are able to predict their financial situation ensures a greater job security for the people working there. Through the results of shifting parts of the commissioning process of the HIM system to a virtual environment, the time on location can be decreased which reduces the cost associated with it.

A common fear among operators in manufacturing environments is that new technological solutions will make their jobs obsolete, and thus make them unemployed. Economic sustainability should not be made on the expanse of workers. This is particularly true in the field of automation. Taking the concept of virtual commissioning, which emerged in the field of automation and applying to the field of manual assembly ensures that the operator is still the key component of the operation. This creates an economic win-win situation for both the company and the operator, where the commissioning of new technology creates less impact and the operator hold job security.

## 5.5 Ethical Aspects

Ethics in the case of this thesis work is if the technological research development leads to something good, evil or a mix of both (Hansson, 2009). Creating a tool for digitally commissioning makes it possible to work in a different way when setting up the HIM system. The commissioning tool reduces the amount of repetitive work while showing the software, and helps the worker. However, the commissioning tool can also lead to reduced travel for the worker, which could be both good or bad depending on the preference of the person. Moving the work to the office could therefore be seen as either good or bad.

The cognitive supporting technology can also affect the perceived autonomy of the worker (Cragg & Loske, 2019). Information support systems that used terminal instructions increased autonomy while pick-by-voice decreased the autonomy (Cragg & Loske, 2019). The supporting artifact developed, therefore helps the worker have alternatives while commissioning the HIM, supporting the straining work without telling them exactly what to do, as in pick-by-voice.

## 5.6 Contribution to Research

The concept of virtual commissioning, which is mainly used in robotics, include parts that are beneficial to other areas of research. Mainly the idea of preparing and moving some of the work from the on-site commissioning. This thesis used these concepts outside the field of robotics and adapted them to a novel field. The results may suggest there is potential in widening and adapting the concepts of virtual commissioning to other technologies that are commissioned in manufacturing industries.

The theoretical use of interoperability as a measurement proved useful and could be developed in this area further. API capability measurement proved potential in the virtual commissioning integration of technologies such as the information system used for this study. Using an API software to connect and integrate with common systems proved efficient and an useful tool. The standardization of the input creates a useful bridge to non-knowledgeable to use new technology in production.

## 5.7 Further Research

Future research should meet the needs of the industry and focus on the further development of all the aspects of pick-by-projection to improve the utility of the technology. The investigation and development of the artifact demonstrated the potential in integration with external solutions using API technology, in an industry setting. Without changing the HIM system, an useful artifact solution was created which shows the potential of cross-platform technology utilization. Further research into a framework and standard for the communication might enable other future solutions. The further research might include 3D-scanned data which are becoming more and more common for companies to have, and how to integrate this into virtual commissioning. Distance virtual commissioning has a potential in a more digital world. Research in this area has originally been done mainly in robotics, but was in this case applied to a different area. Further studies in other fields with virtual commissioning might lead to the same benefits experienced in robotics, where virtual commissioning has reduced stops in productions.

Further economic research is needed to reach a conclusion where to most efficiently apply virtual commissioning and how. Notably the economic evaluation of when and how it is most cost beneficial to deploy. This could be done on similar systems such as the LightGuide system to verify the finding in this study. Corroboration of the data through research in commissioning of other technologies would likewise be useful. Future research may be able to validate or invalidate the results from the experiment, adding to the research effort in the field.

# 6

# Conclusions

This chapter covers the conclusions of this thesis. The conclusions are divided into two parts. The first part is the case specific conclusions regarding the HIM system. In this part conclusions are drawn on the specifics of the results and discussions in the thesis. The second part covers the general area of projection based support systems and draws conclusions in relation to the field in general.

## 6.1 Case Conclusion

The aim of the thesis is to investigate the improvement potential regarding the commissioning process associated with projection based support systems in the industry. This aim was achieved by using the HIM system as a case study. Using mainly a design science methodology, an artifact was developed enabling the virtual commissioning of the HIM system. Through experimental tests, the virtual commissioning of the HIM system was evaluated in terms of time and economic impact.

By mapping out the activities needed to commission the HIM system and analyzing their potential to be digitized, a software artifact was developed. The artifact is able to gather the data needed to commission the HIM system from external sources and transform it into useful information for the HIM unit. The experimental commissions performed show that there is a great potential in applying the concept of virtual commissioning on the HIM system.

The profitability of using the software artifact during commissioning was depending on the size of the project being commissioned and size of the company of which it was being commissioned. For smaller companies there was little to no financial impact in virtually commissioning the HIM system. For medium sized companies, commissioning of larger project shows greater potential of economic feasibility when being virtually commissioned. Finally, larger companies shows the greatest potential of economic gain when commissioning the HIM system by virtual commissioning, which is also increasing with the size of the project.

## 6.2 General Conclusion

On a general level, this thesis shows the potential of adapting the concept of virtual commissioning in fields outside of robotics. With the advancement of industry 4.0, several different IT solutions to aid in manufacturing are being developed. This thesis shows the advantage of developing efficient commissioning processes of these solutions, thus allowing them to be integrated within the industry more efficiently. Utilizing the knowledge gained from the field of robotics and virtual commissioning, software aided commissioning can be used in more technological areas in industry. In industry the importance of a fast commissioning often clashes with the technological difficulty of setting up the equipment at the site. The digitization of a commissioning process could decreases the planned downtime in production, overcoming a major obstacle to integrating new technology, which may contribute to the Industry 4.0 revolution.

The thesis demonstrated the importance of supporting interoperability in new manufacturing software in order to facilitate further development of use-cases outside the original scope. The consequences of improving the commissioning of projection based information systems can lead to a more competitive advantage compared to other similar technologies. In order to reach this improvement, more research is however needed to analyse other aspects of commissioning in information systems.

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# A

# Experiments

This appendix will go over the details of the experiment performed in the SII-lab. The experiment was performed to evaluate the results for research question three. Firstly, the appendix will cover the setup of the workstation on which the experiment was performed. It will then cover the design of the experiment and lastly how it was performed.

## A.1 Experimental setup

The experiment was set up in the Stena Industry Innovation lab (SII-lab) at Chalmers University of Technology, Lindholmen. The experiment setup consisted of five categories: the work area, the containers, tools, the HIM setup and the scanning equipment. Each category is explained in this chapter to clarify the equipment and how it was used.

### A.1.1 The Work Area

The work area used for the experiment was the SII-lab. The existing drone factory, which is a conceptual assembly using industry 4.0, was used as a base for the experiment in the final assembly (Fast-Berglund et al., 2019). The drone factory is split into different assembly stations, one of which was used for the experiment (Fast-Berglund et al., 2019). This assembly station was selected since it represented a similar situation to a regular commissioning of the HIM, where a preexisting assembly station would exist. The selected station had a ready work area with a multitude of parts, each intended for assembly.

The work area consisted of a designated assembly space in the middle of the table with material in containers needed for assembly placed around the work area. Dedicated spaces for tools used in the assembly were also present to the right on the table. Figure A.1 shows a picture of the workstation used.

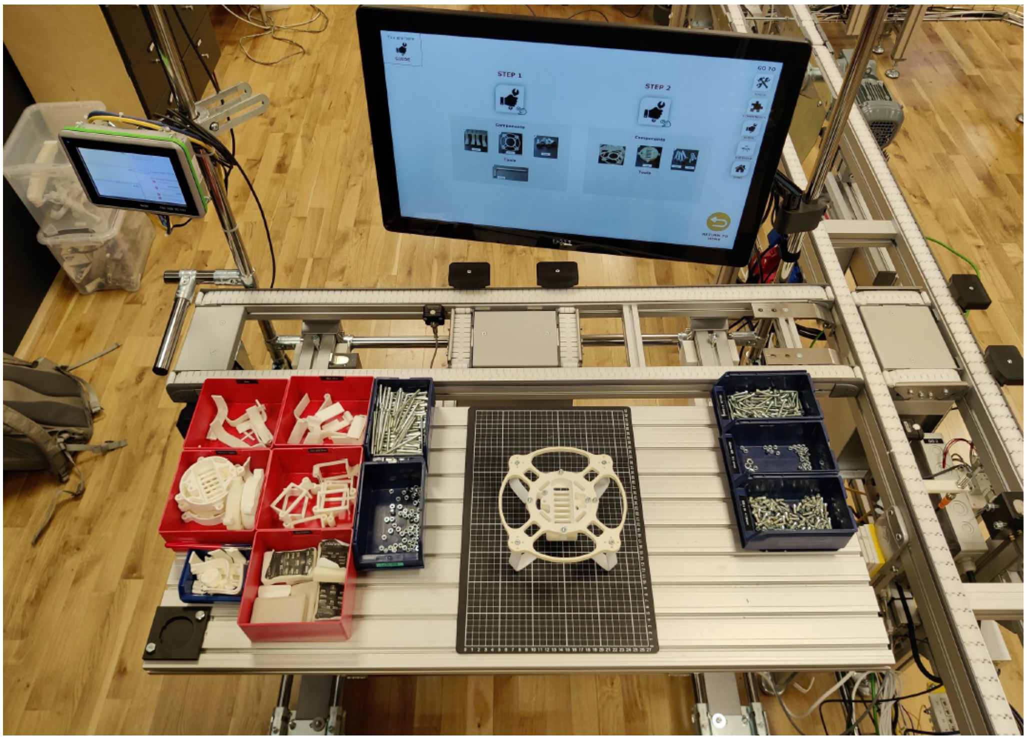


**Figure A.1:** Image of the workstation of the HIM used in the experiment, in the SII-lab.

There existed a description of the assembly work instructions in a power point format that was used to typify a real scenario, where the work instructions often exist. These work instructions were used as part of the basis of the preparation work that was done for the virtual commissioning. The descriptions was then converted manually into the Excel and Cloud Compare inputs, or used during the experiment for the current commissioning.

### A.1.2 Containers and tools

Standardized containers and tools were used in the experiment to represent a typical assembly station. The containers were of four sizes:

- Small blue: 9 x 10 cm
- Medium red: 14.5 x 14.5 cm
- Medium blue: 17 x 10.5 cm
- Big grey: 29 x 39 cm

The tools were placed in a specific area to the right of the table. This was a criteria for functionality of the HIM unit. The only tool used in the experiment was a hex key.

### A.1.3 The HIM setup

The HIM system setup was divided into two categories, the physical and the software. The physical setup consisted of mounting the HIM unit, together with a projector above the workstation. The HIM was pre-mounted to a pipe construction that was adapted to fit the workstation described in chapter A.1.1. The pipe construction was able to be attached to the station without any altering modification to the previous station.

Before starting the experiment, a calibration of the software was performed. The calibration adjusted the HIM unit to the new station. The HIM software setup was different for the virtual commissioning and the current commissioning. For the virtual commissioning, a template was setup where dummy detection's had been created beforehand. The dummy detection were created to facilitate interoperability between the API and the detection's, to send information from the interface to the HIM unit. In the current commissioning only a regular project was created.

### A.1.4 The scanning equipment

Before the experiment started a point cloud scanner was used to map the station into a 3D point cloud. The scanning involved multiple scans of the area from different angle to paint a accurate picture. The station could then be analysed from the office. This information was then used in the Cloud Compare software to find the measurements of were the containers were located and what they contained. This was the preparation for the detections, before the experiment began.

## A.2 Experiment Design

The experiment in the lab was divided into two tests, the first tested the virtual commissioning which used the artifact explained in chapter 4.2 to carry out the tasks. In the second part the experiment was carried out with the current commissioning. Both were filmed and measured to gain data from the experiment. The films also created the possibility to critically asses the experiment afterwards, not disturbing the experiment. Before the real experiment, a trial experiment was performed to find errors in the procedure before the real experiment, which could be improved (Coleman & Montgomery, 1993). The trial experiment was also used to ensure the data gathering system was properly set up to capture the information from the experiment (Coleman & Montgomery, 1993). Furthermore, the experiments were performed before traveling to the real lab, not wasting valuable time in the real setting, with the HIM unit and SII-lab being used (Coleman & Montgomery, 1993).

When starting the experiment, the same information was given out to commission the experiment for the two tests. For the virtual commissioning test, the work instructions were given out together with the scanning data from the work area, to be used in the preparation stage. The current commissioning test were given the same work instructions, but had no use for the scanning data of the SII-lab where the test was being performed. A coordinator was present from the start of the experiment to guide the participant to perform the experiment correctly (Coleman & Montgomery, 1993).

Before the experiment in the SII-lab, the preparation was made for the virtual commissioning, which represented the time spent off-site digitally preparing for commissioning. The preparation was filmed and measured in order to use later in the assessment as off-site time. Both the Excel and the Cloud Compare preparation to be used as input data during the experiment. This included extracting the relevant coordinates from the point cloud scan, labeling them according to type, size and name. These coordinates were then exported to an CSV file structure. The process steps included in workstation were also pre-treated. They were converted from their original format to a standardized excel format, which links each process step to the right detection.

The next steps was to perform the experiment in the SII-lab. Because of the digitization in the virtual commissioning, the procedure was different from the current commissioning. Some steps were prepared beforehand and send to the HIM unit through the interface. For the **virtual commissioning** the following procedure was used:

**Detections:**
- Send detections with variables to template project from artifact
- Remove the spare detections in the template project
- Trigger template that moves the detections to the correct place
- Take time of flight photos in the correct area

**Images:**
- Send images from the artifact

**Process Steps:**
- Send process steps to the template
- Check connection to detection

**Projections:**
- Project pictures/text for the screen
- Project pictures/text on the table

For the current commissioning the methodology was different. Firstly the information from the work instructions had to be interpreted and translated to detections and steps. Secondly, both the detections and the steps had to be created and placed correctly while at the SII-lab. Small procedures such as assigning images had to be placed in the correct place manually. The main difference is however the manual creation of the detection and process steps compared to the virtual commissioning. For the **current commissioning** the following procedure was used:

**Detections:**

- Gather the info for creating the detections
- Create detections from the information at the work station
- Place the detections in the right place in the program
- Take time of flight photos in the correct area
- Correct fill rate for a smooth setup.

**Images:**
- Import all the images needed
- Connect the images to materials or steps

**Process Step:**
- Analyse which process steps are needed in the assembly
- Create steps that are used in the assembly
- Write the text instructions associated with the step

**Projections:**
- Project pictures/text for the screen
- Project pictures/text on the table

The functionality was then tested by using the new commissioning to assemble the product. In order to determine if the functionality was approved, the following had to be achieved:
- Correct detection with light projection that was correctly placed.
- Correct steps which guided the operator in the correct sequence.
- Projections with text and pictures clearly guiding the operator.

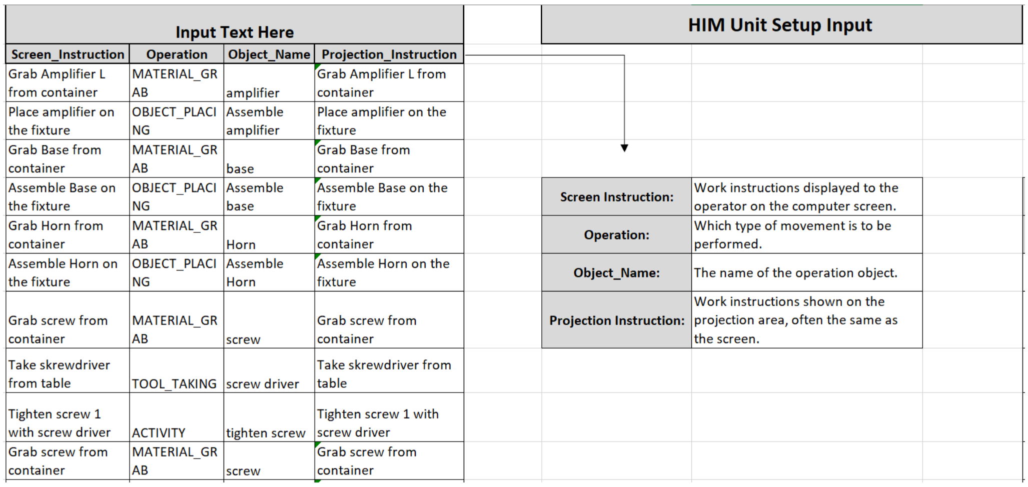
Then these criteria had been filled, the commissioning was approved to be used in the data in the results.

Both the current commissioning and virtual commissioning were performed four times each, for a total of eight iterations.

# B

# Process Excel Spreadsheet

In this appendix the process Excel spreadsheet is shown and explained. The Excel spreadsheet contains four inputs for the user, first the instruction that later are shown on the screen are written down. Then an operation is chosen from a list which fits the movement that is performed. After that, the object name is filled in, this name must match the name of the picture that should be linked to the process step. Lastly, the instruction that should be shown from the projector on the table are written here.



**Input Text Here**

| Screen_Instruction | Operation | Object_Name | Projection_Instruction |
|---|---|---|---|
| Grab Amplifier L from container | MATERIAL_GRAB | amplifier | Grab Amplifier L from container |
| Place amplifier on the fixture | OBJECT_PLACING | Assemble amplifier | Place amplifier on the fixture |
| Grab Base from container | MATERIAL_GRAB | base | Grab Base from container |
| Assemble Base on the fixture | OBJECT_PLACING | Assemble base | Assemble Base on the fixture |
| Grab Horn from container | MATERIAL_GRAB | Horn | Grab Horn from container |
| Assemble Horn on the fixture | OBJECT_PLACING | Assemble Horn | Assemble Horn on the fixture |
| Grab screw from container | MATERIAL_GRAB | screw | Grab screw from container |
| Take skrewdriver from table | TOOL_TAKING | screw driver | Take skrewdriver from table |
| Tighten screw 1 with screw driver | ACTIVITY | tighten screw | Tighten screw 1 with screw driver |
| Grab screw from container | MATERIAL_GRAB | screw | Grab screw from container |

**HIM Unit Setup Input**

| | |
|---|---|
| **Screen Instruction:** | Work instructions displayed to the operator on the computer screen. |
| **Operation:** | Which type of movement is to be performed. |
| **Object_Name:** | The name of the operation object. |
| **Projection Instruction:** | Work instructions shown on the projection area, often the same as the screen. |

**Figure B.1:** The Excel spreadsheet used for process steps input to the artifact.

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