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Virtual Production Line

-Virtual Commissioning

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Abstract

This master thesis has been conducted at Alfa Laval in cooperation with the division of Production and Materials Engineering at Lund University. The objective has been to investigate virtual production with regards to its required resources, benefits and limitations of the technology. Work with production analysis, literature studies, creating a prototype, benchmarking led to our conclusion.

Virtual production can bring new opportunities. Through programming, verifying and validating PLC logic and other equipment in a digital environment before a new production cell is constructed and commissioned. The automation personnel get the opportunity to work in parallel with other disciplines, which could result in shorter commissioning time. This work method gives opportunities to reduce project time overall and could improve the quality of the production cell.

A virtual prototype was created using the software RobotStudio and CoDeSys to verify and validate PLC code and Rapid code. The prototype is a virtual model over a welding cell that welds two corrugated plates together to form a cassette. Several cassettes combined with other components is assembled to a plate heat exchanger. The work conducted with the prototype shows that the required resources to start with virtual commissioning is high. The necessary knowledge by the user is high in several different fields combined with time consuming work.

The technology is not yet fully matured to be able to do a full scale virtual commissioning project. The technology could instead be used for robot programming and partly for verifying and validating PLC code successfully. This master thesis could be viewed as the first step for implementing virtual commissioning at the company and therefore more research is needed, both from the university and from Alfa Laval.

Keywords: Virtual production line, Virtual Commissioning, Digital Twin, Industry 4.0, Industrie 4.0, Automation, Emulation, Simulation, RobotStudio, CoDeSys.

Sammanfattning

Examensarbetet har utförts på Alfa Laval i samarbete med avdelningen för Industriell produktion på Lunds universitet. Målet med examensarbetet var att utreda virtuell produktion ur hänsyn till resurskrav, dess fördelar och begränsningar. Arbetet med produktionsanalyser, litteraturstudie, prototypframtagning och prestandajämförelser ledde det fram till vår slutsats.

Virtuell idrifttagning kan ge stora fördelar. Genom att programmera, verifiera och validera PLC och annan utrustning i en digital miljö före det att en ny produktionscell konstrueras och idriftsätts. Genom att ge automationspersonal längre tid att arbeta parallellt med andra discipliner skapar det möjligheten att förkorta ned idrifttagningsprocessen vilket bör resultera i ett förkortat projekt överlag, med möjlighet för bättre prestanda hos den nya produktionscellen.

En virtuell prototyp skapades genom att använda mjukvarorna RobotStudio och CoDeSys för att kunna verifiera och validera PLC-kod samt RAPID-kod. Prototypen är en virtuell modell över en svetscell som svetsar samman två plattor för att bilda en kassett som tillsammans med andra kassetter och komponenter monteras till en plattvärmeväxlare. Arbetet med prototypen visar på att resurskraven för att börja med virtuell idriftsättning är tämligen höga. Med höga kompetenskrav inom flertalet discipliner kombinerat med relativt tidskrävande arbete.

Tekniken är i dagsläget inte mogen för att utföra en fullständig virtuell idriftsättning. Den kan istället med fördel användas för robotprogrammering samt viss verifiering och validering av PLC-kod. Examensarbetet kan betraktas som en påbörjande utveckling för företaget inom virtuell idriftsättning och därmed behövs mer forskning inom området både från universitet och företaget.

Nyckelord: Virtuell produktionslina, Virtuell idrifttagning, Digital Tvilling, Industrie 4.0, Industri 4.0, Automation, Emulering, Simulering, RobotStudio, CoDeSys.

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List of abbreviations

3D: 3-Dimensional
CAD: Computer-Aided Design
CPS: Cyper-Physical Systems
HIL: Hardware In the Loop
IoT: Internet of Things
IP: Internet Protocol
OEM: Original Equipment Manufacturer
OLE: Object Linking and Embedding
OPC: OLE for Process Control
PERS: Persistent Variables
PLC: Progammmable Logic Controller
PMI: Product manufacturing information
RIL: Reality In the Loop
SFC: Sequential Function Chart
SIL: Software In the Loop
ST: Structured Text
TCP: Transmission Control Protocol
VC: Virtual Commissioning
vFAT: virtual Factory Acceptance Test
VR: Virtual Reality

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1. Introduction

This chapter describes the company, background and objectives to the master thesis. Resources we had at our disposal as well as the delimitations of the project.

1.1. Company description

Alfa Laval is a leading global supplier of products in the areas of heat transfer, fluid separation and fluid handling. They deliver products and solutions to customers within the divisions; Energy, Food & Water and Marine. The company had over 16 000 employees worldwide at the end of 2017, of which about 2000 works in Sweden where the Alfa Laval headquarter is situated. The company was founded in 1883 and is still developing. About 2.5 percent of the company's sales is invested in research and development, which results in 25-30 new product launches every year. (Alfa Laval, 2018)

1.2. Background

Alfa Laval strives to be an innovative company in both product and production development. In the light of the current digitalization in industry, Alfa Laval seeks to investigate the opportunities within the industry 4.0 concept. This master thesis is one step closer to reaching the vision of industry 4.0 in the areas of simulation and digital twin.

1.3. Objective

The objective of the master thesis is to identify how the concept of a virtual copy of a production line can be implemented and what benefits it could generate in terms of production development. The virtual production model should be suited for implementation of new products and product ranges to identify problems and possibilities within existing production areas. The following goals are the main objectives of the project:

- Perform a literature study regarding cases when virtual copies of production lines have been used. Determine what benefits it gave and what resources that was required
- Create a prototype based on a selected process step
- Propose areas at the factory in Lund where a virtual copy would be beneficial
- Propose a way forward to work with the concept of virtual copies based on the findings of the study

1.4. Delimitations

The focus of the project will be to develop a virtual model to test and evaluate virtual commissioning as a working method. Therefore, industry 4.0 is only briefly described as well as other types of virtual production lines. The virtual production prototype is limited to the production facility in Lund and is only representative for one physical production line. The virtual model prototype has several delimitations, explained in the model development section.

1.5. Resources

The resources to our disposal are:

- PhD students from Lund's university.
- Production developers and project leaders at the company.
- Product developers at the company.
- Automation developers at the company.
- Production facility at the company for testing, analyzing and collecting data as well as internal documents and production data.
- Software for modelling a virtual prototype including communication software. RobotStudio for simulation and robot programming. CoDeSys for PLC and HMI development. KEPServerEX for communication.
- Virtual Reality laboratory at IKDC, Lund for testing and evaluating the prototype.

1.6. Confidentiality

All data and information obtained at the company Alfa Laval is to be considered a company secret. Therefore, the results and methods are not representative for the company but for this master thesis. The recommendation is only one possible way of many forward for the company.

1.7. Target audience

The target audience for this master thesis are production developers, automation team members, production technicians and key decision-makers at Alfa Laval. However, several other departments within the company could use this project as a base for knowledge for industry 4.0 and digital production development. The department of Industrial Production at Lund University is also considered a target audience, that could use this project as a base for further research on the areas of virtual commissioning and digital twins.

1.8. Disposition

The master thesis dispositioned and is presented as follows:

- **Introduction** – Gives a short background to the master thesis, whom it is directed to, the objectives and questions the thesis should answer.
- **Theoretical background** – Gives the reader knowledge about the product Alfa Laval is producing in Lund. A brief explanation of the concept of industry 4.0, especially with focus on simulation and virtual production is also presented. The theoretical background also describes industrial automation and a short description of different software used for virtual commissioning.
- **Literature study** – Focused on benchmarking, what types of companies are using virtual commissioning today and what resources is required according to other projects and companies.
- **Production analysis** – An assessment of which production line that could benefit from virtual production or virtual commissioning.
- **Model development** – Explains how we developed the virtual prototype with PLC, robot programming and the communication between the different software used for model development.
- **Model Analysis** – An analysis of the virtual prototype developed during the project. This chapter is focused on the prototypes functions and limitations in its current state.
- **Discussion** – Discussion about the virtual prototype and what issues we had during the development phase. We also discuss the maturity of virtual commissioning as a working method and what is needed for it to be implemented on a wider scale.
- **Conclusion** – Our conclusion is based on the findings of our virtual prototype and virtual commissioning as a technology. This section is linked to the objectives and tries to answer the problems defined under the introduction section.
- **Future Work** – This chapter is a recommendation for future work when it comes to our project, what could be improved, and for researching virtual commissioning as a technology from different aspects.
- **Recommendations for Alfa Laval** – Lists our recommendations for the company, which direction we think the company should move in and what Alfa Laval needs to work on to be able to implement virtual commissioning.

2. Theoretical background

The theoretical background explains the products that Alfa Laval are producing in Lund. The chapter also describes the concept of industry 4.0 with focus on virtual production and simulation.

2.1. Plate heat exchangers

An introduction to corrugated plate heat exchangers regarding construction, applications, advantages and disadvantages.

A plate heat exchanger transfers heat from one media to another trough the plates. The products are used in various industries such as paper and milling, chemical industries, breweries, marine industries and the food industry. A plate heat exchanger transfers heat by leading the different media through two sets of plates. The media goes through every other plate to maximize the contact with the plate set consisting of the other media. This process is illustrated in Figure 1. The construction is composed of the frame, several plates with gaskets between them and bolts and nuts for the assembly. An example of an assembled gasket plate heat exchanger is shown in Figure 2. The plate is the vital part and could be made from a wide spectrum of materials, depending on which liquids are going to flow through the system. The choice of material will depend mainly on its compatibility and chemical inertness in contact with the various fluids, that is the materials degree of resistance to corrosion (Alfa Laval, 2004). In comparison to other types of heat exchanger, the plate heat exchanger permits increasing or decreasing the exchange power even after the system has been installed. It is possible to add or remove plates on gasket plate heat exchangers if the customer suddenly needs more, or less heating or cooling capacity (Alfa Laval, 2004).

A plate heat exchanger made with corrugated plates has a high heat transfer coefficient with large surface areas resulting in small heat exchangers with good capabilities. See Figure 3 for explanations about the corrugated plates different parts. Corrugated plate heat exchangers work best in low to medium pressure and temperature ratio systems. Smooth plates can handle a bigger pressure temperature ratio. The reason why the plates are corrugated is to create turbulence within the flow, increasing the convection, which results in efficient heat transfer between the media (Alfa Laval, 2004). To increase the capability to handle a greater temperature and pressure ratio it is possible to join the plates with welding or soldering instead of with gaskets. However, this prevents the possibility to add or remove plates from the heat exchanger (Sundén, 2006).

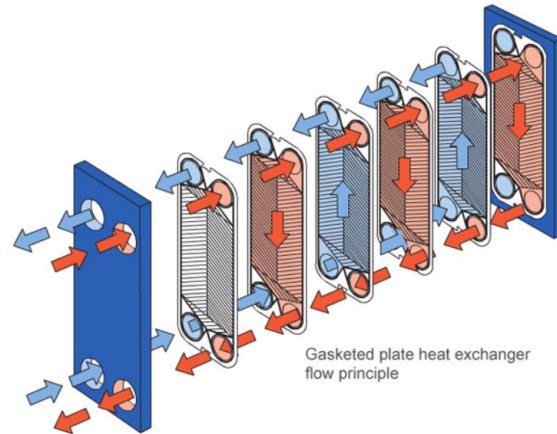


Figure 1: The flow of the two different medias in a plate heat exchanger. Red represents hot media, blue represents cold media (Alfa Laval, 2018).



Figure 2: A heat exchanger from Alfa Laval, ready to be shipped out to a customer (Alfa Laval, 2018).

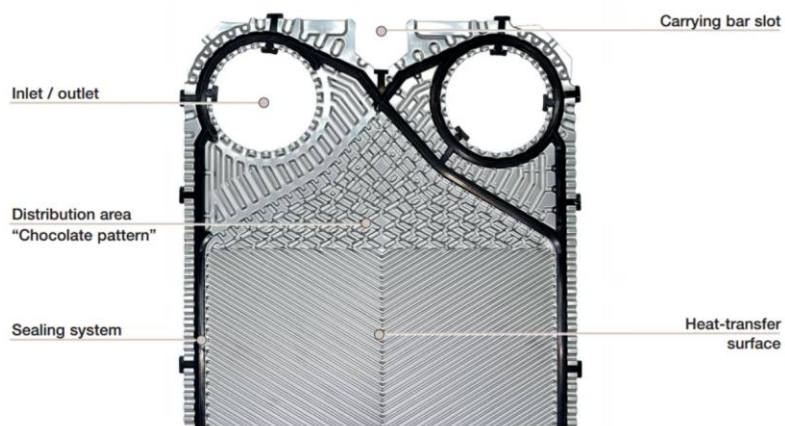


Figure 3: A corrugated plate from Alfa Laval (Alfa Laval, 2018).

2.2. Manufacturing of heat exchangers

The manufacturing of plate heat exchangers starts with flat sheets of e.g. stainless steel or titanium that are pressed into desired shape (Alfa Laval, 2004). At the assembly station, the components are manually assembled. The whole assembly is then compressed by tightening the bolts to a specified measurement. The heat exchanger is then tested for leakage and pressure to ensure the quality of the product. If it is approved in the leakage and pressure test, the heat exchanger moves on to get packaged and prepared for transportation to the customer. Depending on the type of heat exchanger the process can differ, however a general flowchart over the production of the heat exchanger is shown in Figure 4.

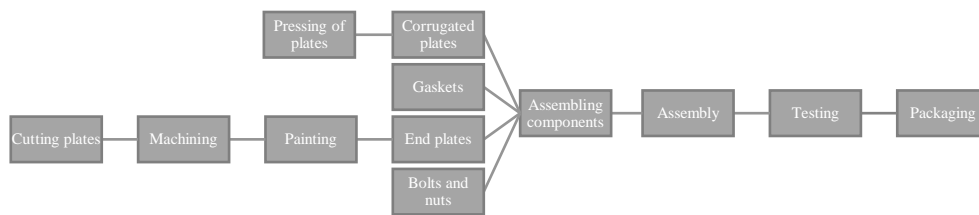


Figure 4: Flowchart over the production of heat exchangers.

The production of heat exchangers falls under the category “Discrete manufacturing”. Quite simplified, you can say that products that can be counted as their own object are produced with discrete manufacturing (Gustaf Olsson, 2005). Further, different types of discrete manufacturing can be identified, depending on the manufacturing batch size or the quantity of manufactured products. According to Ståhl, the division can be made as follows (Ståhl, 2016):

- **One-piece production**, characterized by small quantities, often made by specific customer requirements in mind.
- **Batch production**, which is characterized by medium production batch sizes of one type of product, often manufactured towards stock.
- **Mass production**, characterized by continuous manufacturing one type of product, high production rate, often produced with special tools or machines.

2.3. Industry 4.0

This section introduces the term Industry 4.0. A brief history and explanation of the concept is given, and the importance in the evolving digitalization in industry is presented.

2.3.1. Concept of Industry 4.0

The term Industry 4.0 was first mentioned in the Hannover Messe in 2011 (Pfeiffer, 2016). It refers to a technological shift viewed as the fourth industrial revolution, illustrated in Figure 5. It visions a future where the production is connected to the Internet of Things (IoT). Where intelligent machines, systems and networks are capable of thinking by themselves, exchanging and responding to information to manage industrial production processes. It further envisions that future businesses will establish global networks that incorporate their machinery, warehousing systems and production facilities in the shape of Cyber-Physical Systems (CPS). (Kagermann, et al., 2013)

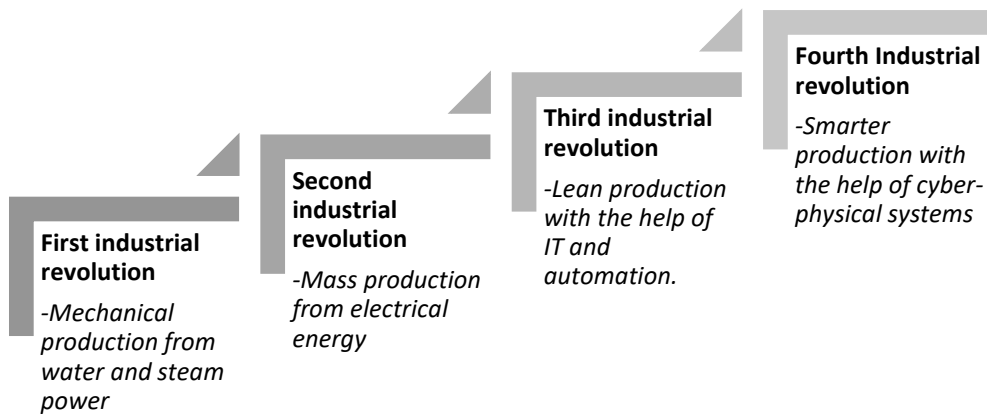


Figure 5: The industrial revolutions (MacDougall, William, 2014).

The implementation of Industry 4.0 can be divided into 9 different technologies that together form a new way of producing products. They are shown in Figure 6. Currently some of the technologies are used single-handedly. However, used together they can change the way we are producing. (Rüßmann, et al., 2015)

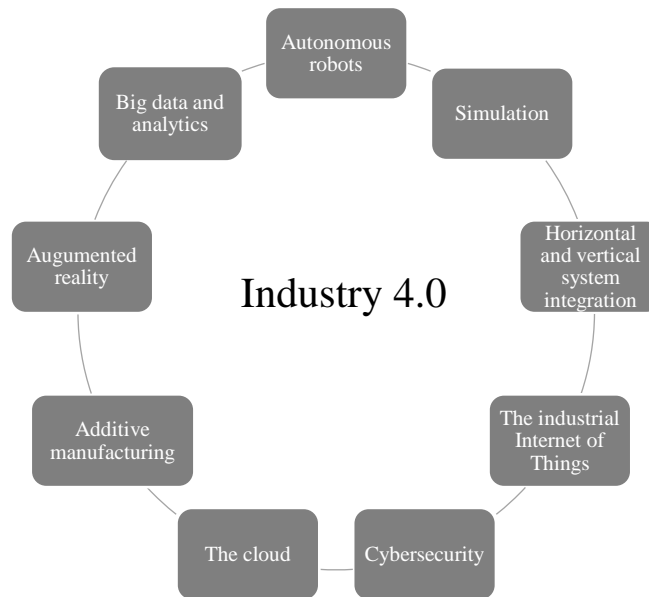


Figure 6: The nine technologies of industry 4.0 (Rüßmann, et al., 2015).

The forecast points that it will take about 20 years to fully implement industry 4.0. During the coming 5 to 10 years important steps will be taken to reach the goals of the new industrial revolution and some companies will be winners and some will be losers in this competition of implementing industry 4.0. (Rüßmann, et al., 2015)

According to the Gartner Hype Cycle illustrated in Figure 7, the chart shows the different technologies within industry 4.0 and the interests in the different technologies. This shows that the new industrial revolution will take both time and investments to reach the visions of industry 4.0. (Gartner, 2017)

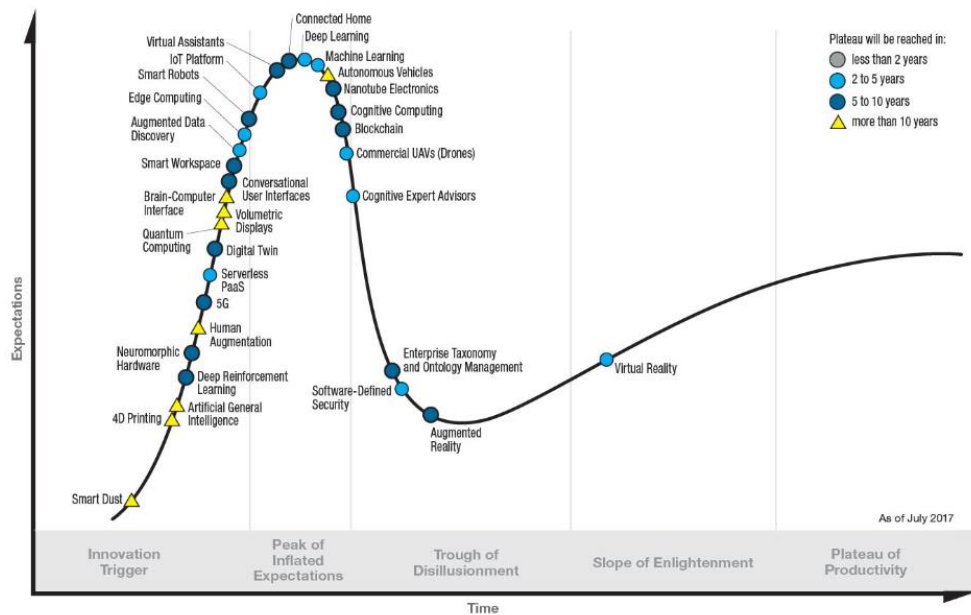


Figure 7: The Gartner Hype Cycle on Industry 4.0 (Gartner, 2017).

Benefits of Industry 4.0

The benefits of implementing industry 4.0 is great according to Boston consulting group. Due to implementing a high-level data system consisting of IT functions, production and logistics the suppliers will benefit greatly from that information. The data from the companies' cloud will be easily accessible for the employees, which will increase the companies' flexibility to make changes within the production. Since every single component produced will have an ID with stored information, it gives the production facility more information compared to today. This technology enables a line to produce several varieties of products easier than today. The quality of manufactured products is foreseen to improve since manual labor is decreasing and data management is increasing. Increased automation will increase the efficiency of the production and logistics as well since autonomous trucks and trolleys will serve the production and the storage facility. An implementation of industry 4.0 can lead to 30 percent faster production as well as 25 percent better efficiency. At the same time mass customization gets possible on a wide scale. (Rüßmann, et al., 2015)

2.3.2. **Autonomous robots**

Automated robots have been used in a wide range of different manufacturing industries. However, the development of autonomous systems is evolving. The goal of autonomous systems implemented in industry 4.0 is that the robots are interacting with each other and with human workers in a new kind of human-machine work team. The price of robots will continue to decrease and at the same time have better utilities and capabilities than the robots of today. Already we can see examples of this taking place. ABB has developed the robot “YuMi” for assembling components alongside humans. Another example is the robot manufacturer KUKA that has developed robots that interact with other robots and adjust their actions depending on the other robot. (Rüßmann, et al., 2015)

Another developer of interactive robots is the Danish company Universal Robots that currently has three different interactive robots in their portfolio. The interactive robots enable the operators to work side by side with humans. (Universal Robots, 2018)

2.3.3. **Simulation**

Today, simulation in the product development phase is commonly used. In industry 4.0 however, the simulations are developed and used in plant operations as well. The goal is that simulations from the production is delivered in real-time to a virtual model. The virtual model can consist of machines, products and even human workers. The virtual model gives the opportunity to analyze new products before the actual physical changeover. This leads to increased quality as well as lowered changeover time. Two German companies created together a virtual model of a cutting process and simulated the process from the physical machining. The result was that they reduced the changeover time with 80 percent. (Rüßmann, et al., 2015)

2.3.4. **Horizontal and vertical system integration**

Currently, it is rare that systems are integrated. This accounts for IT systems as well as the way products and production is developed and implemented. With industry 4.0, the goal is to create a wide integration of both systems and different departments at the company. (Rüßmann, et al., 2015)

2.3.5. **The industrial internet of things**

Today embedded systems are quite commonly used in the various industries. These systems are developed to send information from objects in the production facility to a system that controls and monitor the production. With industry 4.0 the goal is to

include every device in the production, even the products. With a more advanced system, it allows the different devices to communicate and interact with each other and with a more high-level system. Bosch has developed a system in that fashion, that makes the decision making more decentralized and allows the system to do necessary steps depending on where the product is in the production facility. (Rüßmann, et al., 2015)

2.3.6. **Cybersecurity**

With a more integrated IT and production system the vitality of cybersecurity increases. The management of the high-level system is critical, currently major players within the software industry are working together with cybersecurity firms to ensure good cybersecurity. (Rüßmann, et al., 2015)

2.3.7. **The cloud**

The extent of the use of cloud-based solutions will grow with industry 4.0. Due to sharing data within the company, especially if the company have several production sites. Boston Consulting group thinks that cloud-based solutions will develop to have a response time counted in milliseconds. With such a short response time more data can be easier uploaded and accessed resulting in better service for the production facility. (Rüßmann, et al., 2015)

2.3.8. **Additive manufacturing**

Companies today are mostly using additive manufacturing or 3D printing to create prototypes and sometimes produce single components. With industry 4.0 additive manufacturing will be used as a manufacturing method for products with:

- A low production volume.
- Requirements of being lightweight.
- Complex design.

An example is the aerospace industry that are using additive manufacturing for new designs that are lightweight and less demanding in terms of material usage. Additive manufacturing also enables companies to set up decentralized production units that are located close to the customer. (Rüßmann, et al., 2015)

2.3.9. **Augmented reality**

Augmented reality is a wide term that can be used in various activities. For example, augmented reality could be used to send repair instructions over a mobile device to a worker when they are looking at the machine or product they are currently

repairing. The repairing instructions could be shown in real-time as the worker is repairing the object. Augmented reality could also be used for the training of new workers. A German company has developed such a system for virtual training in a plant environment, for personnel to handle emergency situations. In the virtual training mode, the operator can interact with robots and give them instructions and change parameters. (Rüßmann, et al., 2015)

2.3.10. **Big data and analytics**

Analysis of production data is used on a smaller scale already. This helps the company to optimize the production in terms of product quality, energy saving and equipment service. With industry 4.0 the data from several operations such as business, production and from customers will be linked together and will be delivered in real-time to be able to analyze it instantly, resulting in quick decisions making. (Rüßmann, et al., 2015)

2.4. Virtual production

Virtual production is a wide term that falls under the category Simulation in Industry 4.0. In this section we describe different types of virtual production and the possible benefits of the different technologies.

2.4.1. Digital Twin

The virtual twin or digital twin is not a well-defined subject. Academia and industry define it in several different ways according to their viewpoint. This section aims to explain the term, differentiate digital twins and describe what they mean.

According to Parrot & Warshaw (Parrott & Warshaw, 2017), a digital twin can fundamentally be viewed as an evolving digital profile of the historical and current behavior of a physical object or processes. Thus, based on any physical asset, a digital twin can be created with its own defined purpose. Parrot & Warshaw view the digital twin as being based on real-time and real-world data measurements. When used in the digital model it can provide insights on the performance of the physical asset. These insights can be used as a decision factor to take actions in the physical world, such as changes in the manufacturing process or product design. The digital twin can be created in a wide variety of contexts to serve different goals. A digital twin of a manufacturing process represents one type. Another viable concept is to use the digital twin on a product-based application. Related the concept of product life cycle management, where the entire products life cycle is considered: from idea development to use and service. The most holistic view of the digital twin, is the case when the product and production twin interacts with one another. How the actual product performs in the field could be used to develop and optimize the manufacturing process (Parrott & Warshaw, 2017).

Product digital twin

A digital twin viewed in the perspective of a product twin, is a digital copy of one unique item, containing not only computer aided design models (CAD), but also digital information about historical and current behavior of the physical object (Parrott & Warshaw, 2017). Such information can for instance be exact time when it has been manufactured, what machines it has been manufactured in and where it currently is within the production. The metadata on the digital twin is continuously updated as it moves through the product life cycle, involving product design, production and service as seen in Figure 8. The product digital twin can for instance be used to simulate complex deployed assets such as jet engines or large mining trucks in order to monitor and evaluate wear and specific kinds of stress as the product is used in the field (Parrott & Warshaw, 2017).

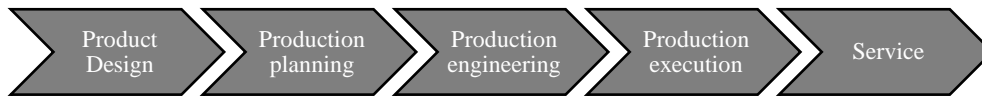


Figure 8: Showcasing the width of a Product Digital Twin.

Production digital twin

The digital twin can also be deployed on the production process or manufacturing system, enabling a coupling of the production system with its digital equivalent that allows one to understand past and present behavior. This can be utilized as a base for optimization and development (Uhlemann, et al., 2018). In this scenario a real manufacturing system is represented in a digital twin, working in real or near real-time parallel to the real production. What is happening in the physical factory floor can be viewed and analyzed in a virtual environment. This digital copy of the production line can be used in optimization of the process steps in a virtual environment without having to interrupt the production at the shop floor. Implementation of new products can be simulated in the digital copy, such that the automation system can be analyzed beforehand, and potential problems can be identified and solved (Volkman, 2016).

2.4.2. Virtual commissioning

The development of a manufacturing system in general, comprises several phases: facility design and planning, mechanical engineering, electrical engineering and automation engineering, which are often sequentially executed. (Hoffmann & Schumann, 2010)

Virtual commissioning (VC) is a concept to prepare and test manufacturing systems and associated control programs through simulation in a virtual environment, before the real systems are realized. The aim is to detect and correct errors generated during planning, design and programming during the engineering phase of the project. With special focus towards the automation controllers present in the system (Hoffmann & Schumann, 2010). This is achieved by building the production cell in a digital environment, and combining PLCs, devices and robots with digital models to validate the control program. Using this concept, the automation engineers can develop the PLC and robot programs while the production cell is being built, as illustrated in Figure 9. This approach aims to decrease the commissioning time when the real production line is set up at the factory, and to reduce the problems at the first start-up. This way of working gives the opportunity to develop and produce products cheaper and with less start-up problems, and less risk when commissioning a new production cell. Because of the parallel work that virtual commissioning enables, the time from idea to the market could be shortened (Stähl, 2016).

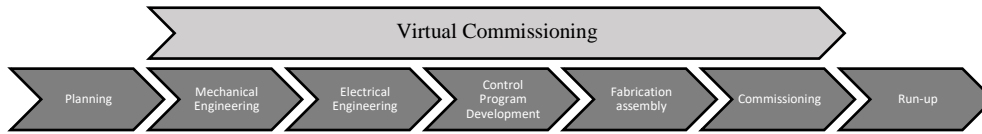


Figure 9: Virtual commissioning as a parallel work process in a production implementation project. Interpreted from (Hoffmann & Schumann, 2010).

A Virtual Commissioning project can according to Makris (Makris, et al., 2012) be divided into three distinct but interconnected subsystems:

1. The mechanical design including actuators, sensors, and behavioral description of a system.
2. The machine control, including its input and output signals.
3. The signal connections between sensors and actuators in the controller.

Approaches of commissioning

According to Auinger (Auinger, et al., 1999 Winter) there are four possible approaches that can be used to validate the commissioning of a production system: (1) real commissioning involving a real plant and a real controller, (2) Soft commissioning or hardware-in-the-loop (HIL), where a real control system is connected to a simulated plant, (3) reality-in-the-loop (RIL), refers to commissioning involving a real plant and virtual controller and (4) Off-line Simulation or Software-in-the-loop (SIL) involving a simulated control system and a simulated plant. The approaches possible configurations to validate the control system is depicted in Figure 10.

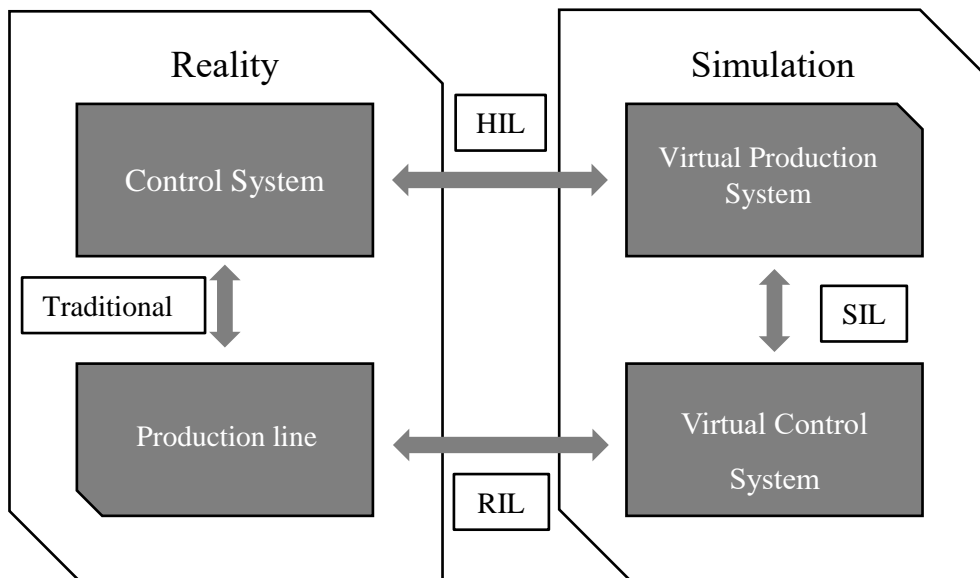


Figure 10: Approaches for validating a control system for commissioning.

A virtual commissioning requires a link between the controller and the 3D simulation tool. This is possible with the HIL configuration, when a real PLC is connected to a simulation model. The second possibility is the SIL configuration, where both the controller and the production system is simulated. Thus, this configuration allows a complete virtual commissioning without needing any hardware of the manufacturing system. (Hoffmann, et al., 2012)

2.4.3. **Flow simulation**

Flow simulation or product flow simulation is a tool for production development. Flow simulation could be used for simulating and analysing throughput, visualization, material flow in production and logistics flow.

Simulation are suitable for when an object or process does not exist in reality, the process is too fast, too slow or does not behave as expected. Simulations are also suitable for when experiments and conventional tests are too expensive, dangerous or simply takes too long. Practical examples of the use of flow simulation could be simulations of complex systems such as product flow in a factory or even vehicle traffic. The software for advanced flow simulation are currently expensive, however the trend is that they are decreasing in cost. Flow-simulation is not currently widespread in the industry. However, the usage is increasing. The industry that is using simulations most is the automotive industry due to hard competition and continues development and optimization. (Ståhl, 2016)

2.4.4. **Benefits of virtual production**

This section explains the various benefits of virtual production regarding virtual commissioning and flow simulation. Some of these benefits could be applicable for both types of virtual production. For example, a virtual model could be used for simulation of extreme scenarios. That would not be possible with real testing without risking machinery and equipment. (Reinhart & Wünsch, 2007)

Virtual commissioning

The economic benefits of a virtual commissioning project have been studied by Shahim and Møller (Shahim & Møller, 2016). In their proceedings they find that the tangible value created by virtual commissioning projects, is less ramp up time, better software quality, more stable software and less on-site work that interrupts the production. But the most beneficial factor they found was the deadline control, by increasing the predictability of a project.

Studies shows that the use of virtual commissioning can reduce the active working hours on the production site with 50 percent. This results in a reduction of the overall time for testing and development within a project. Working with a virtual model also

enables the engineers to test various scenarios without taking time from the production. (Dahl, et al., 2017)

Makris et al (Makris, et al., 2012), presents in their study that virtual commissioning provides a reliable way of validating the operations of a cell prior to each installation. They note that the main benefits of VC involve:

1. Ramp-up time reduction, reducing the total installation time by 15-25%.
2. Reduction in investment cost by decreasing the time for deployment of a new line as well as the time for production tests, prior to having full production volume achieved. Makris et al assesses that the cost can be reduced by up to 15% of the human resources, by reducing the required resources for troubleshooting during the ramp-up process.
3. Enhancement of the reconfigurability of assembly equipment, in the sense that changes can be assessed beforehand in the virtual copy, instead of requiring production stops for onsite testing.

Flow-simulation

In regard to creating a virtual flow model, Ståhl (Ståhl, 2016) presents several aspects that the flow model can improve. They are listed below.

- Decrease the cost per component by having good proportions within the production facility. A virtual model can be used for identifying overcapacity and arrangements can be made to decrease the resources that creates overcapacity. By identifying bottle-necks, the production resources can be moved to that specific area. These measurements increase the overall effectivity.
- Decrease the time for transactions between different products in a production line.
- Decrease the amount and extent of early problems with a new manufacturing unit such as a production line. Since the production line already has been tested in the virtual environment these problems can be eliminated in an earlier stage of the development.
- Increase the knowledge for the system operators, within areas such as limitations of the process and which factors that are crucial for a good result.
- By analyzing the virtual model, a model or a guideline can be developed for unusual but predictable problems. These unusual problems often contain external incidents.

2.4.5. **Virtual Reality in Industry**

Virtual Reality (VR) refers to a fully computer-generated 3D environment, in which engineers can manipulate and interact with a realistic representation of a system or product in real time (Ma, et al., 2011).

The Virtual Reality environment can be experienced by using Head Mounted Displays (HMD), with small displays in front of the eyes. Allowing for a spatial view within the virtual environment. However, in most industrial VR applications, a projection based display system is used, consisting of several projections in different configurations. (Ma, et al., 2011).

From a manufacturing viewpoint, the VR technology can be used for visualizing manufacturing processes, factory layout planning or as a tool for training new workers. The technology can help the engineers to get a better understanding of complex designs of, for example, mechatronic systems. To further improve the understanding of production systems, animations of a production system can be implemented and visualized within the VR environment. In turn this can result in costly errors that can be avoided by reconfiguring the production system. (Ma, et al., 2011)

To create the Virtual Reality environment, there are different methods that an engineer can use. The model can be built by using CAD-models, special rendering software or point-cloud data from scanned real objects (Gong, et al., 2017).

Virtual Reality with Virtual Commissioning

Studies has shown the possibility to combine Virtual Reality with concept of Virtual Commissioning. Allowing the user to interact with the running virtual production model in a realistic and intuitive way. Extending the possibilities for programmers, designers and operators to investigate and validate the system. The PLC logic and safety systems can be tested through interactions within the virtual model, before the physical system has been installed. Additionally, it opens opportunities to use the system to train the operators or maintenance technicians on the future production system before it has been constructed. (Dahl, et al., 2017)

2.5. Simulation & Emulation

Simulation is an experiment using a model, often of a real system, with the aim to understand the model's behavior and causation during a certain timeframe. The use of simulation tools has become increasingly important to analyze, plan, develop and optimize production systems (Ståhl, 2016, p. 287). In the sections below, some theory of simulation is presented, as well as the difference between simulation and emulation.

Simulation

Simulation is a powerful tool available for decision-makers. It makes it possible to study, analyse and evaluate the design and operation of complex processes and systems. The simulation models allow the user to conduct experiments as a way of understanding the behaviour of the system and as a tool to evaluate different strategies for the operation of the system. Thus, it is critical that the simulation model is designed in such a way that the behaviour of the model mimics the behaviour of the real system. (Shannon, 1998)

Banks and Sokolowski suggests three ways that the modeler can choose to best represent the given system (Sokolowski & Banks, 2012, p. 15). They call them simulation paradigms and presents them as: **Monte Carlo simulation**, where each input variable is randomly distributed according to some function and uses these samples to calculate the model's output. This process off random sampling is repeated until there is a knowledge of how the output variables varies given the random input variables. **Continuous simulation**, allows variables to be continuous functions of time. Thus, with continuous simulation, time is the independent variable, and the system variables evolve as time progresses. This type of simulation need to make use of differential equations in developing the model. The last type of simulation that Banks and Sokolowski differentiates, is **Discrete event simulation**. In discrete event simulation, system variables are discrete functions in time. The discrete functions results in system variables changing only at distinct instants of time. Discrete event simulation will advance in time from one event to the next event.

Emulation

All models are approximations of real systems and there will exist measurable differences between the performance of the model and the real system. An emulation model attempts to minimize this gap by replacing parts of the model with control systems that imitate the behavior of real parts. The more precisely defined emulation model, has a different purpose compared to a simulation model. Instead it aims to test the operation of control systems under different loading conditions and to carry out verification procedures. The purpose of it is to ensure the performance or reaction of the control system works as intended. (McGregor, 2002)

The majority of control systems are designed to operate in real time, thus the emulation model should preferably also be executed in real time. McGregor argues that the emulation should not be running at faster speeds greater than real time, as it becomes a potential source of error that the control system timers cannot adapt to. As communication events are asynchronous and unpredictable in the imitated control system, the repeatability of an emulation model will always be uncertain. (McGregor, 2002)

2.5.1. Simulation using game engines

Discrete event simulation (DES) tools are usually used when simulating industrial processes to evaluate a system. These tools tend to require the user to have extensive and specialized knowledge of the software. Game engines, intended for creating computer games, offers the ability to simulate the system in a realistic 3D environment, without requiring the same specialized knowledge that industrially oriented software do. (Polcar, et al., 2017).

The use of game engines is normally more focused on the visualisation element rather than the analysis element of a simulation (Bijl & Boer, 2011). Visualization of a simulated system does however provide a more complete understanding of the systems behaviour. There are several purposes for visualisation, Biji characterizes them in three different groups, *validation, analysis and marketing* (Biji, 2009). Where validation refers to the objective of discovering errors and discrepancies by visualising the system. Analysis refers to the process of gathering information and drawing conclusions from the simulation. Here visualisation can help identifying and locating bottlenecks. The last term, marketing refers to increasing the confidence and convincing engineers and non-engineers of the validity of the result.

The visualization element that can be provided by game engines can also be used as a powerful tool for training operational personnel. 3D visualisation with game engines can give an intuitive and realistic view of a system, without exposing the user to any physical danger or when the consequences of making an error will have a dire impact.

Another aspect of using game engines, is to combine the industrial oriented software with game engines and using it to create a realistic augmented reality environment. Research shows that industrial simulation tools can successfully be combined with game engines. RobotStudio, a 3D-simulation software focused on robotic motion can be combined with the game engine Unity3D. In such a way that motion trails, coordinate positions and safety zones for the robot could be visualized in an augmented reality using a tablet computer (Löfvendahl, 2014).

In comparison to industrial 3D-simulation tools, the game engines do provide a more realistic 3D-visualization. In many cases the level of realism in industrial 3D-

simulation software is sufficient for the purposes the software is created for. However, there are certain applications where a higher level of realism is important, mainly training and marketing purposes. (Bijl & Boer, 2011)

2.6. Industrial automation

2.6.1. PLC

A PLC or Programmable Logic Controller is an industrial computer designed to operate in harsh environments for low level control of automation systems. The PLC operates in real time to be able to handle and react quickly to external events. The PLC operates in a different way compared to a personal computer, the PLC program is executed in scan cycles, taking about 15-30 millisecond on a small PLC. One scan cycle consists of the sequence read-execute-write. The read function, reads all the input variables, current states in the program and saves it to the memory located in the controller. The execution stage then calculates the expression based on the data in the memory and saves the correct outputs. The last stage, writes all the outputs of the logical expression to the outputs of the PLC. (Alaküla, et al., 2015)

The inputs to the PLC can for example consist of data from sensors, data from other equipment or signals from the Human Machine Interface (HMI). The outputs can for instance be signals to start equipment such as motors, signal to turn on a lamp or data to HMI that can be read by the operator.

Programming of a modern PLC can be realized in five different programming languages, either text oriented or graphical. The international IEC61131-3 standard forms the basis of the different types of programming languages that can be used to program a modern PLC. A short description of them is presented in the following section. (Olsson & Rosen, 2005)

- **Ladder Logic Diagram (LD)** - The ladder programming language has its background in the old days when electromechanical relays were used as control devices. A ladder program consists of graphical symbols, representing logic expressions, and where contacts and coils represent outputs. Ladder programs are usually drawn in the form of wiring diagrams, that show the power source and the physical arrangement of the various components of the circuit, such as switches, motors and relays.
- **Structured Text (ST)** - Structured text is a high-level programming language with block structure, similar to how java and C is programmed. It is also similar to the PASCAL language. ST can be used to reduce complicated expressions that would create large structures in for instance ladder. It has support for general programming functions like IF-THEN-ELSE, CASE, FOR, etc.

-
- **Instruction List (IL)** – The instruction list is a text based programming language. Unlike Structured text, instruction list is a low-level language resembling the PLC architectures machine code instructions.
 - **Function Block Diagram (FBD)** – This language expresses the program code in a set of linked function blocks. The function blocks are represented by rectangular boxes, with one or more inputs on the left side of the block and one or more outputs to the right. Inputs and outputs are then linked between the blocks. Each function block has a certain function, for instance logical gates, time delays or as a counter.
 - **Sequential Function Chart (SFC)** – The SFC language provides a graphical scheme of the control sequence. The principle is built on states, called steps in the system, represented by boxes in the graphical view. Transition from one step to the next is made when certain logical expressions are approved, i.e. when the related Boolean expression is true. The transition then proceeds to the following step. Actions can be connected to each step, which can perform different functions, importantly these actions can be programmed in any of the languages in the IEC61131-3 standard.

SoftPLC

With the rapid development of personal computer hardware, several automation software producers started to market products in 1997 called SoftPLC. The SoftPLC uses an open architecture control software engine that can run on standard CPUs. Combining the features of a PLC, such as I/O-control, communication protocols, logic programming with the computational power of a personal computer. Even though it is not designed for real-time systems, due to its high performance it can still be used in demanding automation applications. (Olsson & Rosen, 2005)

2.6.2. Industrial Communication

Communication protocol theory

Transmission Control Protocol (TCP) is a common communication protocol used as a mechanism to transfer data between two applications on different devices. Internet Protocol (IP) is needed to send and handle the data transfer between the devices. Each device must have a unique numerical address, not necessarily fixed, to which the IP protocol can identify. The combination of TCP and IP is commonly referred to as TCP/IP, together they create a set of communication protocols that can operate across complex networks, and is widely used in computer systems in industrial automation. (Olsson & Rosen, 2005)

The basic structure of the TCP/IP protocol, can be considered as a structure with five layers as shown in Figure 11.

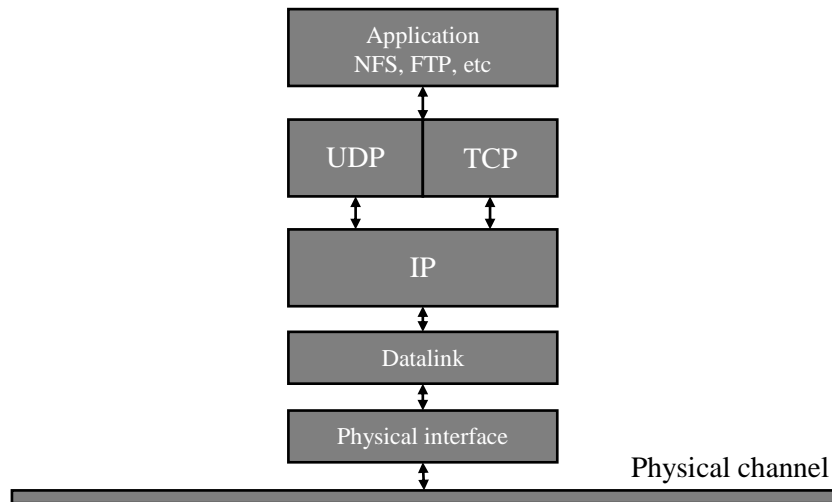


Figure 11: Layered structure of the TCP/IP protocol (Gustaf Olsson, 2005).

OPC theory

OPC (OLE for Process and Control), is a way of connecting a file with objects from other applications. It was initially developed in the 1990's with the purpose to create a standard communication interface. At that time vendors for automation equipment often used their own communication protocol to communicate with devices in the automation system. The possibility to provide a standardized infrastructure for enabling exchange of process data, irrespective of its vendor, made OPC widespread within industry automation. (OPC Foundation, 2018)

OPC uses a client-server approach for the information exchange. The OPC-server encapsulates the data source, such as a device, and makes its information available via its interface. An OPC-client can then connect to the server and access, as well as consume the data available. Where both the client and servers can provide and consume data to the OPC-server. (Mahnke, et al., 2009)

There exists three major OPC specifications that has been developed: Data Access (DA), Alarm & Events (A&E), and Historical Data Access (HDA). The most important one is the OPC DA technology, which is implemented in most products using OPC technology. The OPC DA-clients explicitly select the variables or items they want to read, write or monitor from the OPC-server. The client can then be configured to monitor the data on the server, and only send data when it is changed. The alternative is that the server continuously sends data with a certain update rate. (Mahnke, et al., 2009)

2.6.3. Industrial Robots

The use of industrial robots began during the 1960's and has since become a common equipment in many manufacturing companies. The basic characteristic of an industrial robot, is its versatility, flexibility in performing different tasks and its programmability (Bolmsjö, 2006, p. 39). The definition of an industrial robot, according to the International Organization for Standardization ISO 8373:2012 is: An automatically controlled, multipurpose manipulator, reprogrammable in three or more axes, which can either be fixed or mobile for use in industrial automation applications. (ISO 8373:2012, 2012)

According to Bolmsjö, the use of robots can be divided in to three main areas, described as follows (Bolmsjö, 2006, pp. 50-52):

- **Material handling** – Refers primarily to transfer of objects without the robot participating in value adding to the object. Typical operations are sorting of parts, packetizing and material handling.
- **Process operations** – Means that the robot is actively and directly involved in the work process, with the help of a tool or other external equipment. Normally in such a way that the workpiece shape, surface structure or function changes through the work process.
- **Assembly** – Refers to joining of components or subassemblies which in different operations steps leads to a complete product. An important difference in assembly in relation to the previously described areas, is that assembly often comes late in the value chain.

The demand for industrial robots has accelerated considerably since 2010, due to the trend towards automation within several branches of industry. Between 2011 and 2016, the average number of robot sales increase was 12% per year. The main driver of growth is the electrical and electronics industry, mainly from production facilities in the Asian region. However, the automotive industry is still the most important customer of industrial robots, accounting to a share of 35% of the total supply in 2016. (International Federation of Robotics, 2017)

2.7. Industrial simulation software solutions

According to Ståhl (Ståhl, 2016), the software is so advanced that it is hard for an employee to work with the software part time. Ståhl argues that there should be a dedicated simulation engineer that handles the software within a project group. Since virtual commission consist of a wide range of disciplines such as model building, automation, production development, mechanics and electronics it is sometimes hard for a company to do a virtual commissioning project in-house. In the following section, a handful of simulation software that has support for working with virtual commissioning are presented and briefly explained.

RobotStudio

RobotStudio is developed by ABB, used for modelling, simulation of robot cells and offline programming. RobotStudio can both be used in combination with a real robot controller or with an emulated virtual controller running locally on a personal computer. (ABB AB, Robotics, 2017). RobotStudio has two different parts, the simulation and visualization part, and the controller emulation part. In the simulation and visualization part, simple 3D-models can be created or more detailed geometries can be imported from dedicated CAD-software. The robot can be moved in the 3D-environment and points in space can be defined for the robot to move. RobotStudio automatically simplifies geometrical models created in a CAD software, which results in a reduction of computational power for simulation, and tends to more forgiving regarding different file types imported in to the software. The emulation part of RobotStudio is more focused towards the controller, where actual program code can be written and modified. It also allows the robot code to be exported to the real controller. Further, it can also simulate the movements and sequences of other automation equipment beyond the Robot, such as conveyors or other handling equipment. The disadvantages of RobotStudio is that it can only program robots supplied by ABB. Thus, production systems with robots from other suppliers other than ABB, makes RobotStudio limited in its application area.

Experior

The software is developed by the company Xcelgo. The software provides a wide range of applications such as:

- Physics simulation.
- Discrete event simulation.
- Modern 3D graphics.
- Many means of communications between PLC and IT applications.
- Integration with data and workflow from the project.
- Possibility to implement own software code.

The software comes in four different licenses made for developers, model builders, simulation and OEM. (Xcelgo, 2018)

Process Simulate

Process Simulate is a part of Siemens Tecnomatix portfolio. The software offers help for companies to reduce the risk with ramp-up new production lines and:

- Validate assembly lines.
- Optimize production lines.
- Virtually commission production lines.
- The software is integrated with the Teamcenter platform.
- Simulations with 3D kinetics.
- Dynamic and static collision testing.
- Measurements in 3D.
- Automatic assembly path planning.
- PMI – Product manufacturing information easily accessible.

(Siemens Tecnomatix, 2017)

Emulate3D

Emulate3D is a software oriented towards virtual commissioning, throughput simulation and for demonstrating industrial products. Emulate3D is suitable for building digital twins offline, before the real production line is built. The software also has the ability to build 3D layouts over production line that can be implemented into virtual reality using oculus rift. (Emulate3D, n.d.)

DELMIA 3D experience

Developed by the software company Dassault Systèmes. DELMIA stands for Digital Enterprise Lean Manufacturing Interactive Application. The software provides the user to plan manufacturing processes and resource planning in 3D to optimize lean production systems. The user could also simulate manufacturing assets combined with production planning. DELMIA also provides the opportunity to run a virtual production system to track the real production in real time as the user can do new tests in the virtual environment. (Dassault Systèmes, 2018)

Simumatik3D

Simumatik3D is a simulation software aimed towards virtual commissioning projects, developed by Mikael Ayani. The software is currently free of charge and contains functions to develop and validate PLC code in a 3D environment. Simumatik3D also enables the user to develop a HMI, linked to the PLC. The software is suitable both for educational and commercial use. (Simumatik 3D, n.d.)

Other simulation software

According to Peter Hoffmann (Hoffmann, 2016) there are several other simulation software that could be used for virtual commissioning. The software suggested by Hoffman is listed below:

- CIROS Studio.
- Kuka Sim.
- Tara VRbuilder.
- TrySim.
- Virtual universe.
- Virtuos.
- Visual Components 3D create.

3. Literature study

The literature study is focused on industry 4.0, virtual production, virtual commissioning and simulation. By studying other projects, a benchmarking of virtual commissioning is presented under this section as well.

An extensive literature study was performed and provided a basis for the master thesis. The literature study was based on published work from Lund University Faculty of Engineering (LTH), Chalmers University of Technology (CTH) and other research-institutions. Published books and academical articles also provided the theoretical background for the master thesis.

3.1. Benchmarking

The benchmarking is primarily focused towards the concept of virtual commissioning. The benchmarking has been divided in to two different types of articles and reports. The first type of source is more focused on practical work, where a virtual commissioning project has been conducted. The second type of source has a more theoretical approach, consisting of research articles, where a broader view of the concept is presented. The sources that has been studied are shown in Table 1.

The sources with a practical approach consist exclusively of master and bachelor theses and are presented separately. Several key points of interest will be covered and presented to the reader. They are:

- The company that the work has been done in collaboration with and the type of industry.
- What have been the main challenges in their work.
- What has been required in terms of resources and time.
- What they achieved with their project.
- The conclusion from their work with virtual commissioning.

Table 1: Summary of the sources studied regarding virtual commissioning. Both academical research articles with a broader aspect and studies with a more practical approach on virtual commissioning is covered.

<i>Type of source</i>	<i>Title</i>	<i>Year</i>	<i>Author</i>
Academic research articles	<i>On Virtual Commissioning of Manufacturing Systems</i>	2016	<i>Hoffman</i>
	<i>History and perspective of simulation in manufacturing</i>	2017	<i>McGinnis & Rose</i>
	<i>Survey on the virtual commissioning of manufacturing systems</i>	2012	<i>Lee & Park</i>
	<i>Economic application of virtual commissioning to mechatronic production systems</i>	2007	<i>Reinhart & Wünsch</i>
Master theses	<i>Virtual Preparation of Tetra Pak filling machine</i>	2011	<i>Hollander & Sappei</i>
	<i>Testing and Evaluation of Virtual Commissioning</i>	2017	<i>Johansson</i>
	<i>Virtual Commissioning of Smart Factory</i>	2017	<i>Älegård & Knutsson</i>
	<i>Emulation of a production cell</i>	2016	<i>Halmsjö & Fält</i>
	<i>Virtual commissioning of production process</i>	2017	<i>Winther</i>
Bachelors theses	<i>Emulation of a production cell including robot vision</i>	2017	<i>Einvik & Kurri</i>
	<i>Virtual Commissioning</i>	2015	<i>Johansson & Nilsson</i>
	<i>Virtual Commissioning of a manufacturing system</i>	2017	<i>Putrus Wisam</i>
	<i>ABB Production Cell</i>	2016	<i>Lundström</i>

On Virtual Commissioning of Manufacturing Systems (Hoffmann, 2016)

Hoffmann mentions that positive results with virtual commissioning have been achieved in large companies e.g. from automotive industry. Which are mostly utilizing the complex suites of tools in the context of the Digital Factory. The author argues that SMEs (Small-Medium Enterprise) are forced to improve their engineering and commissioning processes, but suites of tools and methodologies used in the larger industries are not reasonably transferred to SMEs. Hoffmann further discusses the requirements of a virtual commissioning project. He determines it to be a big modelling effort to build the necessary virtual plant models and lack of available methodologies for systematic implementation and reasonable execution of virtual commissioning.

In Hoffmann's opinion, virtual commissioning should preferably be completed before starting procurement and assembly. However, a realistic virtual commissioning is not possible until detailed design has been completed and the real components have been specified.

History and perspective of simulation in manufacturing (McGinnis & Rose, 2017)

This study by McGinnis and Rose concludes that for an effective use of simulation, the enterprise must maintain a staff of simulation experts, whose function is to develop, maintain and execute the simulation models. This is critical to support the factory design and operation decision making. The authors further discuss the issue why there is not a greater application of simulation in industry. They put forward the hypothesis that there are several inhibiting factors. The first of them is the **organizational issue**, in a manufacturing company you will find some people who understands these methods and appreciate their value and some people who will be skeptical. May it be because they have not seen successful applications, or because they have seen unsuccessful ones. There are also **modeling competency issues**. To successfully develop a model of a moderately complicated manufacturing process requires considerable level of expertise. Significant level of experience and mentoring are required for a simulation engineer to be considered competent to create a useful model. This competence can only be sustained through constant practice.

Constructing trivial models is easy, but to construct a large complicated model requires deep knowledge of the tool. One cannot be a part-time manufacturing simulation expert. The authors further explain that **another issue is the data**, whether from a planned or existing system. Almost all simulation projects must deal with inadequate data availability or data quality problems. The authors final issue with simulation, is that it is difficult to provide reasonable estimates for return on investments for simulation studies. However, as the manufacturing processes get more complex, the situation will change and there will be no alternative to simulation.

Survey on the virtual commissioning of manufacturing systems (Lee & Park, 2014)

This paper authored by Lee and Park, identifies and reviews issues in the application of virtual commissioning for automated manufacturing systems. They specifically focus on the concept to connect a virtual plant to a real controller, normally named Reality-in-the-loop. They argue that there exists a gap between the conventional simulation models which describe the dynamic behaviors of manufacturing systems using high level scripts, while the real manufacturing systems are electrically controlled by low level control programs involving sensors and actuators. Although the authors identify the potential of virtual commissioning to significantly reduce time and effort required at the real commissioning stage. They note several obstacles for the implementation of virtual commissioning: The modeling and simulation still requires significant amount of time and effort, and high levels of expertise in terms of automation, discrete event system modelling and simulation.

Although commercial products for virtual commissioning have been developed by major vendors, including Siemens and DELMIA, the authors see a challenge in fully utilizing these technologies. They further conclude that it is necessary to consider various scenarios of virtual commissioning, and denotes the difference between working with virtual commissioning of an existing production system and a newly designed production system.

Economic application of virtual commissioning to mechatronic production systems (Reinhart & Wunsch, 2007)

A German field study with 60 test persons that independently developed a control program for machine showed impressive results. 30 persons developed the control program without the possibility to use virtual commissioning and the other 30 persons had the opportunity to develop the control program with the help of virtual commissioning. The field study showed that for those who used virtual commissioning the approved requirements for the program increased by 100 percent. At the same time the commissioning time was reduced by 75 percent resulting in a reduced time to market with 15 percent. This is visualized in Figure 12.

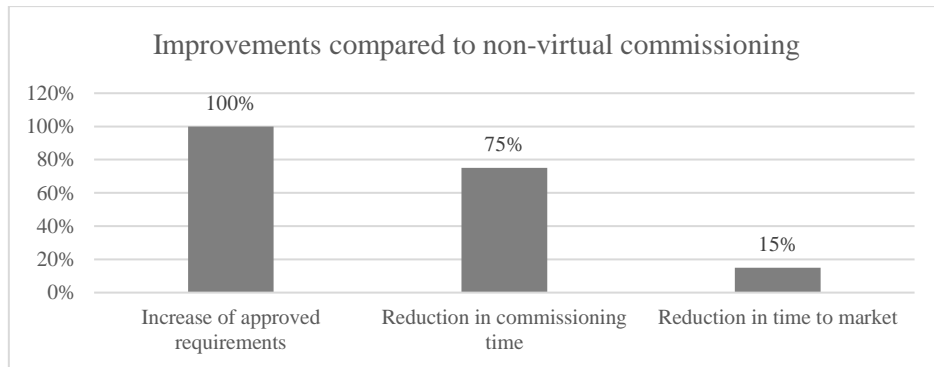


Figure 12: Visualization of improvements for the German field study of the benefits of virtual commission (Reinhart & Wünsch, 2007).

To identify and implement virtual commission where commission is time and resource demanding is vital, to get as much time reduction in the commissioning phase as possible. This also means that the economic savings in terms of money, time and resources is most beneficial in high-commissioning time projects.

Virtual Preparation of Tetra Pak filling machine (Hollander & Sappei, 2011)

Tetra Pak has the intention to reduce the time to market when developing new machines, the master thesis focus on virtual modelling to be able to work in with both mechanical design concurrent with control software. The authors developed a virtual model over the machine TR/28 filling machine and was created in DELMIA by using existing CAD-models, kinematic and program logic.

The resources that are needed are discussed and the conclusion is that it is crucial that work that has already been made is not remade, therefore the need to work interdisciplinary is one key to succeed with this aspect. According to the authors, the simulation software DELMIA has the function to update CAD-models within the simulation when changed in Pro/Engineer. There was no time to implement a controller for the simulation, therefore the simulation can be regarded more as an animation over the process.

According to the authors they see possibilities with virtual commissioning with benefits of integrating the development process. Especially in terms of mechanical construction and automation, to detect problems early in the project.

Testing and evaluation of Virtual Commissioning (Johansson, 2017)

This master thesis done in cooperation with Scania, investigates the feasibility of using DELMIA software from Dassault Systemés 3DExperience to carry out a Virtual Commissioning. The production cell that the digital model is based on, is a manufacturing cell producing a variety of different cogwheels.

The 3D-model of machines and equipment was modeled and imported to 3DExperience, and then connected to a simulated Siemens PLC via OPC protocol. The simulated PLC, emulated in Siemens PLCSim software did not support OPC connection per default, thus they needed a plug-in that extended the PLCSim with a TCP/IP network interface. To connect the signals between the simulated PLC and DELMIA, the KEPServerEX OPC Server was chosen to bridge the signals between the applications. In this project, an HMI-interface was created in WinCC Advanced software, which had integrated communication to the simulated PLC.

The problems that arose during Johanssons project, was that the robot program had to be simplified and remade to a big extent to work in DELMIA, making the validation questionable. In the authors view, the learning phase to execute a virtual commissioning project is quite long. Because of this, they argue that the first project including virtual commissioning will have limited benefits, since the knowledge must be acquired first.

The conclusion of Johanssons work, is that it is possible to carry out a virtual commissioning using DELMIA, but it requires much effort.

Virtual Commissioning of Smart Factory (Älegård & Knutsson, 2017)

This master thesis is a collaboration between ABB, ÅF and Chalmers University of Technology. The goal is to develop a virtual model and examine virtual commissioning. The virtual production line that is developed is a line for manufacturing plastic lenses from plastic sheets.

The model is developed in RobotStudio and has been used to evaluate the construction, robot paths and PLC programming. Due to testing the PLC program early in the project costly mistakes are eliminated. The actual PLC programming is done by another master thesis group but is implemented within the virtual model. Challenges mentioned in this report is the maturity of software solutions for virtual commissioning. The connection between the PLC development software and virtual commission model are according to the authors under developed and needs improvement. The project was still successful in terms of linking the PLC with the virtual model and simulating the industrial process in a 3D environment. However, the authors claim that due to the time it takes to build a virtual model it will take some time until the process of virtual commissioning is generally established as a common working process.

Emulation of a production cell (Halmsjö & Fält, 2016)

This thesis made by the authors Halmsjö and Fält, presents their virtual commissioning project created in cooperation with SKF AB and ÅF. Their virtual commissioning where done in parallel as a real commissioning project at SKF were taken in to operation. Electrical engineers, programmers and mechanical engineers worked concurrently as the virtual commissioning project was done. Their project is based on a productions cell consisting of two robots that serve several different processes with bearings. The virtual model was created in two different software, RobotStudio and Experior to make a comparison of their respective functionality. In both system setups, they used CoDeSys to emulate a software PLC and bridged the communication between the emulated PLC and 3D simulation via a gateway. In their case, they built a simple HMI-interface with the inbuilt visualization functionality in the PLC programming software.

The problem that arose during their project, was that much rework had to be done as new data from engineers became available. Their method was to begin using simple geometrical representations of components and adding them to their model. As soon as actual geometries were defined, the temporary geometrical representations were replaced. As the model became larger and more complex, they discovered that Experior required a large amount of computational power that reduced the accuracy of the virtual commissioning model. However, RobotStudio simplifies the geometrical model which alleviated the computational power requirement.

In the authors view, an important aspect is to establish the communication architecture of the virtual commissioning, before starting with the virtual commissioning modelling work.

Challenges during the project was the delay between different software causing the virtual model to behave in a slightly different way compared to the real production line. The cause of this delay is probably the use of the OPC server and how the simulation software is processing signals.

Virtual commissioning of production process (Winther, 2017)

This master thesis conducted by Winther, was done with the help from Volvo Cars. The project goal was to develop a way to validate the PLC and HMI with a virtual model and hardware interface. The virtual model created, was made in Siemens software Process Simulate and consisted of seven robots, seven fixtures and two turntables and buffers. Parts and components included in the virtual model that weren't necessary for the simulation were deleted to make the simulation work better, simply to reduce the need for computational power.

The main resources needed to perform this validation, were mapped signals combined with a virtual model, which needed to be linked to the PLC to be able to

perform the validation. To connect the signals to the virtual model in Process Simulate a macro were written by the author to auto-generate signals that Process simulate needed to operate. The macro required component names in the virtual model combined with kinematics and logic names. Process Simulate is beneficial when it comes to validating PLC programs according to the author, due to the ability to generate required signals.

The author sees several benefits regarding validating the production line offline. Benefits that the author mentions are:

- Obtaining cycle times.
- Check collision zones.
- Verify signals and alarms.
- Optimizing robot movements to reduce cycle times and energy consumption.
- Test different maintenance strategies.
- Observe the behavior of a production line when single machine units are not working properly.

Emulation of a productioncell including robot vision (Einvik & Kurri, 2017)

This study was done in collaboration with “Elektroautomatik AB”, a Swedish automation company that focuses on delivering complete automation systems to customers. The background to the study was to evaluate to what extent a virtual commissioning model could be used to test the equipment’s functions and carry out the customers FAT (Factory Acceptance Test) virtually.

In the project, the authors built a digital copy of a cell consisting of a robot that handles incoming products stored in pallets. Within the cell, a vision system identifies different components of the incoming pallet, such as cover, the product and the pallet and guides the robot to the correct pickup position. The products are picked up and moved to a conveyor that transports the product to a processing station, that is not included in this model.

The virtual model was created using quite an extensive system, using three different computers communicating with Ethernet via a router. Their main 3D simulation environment was Simumatik3D (Open Source), used to test the movements, programming code and physics in the production cell. RobotStudio was running on the same computer and via an OPC UA synchronizing the robot movements to Simumatik3D.

One of the computers was running the emulated PLC on PLCSim Advanced, an HMI-interface running on WinCC Runtime Professional and the TIA-Portal for programming the emulated PLC, all supplied by Siemens.

A separate computer was in this case used to run a vision software, to emulate the camera existing in the cell. Pictures were imported manually to the camera emulator, and the products coordinates were sent to the robot software.

A challenge that the authors realized, was that the safety system in the cell could not be emulated in their virtual setup. The PLC code that they had gathered from the real production cell, had to be modified to ignore the safety signals for the virtual model to work. In addition to the safety related problem, the authors had difficulties with the communication establishment. The communication between Simumatik3D and the emulated PLC did not work as expected, thus extensive effort and time were needed for debugging. However, because of this they concluded that the virtual model construction can be developed as a separate project, and partly be tested without the PLC communication.

In the authors view, the benefit of a virtual commissioning lies in the ability to debug the programming code and to streamline the process of the FAT. However, that requires a clearly defined test that can be tested in the virtual model, so that a virtual FAT can be done. They also discuss the difficulty in validating the emulation model, because of lacking measurable parameters that were available in their project.

Virtual Commissioning (Johansson & Nilsson, 2017)

This project was conducted with the University of Skövde and Volvo Cars factory that produces engines. The authors explain that Volvo Cars vision is to have a virtual copy of every production line within the company. The project goal was to establish communication between the flow simulation software Siemens Plant Simulation and a PLC-unit. This is performed to enable validation of the PLC-program. The production line that was modelled was not a copy of a real production line, it was a production line virtually made for this project. The virtually created production line handled four different engine blocks from three different machines that were stochastically generated in these machines. Then the engine blocks were transferred with conveyors into two other machines depending on occupancy level and type of engine-block. The model also consisted of a simple turntable.

The PLC logic was coded in Siemens Step 7 and the 3D model was developed with two different software Simumatik3D and Process simulate. These simulation software were then compared in respect to their simulation results. The authors also used a real PLC hardware, Siemens Simatic S7-300. With Siemens own OPC-server a connection between Plant Simulation and the PLC was established. Between Siemens Step 7 and Simumatik3D connection using TCP/IP was established. One computer ran the PLC and the other the simulation software, this was possible due to the connections established.

Problems that arose during the project was using the different software in a correct way. The authors had to do a lot of testing to establish the different communications between the software. However, the tests were successful and the authors succeeded with connecting and validating PLC with both simulation software. The authors discuss the both simulation software and concludes that they are not flawless. Simumatik3D is suitable for controlling detailed PLC and Process Simulate is suitable for validating big PLC programs on a system basis.

Virtual Commissioning of a Manufacturing System (Putrus & Putrus, 2017)

This thesis authored by Putrus & Putrus, presents their virtual commissioning work, done in collaboration with the consultancy firm “Projektengagemang i Skövde”. In their project they work in parallel with a reconstruction of an existing production cell at Volvo Trucks Operations, where a new control system and electrical system were to be installed, as well as programming of the PLC-hardware. The purpose of their project was to build an emulation model of the real production system, intended to fabricate sand cores using the software Simumatik3D. With the help of the model, it was intended to be used for verification and validation of the control systems program and functions.

The authors used Simumatik3D to create the digital model of the manufacturing cell, creating simple 3D-models to emulate the necessary movements within the cell. On the same computer the PLC programming software Tia Portal and the PLC emulator PLCSim Advanced were running.

ABB Production Cell – Virtual Commissioning of ABB Production Cell (Lundström, 2016)

The ABB Production Cell is a concept for building and develop production lines using standardized methods and equipment. The project was conducted in collaboration with ABB and Umeå University. The author develops code for an existing test cell and creates the connections between the different software RobotStudio, AutomationBuilder and PanelBuilder, all developed by ABB. An OPC server was used to connect the different software. RobotStudio was used to develop robot code. AutomationBuilder was used to develop PLC code and PanelBuilder was used to develop the HMI. The virtual model is also verified through Virtual Factory Acceptance Test (vFAT) and compared with conventional FAT. The production line consists of the ABB robot IRB1600, one conveyor, sensors and three processing stations. The vFAT was used to find problems in the code and to evaluate cycle times and to evaluate if the vFAT was accurate compared to the real production line.

Problems that arose during the project was the time to establish connections between the different software and that the softPLC crashed. The author used SC

ConnectivitySmartComponent in RobotStudio and the Add-in took 5 seconds to establish connection with the PLC. Another problem that the author brings up was the comparison between vFAT and FAT. The cycle times were accurate, so was the behavior. However, the I/O was not approved.

The author claims that virtual commissioning can be used to debug code offline in the office instead of in the workshop. The author also claims that the possibilities to extend the virtual model with safety aspects and other functionalities are good.

3.2. Benchmarking analysis

This section can be seen as an analysis and summary of the conducted benchmarking, explaining the most important aspects of the conducted benchmark.

Companies that are using or has done projects regarding virtual commissioning.

Our benchmarking has shown that the following companies has worked with projects regarding virtual commissioning:

- Volvo Cars.
- SKF.
- Scania.
- Tetra Pak.
- ABB Robotics.
- Volvo Group.
- ÅF.

The type of branches that have been identified working with virtual commissioning are: Automobile companies, larger manufacturing companies, consultancy firms and automation companies working for larger companies. To what extent these companies have come in their work with virtual commissioning is varying. Many of them has done virtual commissioning projects to assess the concept of the technology, while others have created a virtual model which has had use in a real commissioning project.

Type of production cells that have been modelled

The type of production lines typically worked with, are isolated cells consisting of one or more robots. The benchmarking has further shown that there exists a challenge to model and create the logic for non-standard equipment and especially processing equipment existing in the cell, e.g. CNC-machines or pressing machines. In most cases processing machines are normally regarded as black boxes, and not included in the simulation. What is usually considered in most cases is the transportation of the products within the cell, for instance on conveyors or by robots.

Thus, most of the project studied focuses on the sequence within the cell, and to validate that the PLC program executes the correct sequence.

Common problems identified

The most common problem identified by studying other master's theses is the establishment of the communication between different software. Further, it takes time to both learn the PLC software and simulation software at a deeper level. At the same time the user should have knowledge regarding communication software, often some kind of OPC server to establish the communication between the PLC software and the simulation software. Due to the need to write programs in different languages combined with establishing a connection with the different software indicates that the competence and skill within the company needs to be broad. For example, the personnel must have competence within PLC programming, competence within IT and server configuration, and in many cases Robot programming as well.

Since the most common problem is communication between the different software used to conduct virtual commissioning, these functions must be developed to ensure a more user-friendly interface. There is no established method for doing a virtual commissioning. The user still needs to develop a method that suits the specific needs for the project that is being virtually commissioned.

Resources required

To be able to conduct virtual commissioning there are several crucial tasks that must be done besides having the competence and skills. CAD-models of the equipment within the cell must be created or available in 3D and the electrical I/O signals must have been mapped or be developed in parallel with the virtual commissioning work. Software for PLC programming and a simulation software is also crucial to conduct virtual commissioning. If the equipment should be able to do different tasks and perform different sequences, for example a robot, these tasks should also have been specified and documented. A digital model could, and should be used as a production development tool and therefore not be viewed as static, but should rather be used as a living documentation. However, some simulation software does not have a link between the CAD-modelling program and the simulation. Therefore, a lot of work in the simulation must be redone after changing a CAD file. Some simulation software supports the linking function and are therefore more suitable when using a virtual model as a development tool.

Achieved results from the studies

The technology and method using virtual commissioning and digital twins are in its infancy. However, many studied projects showed promising results in different areas. PLC testing and validation using a virtual model is a major benefit with virtual commissioning and this aspect was proven to work for several studied cases. Doing an actual implementation of the PLC and robot programs was not extensively conducted, but was proven to work in one studied case in a test environment. This shows that it is possible with modern day technology but the benefits of doing so are not yet fully established.

4. Production analysis

This chapter aims to describe the production analysis conducted at the Alfa Laval factory in Lund. It was performed to determine which production line that was going to be modelled as a prototype in a digital environment.

Several automated or semi-automated production lines at the facility in Lund were analyzed in terms of the conditions for creating a virtual copy. The purpose was to simulate the process steps when producing a product. Depending on the type of production line, different aspect and types of simulations was considered, and differed for each specific production line.

Data and information collection was mainly done in three different ways:

- Production data from different systems and files.
- Interviews with production personnel and office personnel.
- Observations.

The production data gathered from the internal data handling system gave the most recent information about the production lines, such as yearly production and what type of products that are manufactured within the line. The observations gave insight on more qualitative factors, such as how complex the production line is, the general process flow and the sequence of operations within the production line. The interviews with the personnel included staff members at Alfa Laval from Operations Development, Product Development and production staff. Information gathered from these meetings gave answers to what current data were available in terms of CAD-models, production line layout, product data and the conditions for each production line.

Each production line was analyzed with the help of a table that we had developed with several factors that were to be compared. The table is available in Appendix B – Production analysis. In total, ten different production lines were analyzed and compared in terms of how suitable they were in regard to creating a prototype. The production lines that were analyzed is presented in presented in Table 2 and illustrated in Appendix C – Analysed production lines.

Table 2: The different analysed production lines and cells

<i>Pressing lines</i>	<i>Welding cells</i>	<i>Assembly lines</i>
Pressing Line 1	Laser welding cell 1	Assembly line 1
Pressing Line 2	Laser welding cell 2	
Pressing Line 3		
Pressing Line 4		
Pressing Line 5		
Pressing Line 6		
Pressing Line 7		

4.1. Choosing production line

The factors for each production line were graded and then converted into three main factors most relevant to this project. These main factors included: chance of success, potential benefits and potential for further work. There were also two additional factors that indirectly affected the main factors. The type of simulation most suitable and potential problems or challenges. The chance of success takes several important aspects into consideration. Since the project is time-limited, the access to 3D-models, production layout and complexity of the production line will affect the chance of success. Two considerable different production lines were graded a higher score on this factor compared to the others, these were the Assembly line 1 and the Laser welding cell 1. A summary of the grading for these two production lines is shown in Table 3.

Simple model prototypes on both cells were created to assess different software and the chance of success when modelling these two lines. This was done to give a basis for the choices on which simulation software that was going to be used, and which production line to solely focus on creating a prototype of. Assembly line 1 only had detailed CAD-files over certain objects and a model over the whole line was missing. Due to issues with retrieving models and handling detailed models it was hard to build even a simple prototype, because the model inflicted computer crashes. Another issue was the software, for simulations suitable for Assembly line 1 required another software than was accessible. Thus, the simple prototypes resulted in the choice to continue to work with Laser welding cell 1 due to several important factors. The 3D model was almost complete, up to date and compatible with the software RobotStudio. At the same time the benefits were considered good and the potential for future work was good as well since this was a new production line that can be further developed. Part of this choice was also which type of simulation that was going to be performed. At this point of the project, it was determined to work further with Virtual Commissioning, and focus our study on this technology, which will be the main concept of this report from this point onwards.

Table 3: Grading of the two production lines, considered most suitable for creating a digital copy of.

Production line	Laser welding cell 1	Assembly line 1
Chance of success	Medium/High	Medium/Low
Value to the company	Medium/High	High
Potential for further work	High	Low/Medium
Type of simulation	Virtual Commissioning, model base for implementing new products in the line.	Product commissioning simulation, process simulation
Potential problems	Most of the robot simulations have already been done for a VC. However, simulation for the whole production cell has not been done.	Which simulation software to use

5. Model development

This chapter gives a short description of the production cell that was modelled in a digital environment and describes how the virtual model was developed. A virtual model test was also conducted to test different functions of the virtual model. Finally, an analysis of the virtual model is presented.

The method used for building the simulation prototype, is based upon the structured way proposed by Banks and Carson (Banks & Carson, 1984). This is a structured way to systematically work and use simulations in projects. It has further been developed to better suit this specific project. The work method that has been used as a guide in this project is available in Appendix A –Modelling project flowchart. Much of the work has revolved around the model building and verification stage that is part of Banks work method. In this project the model building has consisted of concurrent work involving programming of the PLC, programming the robot and the simulation model, as well as linking the communication between the software. This work method has been an iterative process, which in practice means that it has been built up and tested piecewise. The work method is illustrated in Figure 13.

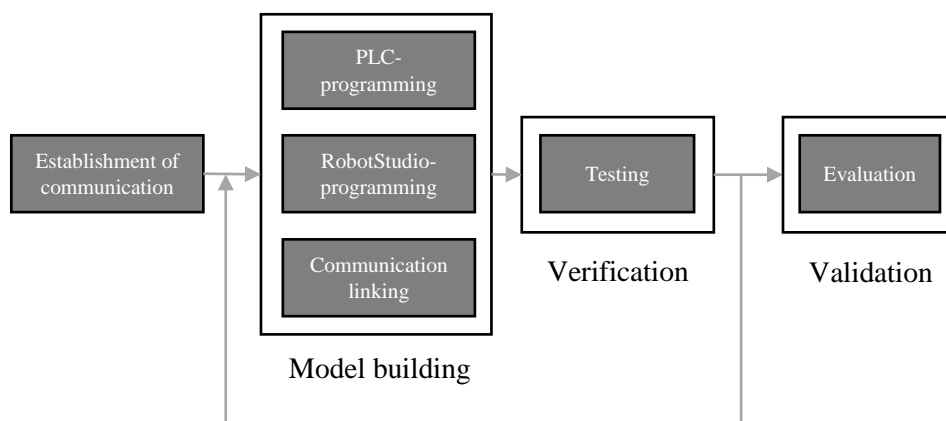


Figure 13: Visualization of the model development work method.

A list of requirements was developed, based on information and data gathered from the real production line. Since the virtual model is a prototype it is not necessary for the prototype to contain all the functions from the real model. We wanted to develop a virtual model that could perform a complete cycle with different variations. The list of requirements can be viewed in Table 4. The list is divided into different sections depending on the category. The last category “Operator” is only for visualization since the real operator is performing those tasks in the real production cell. The goal with the model is to fulfil as many of the requirements as possible, especially the requirements marked as priority 1.

Table 4: The list of requirements used in the model development process

List of Requirements			
Number	Category	Priority	Requirement
1	Robot movement	1	Pick up the weight from the fixture
2	Robot movement	1	Leave the weight on the fixture
3	Robot movement	1	Pick up a welded cassette
4	Robot movement	1	Leave the welded cassette on the turner
5	Robot movement	2	Leave the welded cassette on the pallet
6	Robot movement	1	Leave the welded cassette on the defected pallet
7	Robot movement	2	Position the welded cassette over the fixture for inspection
8	Robot movement	2	Position the welded cassette over the pallet for inspection
9	Turntable movement	1	Turn when needed
10	Turner movement	1	Turn the cassettes and leave them on the pallet
11	Welder movement	2	Weld a cassette

12	Safety	2	The cell should be safe for personnel and the cell itself
13	Safety	2	The robot, turntable and turner should not operate while the light curtain is broken
14	Safety	2	The emergency stop button should shut down every machinery within the cell
15	PLC	1	The PLC decide every movement of every unit in the cell
16	PLC	1	The PLC and the machinery use handshaking
17	HMI and Operator Panel	1	The HMI and operator panel is interactive for the user
18	HMI and Operator Panel	2	The HMI shows production information
19	HMI and Operator Panel	1	The HMI visualize the status of the system
20	Special events	2	The model can start from an empty cell
21	Special events	2	The model can empty the cell for a change-over
22	Special events	2	The model handles different products
23	Cycle	1	The model can run several cycles in run mode
24	Operator	2	The operator can load a cassette on the fixture
25	Operator	2	The operator can move and inspect the welded cassette

The virtual commissioning prototype has limitations described below, these have been developed over the course of the project.

- No verification of the real PLC or robot program will be performed.
- The prototype will be limited and not contain all the functions of the real production line.
- The HMI and operator panel is developed for the perfect user, unexpected behavior of the prototype can occur if the user uses the HMI and operator panel in a way it is not configured for.
- Only the robot in the cell is simulated with its own rapid code, the other equipment is partly simulated using animations as a reaction on the PLC code.
- The virtual factory acceptance test is not compared to a real factory acceptance test.

5.1. Characterization of the production cell

The characterization of the production cell briefly explains how the real production cell works, its purpose, the different equipment and how the communication works within the cell. The virtual model is then based on the actual production cell, making it important to define the different tasks and communications thoroughly.

The function of the laser welding cell 1 is to weld two corrugated plates together in to one unit, called a cassette. This removes the need for using a rubber gasket between the plates, which enables the customer to use media that otherwise would react with the rubber gasket, which substantially reduces the lifetime of the gasket.

The principle construction of the Laser welding cell 1 consists of three main equipment's: an ABB robot, a CNC-welding machine including an attached turntable, and a turner unit. The cell is managed by one operator that has the role to load the plates on the fixture and inspect the welded cassettes to decide if they are approved or not. The principle layout of the cell with the main components and equipment can be seen in Figure 14.

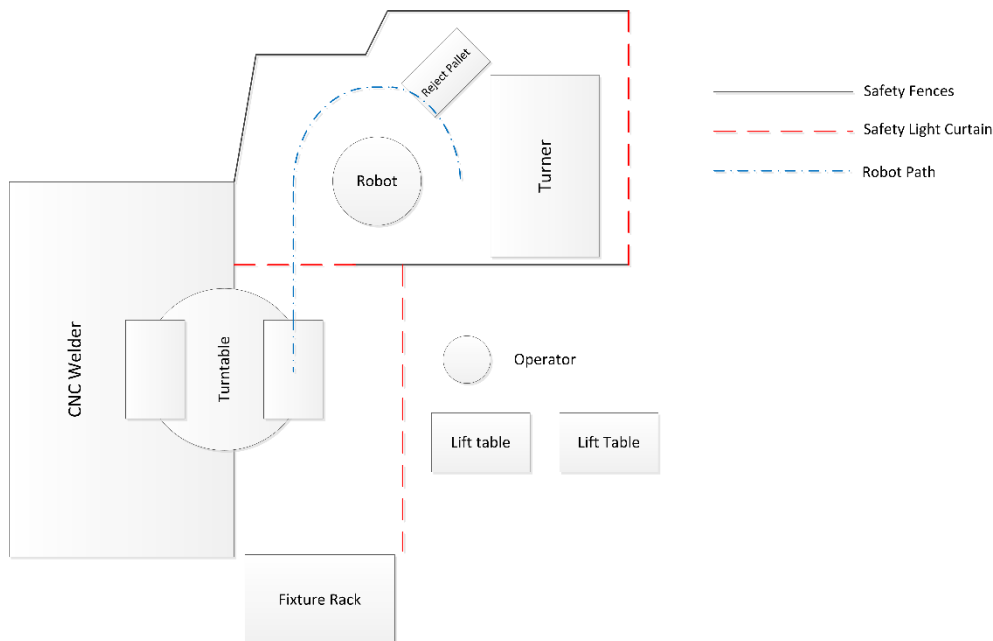


Figure 14: Principle construction of the Laser welding cell 1.

Production cycle

A simplified description of a production cycle in the cell starts with the operator loading two corrugated plates on a fixture, placed on the turntable connected to the CNC-welder. The robot places a weight on the plates to stabilize them during welding. The turntable rotates the plates in to the welding cell, which begins its process of welding the them together. Once the process is complete, the turntable rotates again and the robot picks up the now called cassette and the weight from the fixture. The robot places the cassette on the turner unit, which rotates the cassette up-side down and places the cassette on a pallet with welded cassettes. The robot then returns to its original position over the rotation table and the cycle is finished.

PLC

The PLC controls the sequencing and actions for the equipment within the cell. It has the overall responsibility to make sure that the process is running in a correct and safe way. That the status of the cell is shown to the operator and that the operator can specify parameters for the production process. The PLC communicates with the controllers in the Robot and the CNC-welder, the HMI-interface, as well as with the sensors and actuators present in the cell.

Robot

The ABB robot is programmed in short sequences with a relatively fewc move instructions, referred to as orders. The PLC-controller in the cell sends data to the robot with information on what order to run. Once the robot has done the sequence it sends a signal to the PLC that it has completed the order. At this position, the robot waits until it receives further instructions from the PLC. In other words, the programming in the Robot is relatively simple, consisting of procedures with input parameters such as offset coordinates. The sequences that the robot can perform is pictured in a flow diagram in Figure 15.

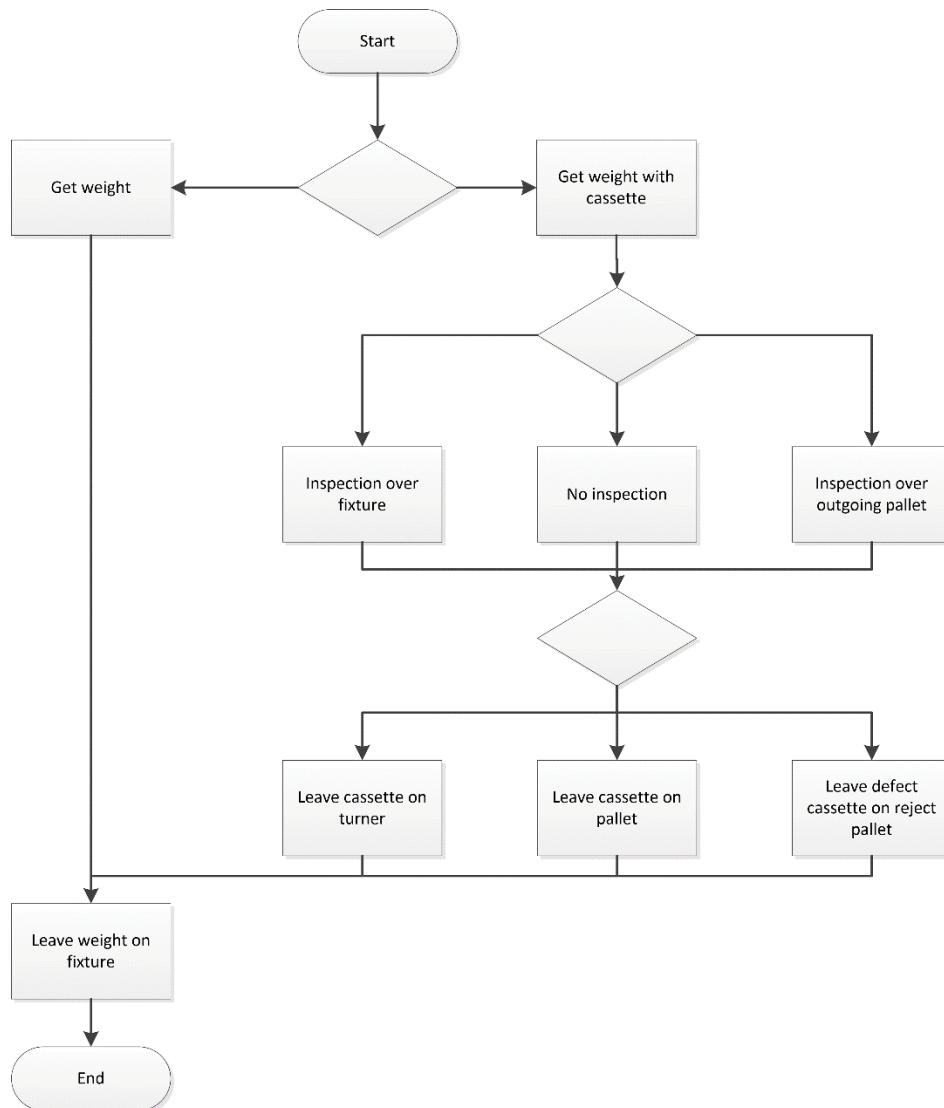


Figure 15: Flowchart of the ABB Robot sequences.

CNC-welder

The CNC-welder is welding two corrugated plates together to build a cassette. The welding path is programmed as a CNC-machine, with coordinates that together forms a welding path around the plates that the machine follows. The welder also has a turntable built in, so that when the cassette inside the machine is being welding, the operator can load new plates on to the turntable. The turntable rotates when the welding process is done and when the operator has loaded the fixture on the turntable with new plates.

Turner unit

As the cassette has been welded and the product has been approved by the operator, the robot picks up the cassette and moves it to the turner. The cassette is placed on the turner unit, which grips the cassette with vacuum grippers. It is then rotated up-side down, lowered and released on a pallet.

Communication

The communication within the production cell, is based on a PLC having the overall control over the equipment. There is no direct communication between the CNC-welder, ABB robot, turning unit or the HMI-interface. This means that the PLC has the responsibility of sequencing all the processes in the cell, and is thus a critical component to have correct programming. The principle of the communication in the work cell is shown in Figure 16. What is not shown is the communication with the surrounding equipment such as the safety system, sensors and pneumatic systems in the cell.

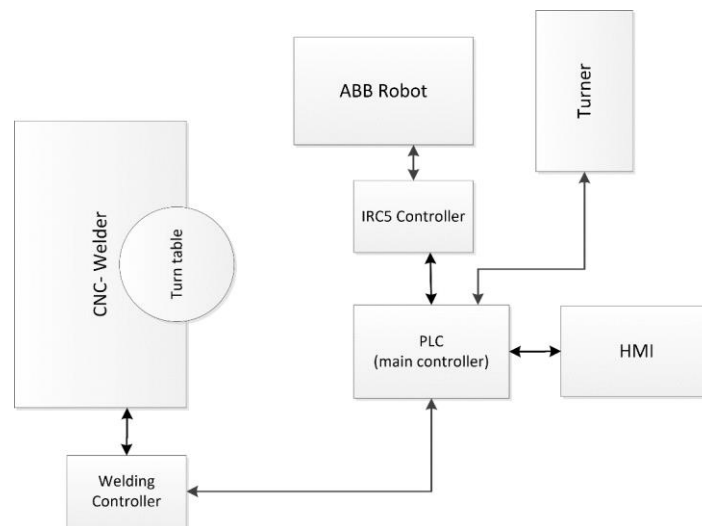


Figure 16: Communication in the Laser welding cell 1.

5.2. Defining the purpose of the simulation

The purpose of the simulation regarding the Laser welding cell 1 was to create a virtual prototype, including the automation sequences. That provides adequate precision to allow for collision analysis, that can be identified for new products that will be commissioned in the production cell. This requires that the robot, flip-board, rotation table and stacking equipment is modelled in high detail, and that the sequences of movement, as well as the timing corresponds to the real production cell. Especially for the robot, which performs most of the tasks in the cell, it will require a detailed layout that needs to be validated in terms of precise positions of equipment, including fences and surrounding equipment.

The welding process is not the focus of this simulation, and thus its process will not be modelled in detail. The reason being that the welding-machine is controlled by an isolated control system. However, animations showing the product flow will be implemented including the welding process, turntable and turner. That reacts on signals from the PLC, linking the whole system together.

5.3. Data collection

As we learned both from the literature study and from the benchmarking, accessible data is crucial for a virtual commissioning project. The accessible data was also one key criteria analysed in the production analysis. For the welding cell we had access to a complete 3D model over the cell and mapped sequences. This data was initially collected when the virtual model over the cell was initiated. The operator panel is a copy over the real panel. The HMI is made by the authors since it was not finished in the real cell, since it was an ongoing project. The tags used in the PLC and RobotStudio is developed by the authors, since the real cell is more complex than the virtual prototype.

5.4. Establishment of communication

The system setup for simulating the production cell in the virtual environment was created using two workstations, illustrated in Figure 17. On workstation I, the simulation is visualized and the control code for the robot is executed. Workstation I works in a passive way, it waits for signals from the softPLC located on Workstation II, where also the HMI interface is located. Between the workstations signals are sent via TCP/IP, setup by an OPC server on Workstation I. The separately defined signals in the software applications are linked and allows for communication between the applications. The principle configuration of the system set-up is shown in Figure 17.

A brief explanation of the software used in this project are presented below:

- **RobotStudio** – The main simulation software, providing features to design a robot workstation, program the robot controller and visualize the simulation graphically.
- **ABB IRC5 OPC Server** – Displays and makes aliases for the OPC items defined in the virtual robot controller (IRC5) available to other software.
- **KEPSeverEX** – An OPC server that can access items from applications running on different devices. Allows linking of variables on applications running on different devices.
- **CoDeSys Control Win V3** – Software that emulates the PLC, working as a SoftPLC. In the software a symbol list can be generated, which the OPC-server can read and get access to the variables.
- **CoDeSys V3.5** – Programming environment, where the emulated controller is programmed and the HMI is designed.
- **CoDeSys Gateway V3** – Software that creates a gateway, so that the OPC-server and PLC programming software can connect to the softPLC.

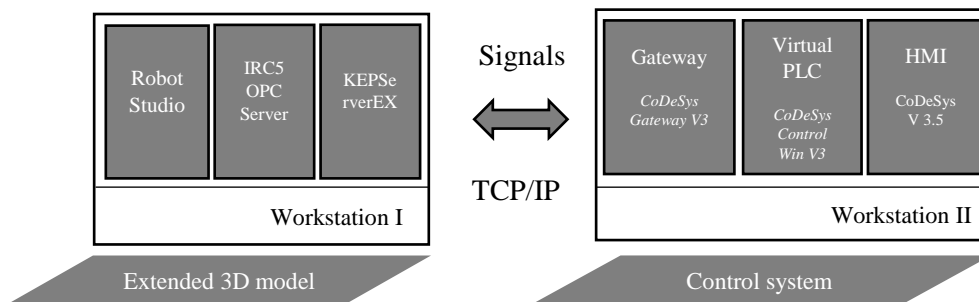


Figure 17: System setup, running RobotStudio and OPC servers on workstation I, and the softPLC, gateway and HMI interface on workstation II.

To establish communication between the softPLC and RobotStudio, ABB IRC5 OPC Server is required, to open up access to the signals defined in the robot program. The function of the IRC5 OPC-Server is to generate aliases and tags from the soft controller simulated in RobotStudio. The tags generated, is then linked in the KEPSeverEX OPC Server, with the tags downloaded from the softPLC. The linking of the variables in KEPSeverEX is shown in Figure 18. The complete communication set-up is illustrated in Figure 19, where the different programs used and their communication coupling to each other is shown.

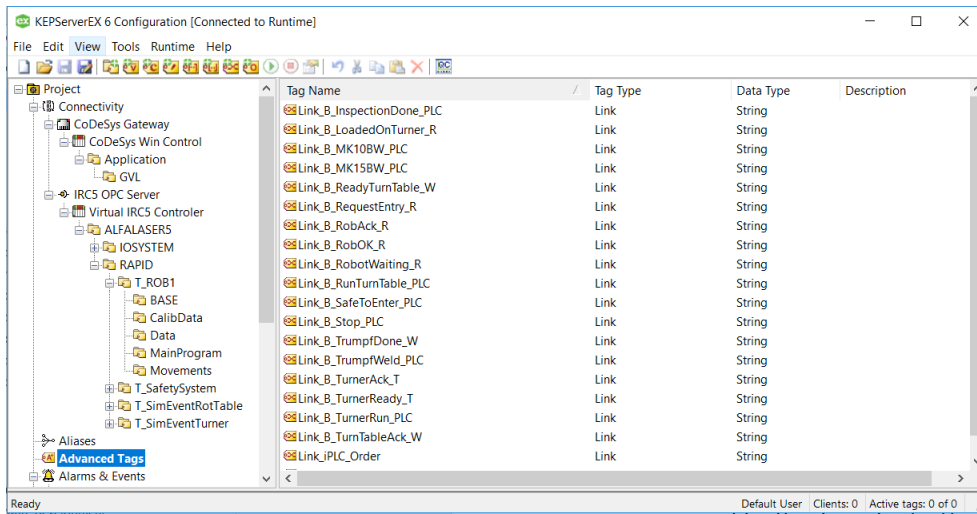


Figure 18: KEPServerEX, linking of the tags between RobotStudio and the softPLC.

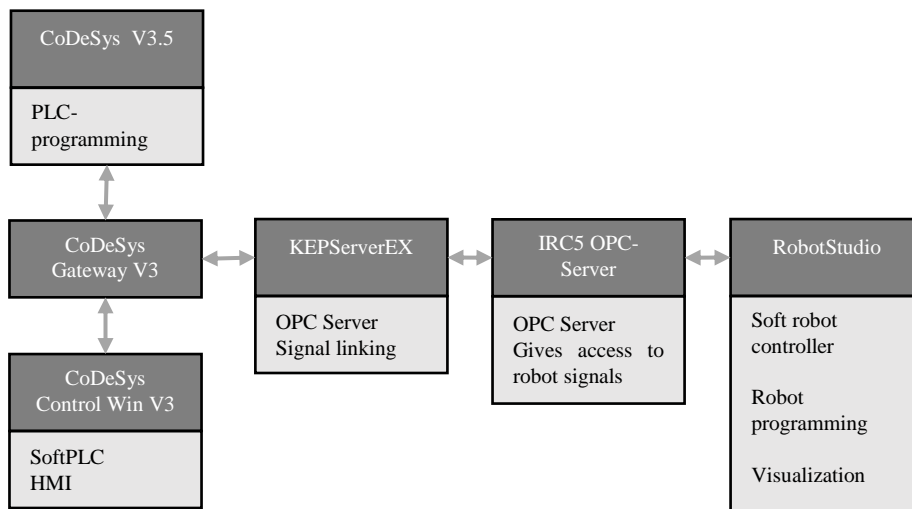


Figure 19: OPC server and client set-up for communication between the applications on the two workstations.

5.5. PLC programming

The PLC programming is made with the software CoDeSys and the programming languages that is used is SFC (Sequential Function Chart) and ST (Structured text). Several different main programs made in CoDeSys are running simultaneously within the main task due to the link between the different machines in the cell. The programs that are running are:

- **Robot program** – Decides robot tasks and sequences.
- **Welding and turntable program** – Decides tasks and sequences for the welding machine as well as for the turntable.
- **Turner program** – Decides tasks and sequences for the turner.
- **Safety program** – A program that is running to ensure the safety of personnel and the cell itself.
- **Changeover program** – A program that handles the issue of change overs, this program is running different operations from different programs to ensure that a changeover is correctly done.

These different programs form the PLC together. To simplify it, the PLC is the brain of the cell that keeps track of every device, what they should do and when they should do it. The different PLC programs interact with each other to keep track on where in the manufacturing process the product is.

Variables have been declared and used as both global variables and local variables within the different programs. The type of variables that have been used for the different PLC programs are listed in Table 5.

Table 5: The different variables used in the PLC

Type of variable	Contains
BOOLEAN	True/False
DINT	-2147483647 to +2147483647
TIME	0 to 4294967295

The Boolean variable is used to handle simple signals from the equipment or internal within the PLC. Boolean variables are also often used in different functions within actions, for example in “IF cases”. The DINT variable is used in various counters as well as when the PLC sends a specific job to the robot. The TIME variable is used as a delay between different steps due to delays in the communication with the OPC server.

CoDeSys executes the step with its associated action and when the condition to move on to the next step is true the PLC transitions to the next step. An example of this scenario is visualized with code from the turner program and shown in Figure 20.

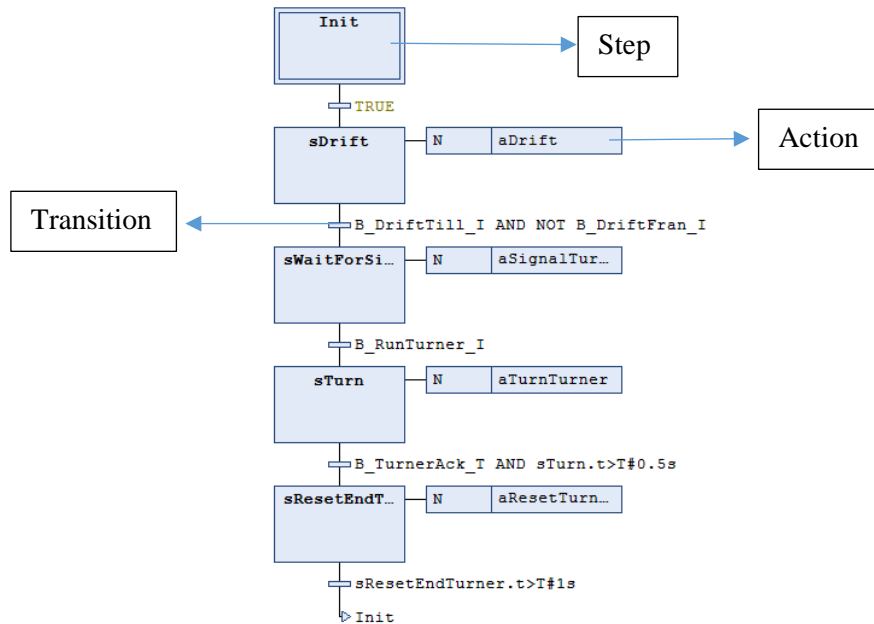


Figure 20: PLC code made with SFC and ST to control the turner equipment.

Steps modelled as branches could also be implemented, for example if the user wants the PLC to choose different steps depending on various factors or variables. An example of this is shown in Figure 21 and is one part of the robot program. The example shows which step the PLC should enter depending on if the welded cassette is going directly to the pallet, to the turner, or have been disqualified due to quality issues and going to the reject pallet.

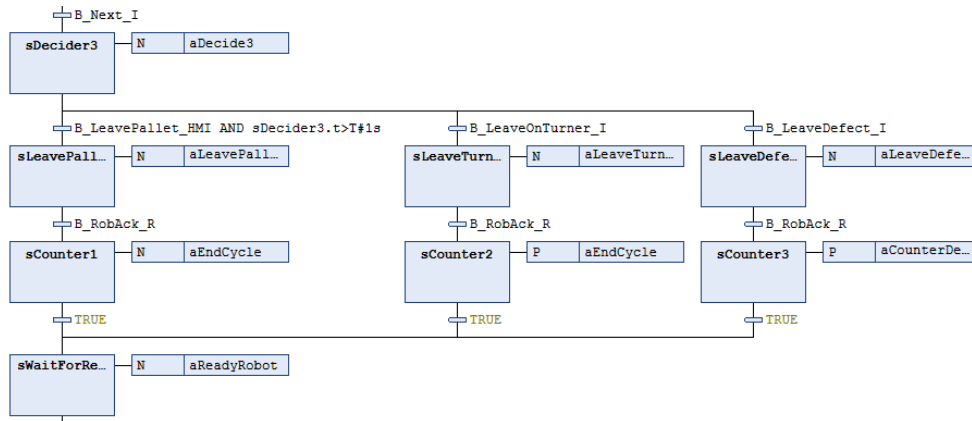


Figure 21: Steps modelled with branches with different actions.

Another method that has been used when building the PLC is parallel steps, where the steps and associated actions in a branch are executed simultaneously. This could be applicable when for example wanting to diversify the code, so the user easily could see which parallel step that actually was chosen due to underlying variables. Every step and action could in theory be in the same step with only one action but using branches the code is more readable and easier to troubleshoot. An example of parallel branches is shown in Figure 22, taken from the safety program.

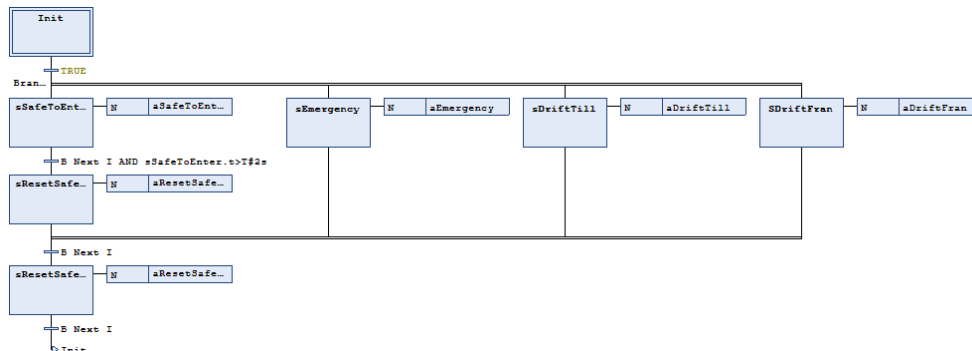


Figure 22: Parallel steps that are executed simultaneously.

5.5.1. Counters

Several counters are implemented in the PLC. Internal counters to keep track on which path the PLC should enter for every loop. External counters have also been implemented, to show the operator how many cassettes that are OK and placed on

the pallet and how many cassettes that are rejected and placed on the reject pallet. The counters are made by using DINT variables that gets their current value plus one for different steps, starting from zero when running the PLC for the first time. For example, the variable that keeps track on how many cassettes that are rejected gets their value plus one when the PLC enters the step sCounter3, visualized in Figure 21. This value is then linked to the HMI so that the operator easily can see how many cassettes that are rejected.

5.5.2. Handshakes

The PLC programs and the different equipment in the cell are communicating with a method called handshaking. The basic principles of this is that the PLC waits for a signal that the equipment is ready, then sends a signal to the equipment to perform a specified action. After the equipment has received the signal it sends another signal to the PLC telling the PLC that the equipment has received the signal. The PLC moves on the next step and waits for a signal from the equipment yet again. This is illustrated in Figure 23.

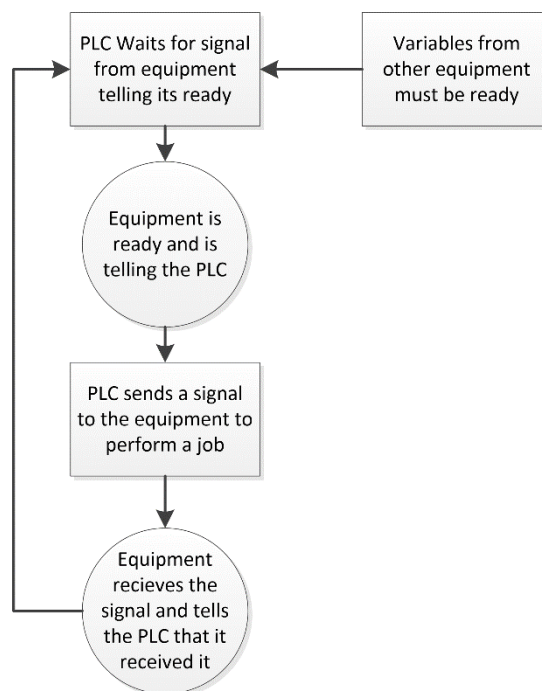


Figure 23: Handshake between the PLC and equipment.

5.5.3. Handling special events

There is a need to handle special events in the virtual model from the PLC. When the cell is started from its home position, ergo when the cell is empty the PLC must handle this case. Instead of a normal cycle for the robot, the robot picks up the weight, waits for the operator to load the cassette and then leaves the weight directly. In a normal cycle it will leave the welded cassette on the turner before it leaves the weight.

When the cell is empty, the function “jump” is implemented in CoDeSys. When a certain step is finished and the transition is made, the next step is specified to another step further down in the code. For this scenario, when the step “Get weight” is finished the code jumps down to “Leave Weight”. The step “Leave Weight” has a condition that the light curtain must be reset, ergo that the operator has loaded the fixture with new unwelded cassettes and then pressed reset light curtain on the operator panel. To decide if the PLC should execute the code for this scenario a step for the decision is established. The decision step is based on a counter that knows when the cell is started from home position (empty cell) or is in normal production mode. The jump is visualized in Figure 24 and it is the actual code from the robot program. The arrow indicated the jump.

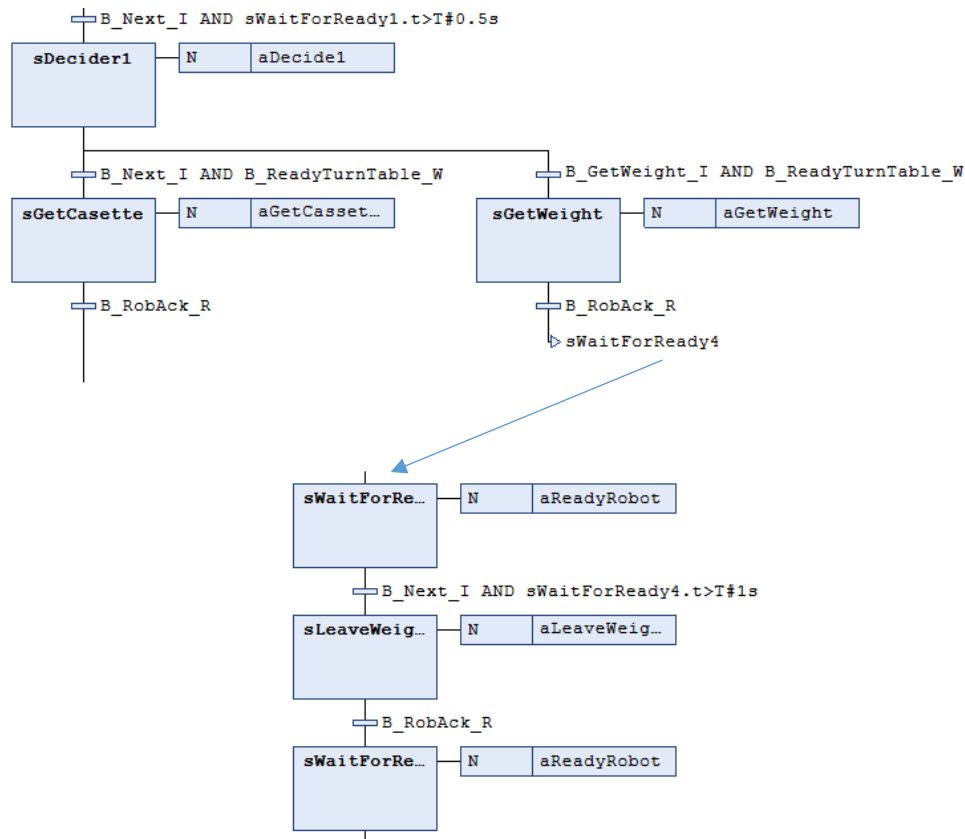


Figure 24: Example of a jump that is used to solve the special event.

The result of PLC programs is visualised in a simplified flowchart, see Figure 25. The figure should be read from top to bottom with external steps from right and left. Start by reading the robot program. This is a simplification of the functions from the PLC. The actual PLC code can be found in Appendix D – PLC Programs. Since the PLC-model is interactive with the machine operator, certain conditions from the HMI must be fulfilled for the PLC to continue. This is a part of the safety program, so that the operator cannot hurt himself, others or damage the cell. As stated, Figure 25 is simplified, it does not contain:

- Any handshakes from the equipment and the PLC.
- Any solutions for the special events.
- The choice to inspect welded cassettes over fixture or over the outgoing pallet, this leads to approved or disapproved cassettes depending on the operator. Which in turn leads to the cassette being left either on the turner or the pallet for defected units.

- The choice of leaving the welded cassette directly on the pallet, therefore skip the turner-process.
- Description of the safety program, for example must the light curtain be reset if the turntable or turner should move or if the robot should enter the loading space for unwelded cassettes.

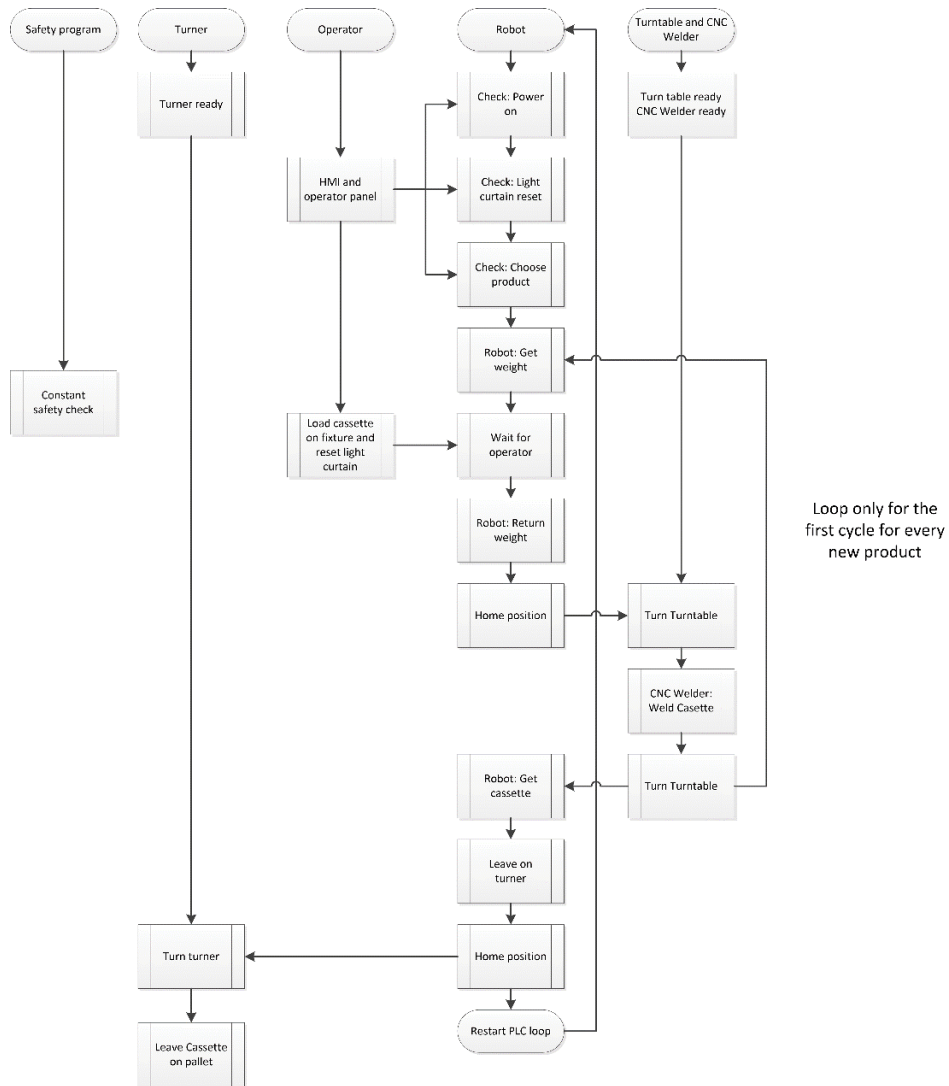


Figure 25: A simplified flowchart over the PLC model.

5.6. HMI

The HMI and operator panel is built within the structure of the PLC itself using the Visualization manager from CoDeSys, see Figure 26. The HMI is seen on the right side while the operator panel is located on the left side of the figure. Different buttons are linked to different Boolean variables that initialize different processes within the PLC programs. Combined with the HMI an operator panel is made on the same premise, with different buttons that are used more frequently. The HMI enables the user to:

- Change the running products between two kinds.
- See the produced units within the currently running product, in two different ways. One counter in the HMI are counting finished products that have been approved in terms of quality and left on the outgoing pallet. Another counter is counting the defected units that are not approved in terms of quality and left on the reject pallet.
- Enable the user to demand inspection over either the fixture or the outgoing pallet, depending on where the operator want to inspect.
- Enables the operator to see if the robot is in its state “safe to enter” which means that it is safe for the robot to enter the loading part of the cell where the operator could be, without inflicting with the operator.
- Enables the operator to see if the robot is online and ready to be assigned a task from the PLC. This helps when troubleshooting problems in the cell.

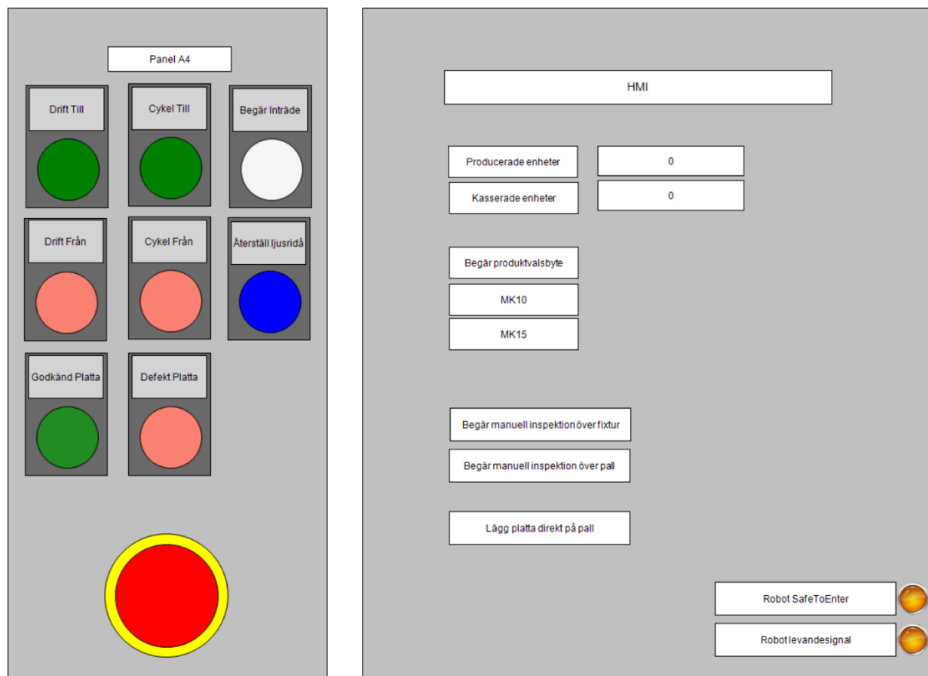


Figure 26: The HMI and operator panel.

The operator panel enables the user to:

- Set the running mode on or off for the complete cell.
- Reset the light curtain after entering the cell for inspections or loading unwelded plates.
- Approve or disapprove inspected plates.
- Enables the user to stop the robot with the emergency button.

The different buttons are labelled in Swedish since the production cell is located in Lund, Sweden. For easy use during the simulations and to represent the reality, the buttons from the operator panel glow whenever the underlying Boolean variable is true. When the underlying Boolean is false, the buttons return to the normal colour. In the HMI the buttons turn green when the underlying Boolean value is true and has a white background when the Boolean is false. The HMI and operator panel is interactive for the user, therefore the underlying Boolean value of each block or button changes whenever they are pressed. Exceptions from this phenomenon is the HMI buttons “Robot Safe To Enter” and “Robot live signal”. These buttons only show the underlying variable with being marked green and with a glowing lamp when they are set as true and are not changeable within the HMI. The buttons are configured as that due to safety for the operator. Figure 27 shows that the power is on and the function “Demand inspection over fixture” is active as well as the robot is online and it is safe to enter the loading area for the robot. An illustrative example of how the user can use the operator panel and the HMI.

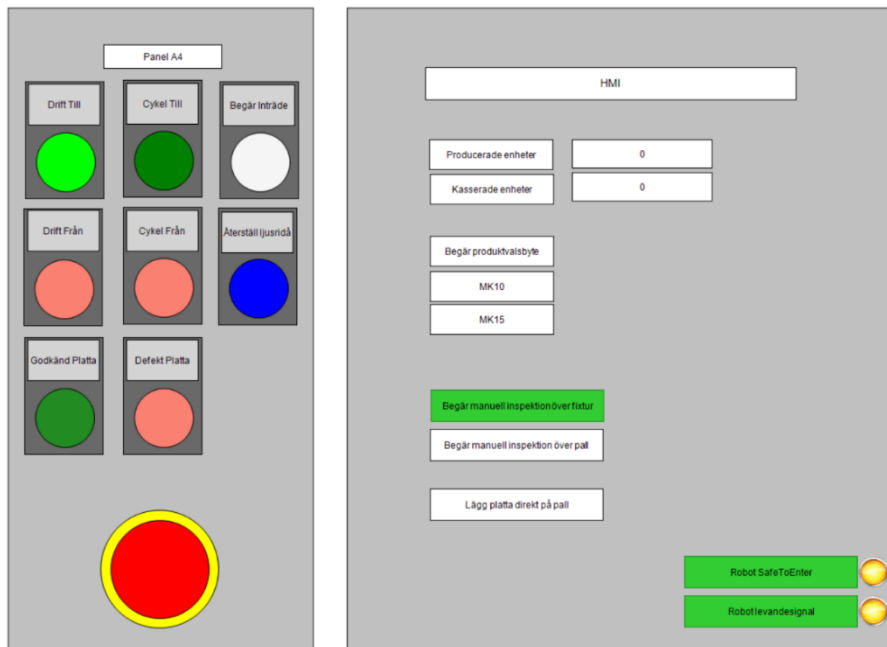


Figure 27: Example of active buttons and HMI blocks.

5.7. Robot program

This section describes how the RAPID programming were done and generally how an ABB Robot is programmed in relation to work objects, points, paths, procedures and Smart Components.

The program created to emulate the robot within the production cell was based upon the sequence of operations that was gathered during the characterization of the Laser welding cell 1, described in section 5.1. The definition of where the work objects coordinate systems were already thought out, as well as a general specification on where the robot start and end position were to be positioned for each robot sequence. In the following section, the process from defining the coordinate systems, creating targets placed in space, programming procedures and finally generating the robot program is described.

RobotStudio modelling construction

An important concept to understand is that there are two separate parts in RobotStudio. The simulation and modelling part and the RAPID programming and controller part.

The simulation and modelling part is where the model of the production cell is created and configured, and where the work objects, targets in space is defined. The simulation part is then synchronized and reconfigured to actual code that can be run both on the software robot controller and an actual controller.

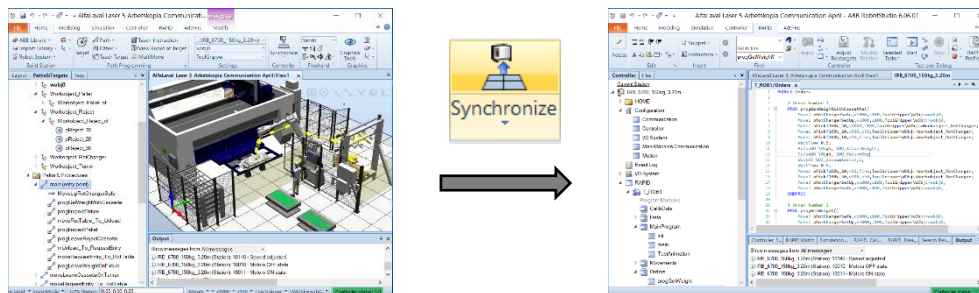


Figure 28: Illustrates the two different parts of RobotStudio. The simulation and modelling part, where objects are converted to RAPID-code.

Work objects

The work object is a coordinate system used to describe the position of a workpiece in relation to where the robot is positioned. The work object consists of two frames, in essence two coordinate systems, the user frame and object frame. The object frame is the reference to which all programmed positions of the robot will be related to, where the object frame is in turn related to the user frame. The user frame relates to the position of the local coordinate system in relation to the world coordinate system, essentially the base of the robot. Figure 29 shows a pallet in the production cell used

for unloading rejected products on, with its user frame, object frame and a target for the robot manipulator defined.

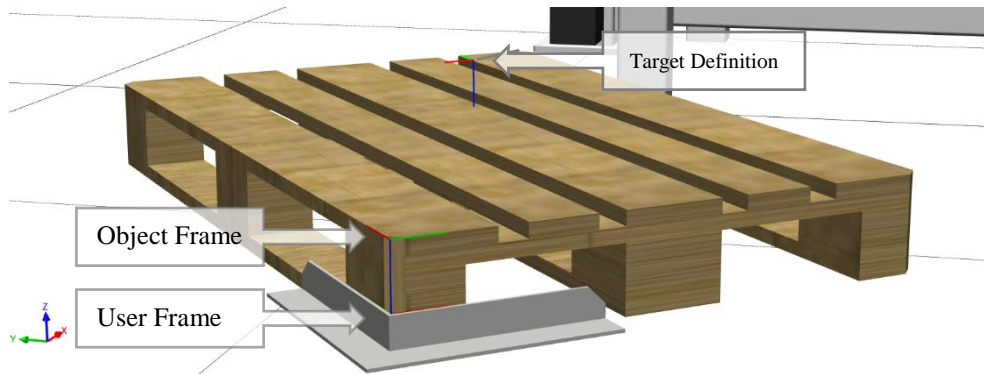


Figure 29: Illustrating the definition of User frames, Object frames and targets.

TCP definition

The Tool Centre Point (TCP) coordinate system, refers to the centre point of the tool attached to the robot. The production cell uses several tools, weights to stabilize the plates during welding and grippers for moving the plates from the fixture to the outgoing pallet. The coordinate system of the robot manipulator the TCP, needs to be adjusted since the tool attached extends the end of the robot manipulator.

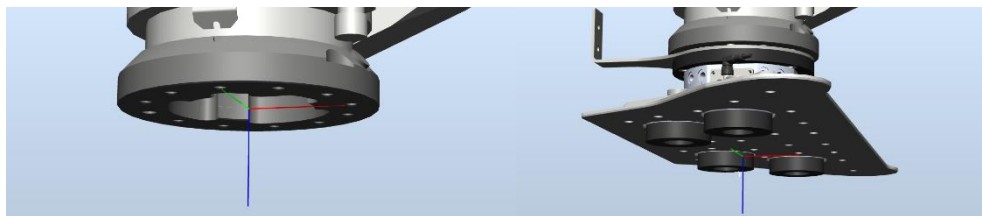


Figure 30: TCP, shown as a cartesian coordinate system changing as a tool is attached to the robot.

Targets

During robot programming, both done offline and online, targets are placed in 3D-space where the robot will move. The targets are placed in relation to the workobjects reference, commonly the base of the robot or workobjects relating to workpieces. The targets are further relating to a specified tool, having its own defined TCP.

An important concept to understand, is that there are normally several different ways in which the robot joints can be configured to a specific target in space. One target in space, can have several different configurations of the robot joints. Different configurations between closely spaced targets, can give unpredicted and unwanted joint movement as the robot moves between them. This presents a risk factor if the

configuration does not match. Resulting in errors while the robot program is executed, or in unpredicted movements that damages equipment.

Move instructions

How the robot travels between targets can be defined in different ways. Linearly between the targets or in a circular motion, or where the robot joints will move as little as possible. For an ABB robot, that is used in this simulation, the paths can be grouped in the following movements:

- **MoveL** - Linear movement between two defined targets.
- **MoveC** - Circular movement between two defined targets, requiring a reference target for the origin of the circle.
- **MoveJ** - Movement between two targets, where the movements of each joint is minimized. However, the movement between the two targets in space is not fully predictable.

In addition to the type of move instruction and the defined targets in relation to a work object, the instruction must also have parameters on motion data, such as speed, precision and a reference to the tools TCP, mounted on the robot manipulator.

Procedures

The paths have further been grouped to create a sequence of paths or with action instructions in the controller. That is used for setting and changing parameters, or waiting for a certain input signal before continuing. In the RAPID program, these have been named procedures.

Program Modules

The robot sequences are determined by the virtual PLC. The robot has been programmed to wait in position until it gets an order from the PLC to execute a specific sequence of movements. As the order is received, a handshake between the robot controller and virtual PLC takes place to ensure that the order has been received by the robot, the PLC can continue executing its program.

The programmed orders use both its own internal defined movements and movements that are shared between the orders.

In total there are ten different orders that the PLC can call for. The order of them are controlled by the PLC. This structure implies that there is a certain risk in the virtual commissioning system. The Robot controller will execute programs called for by the PLC, even if they are called in the wrong order.

Task

A task is the complete robot program which executes either alone or together with other tasks. The task contains the modules containing data declaration and routines for a specific task.

To allow the simulation to execute movements of the equipment and robot in parallel. The controller in this project is configured to allow for multitasking, this means that several programs within the controller can be executed in parallel. Each task has its main program, where the program execution starts once the controller is in run mode. Four separate tasks are running on the controller: The standard task for the robot program, a safety task handling the light curtains, a laser welding task handling the animation of the weld sequence and the rotation table, and a Turner task handling the unloading sequence of welded cassettes. These different tasks can be seen in the software controller in Figure 31. The main program that controls the order handling and handshaking between the PLC and robot controller is available in Appendix E – RAPID code.

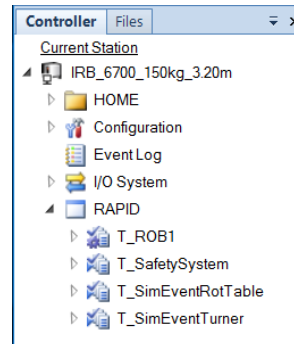


Figure 31: Showing the 4 different tasks that are running in parallel.

Smart Components

Smart Components (SC) available in RobotStudio allows for more advanced control of the objects in a simulation. The SC can be programmed to react on signals generated in the simulation and define outputs to communicate with the robot or robot cell. In this simulation, SC are used for the machine equipment that interacts with the products and the tools for the robot that grips and holds the product during transportation in the cell. Figure 32 shows the logic for attaching the weight to the gripper. The signal to grip the weights originates from the RAPID-code which sends the signal once the robot is in the correct position.

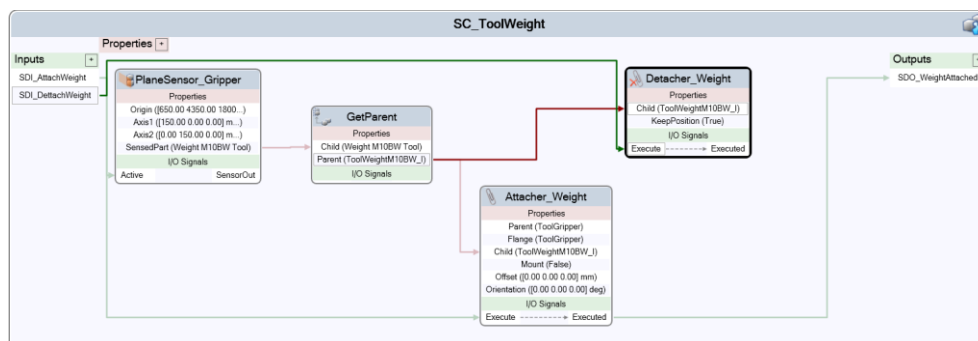


Figure 32: Part of the logic in Smart Components that attaches and detaches the tool from the gripper.

Defining I/O signals

For the robot controller to communicate with the PLC, it was required to define and create the input and output signals in the controller. In the robot controller there are two types of signals used. The first type of signals communicates with the virtual PLC. These are defined in the RAPID code as persistent variables (PERS), which allows the IRC5 OPC server to find it and create a tag referencing to it. The second type of signals used are signals for simulation purposes, used internally within RobotStudio. These signals are mainly used to communicate between the RAPID-program and the SC created for the simulation. For instance, to rotate the turntable where the fixture and cassette is placed, once the rotation is finished. The smart component sends an output signal to the virtual IRC5 controller, indicating that the sequence is finished.

5.8. Model testing

The model test is a method to see that every requirement and sequence is working properly in the virtual environment. This could be used for debugging PLC code or Rapid code and to verify the production lines behaviour in different situations. The working method used when conducting the model testing is described in Figure 33. The model test is conducted with a protocol developed by the authors to confirm different sequences and to explain the use of different variables within the PLC and Rapid code. The protocol is presented in Table 6. The protocol is simplified in terms of conditions and used tags since the PLC and Rapid code have a big amount of internal conditions and tags that are used. The focus in the model test is to verify different sequences and compare the conducted test with the expected behaviour.

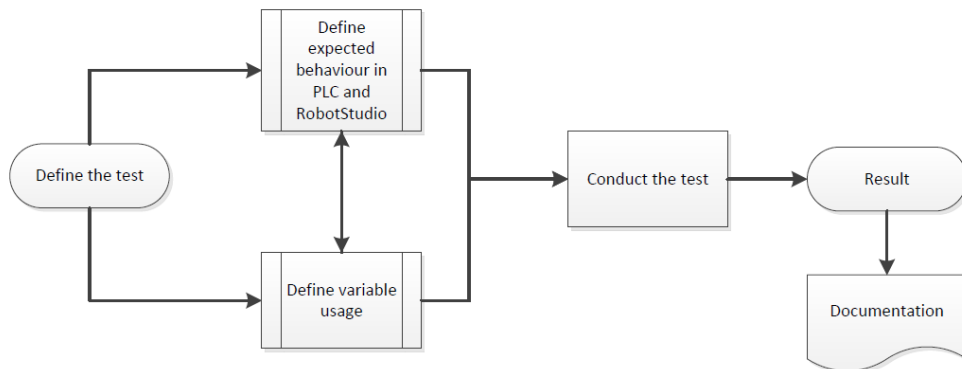


Figure 33: Working method for conducting the model test.

The “cycle 1” and “cycle 2” tests in the model test protocol is a combination of the different sequences and forms together a complete cycle for producing welded cassettes. The cycle tests could be seen as a test for evaluating the complete model.

Table 6: The test protocol for the model showing the models various functions

Test Protocol for the model							
No.	Name	Main Tag used	Type of equipment	Expected behavior	Conditions	Verification	Comments
1	Sequence 1	I_Order_PLC	Robot	The robot picks up the weight from the fixture	PLC in running mode, Product type chosen, light curtain reset, robot waiting for task	YES	The conditions must be true for every new cycle
2	Sequence 2	I_Order_PLC	Robot	The robot lays down the weight on the fixture	Light curtain reset, robot waiting for task	YES	
3	Sequence 3	B_RunTurnTable_PLC	Turntable	The turntable turns	Light curtain reset, robot waiting for task, CNC-welder is waiting for a task	YES	
4	Sequence 4	B_WelderWeld_PLC	CNC-Welder	The welding process starts	CNC-welder is waiting for a task, the turntable must have turned	YES	
5	Sequence 5	I_Order_PLC	Robot	The robot picks up the welded cassette and moves to the turner, then goes to its home position	The Turntable must have turned, the light curtain must be reset	YES	
6	Sequence 6	B_TurnerRun_PLC	Turner	Turns the welded cassette on to the pallet	The turner must wait for a task, the cassette must be loaded on the turner	YES	
7	Sequence 7	I_Order_PLC	Robot	Places the welded cassette over the fixture for inspection	Inspection over fixture must be chosen in the HMI, the light curtain must be reset	YES	
8	Sequence 8	I_Order_PLC	Robot	Places the welded cassette over the pallet for inspection	Inspection over pallet must be chosen in the HMI, the light curtain must be reset	YES	
9	Sequence 9	I_Order_PLC	Robot	If cassette is approved from sequence 7 or 8, it should move the cassette to the turner	Light curtain must be reset, the inspection must be approved in the HMI	YES	

10	Sequence 10	I_Order_PLC	Robot	If cassette is disapproved from sequence 7 or 8, it should move the cassette to the pallet for defect units	Light curtain must be reset, the inspection must be disapproved in the HMI	YES	
11	Sequence 11	I_Order_PLC	Robot	Robot should leave the cassette directly on the pallet instead of the turner	The sequence must be chosen in the HMI	YES	Alternative to sequence 5, same conditions
12	Cycle 1	All	The robot, turner, turntable, welder	The cell should perform a complete cycle		YES	Starts from an empty cell, no cassettes in the line
13	Cycle 2	All	The robot, turner, turntable, welder	The cell should perform a complete cycle		YES	Starts with cassettes in the cell
14	Cycle 3	All	The robot, turner, turntable, welder	The cell should empty the cell for a changeover		NO	Starts with cassettes in the cell
15	HMI 1	Several	HMI and operator panel	The HMI should react when buttons are pressed and underlying boolean values change	Boolean values can change in the PLC, RobotStudio or in the HMI	YES	
16	HMI 2	Several	HMI and operator panel	The HMI should visualize welded units on the pallet and defected units on the pallet for defected units		YES	

6. Model analysis

The analysis of the model is based on the conducted model test and through the model development combined with the initial list of requirements over the prototype illustrated in Table 4. The limitations and the functionalities are focused in this chapter.

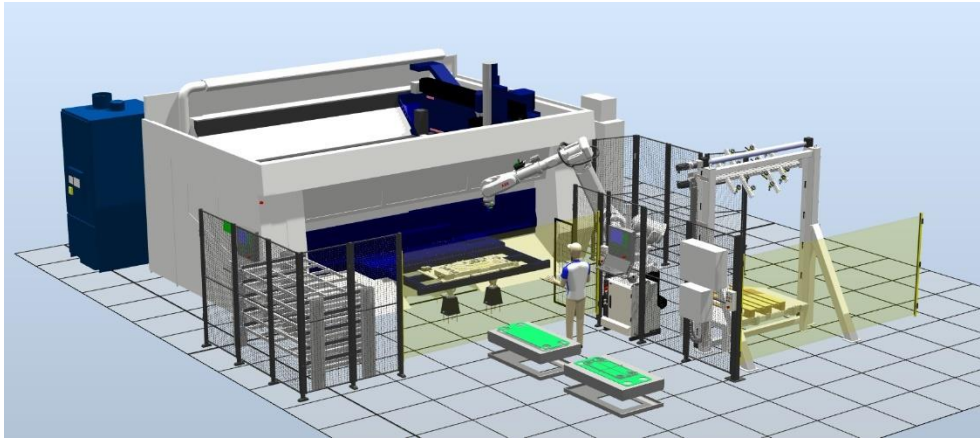


Figure 34: The virtual 3D-environment in RobotStudio.

6.1. Model functionality

The result of the virtual prototype is a model that can handle most of specified requirements stated in Table 4. The virtual 3D-environment is shown in Figure 34. One of the most important functions of the virtual prototype is that it is linked to the software PLC containing the HMI and operator panel making it interactive with the user. The PLC and the equipment are performing proper handshakes for every action which was one of the important requirements. It is possible for the user to run complete cycles with different variations such as inspections and to choose the consequence of an inspection. The safety system is working partly, resetting the light curtain works in a satisfying way. The emergency stop button works partly, it is only stopping the robot but not the other equipment.

6.2. Model limitations

The virtual prototype is a simplified version of the real production cell, both when it comes to the PLC programming and the Rapid code. There are certain limitations and differences between the virtual prototype compared to the real production cell. The most prominent differences will be described and analysed in this section.

Signal handling and communication

In the real production cell, the signals are communicated via I/O modules connected to the PLC and IRC5 controller, in the form of bytes. In the virtual model, these signals are sent as single Boolean or integer values that are handled by the software. The number of signals used in the virtual model is much less, compared to what is used in the real control system.

Emulation of the welding machine

The physical welding machine has a separate control unit. Working similarly to a CNC-machine. In the virtual model, this control system is not emulated, instead it is programmed as a simplified task running in parallel to the main task on the software PLC. The system does not emulate the real welding controller, as is done with the IRC5 and PLC controller. This becomes an important limitation in the system model which restricts the viability of doing a full virtual commissioning.

HMI-functionality

The recipe handling used in the physical production cell that sends parameters to adjust coordinates to the robot, such as when different products are run in the system, is not included in the virtual model. The structure to implement this function exist in the PLC but is not implemented in the simulation software RobotStudio.

The HMI is developed by the authors instead of using an exact copy of the real HMI. Therefore, all the functions available in the real HMI is not included in the virtual prototype. The HMI does not show any warnings or errors from the cell but presents simple production data such as the number of welded cassettes and rejected cassettes. The operator panel is a copy of the actual panel but has limitations as well. Three of the buttons in the operator panel is not linked to a variable and is therefore only for visualization. The visualization indicator in the HMI that tells the operator that the robot can enter the loading area is not working properly in all the sequences.

Error handling and unexpected events

The model is coded for the perfect operator, in the sense that the model can only handle expected input from the operator panel. It cannot handle, for instance, the case when the operator has chosen to inspect the cassette both over the fixture and at the turner unit. If this scenario occurs, the PLC will choose to inspect over the fixture. Neither can it handle events such as loss of vacuum in the gripper, which should stop the robot and give an error message. The model assumes the perfect user and that nothing unexpected happens in the cell.

The same goes for the safety systems that exist in the real production cell. SafeMove areas for the robot, light-curtains and emergency stop has not been implemented in the models PLC and RAPID code or only partly implemented.

Static behaviour in the model

The 3D-objects in RobotStudio has been defined with inactive behaviour, meaning that the objects in the model does not take part in the physics simulation. Every part is static, and does not interact with other parts in the model or apply the laws of physics.

7. Discussion

In this chapter we discuss our thoughts and explains the result of the prototype, the possibilities and limitations of the model, virtual commissioning and the future development of the technology. As well as the thesis project and major obstacles that arose during the project.

7.1. Model prototype

The model prototype has been built to better understand the concept of a virtual copy, how it can be created and what benefits it could generate. Initially the purpose of the thesis was to study the broad aspects of having virtual copies of production lines. What type of simulation, which production line to model, and what type of software to use when creating the model prototype was determined concurrently as the production analysis was conducted.

The objective of the thesis was to simulate the process steps for a product and create a model prototype. The focus of the project was determined to aim towards one type of simulation, in our case it was decided to work towards the concept of virtual commissioning. The software to create the prototype was determined as the project was ongoing and a certain learning phase has been required to get comfortable with the different software.

Even though our model is a simplification compared to the real production cell, the model has shown that it is fully conceivable to establish communication and verify PLC logic with the simulation program RobotStudio. We have recognized that there are difficulties to create logic and to simulate sensors and hardware components in the model. Our view is that it is not conceivable to simulate every component in a virtual environment and expect the model to be an exact copy of the real production line. The virtual model will always be a simplification compared to the real cell. However, it is fully feasible to use a simplified simulation model as a tool to program the basic structure of the PLC code and to test and verify this code.

7.2. Modelling challenges

Overall, the work with developing the model was functioning in a satisfying way. However, some issues were raised during the project and under this chapter we intend to discuss these issues.

When developing the model, the major difficulties were to learn the software that we chose to use and establish the communication between the different software. We also had to learn programming languages such as rapid, structured text and SFC. We had knowledge about programming before the project, thus were this relatively easy when compared to the difficulties of learning about the communication and the

different software. We experienced the project technically advanced in several aspects, which made it hard to explain what we did for personnel not working with automation. The actual 3D model could be seen as the tip of an iceberg, where a large part of the work is unseen by the common user of the virtual model.

We discovered quite fast that explaining communications, robot programming and PLC programming tended to be quite difficult for someone that have never seen the cell or even a picture over it. However, when showing the prototype with the visualisation from RobotStudio combined with the HMI and operator panel from CoDeSys to new personnel it became much clearer how the production cell worked. This shows that the visualisation from RobotStudio and virtual commissioning in its whole could be used as a learning tool. It was also easier to explain the communication and the work behind the model when we showed the simulation, making the model a virtual learning tool.

7.2.1. **Communication**

One of the major issues during the project was the communication between the PLC, OPC Server and RobotStudio. To establish the communication between the software used for the system required much time and effort.

Further, communication was established between two different computers on the internal company network. Which meant that the communication had to be reconfigured as the system was restarted, since the IP addresses of the computers and the emulated PLC were changed. Which we had no admin privileges to control or change.

The OPC-connection used, also created a time delay in the update frequency of the signals in both the software PLC and in RobotStudio. Thus, a slight time delay in both programs had to be used, otherwise the handshaking procedure would not work correctly. In turn, these wait times caused some sequences to wait before they started. But without the solution with time delays the simulation behaved in a non-expected way.

Therefore, the model is not optimized in a satisfying way. We focused on making the PLC and robot sequences correct and making the model stable. With more time, this issue could be slightly decreased. However, it would not be completely solved since the communication between the different software, especially between different computers is prone to require a certain time. The optimization of the time delays is considered to be accepted for a prototype but could still be improved further.

7.2.2. PLC

The PLC was developed to handle all the sequences in the system and to keep track on when and what the equipment should do. This is working correctly, but there are much room for improvement and further development. The opportunity also exists to develop and test unexpected scenarios in the PLC, for instance to handle special events and different cases of button presses on the operator panel. However, the effort to test all these scenarios would be very time consuming and have limited benefit in regard to our project.

The software used for developing the PLC code, CoDeSys, was overall functioning well but there we had some issues. For example; one problem with CoDeSys was handling the variables. At the beginning of the model development, when the PLC programs were small, the variables were quite easy to handle and to work with. But when the programs were developed further and became larger and more complex the handling of variables became harder. When a variable is changed the user must change all the variables manually instead of a simple command such as “replace”. A function like that would make the software better. Especially in our scenario when we are working with different software that is communicating with each other. There is quite a bit of work just changing the name of a variable since it must be changed everywhere in CoDeSys, in the variable configuration manager in CoDeSys, in the OPC server and in RobotStudio.

Another problem with CoDeSys is the troubleshooting function that sometimes worked good and sometimes not at all. This issue meant that building models and especially debug code took longer time than necessary.

7.2.3. HMI and Operator panel

The HMI is not fully developed due to several factors. The three buttons that are not linked in the operator panel is due to the fact that the virtual model is just a prototype. The visualisation block in the HMI, that is showing the operator if the robot is allowed to enter the loading area, is not working for every sequence. This has to do with the solution of resetting the light curtain. In the real production cell something must come in between the light curtain to brake the signal. In the simulation model this is simulated so that the PLC is braking the light curtain whenever the operator is expected to brake the light curtain. For example, when the operator is loading the fixture or inspecting the welded cassette. This is resulting in that the block showing “Robot safe to enter” is not working the way it is supposed to do.

7.2.4. RobotStudio

RobotStudio has been the primary simulation environment used to visualize the production cell. Programming the robot movement was straight forward to get started with. There are quite extensive amounts of helpful sources such as learning videos and literature available, which we have used with advantage in this project. It is clear that RobotStudio is much more focused on the robot aspect in a production cell. Off-line programming of robots has existed for decades and is established as a common working tool. Compared to virtual commissioning, when other equipment in the cell is also included, the functionality of RobotStudio is less user friendly. As an effect, it has been more cumbersome and has required more time to program and animate the other equipment in the cell. The smart component model in RobotStudio, used for several components in the cell, has such a large number of functionalities that it became overwhelming at start. There is a graphical interface to the logic part of the programming, but when the logic developed it quickly became a confusing tangle of signal connections and logic events. Another disadvantage with RobotStudio is that the 3D-modelling functionality is simple in its implementation. Simple geometries such as boxes, cylinders or spheres can be created directly in the environment. But to create and use more complex 3D-models requires a CAD software. The CAD models must be imported and converted within RobotStudio. The geometries of the 3D models cannot be changed once imported or created in RobotStudio.

7.3. Maturity of virtual commissioning

The maturity of virtual commissioning we currently considered to be low, especially when it comes to the software used in this project. Other vendors of software could have better solutions, however not tried in this project. Several companies are researching and developing virtual commissioning software and it is likely that new and more user-friendly software will be released. It is difficult to speculate when virtual commissioning will be mature enough to be an integrated approach for commissioning new production lines. Once the technology has matured enough, we think virtual commissioning is going to be a standard work procedure when it comes to commissioning new production lines. This has been the case for other technologies such as off-line programming of robots, Finite Element Method (FEM) and Computer Aided Design (CAD) software.

The risk of working with a new technology like virtual commissioning is that the time and effort for learning is quite extensive, resulting in that the first projects with virtual commissioning would be more expensive than the conventional way of working. The companies interested in this technology should not rush to be the first that successfully implement virtual commissioning on a wider scale, but should rather follow the development carefully and work towards virtual commissioning. This could also be applicable in industry 4.0 in general. Like other technological leaps forward, it will take time to implement both new software and to develop and implement new work methods. The companies need to be patient but still follow the development of the technology carefully to be successful in the long run.

When virtual commissioning has become a standard way of commissioning new production lines, a collective database with complete 3D models over production lines can be compiled. This results in other possibilities with virtual production, for instance to build complete digital factories in 3D-environments. Which further extends the function of virtual copies of production lines, from cell level towards factory level. Opening possibilities to view the production on a larger scale, for instance to analyse and improve the production flow in terms of logistics and product processes within the factory.

When more of production and product development can be done offline, it will improve both the production and products. One can speculate that the acceleration of new product launches will increase. It is reasonable to assume that the physical output from the production will also be greater. Since the production lines themselves are better engineered and optimized. As well as the production and product development departments take less time from the production when working offline.

7.4. Software development

As stated in the chapter before, the software is not fully developed to conduct a complete virtual commissioning. To be able to implement virtual commissioning on a wider scale within different industries the software must become more user friendly, to save time in terms of establishing connection and programming.

In a best-case scenario, we would like to have a software package that could easily communicate with each other, for example with an OPC server. The server must be easy to configure and a plug and play feature would have increased the user friendliness. We would also like to have automated tag-generation between the different software, so that the user only has to define the variable once instead of one time in the PLC, one time in RobotStudio and finally also link these variables in the OPC server. This has been the case in our project. If the simulation software had a link between a CAD software and itself that would improve the virtual model as a production development tool. Changes in the CAD-environment would automatically be updated in the simulation software, such that the mechanical construction and the controller program could be developed concurrently. This would permit that parts in the model to easily be changed, but maintaining its underlying signal connection with the PLC.

We think that user friendliness and software compatibilities are a key factor to launch virtual commissioning on an industrial scale. In its current state it requires that the user has extensive knowledge in several technical areas; automation, modelling, programming and Internet technology. With the current technology, a large amount of time is needed to establish and handle the communication between the different software. This could be better utilized for programming and testing the developed PLC code.

7.5. Production analysis

Some of the observed production lines and the machinery itself was old and lacked documentation. This caused these production lines to be valued less in the production analysis. Our experience from this project is that specific machinery such as a press or a stamp is hard to simulate. It is easier to work with robots or other standardized equipment. Often because a robot is a standard component even if it has unique tasks and sequences in every production line. The production analysis gave us a good understanding over the production which helped us in the further work conducted, for example how the process of welding cassettes works.

The production analysis was conducted in parallel with benchmarking and the literature study. This resulting in that testing and evaluating virtual commissioning was seen as a good choice when building the prototype. Other potential simulations

were flow simulation. Which are more suitable when analyzing the whole production instead of a single line or cell.

In the production analysis we got suggestions of considering areas of production lines that had problems with sensors, vibrations and other problems that caused the line to stop. It is difficult to make a model with these random occurring faults and get a simple technical solution for the problems from a virtual model.

In a flow simulation it is possible to assign problems and variables into the model but in the end, it will only give the user the same information that were assigned to the model. A flow model could instead be used as an analysis tool of benefits regarding solving the problems. For example, if a production line is stopping due to sensor problems, a flow model could be used to see the economic benefits of solving such a problem.

8. Conclusion

This chapter presents our conclusion focused on our developed model prototype and what it can be used for in its current state. As well as our conclusion on virtual commissioning as a technology, based on our prototype and the findings from the benchmarking and literature study.

8.1. Model prototype

Since the virtual model is a prototype, the current value and benefits of using the model is limited and the model should be seen as a test for implementing virtual commissioning as a working method. It can be used however, for educational purposes to show the process flow within the cell without being present at the production site. For example, if a new production development project is initialized, all the team members could easily get an overview of how the production line functions. The model could also be used for showing new personnel the product flow within the cell. These two scenarios can be applied in virtual reality as well, to maximize the educational purpose.

The model could also be used for trying different scenarios regarding cycle times. For example, could the welding process time be changed as well as cycle times for the other equipment. Therefore, the virtual model be used as an assessment tool for new projects within the current production cell.

Other benefits regarding the virtual prototype is to assess and test new robot sequences for a new product that could be launched in the production line. So that no crashes occur and thus decreases the risk for damaging the equipment or the personnel. A new product launch would likely result in new cycle times for the welder, that could in turn also generate a new production development project on the physical production cell to improve cycle times with changed parameters on the different equipment. A major benefit of the virtual model as a production development tool is that when working in a virtual environment, it does not take production time from the physical production cell.

The required resources that has been needed to develop the prototype, has included several different software. Most importantly has been the simulation tool, communication software and the emulated PLC, as well as a software to program the PLC. The model development has required quite a steep learning curve, because of the number of software needed to establish the system. We can decidedly conclude that initial virtual commissioning projects will require time, not only to establish the system, but also to gather sufficient knowledge to perform a virtual commissioning project.

8.2. Virtual Commissioning

Virtual commissioning is partly possible with the technology accessible today. However, a full virtual commissioning is difficult to accomplish, mainly because manufacturing processes and hardware signals are problematic to emulate. The technology could rather be used for offline programming and to test parts of the PLC. Virtual commissioning brings out the possibility to test and validate PLC code early in the project. However, some PLC programming is still needed to be conducted in the conventional way.

Building a virtual commissioning model and simulating it, requires that the user has extensive knowledge surrounding PLC-programming and the software used to build the simulation model. The personnel also need to have competence on configuring the communication between the PLC software and the simulation software. Thus, is the competence needed both deep and broad, making it hard to work with virtual commissioning. If virtual commissioning is going to be launched in an industrial scale, the working method needs to be structured like a project. With a project leader, PLC-programmers, Robot-programmers and mechanical engineers which are constructing the production line. Together, these roles can fulfill the competence required for doing a virtual commissioning project on a wide scale.

Developing a digital twin after the production line has been conventionally commissioned has limited benefits according to us. It is difficult too, since the time and effort needed to build a virtual model over an existing line is too extensive in relation to the benefits it could generate. It can be useful to build a digital twin over an existing production line, if the line is going to be modified and rebuilt, and new PLC code needs to be developed. Then the virtual model can be used a working document and later also commissioned into the existing and rebuilt production line.

Working with virtual commissioning, we have noticed that it works best when using standard libraries as components in the model, for example, robots. Working with specially made equipment is harder, since the connections with real hardware signals is harder to implement. Thus, it is our recommendation to use virtual commissioning in cells or lines containing as much standard equipment as possible. For example, welding cells with robots. Using virtual commissioning for pressing lines is harder since the presses often are unique.

In the future, when the technology has matured it could work great as a production development tool as well as decreasing the time for commissioning new production lines. However, it will still be difficult to use existing PLC programs in combination with a simulation tool. Even with a more mature technology, we are still doubting that a virtual copy of an existing line will be economically defensible. Another major benefit is that it will decrease the intensity of work demanded from the automation department in the programming phase of the production. The automation team could

work continuously over a longer period of time, with offline programming as well as offline validating of PLC code and robot code when working with virtual commissioning. The goal of maximizing the benefits is to use the virtual model as much as possible, both when it comes to trying out changes in the line and to optimize PLC code and robot movements.

9. Future work

During this thesis many interesting topics has arisen, that due to the time limit of this thesis has not been included. This chapter gives some suggestions on future work that can further extend this thesis work, and topics that can improve the concept of virtual commissioning.

We recommend to further analyse and research the possibilities to implement digital copies of production lines. The benefits and requirements of virtual commissioning is still on a theoretical level. More research needs to be conducted regarding how much of the work from the digital model can be transmitted and used in the real controller within the production line. Further investigations need to be done on different work methods to work in a cross functional way with other project members involved in a production development project. We recommend to further investigate when the virtual commissioning model development should begin, and what relevant milestones to have regarding a virtual commissioning project. These research topics presents a major change of working for any organisation and presents a challenge to implement, especially for a big organisation. Therefore, we recommend investigating the impact on an organisation to change the way of working with production development in terms of resources, time and competence. Before these research questions has been answered, there will be a restriction before the technology will become widespread in industry.

Further possibilities on the prototype

The prototype could be developed to contain more functions and sequences to mimic the actual production cell, some of these functions are hard to simulate in the chosen software. The welder, turntable and turner are only animations and are not properly simulated in the virtual prototype. The PLC could be developed to contain a better suited safety-system as well as a better HMI and operator panel with more functions.

The virtual prototype made in this project works with static objects. Making the objects obey the law of physics with an inbuilt physics engine in RobotStudio could improve the model. With the use of a physics engine other simulations could be conducted such as dropping the cassette in different places to see what happens to the operator and the cell itself. Thus, it could be used to simulate errors and accidents caused by the errors, making it a part of the safety validation of the cell.

It would be interesting to use the virtual model for simulations such as collisions when commissioning new products. For example, a stress test with larger cassettes. To evaluate how well the virtual model handles collisions and virtual commission of new products.

Virtual reality in combination with virtual commissioning

In this thesis, the concept of virtual reality in combination with the simulation model, has only briefly been touched upon. The model built in RobotStudio has been used with an Oculus Rift 2, to evaluate the possibilities of the virtual reality concept. As the virtual reality function is integrated in RobotStudio, the set-up is relatively easy to perform and get started with. The functionality in the virtual reality environment was limited in our test with VR since the PLC was not linked to RobotStudio due to limitation of computer power. Linking the PLC to RobotStudio and visualizing the simulation in virtual reality is however possible. An interesting future work is to investigate if an HMI-interface could be developed and used as an add-in within the virtual environment. To add value to the virtual commissioning model, and making it interactive and a more powerful tool for verification and as a training tool for operators.

Testing a virtual commissioning package solution.

In our project we have used several different software and connected them via an OPC-server. It has been possible to connect the software but not without time and effort. A potential for future work exists in investigating virtual commissioning software solutions, that are commercially available from software providers. To evaluate how the development has continued and to further investigate the differences between the software currently available on the market.

10. Recommendations for Alfa Laval

This chapter is our proposition for a way forward at the Alfa Laval factory in Lund, and is aimed towards the staff at Alfa Laval. Based on the findings from this thesis work, we present what type of production lines are beneficial to create virtual copies of, and how to work further with the concept of virtual production lines.

10.1. Types of production lines

Our thesis has shown several important aspects when it comes to creating virtual copies of production lines. It takes much effort, knowledge and time to create even a simple digital model of a production line.

Data availability is a key factor when it comes to creating virtual copies of production lines. 3D-models, sequences of operations and mapped in and out signals in the control system are requirements if a beneficial digital model is to be created. Thus, do we not recommend creating virtual copies of older production lines or production lines that lacks these types of data.

Neither do we recommend creating virtual copies of existing production lines as a tool for optimization of cycle times, or for minor layout changes. The main limit is the time required to build the model in a digital environment, compared to the benefits it would create. Even though it is possible to gather the programming code that is run on existing production lines, it is much easier said than done to create a digital model and using it. It still requires significant simplification and delimitations.

We do not see the possibility to create an exact copy of a production line in a virtual environment, because of the difficulties in handling the large number of sensors that exists in a real production environment. The digital copy will always be a simplification of the real production cell.

10.2. A way forward for Alfa Laval

Our proposition for a way forward at the factory in Lund

We do not recommend Alfa Laval to start fully implementing the work method for virtual commissioning as a complement to their projects. We see a large potential with the concept of virtual commissioning. However, the software and set-up is not currently convenient enough to be used in an efficient manner. Combined with the steep learning curve to create the virtual commissioning model, it simply requires too much time. Instead we recommend that Alfa Laval investigate the concept further, by extending this thesis work. A good opportunity would be a more specified thesis project, that runs parallel with a real commissioning project. Where the project group work in close contact with the automation development team at OD-TD and the project manager. The aim then is to have more time available to focus on the model development, and have the support of the automation team. Not only benefiting the further study of the concept, but also to support the automation team in their work to program the real production line. The knowledge exchange will also be good when working closer with the automation team, for both parts.

Working forward with virtual commissioning

It is important that a virtual commissioning project starts at a suitable time. The project that we recommend Alfa Laval to work further with, should begin once most of the construction model and the electrical wiring has been established, as illustrated in Figure 35. It is possible to start the virtual commissioning project even sooner with other software solutions, another argument for evaluating the different software solutions more.



Figure 35: Suitable time to start a project focused on virtual commissioning

Data from suppliers

The concept of creating a virtual production line, requires an extensive amount of data. If virtual copies of production lines are going to be launched on a larger scale at Alfa Laval, data from suppliers are crucial. Especially 3D-models over the production line. This to ensure less work for the engineers that are going to develop the virtual production line. Regardless of whether Alfa Laval chooses to work further with virtual commissioning as presented in this thesis, we recommend that they always request to obtain 3D-models and other data from suppliers. The data from suppliers could be useful, or even crucial in the future.

Approaching virtual commissioning

The conclusion from our thesis work relevant to the Alfa Laval factory in Lund, is to develop the process for production line and production cell investment projects, by building and developing digital copies of production lines early in the project phase. By creating simple models of production layouts, the different layout proposals can be compared and discussed within the project team.

As the proposals are evaluated and in the end when one production layout has been chosen. The work of creating a digital copy can begin once the electrical system has been constructed and most of the mechanical constructions. This is an important consideration, to reduce the risk of more work due to changes in the construction or electrical system.

The virtual production line can then be built from the CAD-models provided by the mechanical department. The simulation model can then be programmed to sequence the operations and movements that is planned to be present in the system. By then creating a communication link between the simulation software and a virtual PLC. The programming of both the PLC and eventual robots can be done prior to the real commissioning. With the establishment of communication between the system parts, the programs can be debugged and the handshaking between different programs can be solved. In the end, there is potential to decrease the commissioning time before a production line can be ready for real production.

Working with a different kind of virtual copy

During the production analysis we came across another production line that were interesting in terms of building a virtual copy of. It was Assembly line 1. If the company is interested in building a flow simulation model over a line, Assembly line 1 is suitable for that kind of simulation. However, this kind of simulation differs a lot from virtual commissioning and more research in this area would help the company to get better knowledge about other possible ways of working with virtual copies. The software used in our project is not suitable for that kind of simulation, therefore another project group must find suitable software for conducting a product flow simulation. Our recommendation is that the company initialize a master thesis project about a product flow simulation on the semi-automatic assembly line with the possibility to work in a 3D-environment to be able to test collisions and other important aspect if a new product would be launched in the semi-automatic assembly line.

Implementing a PLM-system for production systems

A PLM-system for the different production lines would be beneficial to implement, therefore we recommend doing that as soon as possible. For example, could 3D-models, electrical drawings, layouts, PLC-code and other interesting information of every production line be stored in a database. That would help the production development in terms of easy accessible data and decreasing the risk of redoing work, the files would be considered living documents until the production line is taken out of production. This conclusion and recommendation is out of our scope, but we noticed that we could have had help from a production PLM system, so could other personnel that works with production development.

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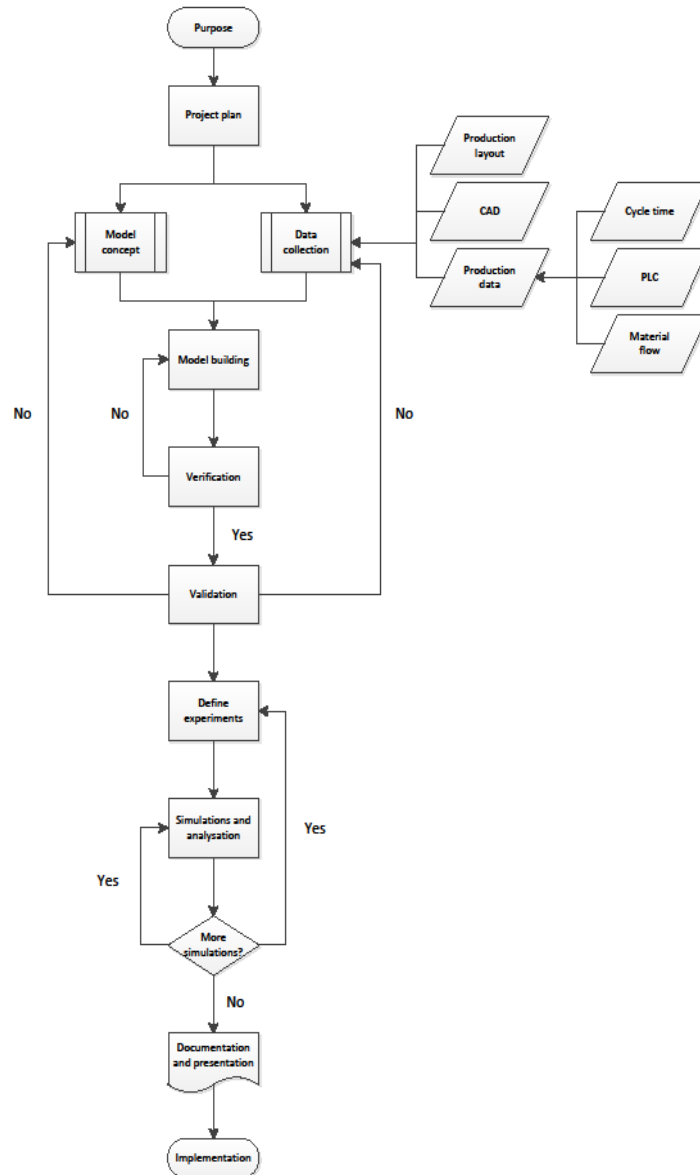
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Appendix A –Modelling project flowchart



Appendix B – Production analysis

Guide for production analysis

The automated or semi-automated cells at the facility in Lund needed to be analyzed in terms of potential for creating a virtual production model. To make a comparison between them, a variety of factors affected the suitability and effectiveness of a virtual production line. Since this project had a strict timeframe, the possibility for implementation within this time frame was an especially important factor. The factors that were considered has been summarized in Table 7.

Since each production line considered is unique, both concrete and intangible factors was considered during the production analysis. To get an idea on how suitable the production line was to create a digital copy of and to be able to compare the production lines in relation to others.

Table 7: Guide for analysis of production cells

Production line	A	B	C	D	E	F
Complexity of line						
Grade of automation						
PLC-code available						
CAD-models available						
Possibility of gathering data for 3D models						
Production cell layout available						
Probability of layout changes						
OEE=performance*quality*availability						
Normal Batch size						
Yearly production						
Age of production line						
Total investment cost of production line						
Occupancy level						
Number of shifts						
Number of workers per shift						
Number of different components						
Frequency of change-over						
Normal change-over time						
Probability for new products in the line						
Potential of optimization in cycle times, quality, waste reduction etc.						
Type of control system						
Current datalogging						
Complexity of HMI system						
Available data in MES-system						

The factors for each production line was analyzed and converted into three main factors that we deemed relevant to this project.

The **chance of success** was of high importance, since the project was time limited. The goal was to develop a useful prototype so that the concept of a virtual copy could be analyzed.

The **value** of making a virtual copy, in terms of potential advantages is another factor that were considered. This was to determine where a virtual copy would be most effective to implement in terms of value created for the company, for instance as a useful analytical tool.

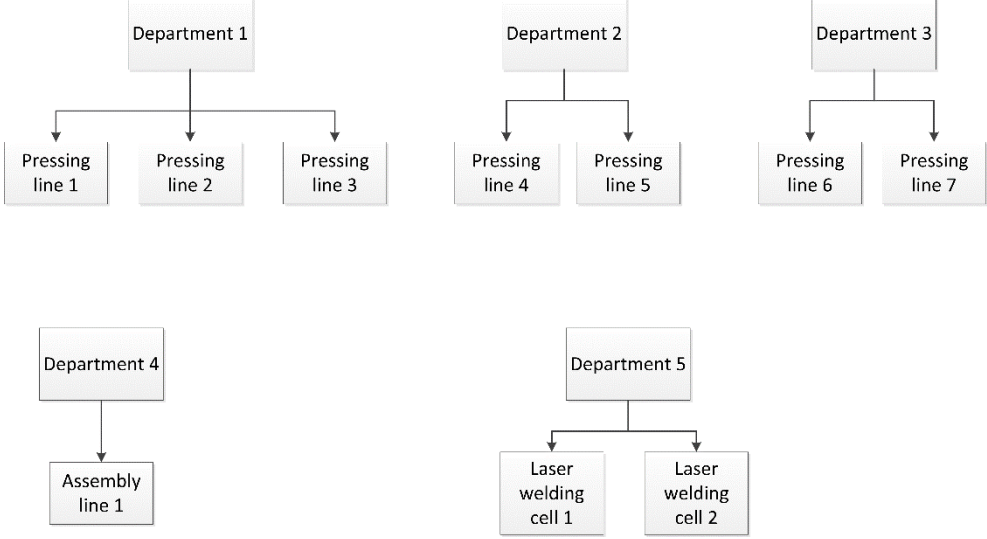
The last factor was the **potential for further work**, since this project looked at only one part of the production. The potential for further work, in terms of expanding the virtual copy to more production cells was considered. The goal was to create a virtual copy that give conditions for the company to further develop the project. If the case study were to show potential value to the company.

These three main factors that were the deciding basis for the choice of which production line to create a prototype of, is principle shown in Table 8. The analyzed production line was graded from low, medium or high on these factors, based on the information gathered from the production analysis.

Table 8: The main factors that will determine what production line is chosen for further analysis

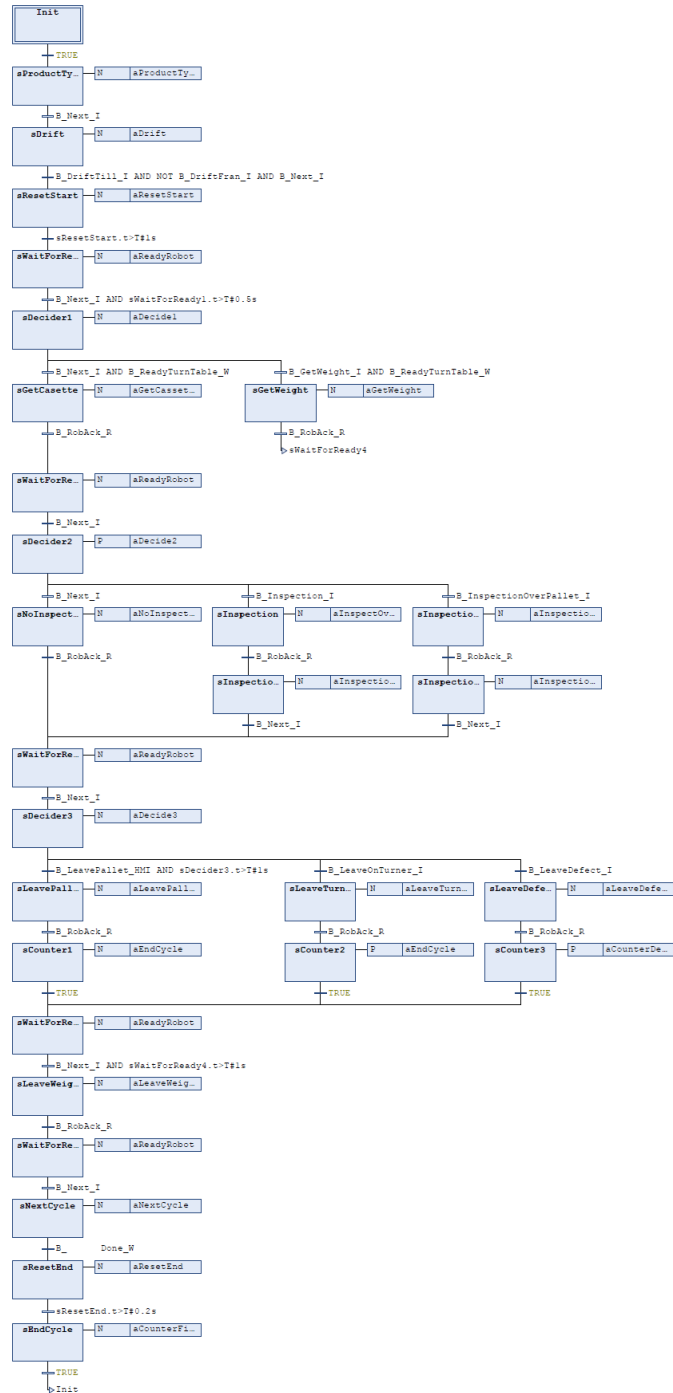
Production line	A	B	C	D	E	F
Chance of success						
Value to the company						
Potential for further work						

Appendix C – Analysed production lines

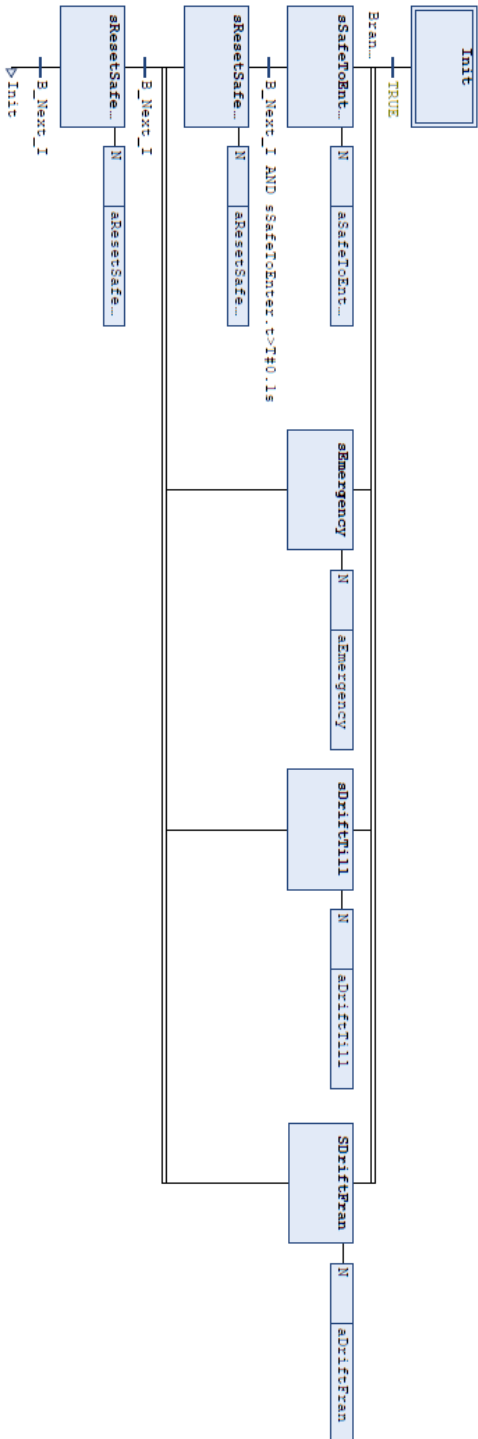


Appendix D – PLC Programs

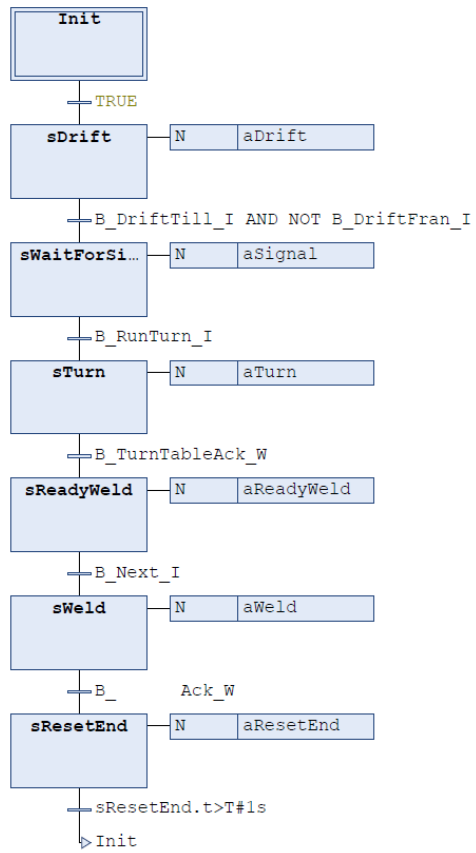
Robot Program



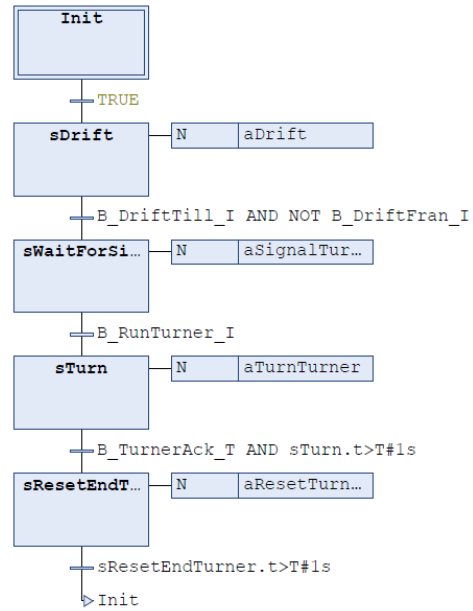
Safety Program



Welder and Turntable Program



Turner Program



Appendix E – RAPID code

```
PROC main()
  ! Initialize Robot
  init;

  ! Continous loop that waits for task from the main PLC
  WHILE TRUE DO
    B_RobotWaiting_R := TRUE;
    ! iPLC_OrderNumber
    TEST I_Order_PLC
    CASE 1:
      B_RobotWaiting_R := FALSE;
      B_RobAck_R := TRUE;
      progGetWeightWithCassette;
    CASE 2:
      B_RobotWaiting_R := FALSE;
      B_RobAck_R := TRUE;
      progGetWeight;
    CASE 3:
      B_RobotWaiting_R := FALSE;
      B_RobAck_R := TRUE;
      progInspectPallet;
    CASE 4:
      B_RobotWaiting_R := FALSE;
      B_RobAck_R := TRUE;
      progInspectFixture;
    CASE 5:
      B_RobotWaiting_R := FALSE;
      B_RobAck_R := TRUE;
      progNoInspection;
    CASE 6:
      B_RobotWaiting_R := FALSE;
      B_RobAck_R := TRUE;
      progLeaveCassetteOnTurner;
    CASE 7:
      B_RobotWaiting_R := FALSE;
      B_RobAck_R := TRUE;
      progLeaveCassetteOnPallet;
    CASE 8:
      ! Leave Cassette on stand will not be used
    CASE 9:
      B_RobotWaiting_R := FALSE;
      B_RobAck_R := TRUE;
      progLeaveWeightOnFixture;
    CASE 22:
      B_RobotWaiting_R := FALSE;
      B_RobAck_R := TRUE;
      progLeaveRejectCassette;
    CASE 30:
      B_RobotWaiting_R := FALSE;
      B_RobAck_R := TRUE;
      progRiggPos;
  DEFAULT:
```

```

ENDTEST
IF NOT B_RobotWaiting_R THEN
    B_RobAck_R := FALSE;
ENDIF
WaitTime 0.05;
ENDWHILE
ENDPROC

PROC Init()
    B_RobOK_R := TRUE;
    B_RobotWaiting_R := FALSE;
    B_RobAck_R := FALSE;
    B_LoadedOnTurner_R := FALSE;
    SetDO SDO_VacuumOn,0;
    WaitTime 5;
    SetDO SDO_StartSimtasks,1;
ENDPROC

PROC TestAnimation()
    ! Test sequence for running the robot without the PLC connected
    B_SafeToEnter_PLC := TRUE;
    progLeaveWeightOnFixture;
    PulseDO \High, SDO_OperatorLoad;
    WaitDI SDI_OperatorLoaded,1;
    progLeaveWeightOnFixture;
    WaitRob \InPos;
    PulseDO \High, SDO_TurnTableToPosTwo;
    WaitDI SDI_TurnerRotated,1;
    PulseDO \High, SDO_WelderRunCycle;
    progGetWeight;
    PulseDO \High, SDO_OperatorLoad;
    WaitDI SDI_OperatorLoaded,1;
    progLeaveWeightOnFixture;
    WaitDI SDI_WelderDone,1;
    PulseDO \High, SDO_TurnTableToPosTwo;
    WaitDI SDI_TurnerRotated,1;
    PulseDO \High, SDO_WelderRunCycle;
    progGetWeightWithCassette;
    progNoInspection;
    progLeaveCassetteOnTurner;
    PulseDO \High, SDO_TurnerLeaveOnPallet;
    PulseDO \High, SDO_OperatorLoad;
    WaitDI SDI_OperatorLoaded,1;
    progLeaveWeightOnFixture;
    PulseDO \High, SDO_TurnTableToPosOne;
    WaitDI SDI_TurnerRotated,1;
    progGetWeightWithCassette;
    progLeaveCassetteOnPallet;
    progLeaveWeightOnFixture;
    Stop;
ENDPROC

```