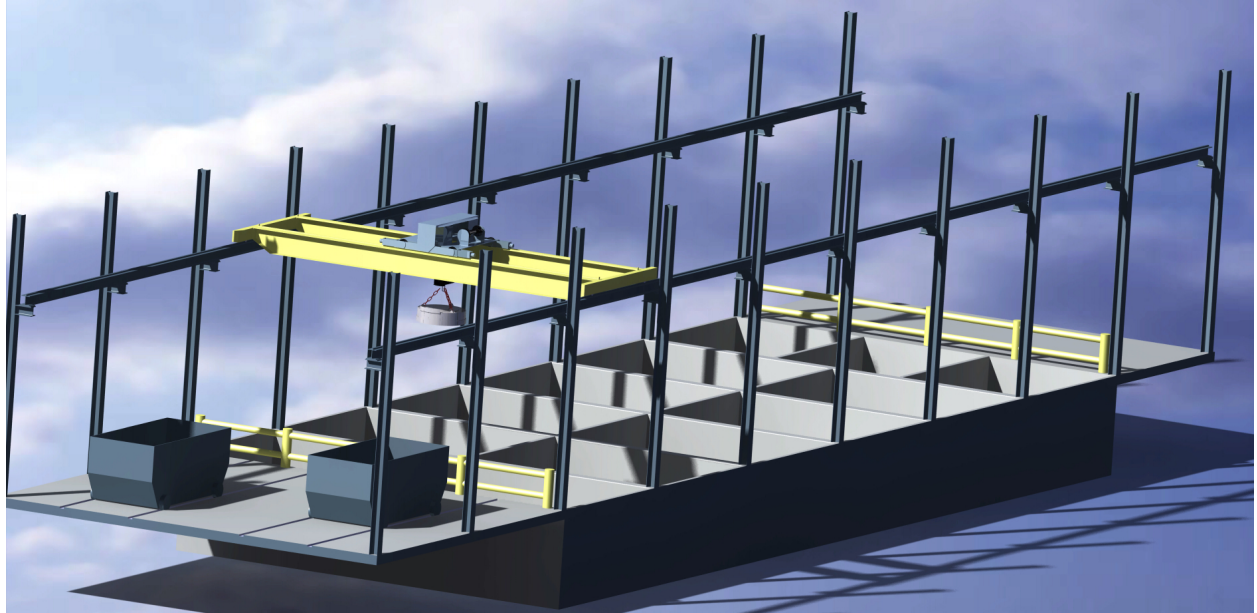




**CHALMERS**  
UNIVERSITY OF TECHNOLOGY



# **Automation and virtual commissioning of an overhead crane**

Master's thesis in Production Engineering

Fredrik Rapphed

Tarek Al Shafie

**DEPARTMENT INDUSTRIAL AND MATERIALS SCIENCE**

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CHALMERS UNIVERSITY OF TECHNOLOGY  
Gothenburg, Sweden 2022  
[www.chalmers.se](http://www.chalmers.se)



MASTER'S THESIS 2022

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Automating a pre-existing material handling process with an  
overhead crane using a virtual commissioning method.

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Tarek Al Shafie

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Supervisors:

Thudor Sonnerup, SKF Mekan

Omkar Sahlunke, Chalmers, Department of Industrial and Materials Science

Examiner:

Johan Stahre, Chalmers, Department of Industrial and Materials Science

Master's Thesis 2022

Department of Industrial and Materials Science

Chalmers University of Technology

SE-412 96 Gothenburg

Telephone +46 31 772 1000

Cover: Rendered image of a CAD assembly of the material hall, crane and carts.

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## Abstract

SKF Mekan, a factory within the SKF Group that produces housings, locknuts, sleeves, and guiding rings for the bearing industry, aims to investigate how to reduce costs, increase capacity by increasing the level of automation in their production facilities to remain as competitive as possible in a quickly evolving market. Specifically, a material handling procedure carried out by an overhead crane that delivers materials to melting furnaces has been identified as eligible for automating. The material is taken from what is referred to as a scrapyard where the inventory of metals is kept which is then gathered by a crane utilizing an electromagnet cylinder. The goal of automation is to reduce costs, clearly and accurately display inventory levels and increase the storage capacity in the scrapyard.

In order to evaluate the effectiveness of the automation sequence, a virtual commissioning method was investigated. This digitalization method allows automation procedures to be tested and verified before real-life implementation. It is done by connecting three components; Programmable Logic Controller (PLC) logic which is the automation sequence, a physical model created digitally of the system to be simulated, and lastly, a logical device that connects inputs and outputs between the physical model and the PLC Logic. By connecting these the instructions given by the PLC can be executed by the physical model with kinematics and physics. This allows for a comprehensive view of the full system running digitally in a realistic environment.

Some delimitations for the thesis were made. The virtual commissioning methodology has been utilized but the thesis does not achieve the level of detail required to complete a virtual commissioning project of the crane's automation, some functionality has not been implemented due to time constraints.

The following results were obtained. The material hall and crane have been constructed in 3D using the Computer-Aided Design (CAD) software CATIA from Dassault systèmes. An automation procedure has been developed in TIA Portal, simulated using PLCSIM Advanced, and connected to a developed HMI using WinCC. Suggestions for sensors and additional hardware have been made, and the authors recommended additional safety measures. Neither the logical model nor the final virtual commissioning step of connecting the PLC, physical model, and logical model was completed due to not receiving the required software in the given timeframe. However, this thesis is considered a helpful framework that provides the theory and methodology to complete the virtual commissioning in future.

---

Keywords: Automation; Digitization; Industry 4.0; Overhead crane; PLC; PLC coding; SiL; TIA Portal; Virtual commissioning.



# Acknowledgements

Learning a new language is always quite an achievement. We are delighted to say that we learned a new language, PLC language. During this learning process, we had the chance to meet and work with amazing people who helped us get through a challenging task.

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# List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

|     |                                  |
|-----|----------------------------------|
| CAD | Computer Aided Design            |
| HMI | Human Machine Interface          |
| IO  | Input Output                     |
| OEM | Original Equipment Manufacturer  |
| PID | Proportional Integral Derivative |
| PLC | Programmable Logic Controller    |
| SOP | Sequence Of Operations           |
| VC  | Virtual Commissioning            |



# Contents

|  |              |
|--|--------------|
| <b>List of Acronyms</b>  | <b>ix</b>    |
| <b>List of Figures</b>   | <b>xv</b>    |
| <b>List of Tables</b>  | <b>xviii</b> |
| <b>1 Introduction</b>  | <b>3</b>     |
| 1.1 Background . . . . .   | 3            |
| 1.1.1 Sustainability . . . . .                                       | 3            |
| 1.1.2 Stakeholders . . . . .   | 4            |
| 1.1.3 Objectives . . . . .   | 4            |
| 1.2 Purpose . . . . .  | 5            |
| 1.2.1 Delimitations . . . . .  | 5            |
| 1.2.2 Project aim & research questions . . . . .                     | 6            |
| 1.2.3 Thesis structure . . . . .                                     | 6            |
| <b>2 Theory</b>  | <b>9</b>     |
| 2.1 PLC . . . . .  | 9            |
| 2.2 PLC programming . . . . .  | 9            |
| 2.2.1 Totally Integrated Automation Portal V17(TIA Portal) . . . . . | 11           |
| 2.2.2 S7-PLCSIM Advanced V4.0 . . . . .                              | 12           |
| 2.2.3 SIMATIC WinCC Runtime Advanced . . . . .                       | 12           |
| 2.3 NX MCD . . . . .   | 12           |
| 2.4 SIMIT . . . . .  | 12           |
| 2.5 CATIA v5 . . . . .   | 13           |
| 2.6 Virtual commissioning . . . . .                                  | 13           |
| 2.7 Greenfield & brownfield . . . . .                                | 14           |
| 2.8 Safety measures . . . . .  | 15           |
| <b>3 Methods</b>   | <b>17</b>    |
| 3.1 Literature study . . . . .                                       | 18           |
| 3.2 Qualitative study . . . . .                                      | 18           |
| 3.2.1 Crane operator interview and visual observations . . . . .     | 19           |
| 3.2.2 SKF Mekan stakeholder interview . . . . .                      | 20           |
| 3.2.3 SKF automation engineer interview . . . . .                    | 20           |
| 3.3 Technical methodology . . . . .                                  | 20           |
| 3.4 CAD construction . . . . .                                       | 21           |

|          |   |           |
|----------|---|-----------|
| 3.5      | PLC coding approach . . . . .   | 22        |
| 3.6      | HMI design . . . . .  | 22        |
| 3.6.1    | Conceptual design . . . . .   | 23        |
| 3.6.2    | Design and program . . . . .  | 23        |
| <b>4</b> | <b>Results</b>  | <b>25</b> |
| 4.1      | Literature study findings . . . . .                                   | 25        |
| 4.2      | Qualitative study . . . . .   | 26        |
| 4.2.1    | Interview with crane operator and visual observations . . . . .       | 26        |
| 4.2.2    | SKF Mekan stakeholder interview . . . . .                             | 28        |
| 4.2.3    | Interview with SKF automation engineer . . . . .                      | 29        |
| 4.3      | Physical device modelling . . . . .                                   | 29        |
| 4.3.1    | Building structure . . . . .  | 30        |
| 4.3.2    | Crossbeam and trolley . . . . .                                       | 31        |
| 4.3.3    | Magnet, scale, and hook . . . . .                                     | 32        |
| 4.3.4    | Material carts . . . . .  | 32        |
| 4.4      | System control modelling and HMI . . . . .                            | 33        |
| 4.4.1    | Custom data types . . . . .   | 33        |
| 4.4.2    | Ensuring collision free movement . . . . .                            | 34        |
| 4.4.3    | Move X,Y . . . . .  | 34        |
| 4.4.4    | Pick & Place . . . . .  | 35        |
| 4.4.5    | Recipe gathering . . . . .  | 36        |
| 4.4.6    | Reshuffling . . . . .   | 37        |
| 4.4.7    | Smaller functions . . . . .   | 38        |
| 4.4.8    | HMI . . . . .   | 39        |
| 4.4.9    | Connection of PLC and HMI . . . . .                                   | 43        |
| 4.4.10   | Alarm system and eliminating faulty inputs . . . . .                  | 43        |
| 4.5      | Logical device modelling and virtual commissioning . . . . .          | 44        |
| 4.6      | Hardware . . . . .  | 44        |
| 4.6.1    | PLC hardware . . . . .  | 44        |
| 4.6.2    | Crane HMI hardware . . . . .  | 44        |
| 4.6.3    | Gates HMI hardware . . . . .  | 45        |
| 4.6.4    | Sensors . . . . .   | 46        |
| 4.6.5    | Implemented safety measures . . . . .                                 | 47        |
| <b>5</b> | <b>Discussion</b>   | <b>49</b> |
| 5.1      | Error sources . . . . .   | 49        |
| 5.1.1    | Omitted & assumed CAD details . . . . .                               | 49        |
| 5.1.2    | Picking material from box centers . . . . .                           | 49        |
| 5.2      | Recommendations for further work . . . . .                            | 50        |
| 5.2.1    | CAD verification . . . . .  | 50        |
| 5.2.2    | Additional safety measures . . . . .                                  | 50        |
| 5.2.3    | Manual steering override . . . . .                                    | 50        |
| 5.2.4    | Box screening mechanism . . . . .                                     | 51        |
| 5.2.5    | Utilize virtual commissioning for investment<br>proposition . . . . . | 52        |

|          |   |            |
|----------|---|------------|
| <b>6</b> | <b>Conclusion</b>                           | <b>53</b>  |
| 6.1      | Solutions to objectives . . . . .           | 53         |
| 6.2      | Answers to research questions . . . . .     | 54         |
|          | <b>Bibliography</b>                         | <b>57</b>  |
| <b>A</b> | <b>Gantt schedule</b>                       | <b>I</b>   |
| <b>B</b> | <b>Interview questions and observations</b> | <b>III</b> |
| <b>C</b> | <b>Additional CAD images</b>                | <b>V</b>   |
| <b>D</b> | <b>PLC code and fuctions</b>                | <b>VII</b> |
| <b>E</b> | <b>HMI screens</b>                          | <b>XIX</b> |





# List of Figures

|      |   |      |
|------|---|------|
| 2.1  | An example of ladder logic. . . . .                                   | 10   |
| 2.2  | An example of SCL code. . . . .                                       | 10   |
| 2.3  | An example of sequential programming. . . . .                         | 11   |
| 3.1  | Methodological approach. . . . .                                      | 17   |
| 3.2  | Virtual commissioning method adapted from [27]. . . . .               | 21   |
| 3.3  | Example of conceptual design for the HMI. . . . .                     | 23   |
| 4.1  | Boxes in scrapyard and eligible loading gates. . . . .                | 27   |
| 4.2  | Boxes in scrapyard and their max capacity. . . . .                    | 28   |
| 4.3  | Rendered CAD image of the full scrapyard with all components. . . . . | 30   |
| 4.4  | Rendered CAD image of the box dividers. . . . .                       | 31   |
| 4.5  | Rendered CAD image of the crossbeam and trolley. . . . .              | 31   |
| 4.6  | Rendered CAD image of the magnet, scale and hook subassembly. . . . . | 32   |
| 4.7  | Rendered CAD image of a material cart. . . . .                        | 33   |
| 4.8  | Visualized PickPlace sequence . . . . .                               | 36   |
| 4.9  | Figure detailing the recipe function. . . . .                         | 37   |
| 4.10 | Figure detailing the reshuffle function. . . . .                      | 38   |
| 4.11 | HMI main screen. . . . .  | 40   |
| 4.12 | HMI inventory screen. . . . .   | 41   |
| 4.13 | Features of the selected 9" comfort panel. . . . .                    | 45   |
| 4.14 | Features of the selected 4.3" comfort panel. . . . .                  | 46   |
| 4.15 | Coordinate system in the scrapyard. . . . .                           | 47   |
| 5.1  | Spacing of electromagnet placements in box. . . . .                   | 51   |
| A.1  | Gantt schedule. . . . .   | I    |
| C.1  | Rendered CAD image the full assembly from a top view. . . . .         | V    |
| C.2  | Lightsensor on bracket. . . . .                                       | V    |
| C.3  | Reflex for lightsensor on bracket. . . . .                            | V    |
| D.1  | Main code figure 1. . . . .   | VII  |
| D.2  | Main code figure 2. . . . .   | VIII |
| D.3  | Main code figure 3. . . . .   | VIII |
| D.4  | Main code figure 4. . . . .   | IX   |
| D.5  | Main code figure 5. . . . .   | X    |
| D.6  | Main code figure 6. . . . .   | X    |

|   |       |
|---|-------|
| D.7 Magnet change function. . . . .                 | XI    |
| D.8 Reshuffle function. . . . .                     | XII   |
| D.9 Move X,Y function figure 1. . . . .             | XIII  |
| D.10 Move X,Y function figure 2. . . . .            | XIII  |
| D.11 Recipe function. . . . .                       | XIV   |
| D.12 Weight change function figure 1. . . . .       | XV    |
| D.13 Weight change function figure 2. . . . .       | XVI   |
| D.14 Pick & Place function figure 1. . . . .        | XVI   |
| D.15 Pick & Place function figure 2. . . . .        | XVII  |
| D.16 Pick & Place function figure 3. . . . .        | XVII  |
| D.17 Pick & Place function figure 4. . . . .        | XVIII |
| D.18 Pick & Place function figure 5. . . . .        | XVIII |
|   |       |
| E.1 HMI main screen. . . . .                        | XIX   |
| E.2 HMI inventory screen. . . . .                   | XX    |
| E.3 HMI Material recipe screen. . . . .             | XX    |
| E.4 HMI Material recipe popup screen. . . . .       | XXI   |
| E.5 HMI Material recipe confirmation popup. . . . . | XXI   |
| E.6 HMI Material manual move screen. . . . .        | XXII  |
| E.7 HMI Material manual move popup screen. . . . .  | XXII  |
| E.8 HMI manual move confirmation popup. . . . .     | XXIII |
| E.9 HMI Admin screen. . . . .                       | XXIII |
| E.10 HMI process records screen. . . . .            | XXIV  |
| E.11 Gate HMI start screen. . . . .                 | XXIV  |
| E.12 Gate HMI material amount selection. . . . .    | XXV   |
| E.13 Gate HMI popup confirmation screen. . . . .    | XXV   |

# List of Tables

|     |  |    |
|-----|--|----|
| 3.1 | Keywords during literature study. . . . .          | 18 |
| 4.1 | Papers reviewed in the literature study. . . . .   | 26 |
| 4.2 | All possible movement combinations. . . . .        | 35 |
| 4.3 | Conceptual Design Contents. . . . .                | 39 |
| 5.1 | Investment Analysis Direct/Indirect Costs. . . . . | 52 |



# 1

## Introduction

The industries of the world are moving towards automation at a rapid pace. SKF Mekan intends to equal these developments and create a high-end automation example on its manufacturing site. This thesis is supposed to serve as an initial project intending to increase SKF Mekans degree of knowledge within automation and keep it competitive in terms of manufacturing.

### 1.1 Background

SKF Mekan is a large manufacturer located in Katrineholm, Södermanland, Sweden, that provides "...bearings, units, housings, seals, lubrication solutions, actuation systems, magnetic systems, and maintenance products, as well as asset management, consulting energy and sustainability management, and services contracts. SKF Mekan conducts operations internationally." [1]. Since SKF Mekan produces the most significant number of different products within the entire SKF sphere, it is required to address the number of operators and the amount of manual labour. SKF Mekan has identified that many manufacturing processes tend to become rather manual labour heavy when specialized. Creating effective and low labour production routines can make Mekan successful over the long term as a manufacturing site.

The project location is the scrapyard, a large hall containing 13 boxes that hold different types of metals. For many of the boxes, an adjacent gate opens to the outside. This allows for direct delivery of material to the scrapyard. The crane is fitted with an electromagnet cylinder to pick up the material from the boxes. Many different metals are required to feed the furnaces that provide casting operations with the material. Potential savings were identified in this process of delivering material to reduce costs. The highest cost is caused by the operator delivering the wrong amount of material, resulting in a high cost of the alloying materials required to compensate for the faulty delivery.

#### 1.1.1 Sustainability

Automating the crane could remove the operator's salary costs and increase the efficiency of the crane and the foundry operations, which is in line with the United Nations' 9:th sustainable development goal. Primarily targets 9.4 and 9.5, which aim to retrofit existing industries to make them more resource-efficient and upgrade technological capabilities of industrial sectors [2].

Moreover, this automation project aligns with the United Nations 12th Responsible Consumption and production. More specifically, targets 12.2 "By 2030, achieve the sustainable management and efficient use of natural resources". In addition, the target 12.5 "By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse" is in line with this automation project since this project will increase the recyclability of the scrap materials while, at the same time, reducing the usage of the alloy materials [3]. Moreover, this automation project will also increase the awareness of sustainability in this facility of SKF Group. Therefore, it is aligned with target 12.6, "Encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle" [3]. Finally, sustainability is about doing more and better with less, which is precisely the core of this automation project.

### 1.1.2 Stakeholders

To claim that a specific project is successful, it should fulfil its goals and objectives and meet the stakeholders' expectations. The stakeholders are personnel who are interested or have invested in the project [4].

Stakeholders in this project are divided into two groups. First, internal stakeholders such as SKF top management, project team members, supervisors, peers, and internal customers. And the second group is the external stakeholders, who might include external customers, Chalmers university, contractors, subcontractors, and suppliers.

### 1.1.3 Objectives

In this automation project, five critical issues are to be considered. The problem-solving background for these issues is presented below:

#### 1. Accurate deliveries

The current deliveries from the crane are sometimes inaccurate and inconsistent. Specific Measures should be taken to reach specified target weights more accurately constantly. These inconsistencies can result in an incorrect distribution of metals, making for a faulty metal composition that needs to be re-balanced with alloys which is a costly operation. Furthermore, the weight of delivered material should be used to update inventory levels.

#### 2. Collision avoidance

Ensure that the crane will not collide with objects during its automation. While the crane moves, it is expected to face obstacles such as the storage area box walls and truck unloading area obstacles. There might be additional obstacles in the way that are currently unknown. These obstacles should be considered to avoid collisions within the crane's workspace.

### 3. Safety assurance

The crane's working area is directly over the scrapyard. Personnel occasionally enter the area to load new material either through external gates or internally. Therefore, safety measures are critical aspects to be considered when modelling the automation process to ensure personnel within the area are always safe when the crane is operational. Safety for the personnel is ensured by the crane being stationary while personnel are within the operational area.

### 4. Crane automation and priorities

Crane automation and delivering materials correctly according to set priorities. The company has a higher demand for crane usage, making it a priority to automate it. The crane process could be completely automated by gathering material for each new melt. Currently, an operator performs this job, tallying up to three hrs/day or more. The operators tend to miscalculate the weights and thus receive incorrect distribution on the incoming melt material and need to re-balance the total weight with alloy elements - which results in a costly operation.

### 5. Re-organize material for efficient storage

Ordinarily, the storage boxes that hold material are loaded through gates where trucks unload material from the outside. Some of the gates are permanently blocked due to ongoing projects at the factory. In addition, some of the box's gates are temporarily closed due to current construction works. Due to this, half of the storage boxes can not be directly loaded from the outside which will require material to be loaded only through one side of the scrapyard and then moved internally by the crane to the boxes that have their gates blocked, this is referred to as reshuffling. The weight of the material being loaded into the storage from trucks is not updated in any inventory system. The delivered quantity should be known and used to update inventory levels.

## 1.2 Purpose

SKF Mekan depends on its efficiency, wherein low labour routines are very cost-effective processes that can provide a competitive advantage. Therefore, this thesis aims to investigate how to automate the crane to make it more cost-effective by eliminating costs such as re-balancing with costly alloys and the operator wages. Furthermore, the thesis aims to keep inventory levels in the scrapyard updated and accurate.

### 1.2.1 Delimitations

The project will involve work at SKF Götaholm head office in Gothenburg with limited on-site visits to the SKF Mekan factory, located in Katrineholm, where the crane is located. This is due to the location of the project members' residence. The location constraints would limit the possibility of visiting the workplace if needed on short notice. Moreover, there are more travel constraints due to Covid-19 restric-

tions applied by the Swedish authority and the company.

The thesis will not address how to manage employees who previously handled the crane, which will have reduced work tasks due to the implementation of the crane's automation.

SKF is currently developing internal standards for automation procedures during the duration of the thesis. These were not applied to this thesis.

This thesis will not fully achieve virtual commissioning due to the software NX MCD and SIMIT not being made available.

It is not in the scope of this thesis to examine the development or implementation of a coordinate system. An assumption is only made that it would exist to support the future implementation of the automation procedure.

The implementation of the real-world crane's automation will not be done in this thesis. The thesis will primarily consist of a technical study to develop logic for automating the process.

The project will have a timeframe of 20 weeks to complete all segments, which are given a detailed time plan in a Gantt chart in appendix A.1

### 1.2.2 Project aim & research questions

This master thesis aims to develop a solution that automates the materials gathering process for the crane at SKF Mekan in Katrineholm. The solution will be verified through the use of simulations. The research questions the study sets out to answer are:

1. How can an automation project for an existing process be evaluated without interfering with the operational process?
2. What are the different tools and requirements are needed for evaluating an automation project virtually?

### 1.2.3 Thesis structure

The thesis is structured as follows:

**Chapter 1, Introduction**, explains the background of the thesis and the added values of executing the project. Therefore, background and objectives, stakeholders, purpose and aim, research questions, and delimitations.

**Chapter 2, Theory** covers the theoretical framework for virtual commissioning, the difference between automation in brownfield and greenfield, different hardware and software used in automation projects, and safety measures taken into consideration.



**Chapter 3, Methods** represent the approach adopted to gather information to complete the thesis, such as the literature study, qualitative analysis, technical methodology and procedures.

**Chapter 4, Results**, includes the findings after executing the project as defined earlier in the "Methods" framework. Semi-structured interviews and the findings from applying the automation using PLC and HMI and the associated simulations.

**Chapter 5, Discussion**, discusses different errors and weaknesses points that need to be addressed. In addition, recommendations for optimal execution are provided and discussed.

**Chapter 6, Conclusion**, discuss if the thesis has achieved the objectives mentioned in the introduction. And then answers the research questions.



# 2

## Theory

The following theory section explains all concepts required to understand the methods and results of the thesis.

The software chosen comes from the Siemens toolchain. Firstly, SKF uses much of Siemens in their current applications, making the results from the thesis more applicable for SKF Mekan later on. Secondly, there is support in literature in favour of the Siemens toolchain working in an automation process, [5, 6, 7].

### 2.1 PLC

Programmable Logic Controllers, PLCs, are, according to [8] ".. computer-based, solid-state, single processor devices that emulate the behaviour of an electric ladder diagram capable of controlling many types of industrial equipment and entire automated systems." PLCs are commonly the central part of an industrial automated system since they can be fully adapted for any application and share joint control with any other controller in the industry, [8]. PLCs can be of different sizes and support various functions or have different amounts of input/output (I/O) used to connect the PLC to components such as sensors, motors, and actuators. A PLC can also be modular, allowing for different modules such as extra memory or additional I/O to be connected per the device's demands in the specific application. The PLC can be summarised to have three tasks according to [9], "...a PLC checks the information inputs, goes through the program and changes the outputs. Then, it circles back to the top and starts once more."

### 2.2 PLC programming

PLC programming can be achieved differently since many PLCs support different coding languages. The most common ones are Ladder logic, Structured control language (SCL) and sequential programming. One fundamental concept for PLC programming is tags. These are inputs and outputs defined by the user to have physical locations on the PLC.

#### **Ladder logic**

This approach represents the code as lines or rungs which have signals sent through them. On the rungs, different bit-logic operations can be put, such as normally open gates, which do not pass a signal unless true and normally closed gates that do not

## 2. Theory

pass a signal unless false. Each rung can be connected to an output, [10]. See figure 2.1 for an example of ladder logic in TIA portal.

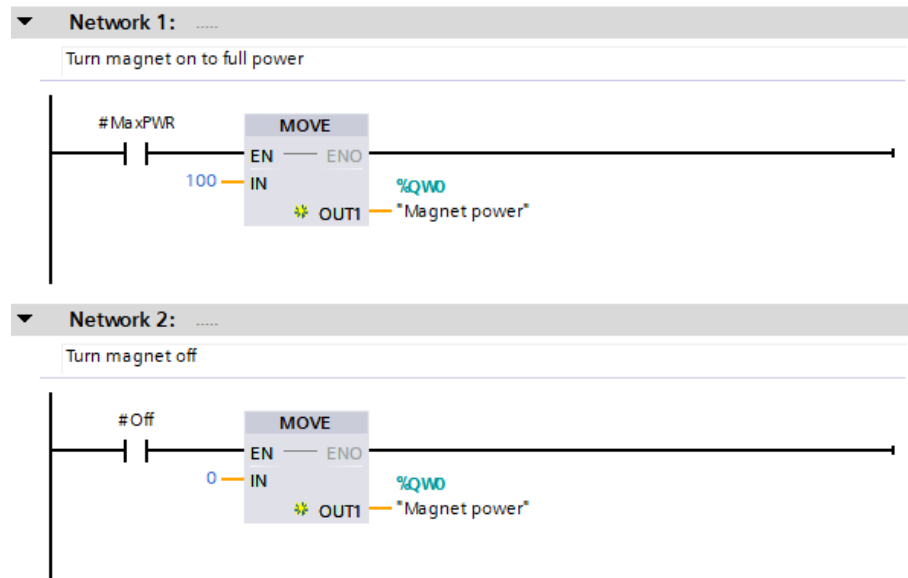


Figure 2.1: An example of ladder logic.

## SCL

SCL is a text-based programming language used to program in a PLC. Some operations are easier to perform if they can be programmed using written code. SCL allows for standard coding functions such as for and while loops and if statements, [10]. See figure 2.2 for an example of SCL code in TIA portal.

```
2 FOR #PickCtr := 8 TO 10 DO // index is pushed from 7 --> 8 due to box 13 having index 7
3   IF #FoundPnP = TRUE THEN //do not continue looping if boxes have been found
4     EXIT;
5   END_IF;
6   IF #Boxes[#PickCtr].Material Type = 'Empty' THEN
7     //Will not pick from an empty box
8     CONTINUE;
9   END_IF;
10
11
12 FOR #PlaceCtr := 1 TO 7 DO
13   IF #Boxes[#PlaceCtr].Capacity >= #Boxes[#PlaceCtr].Material Amount + #Boxes[#PickCtr].Material Amount
14     AND #Boxes[#PickCtr].Material Type = #Boxes[#PlaceCtr].Material Type THEN
15     // Same material and placebox can hold all of pickbox's material, found boxes
16
17     #PickBox := #Boxes[#PickCtr];
18     #PlaceBox := #Boxes[#PlaceCtr];
19     #FoundPnP := TRUE;
20     EXIT;
21   ELSE
22     CONTINUE;
23   END_IF;
24 END_FOR;
25 END_FOR;
```

Figure 2.2: An example of SCL code.

### Sequential programming

Sequential programming or S7-Graph, referred to in TIA Portal, is a programming language consisting of steps and transitions. A step executes an order, and a transition is a condition that has to be met for the code to progress. Sequential programming is often used for large sequences with specific steps that are supposed to be executed in order, [10]. See figure 2.3 for an example of sequential programming in TIA portal.

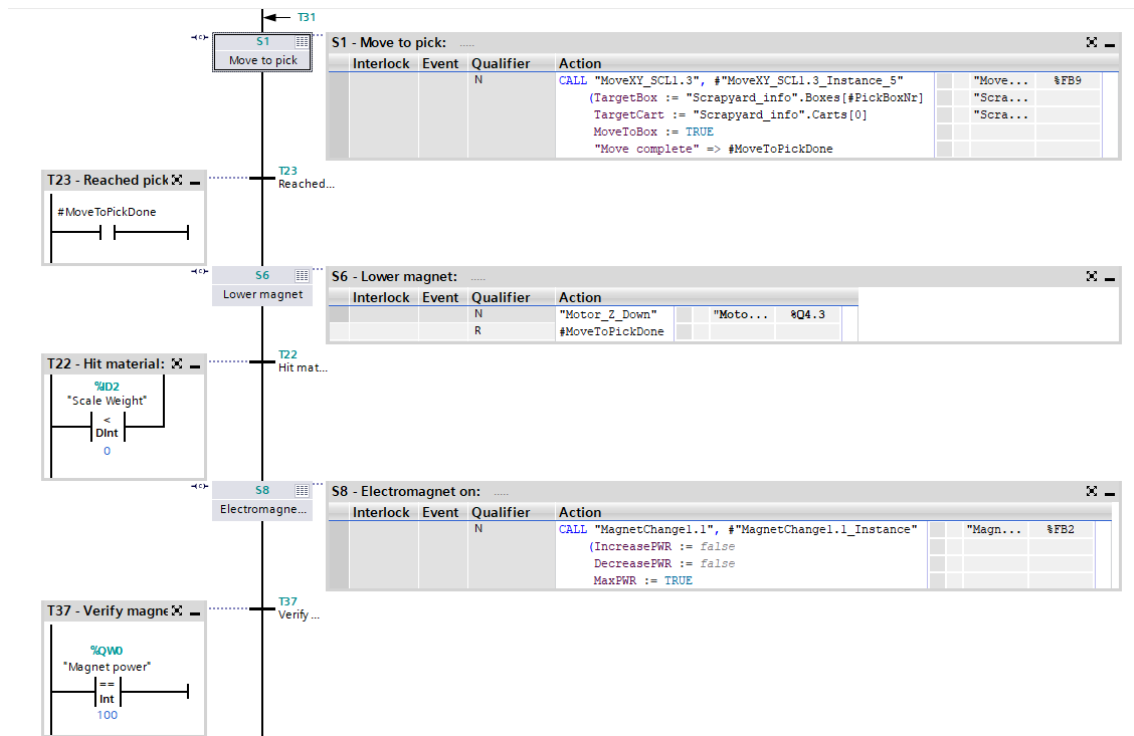


Figure 2.3: An example of sequential programming.

#### 2.2.1 Totally Integrated Automation Portal V17(TIA Portal)

TIA Portal is an interface software which includes SIMATIC tools on an all-in-one platform to help build a productive and efficient automation process. Two primary devices are involved in successful automation: PLC to control the system and Human-machine interface (HMI) devices to provide a visualization tool and receive user inputs. TIA Portal is a program which allows the user to integrate vital features in automation, including but not limited to safety and security, control and programming, HMI design and testing, and motion drives [10]. In this thesis, TIA Portal is mainly used to create the PLC Code and HMI alongside testing these parts.

The selection of TIA Portal to handle the automation in the thesis was not only because SKF uses the same software in other projects but also because of the usability of the software and the various modes of coding you can use on the same platform, [10].

### 2.2.2 S7-PLCSIM Advanced V4.0

PLCSIM Advanced is a Siemens software which creates an instanced virtual programmable logic controller on the user's computer [11]. This virtual controller can then be connected with TIA Portal and functions similarly to a physical PLC, enabling the PLC program to be downloaded to a PLC. Furthermore, using this virtual tool allows for testing program logic within the virtual environment by changing values of variables on the PLC through TIA Portal; a sequence of automation can be progressed and checked for logical errors before the PLC is connected to any actual equipment.

### 2.2.3 SIMATIC WinCC Runtime Advanced

SIMATIC WinCC (Windows Control Center) is a Siemens software that, through interfacing in TIA Portal, is, according to [12], a "... scalable process-visualization system with numerous high-performance functions for monitoring automated processes.". It is used to create user interfaces and monitoring of automation. The software is usually used to create, simulate and evaluate the different HMI's connected to the PLC. The simulation can be connected to the PLC and send and receive signals similar to an actual HMI, which allows for testing of the connection between HMIs and PLC.

In this thesis, the crane functions such as the materials gathering, manual moving between boxes, inventory control, etc., are presented on the HMI. When comparing the existing manual process for managing the crane tasks with the end product, the suggested approach can enhance the process significantly when it comes to precision and constancy of the crane functions, provide a complete automation solution, assure safety at the workplace, and eliminate unnecessary costs [13].

## 2.3 NX MCD

NX MCD (Mechatronics Concept Designer) is a Siemens Software program that allows for multi-disciplinary machine design and testing from electrical, mechanical and automation engineers. There are many tools and functions included in NX MCD. However, the primarily used function in the thesis is the physics-based simulations to which functional, active components such as actuators, sensors, and motors can be added. The created CAD files will be put in a simulated physical environment with physics and allow for the creation and connection of active elements, [14].

## 2.4 SIMIT

SIMIT is a Siemens software that enables automation application testing, which allows for early process optimization. The process can result in reduced commissioning times. In the thesis, SIMIT will organize the active components and their signals

passed through PLCSIM Advanced and SIMIT and connected with NX MCD. Furthermore, specific scenarios can be created for testing [15].

## 2.5 CATIA v5

CATIA v5 is a CAD software developed by Dassault Systèmes. CATIA has many uses. Within the mechanical design, CATIA allows for specification-driven modelling for solid, hybrid and sheet metal part design, alongside assembly design, [16]. It was chosen due to CATIA files being compatible with Siemens NX MCD, [17], and because of the authors' prior knowledge and access to the software.

## 2.6 Virtual commissioning

Commissioning of an automated system is a process that can be likened to pre-production within the implementation of an automated system that, according to [18], "... makes visible whether the systems and components are planned, designed, produced and installed correctly according to the user requirements.". Conventional implementation of an automated system follows a linear sequence where firstly, the layout and assignment of machines are created. Secondly, detailed planning is carried out of, for example, the kinematics of industrial robots that are done using offline programming to ensure no collisions will occur. In the next step, electrical detail planning is done for the system's energy supply and control signals. Then finally, the commissioning of the system will be carried out, where all previous steps have to be implemented at once to create a functioning automation cell, and each component has to be verified working alongside all other components, [18]. The issue with commissioning is that there are often undiscovered bugs and faults won't be apparent until the real commissioning, making it very time-consuming. If this testing can be performed virtually, it could be without the risk of damaging equipment. It would also allow errors to be found before the real commissioning, which would be far more time-efficient and less costly, [19, 20, 5]. Hence, why the concept of virtual commissioning (VC) is increasingly trending in manufacturing industries [21].

Since machines are increasingly more complex, building and testing the actual machine is costly and time-consuming. This is due to failures and deficiencies of the machine and program often being discovered in the last stage of commissioning, for example, during the factory acceptance test (FAT), [6]. There are two types of virtual commissioning, hardware in the loop (HiL) and software in loop (SiL), [22].

Hardware in the loop (HiL) means that the simulation process is associated with a physical PLC. In contrast, software in the loop (SiL) means that simulation is associated with a virtual PLC. The main difference is that SiL does not give a realistic reflection to the machine because it tests and edits the machine component, part, or function individually. On the contrary, HiL executes the process in a predetermined order, providing an accurate simulation of the physical system, and, if it is dimen-

sioned perfectly, it has a good reaction time (the consumed time between taking the order by PLC and reacting to it). However, the drawbacks of HiL are extra cost and more time [22].

On the other hand, SiL provides more flexibility to try different characteristics of system components like size and type without linking them with each other, which will eventually shorten the process duration and enhance the quality. However, SiL has its pitfalls, as the system is affected by the limits of the used software platform. In other words, the software platform could enhance the SiL process or increase the responsiveness of the system.

The response time is the main feature that affects the selection between SiL and HiL to perform effective virtual commissioning. For machines with a response time of less than 1 ms, the suitable type of test is in HiL associated with Real-Time Operating System (RTOS) to give an accurate system simulation. While if we want to test the same machine using the SiL approach, an adjustment should be made to the time as a replacement to the RTOS to remove the time discrepancy from the control loops. Moreover, the type of machine that is being virtually commissioned plays a significant role in the requirements of the PLC, [6].

Due to project requirements and adding more simplicity, the authors chose the SiL approach to execute this automation project.

## 2.7 Greenfield & brownfield

One of the most critical work prerequisites in any automation project is whether the workplace is green or brownfield. The nature of the workplace is essential to give a feasible economic and technical evaluation, [23].

A greenfield is an industrial term used when an industrial factory or production system is newly designed and constructed, starting with the engineering design drawings till the commissioning phase. The greenfield usually gives the engineers more freedom to set regulations and work standards that suit the new system. Moreover, the greenfield is advantageous for planning time and flexibility to make a modern manufacturing environment with a high technical resolution with the suitable infrastructure for future projects within the workplace. However, greenfield investments are highly costly, and validation of the new system might be an issue because of a lack of history and prior knowledge [20].

While the brownfield is an existing facility often in the operation state, an automation project in a brownfield will integrate new technology in software or hardware in the current system. The additional parts will require a shutdown to one or more parts of the existing system in the installation and commissioning phase. The main advantages of this scenario are the historical data and knowledge from the modified or replaced system, which could be used to verify the new system. Moreover, the existing equipment and the inherited systems within the area can be used, and as



a result, the investment cost could be reduced significantly. However, the work in brownfield has disadvantages, such as the restrictions that the old system will apply to backward compatibility, [20].

If SKF Mekan is taken as a case study, the workplace is a brownfield since the scope of work is to automate an existing overhead crane and add additional functions and duties to it. Notably, there are many trade-offs when it comes to the project environment for this case study, and the following are some of the observations:

**Advantages:**

1. There is a weight scale on the crane which can be used in the weighing process and inventory control.
2. There are safety standards of the crane operation that can be used in the automation process.
3. The signals from the light fences used in the wagon area can be utilized in the automation process as safety features.
4. Initial estimation of the cost is very low compared to greenfield project.
5. Gates are controlled by sensors that open whenever a truck approaches to deliver the material. The same door signal can be used as part of the crane automation process.
6. The automation project can utilise cognitive support devices embedded in the crane, such as lights and alarm sounds.

**Disadvantages:**

1. There is no weighing system for the individual boxes, and therefore it is unknown how much material is in each box, making the inventory control difficult.
2. There is no coordinate system that the crane uses to navigate. This would have to be implemented in some way for an automated solution

## 2.8 Safety measures

The automation of overhead cranes could include high-risk activities that might compromise the safety measures and subject the personnel in the workplace to fatal consequences [24].

According to [24], an efficient safety analysis should be part of any automation project aiming to prevent collision accidents that might jeopardize workers or workstations in any production facility.

SKF follow its in-house safety standards. Standards like "STD-67-00 SKF Machine Safety Requirements" and "SIAS - SKF Automation safety requirements (Edition 1.0.0/2022)." and the Risk assessment format that SKF follows in automation projects are the primary standards that aim to create a safe work environment. SKF safety standards were considered when the PLC and HMIs were made.

As per SKF, the risk assessment fulfilment shall be completed and documented during the project's design stage.



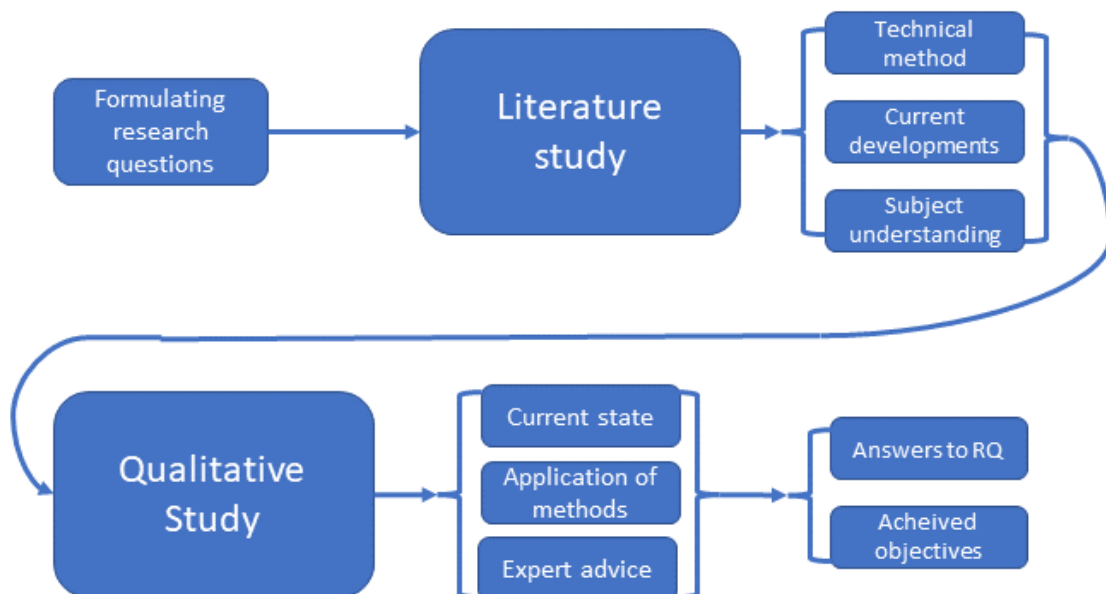
# 3

## Methods

This section explains the scientific and technical framework used to structure the methodology of the thesis. For an overview of the methodological approach, see figure 3.1.

A literature study was conducted to answer the research questions and understand current developments in similar fields. The literature study is essential to validate a more in-depth understanding of research on similar automation projects and how the simulations and PLC programming were carried out. Furthermore, a technical methodology should be identified.

A qualitative study was carried out to supplement the literature study learnings, understand the case's current state and examine how information attained in the literature study could be applied. Two qualitative approaches were chosen. The first is unstructured observations during the site visit to the facility that define the current process and semi-structured interviews with key personnel with either detailed knowledge about the scrapyard and crane or automation in general. The results of these interviews and observations, alongside a technical methodology, will then result in achieving the objectives set in section 1.1.3.



**Figure 3.1:** Methodological approach.

**Table 3.1:** Keywords during literature study.

| Keywords                  |                                     |
|---------------------------|-------------------------------------|
| Automation                | Overhead Crane                      |
| Virtual Commissioning     | Programmable Logic Controller (PLC) |
| Discrete Event Simulation | PLC Programming                     |

## 3.1 Literature study

In order to ensure high reliability of the sources, Chalmers discovery services were used to search literature from various scientific databases. The selected databases were Scopus, Science Direct, Google scholar and Web of Science. The keywords used for the literature study can be seen in table 3.1.

The literature selection was based on finding literature that supports the automation project domain related to SKF Mekan. Relevant articles will be prioritized by the following process:

1. Review the abstract.
2. Conclusion and discussions.
3. The literature content.

If the paper was appropriate to the research scope, it will be considered acceptable; else, it will be excluded from the literature study. Additionally, the literature selection concentrated on gathering peer-reviewed papers published as recently as possible to ensure that the information collected is up to date. The literature study will complement the data collected from qualitative and quantitative analysis. Therefore, enhancing the quality of the research conducted.

## 3.2 Qualitative study

Interviews are a great methodology for collecting information about different topics. However, it requires preparations and prerequisites in order to have a successful interview that will serve its purpose. Therefore, it is of great interest that the interviewer identifies the interview type that needs to be conducted, whether it is structured, semi-structured or unstructured [25, 26].

### Structured interviews

They are usually used when the questions and their order are prepared in advance, so the interviewee will be asked a pre-prepared question in the designed sequence by the interviewer. The advantage of this method is that it's easy to follow and compare the answers and build an objective opinion about the topic. On the contrary, structured interviews are difficult to create. And the questions should be followed strictly by the interviewer, which will hold back the innovation and hinder the following discussions [26].

### Unstructured interviews

In this type, there are no pre-prepared questions beforehand. Otherwise, the questions are generated through the discussions that take place during the interview. Although, this type provides more spontaneous and honest answers. However, it carries pitfalls also because it is hard to organise and evaluate the information gathered during the interview [26].

### **Semi-structured interviews**

In this type, there are only a few pre-prepared questions while the balance questions are generated during the interview. Semi-structured interviews were used heavily in this thesis because of the high level of flexibility the structured interviews provide and the high-quality information that is usually provided by the structured interviews. The key factor in choosing the semi-structured interviews was the limited knowledge the authors have in the field of automation since all the knowledge was gathered from the literature study rather than a solid practical experience in this field [26].

Different sources were used to enrich the methodology with more knowledge from experienced engineers who previously worked with similar automation projects and from persons in direct contact with the overhead crane that will be automated. A total of three interviews were conducted with, with one person interviewed each time except for the stakeholder interview where two stakeholders were interviewed. All interviews were conducted in a semi-structured manner where some questions were prepared prior to the interview but relevant topics that came up naturally were also explored and discussed. This allows for the authors to both receive answers to specific questions alongside exploring the subject further and potentially receiving additional useful information, [25, 26]. For lists of the prepared questions for the different interviews and observations to be made, see appendix B, questions that did not produce answers are not included.

In case of missing information, the company supervisor for the thesis provided answers and assistance.

#### **3.2.1 Crane operator interview and visual observations**

This interview was conducted early when understanding the crane's operations and surroundings was vital. The interview was conducted during a guided tour of the scrapyard and the foundry, where visual observations were made. Questions were asked throughout to verify the observations made or elaborate on why things were a certain way. Some questions were prepared before the interview, which concentrated mainly on the crane's different functions, the collision avoidance system in place, the precision of the electromagnet weighing system and the safety measures taken to ensure personnel safety while the crane is in an operational state. The interviewee and guide was the crane operator, who is highly knowledgeable of the crane and its surroundings in daily operation.

#### 3.2.2 SKF Mekan stakeholder interview

Some details about the scrapyard were unknown, specifically regarding the properties of boxes and procedures in the material hall. An interview was held with SKF Mekan stakeholders of the thesis who are also in charge of the material hall for details of capacities, different materials and deliveries.

#### 3.2.3 SKF automation engineer interview

In order to properly construct the automation for the thesis, an automation engineer at SKF was interviewed about the general process and to receive general advice. The thesis and its aim were explained to the interviewee first, and then questions were asked regarding automation.

### 3.3 Technical methodology

The methodology for developing the model is adapted from the concurrent engineering design methodology for virtual commissioning proposed by [27], which involves four steps.

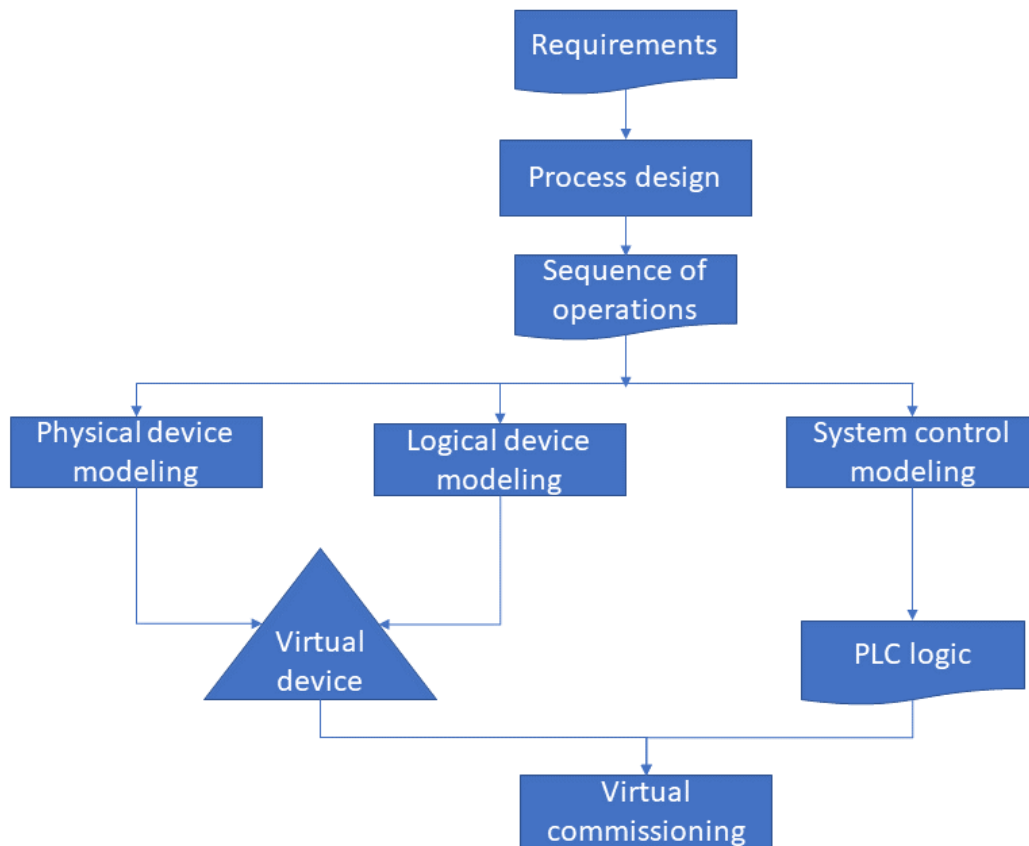
The first step is process modelling. Requirements of the process are taken as inputs, and the methods and processes are identified that produce the expected result. An SOP (sequence of operations) is generated from this step, which details what tasks the device should carry out. The three remaining steps can be addressed simultaneously using this SOP: physical device modelling, logical device modelling, and system control modelling. However, this thesis will conduct the following steps in the presented order due to not having the resources to conduct the parts simultaneously.

Physical device modelling is the process of generating the geometry and kinematics of the model. This part is the mechanical design of the VC project. This is done by creating CAD models of each part connected by moving joints, either prismatic or rotational. Physical attributes like weight and gravity are also applied to all the components in this step. The OEMs of the device typically supply these models.

Logic device modelling concerns the electrical design, which functions as a communication system to the PLC from the mechanical CAD model. This is done by taking the SOP from step 1 and allocating two symbols for each task or function, one output symbol that triggers the task and one input symbol that notifies the PLC that the task has been carried out. For example, the task T\_MOVE is initiated using the output symbol O\_MOVE, and then the completion is verified using the input signal I\_MOVE. Ziegler's DEVS (Discrete event system specification) is most often used for modelling the logical device. The physical device and logic device are then combined into a virtual device that mimics the behaviour of the actual device.

The step of system control modelling is where the actual PLC code is produced. The code then communicates through the defined input and output symbols with

the model. The PLC ladder logic should consist of a line for each task and check the initiating condition of each task. The methodology is shown in figure 3.2.



**Figure 3.2:** Virtual commissioning method adapted from [27].

### 3.4 CAD construction

To complete the step of physical device modelling in a 3D environment [27, 28] recommends finding existing CAD files or libraries of the components from the OEMs to shorten the time required for this step while making the CAD geometry more accurate. However, this was not available for the components relevant to the thesis, so the CAD geometry was constructed manually.

To construct the CAD, digital drawings to scale the crane and surrounding structures were provided by SKF Mekan. However, most required measurements were not given in the drawings. More detailed measurements were retrieved by accessing the digital drawing through CAD software and measuring it directly to then be used to construct the 3D geometry of the different components.

The approach for constructing the actual geometry was to create fully constrained sketches and then create solids from them. In some cases, a generative shape design toolbox was utilized to create wireframe geometry of more complex shapes. Each

part was modelled separately and then assembled with the correct constraints leaving the desired degrees of freedom. For example, wheels on the cross beam were modelled separately to be later assembled with constraints set so that the wheels could only rotate.

## 3.5 PLC coding approach

The general process of PLC programming was first to understand all functions that required coding. This was done by generating a plan for how to program each step. Firstly the inputs and outputs that would be necessary were defined, and then the sequence for the primary code process, the *Pick&Place* sequence, was defined. According to SKF control software requirements, [29], programs should be developed to be reusable. This was kept in mind during the development of all programs and functions. Furthermore, the program was developed to be object-oriented as per SKF standards, [29]. The program is modular by having functions for each sub-process which are then re-used by more specialized functions. Sub-functions may also include functions within themselves which are more general and flexible in their uses. This approach allows smaller portions of programming to be tested in isolation to verify their functionality. Furthermore, this makes later writing the code more straightforward due to the re-usability of pre-existing and tested functions. Comments were made to clarify the functionality of the program where necessary.

Along the way, the progress in the PLC programming was shown to SKF employees who were stakeholders in the project to ensure the PLC program was representative of the automation process that was imagined. It was changed if something deviated from the stakeholder's idea of automation.

Extensive testing was necessary to ensure that the created program functioned as intended. The PLC program in TIA Portal was connected to PLCSIM Advanced, where the program was downloaded to a simulated PLC. Once downloaded and the TIA Portal program was online with the simulated PLC, the values of the different variables were changed within TIA Portal to progress the code. To ensure there were no undiscovered logical faults, the different cases of input combinations that would produce a different result were listed in a spreadsheet and then tested to see if the code would produce the expected output or not.

## 3.6 HMI design

Human-Machine Interface is a great device that visualizes the automation and interacts with the user that operates the device. Moreover, the HMI screen can change the values of the tags and execute the equipment functions [13]. When designing the Human-Machine interface of a manufacturing machine, the device should be flexible and practical for the customer. Aspects like usability and functionality should be prioritized during the design process. Furthermore, since every designer has their view on how to design each window substance, pop-up windows, layouts, alarms etc.

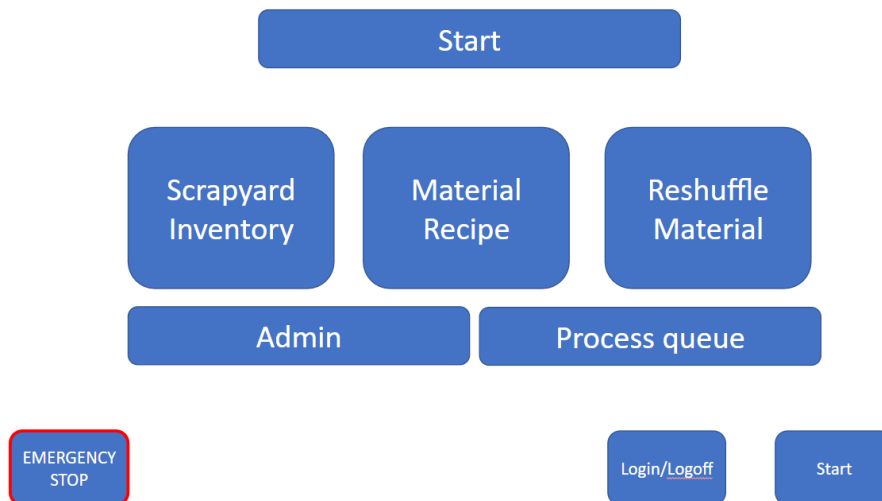


both the designer and the customer should keep in mind that some designs are better than others [30]. However, the developer's aim should be to provide an interface that is efficient, transparent, friendly and easy to use. These goals are utilized to reduce downtime while increasing the machine's productivity and to assure safety at the workplace.

The following section goes through the design principles and methodology used to develop the HMI.

### 3.6.1 Conceptual design

The first step in designing the required HMI for the project was building a conceptual design in PowerPoint. The conceptual design included all the required windows, pop-ups and the security level suggested for each page in the HMI. An example of the conceptual design can be seen in figure 3.3.



**Figure 3.3:** Example of conceptual design for the HMI.

### 3.6.2 Design and program

The first step is to create the connections between the PLC and the HMI devices. Making the connection and the virtual networks is a significant part of connecting the PLC program to the HMI functions to test and simulate the program and remove faulty parts or modify it before delivering the final product to the end-user.

Later, during the work through WinCC to build the designed platform, the SKF standards to create the HMI were received. Including the standards of layout, fonts, and different topics. However, not all of the aspects were covered in the design. Since WinCC was chosen to design the HMI, and because of the lack of experience in this field, the main qualitative information gathering for the thesis was through articles, books and tutorials on the Siemens website.

The I/O list in the HMI variables table is essential for the HMI design. The required I/Os that will facilitate the crane's different tasks should be defined and created. Afterwards, the HMI I/Os should be associated with the PLC I/Os that serve the same function in the PLC code. It is essential to configure the I/O Field when used in the HMI in terms of input/ output tag [13].

After setting each window or function, simulation of the connection between PLC and both HMIs was a continuous process. PLCSIM advanced and wincc were used for testing to ensure that the buttons and functions were operational. Safety features such as the emergency stop button were tested and verified.

# 4

## Results

The results from the qualitative study, literature study, physical device modelling, logical device modelling and system control modelling are detailed in the following section. A section regarding the total result of applying and working along the virtual commissioning methodology is presented. Lastly, the required hardware for the automated sequence to function as intended is presented.

SKF has confidential information regarding the material amounts and ratios that make up their material compositions. To respect this, all materials in this report are referred to as Mat 1, Mat 2, etc. Furthermore, no combinations of materials are derived from SKF Mekans compositions.

### 4.1 Literature study findings

According to [5], virtual commissioning allows for the development and validation of PLC using simulations as a means of verification which is safer and can be done completely virtually if SiL procedures are adopted. By using the created simulation model from virtual commissioning as a base, a digital twin can be produced for the system, [5]. Virtual commissioning is advantageous to regular commissioning due to the ability to detect errors with everything still in software form, [31, 32]. An automation project can be done much more cost-effectively by utilising a virtual commissioning process, [32]. Dependent on if the project is brownfield or greenfield, there are different advantages; for greenfield, there is more freedom to make choices, while for brownfield, there is existing knowledge about the process and equipment can be reused [20]. A concurrent design methodology for virtual commissioning is described in [27]. Recent implementations and different types of the virtual commissioning process and how the process can be supported by Siemens software are given by [7, 5, 6].

There were 57 literature reviewed during the literature study (excluding five SKF standards and procedures). However, due to time limitations, all subjects discovered were not utilized due to the vast scope of the area. The detailed literature can be seen in table 4.1.

**Table 4.1:** Papers reviewed in the literature study.

| Literature topic                    | Number of re-viewed papers |
|-------------------------------------|----------------------------|
| Virtual Commissioning               | 19                         |
| Automation, Automation Software     | 17                         |
| Programmable Logic Controller (PLC) | 8                          |
| Overhead Crane                      | 5                          |
| Methodology                         | 3                          |
| Others (CAD, PM, Brownfield..)      | 5                          |

## 4.2 Qualitative study

The main results from three semi-structured interviews are detailed in the following section. Unless specified, miscellaneous information was provided by the company supervisor, who is well invested in the crane and its operations, such as the cost data for the operator and the alloys used to compensate for the lack of weighing accuracy of the crane, drawings, software access etc.

SKF Mekan provided information regarding the crane in its current state. Drawings as PDFs for the building, scrapyard, electromagnet, crossbeam, and trolley were identified and used. Digital drawings were also provided for the layout of the scrapyard and the crossbeam and trolley. These drawings were used in the construction of the CAD.

To model the behaviour of the crane, information regarding the speed of the motors for the crane, lifting capacity and magnet specifications alongside safety functions were identified in the provided documents.

### 4.2.1 Interview with crane operator and visual observations

The results from both the semi-structured interview with the crane operator as well as the visual observations are presented below.

#### Overhead crane

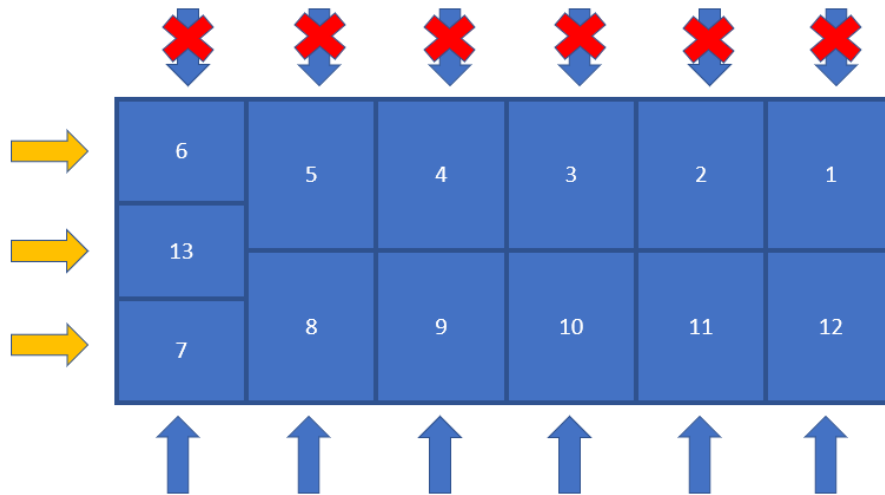
The crane is a standard overhead crane made by the company Dekra. The crane is being controlled from a control room located above the floor level to give the operator a good view of the crane and the material boxes. To control the crane, a joystick is used that moves the crane in three dimensions X, Y, and Z. The controls allow the operator to adjust the magnet's power using various buttons. Four cameras are fixed on the crane to show the operator the exact location of the crane and its surroundings. There is no automatic collision-avoidance system for the crane. Instead, it relies on the operator's experience for safe navigation. The crane has a stabilizing control system, however, due to the slow movement, there is little induced sway,

and it is rarely used. When the crane is not used, it is placed on the floor under the control room.

According to the operator, it is challenging to deliver the accurate weight of the material, especially the scrap material with a high variation of shapes and sizes. This variation makes the precision of loading the exact weight difficult for the operator, and deliveries are inaccurate by 5 to 25 kg per load.

### Scrapyard

The scrapyard consists of 13 concrete boxes that hold material in the shape of metal powder or scrap materials. Scrap materials, such as faulty bearings, housings, and chips, come in different shapes. The layout of the scrapyard is in figure 4.1, the blue arrows indicate where the material is loaded by truck, and the yellow lines indicate where the material is loaded internally using forklifts.



**Figure 4.1:** Boxes in scrapyard and eligible loading gates.

All boxes except for box 13 are coupled with a gate that opens to the outside. Trucks unload material from the outside to the boxes through these gates. Some of these gates are permanently blocked due to ongoing projects at the factory, and some are temporarily closed because of construction, see the crossed-over arrows in figure 4.1. Due to this, half of the storage boxes are not directly loaded. The material inventory in the scrapyard is not currently monitored.

### Materials after offloading

The crane is offloading the materials to two carts that move on rails. The carts will move once they have a signal from the furnace operator ordering raw materials to fill the smelters. Then the operator gathers material after demand when the furnace's molten metal level is low.

### Current safety measures

Notably, there are no safety measures for the crane itself except the instructions

given to the operator not to use the crane above an active loading area (in case there is a truck offloading the raw materials through a gate). However, there are light sensors for the gates and the cart tracks. While a truck breaks the light fence the gate will open, otherwise, the gate will close. If someone breaches the light barriers for either cart, the crane operator will have a light turn on, one for each railway. While this light is on, the carts can not move, a button must be pressed outside of the light fence to reset the light fences and make the carts able to move again.

4.2.2 SKF Mekan stakeholder interview

The boxes are said to be able to hold different amounts of materials. As seen in figure 4.2, boxes numbered 8 to 12 can hold the most material, 150 metric tonnes, boxes 1 to 5 can hold 100 tonnes of material and boxes 6,7 and 13 can only hold 40 metric tonnes.

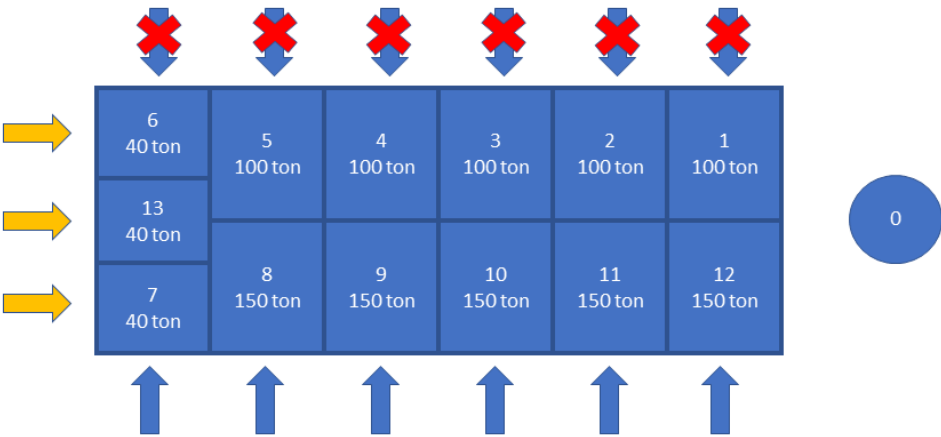


Figure 4.2: Boxes in scrapyard and their max capacity.

The stakeholders clarified that a maximum of nine materials are in the scrapyard at once and which materials are used the most often. Due to the frequency of use for the material being loaded into boxes 10, 11 and 12, these boxes should not have their material moved internally since their current locations are close to the carts that are delivered to.

The quantity of material is known for the ordered material that is being delivered by truck. Upon delivery, the truck driver should know how much material and what type is being delivered to the scrapyard. The quantity of deliveries is not logged into any inventory system currently.

The stakeholders explained that the primary costs are salary for the operator, additional alloy materials in the furnace to compensate for delivery errors, maintenance, and power costs.

### 4.2.3 Interview with SKF automation engineer

For safety precautions, the interviewee recommended implementing limit sensors that stop objects from moving to extreme locations, such as the crane moving close to walls. This was further elaborated on and can be achieved using light sensors or similar that detect an object crossing a defined line. Furthermore, emergency stops buttons should always be available, and safety is a top priority in automation.

SKF are in the process of developing its internal standards for automation and adjacent subjects. However, the standards will not be complete within the thesis' timeframe. Although the interviewee shared the current versions of standards.

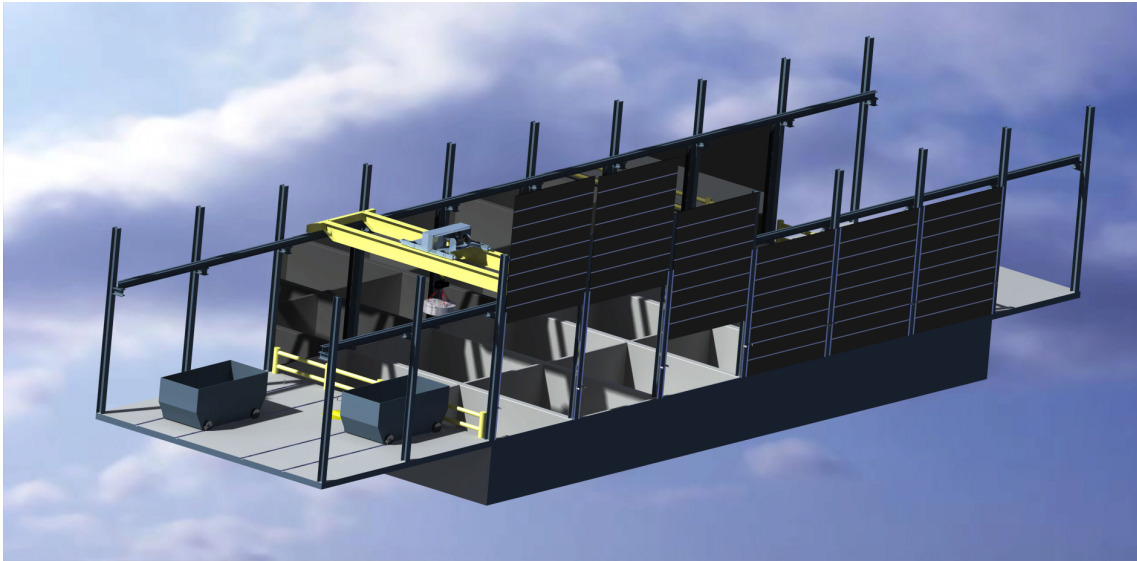
The interviewee reasoned that an S7-1500 PLC would be the best choice since it is the fastest modular model with more I/Os, which is essential for large applications. Furthermore, it can use controllers such as PID (proportional, integral and the derivative) controllers within the PLC internally. The S7-1200 series manages this as well but not as well. The interviewee stated that the choice of an S7-1500 PLC will future-proof the automation for further improvements. The interviewee did not specify what exact CPU of an S7-1500 should be used but instead referenced Siemens documents which compare the CPUs.

Lastly, some recommendations were made regarding the coordinate system that multiturn absolute encoders that register the rotation of the wheels on the crane would be the best solution for a coordinate system according to the interviewee's experience.

## 4.3 Physical device modelling

A render of the finished CAD assembly of all components can be seen in appendix 4.3, A figure for a render of all components from a top view can be seen in C.1. The scope of the CAD construction includes the following structures:

- Building structure and rails
- crossbeam and trolley
- Magnet and scale
- Material carts

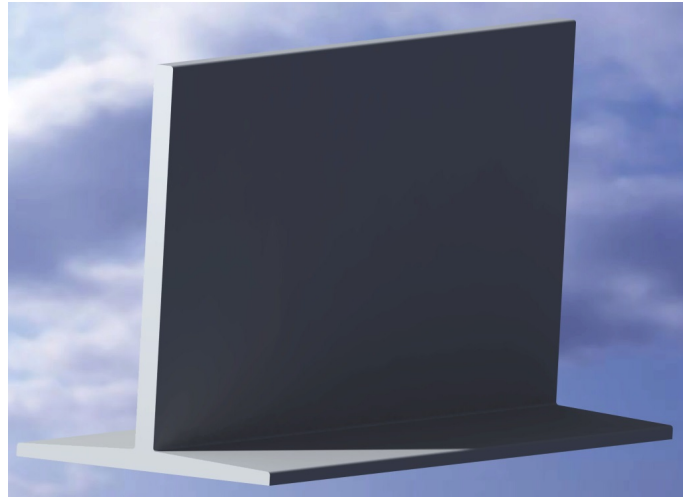


**Figure 4.3:** Rendered CAD image of the full scrapyard with all components.

### 4.3.1 Building structure

The building contains the boxes in the scrapyard, the surrounding floor, rails on the floor for the carts to travel by, and the beam structure holding up the crane crossbeam. Each box with an external opening has a gate sub-assembly connected to it with light sensors. These components can be seen in 4.3. The outer geometry enclosing the box area alongside the flooring is made as one part before and after the boxes. The internal box dividers were modelled separately from the outer geometry since they have supporting feet in the provided drawings. The supporting feet indicate that they can be moved around to arrange different box configurations, as seen in the last row of boxes, where there are three smaller boxes. See figure 4.4 for an image of the dividers. There was no specified height for the safety rails that enclosed the box area. The height was instead estimated through images taken during the visit to the scrapyard.



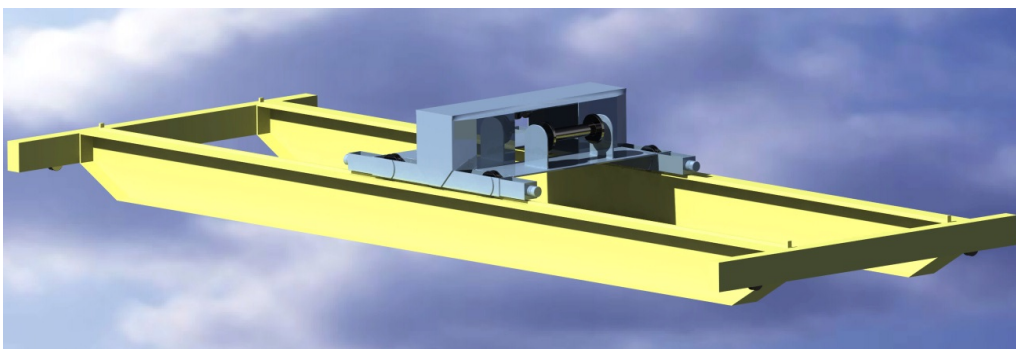


**Figure 4.4:** Rendered CAD image of the box dividers.

### 4.3.2 Crossbeam and trolley

The crossbeam and trolley are essential components of the material hall. These were accurately constructed with the help of digital drawings of the actual products, see figure 4.5. The crossbeam has five components and two types of parts, the crossbeam itself as one part and four wheels, one in each corner. The wheels have a groove to accept and move in constraint to the rails on the supporting structure. The crossbeam has rails similar to the supporting structure to guide the trolley wheels.

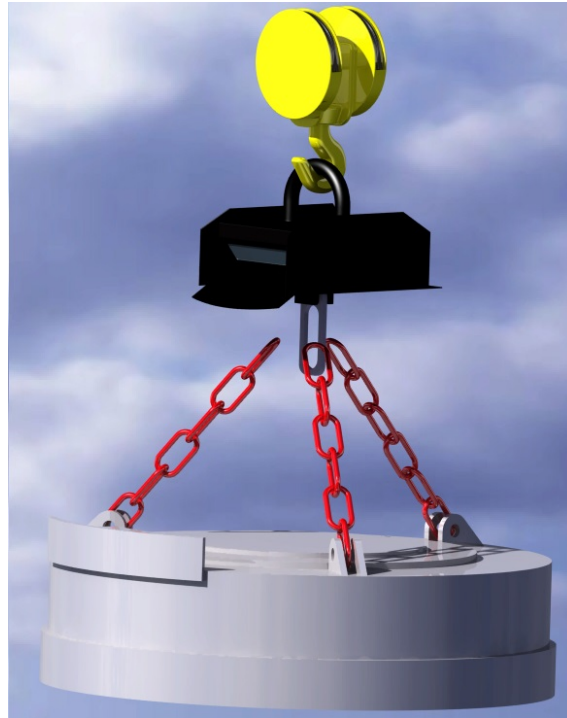
The trolley consists of four components: the trolley frame, four trolley wheels, the cable spindle, and one set of cable wheels to guide the cable within the trolley. The trolley wheels have grooves to accept the guiding rail on the crossbeam, similar to the crossbeam wheels.



**Figure 4.5:** Rendered CAD image of the crossbeam and trolley.

### 4.3.3 Magnet, scale, and hook

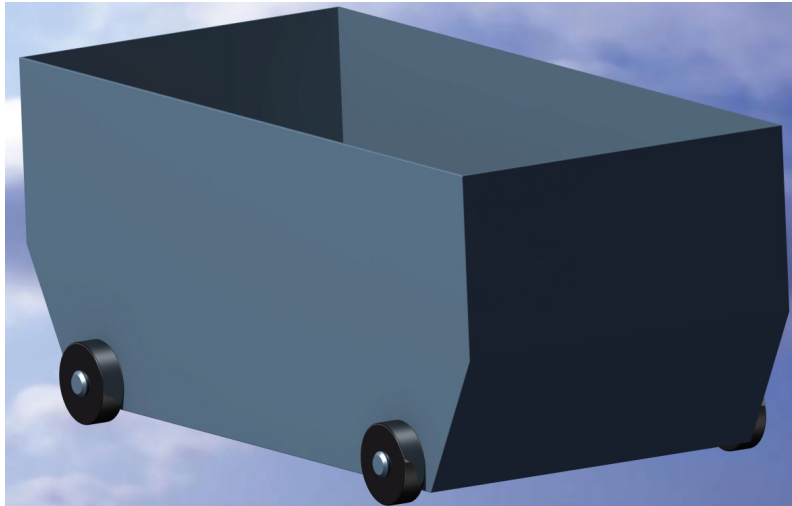
The magnet and scale subassembly consists of 7 components, totalling 24 parts. The different parts, from top to bottom in figure 4.6, are the crane hook, two crane hook wheels for the cable, the scale, a larger chain link, and 18 smaller chain links (red), and the electromagnet.



**Figure 4.6:** Rendered CAD image of the magnet, scale and hook subassembly.

### 4.3.4 Material carts

The carts consist of five components, the cart body and four wheels. There were no drawings or references for the geometry of the carts except for the rails on the floor that can be seen in the building structure, see figure 4.3. Therefore, the carts were given a simplified geometry using only one crucial dimension: the width between the wheels for the rails on the floor. For an image of the assembled carts, see figure 4.7. Each cart has a lightsensor and lightsensor reflex to see whenever the cart is in the correct location, see appendix C.2, C.3 for rendered images of the lightsensor and lightsensor reflex.



**Figure 4.7:** Rendered CAD image of a material cart.

## 4.4 System control modelling and HMI

The system control modelling created as PLC logic was constructed using functions. The most basic functions are called and utilized several times in different processes, making creating larger functions easier since most of the code can be re-utilized from the basic functions. The functions are presented from most fundamental to most specialized. For each function, a sequence of operations (SOP) is also given where the steps in the function are given.

The objective of crane automation and priority listed in section 1.1.3 is achieved through the combinations of the recipe function, the P&P sequence and the Move X, Y function.

### 4.4.1 Custom data types

A custom data type was defined for each with the necessary information to store information regarding the boxes and the carts efficiently. For the boxes, there are seven values defined;

1. X\_Coordinate (Int): The location of the centre of the box along the X-axis, measured in mm from the starting position of the coordinate system defined in 4.15, is used for navigating to the box's X-coordinate. Value is of type integer due to the value range being from -4446 to 4446, and an integer has the value range of -32 768 to 32 768, [33].
2. Y\_Coordinate (UInt): The location of the centre of the box along the Y-axis, measured in mm from the starting position of the coordinate system defined in figure 4.15, is used for navigating to the box's Y-coordinate. Value is of type UInt because the range is strictly positive and requires defined values in the interval of 0-36 000, and UInt has the defined value range of 0 - 65 353.
3. Material Type (String): The type of material that is currently in the box. It is set to 'Empty' or a value between 'Mat 1' and 'Mat 9'. Chosen to be of type

string due to the value needing to fit up to 5 characters, a string can fit 254 characters, [33].

4. Material Amount (UDInt): The amount of material that is currently in the box. Can hold values between 0 - 150 000. An unsigned double integer (UDInt) can hold values from 0 - 4 294 967 295.
5. Loadable box (Bool): Specifies if the box can be loaded from the outside or not by a truck. The data type is chosen to be boolean since it can be either TRUE or FALSE. This is true for boxes 7 to 12 and set to false for all others.
6. Capacity (UDInt): Specifies the maximum material capacity that a box can hold. There are three different sizes of boxes, those that can hold 150 000 tonnes, 100 000 tonnes and 40 000 tonnes.
7. Number (SInt): The number of the box according to the provided layout of the boxes that can be seen in 4.15. This value was implemented since the boxes are not in ascending order. It was easier to order an array of boxes in ascending indexes going from box number 1 to 6 to 13 to 8 to 12 for programming purposes. The value is chosen as Short int (SInt) since the values range from 0 to 13, and SInt can hold values between -128 to 127, [33].

The custom data type for the carts is very similar to the one for the boxes. It contains X\_Coordinate, Y\_Coordinate, Material Amount, and Material Type of the same data types as the boxes with the same reasoning. However, the carts have two additional booleans defined. One is called Accessible, which is set true if a light sensor is triggered by the cart being in the position where the crane can load into it. Another is called SendToMelt, which is activated when an order has been completed. This boolean activates motors on the cart to move it out of the material hall to the melting furnaces.

### 4.4.2 Ensuring collision free movement

The objective of collision avoidance can be solved by using predefined coordinates for each box and cart alongside an assumed coordinate system that gives the current position of the crane. The navigation of the crane can be set to only move to predefined locations, such as carts or boxes. Carts can only be loaded if their accessible boolean is true, indicating they are in the predefined location. The crane moves to these locations firstly in X and Y axes with the electromagnet above all obstacles and then lowers the electromagnet. This ensures that the correct location is reached and that no objects can collide with the crane while moving to targets.

### 4.4.3 Move X,Y

Move X, Y is initiated by the P&P sequence. The input for this function is simply one X coordinate and one Y coordinate, which are the target locations to which the crane should move. The function then examines where the crane currently is and decides if the motors in X and Y directions should move in the positive or negative direction to reach the target coordinate, the definition of the coordinate system is given in figure 4.15. This simple function makes the other functions easier to read

**Table 4.2:** All possible movement combinations.

| Combinations |     |
|--------------|-----|
| X+           | Y+  |
| X+           | Y-  |
| X+           | Y=0 |
| X-           | Y+  |
| X-           | Y-  |
| X-           | Y=0 |
| X=0          | Y+  |
| X=0          | Y-  |
| X=0          | Y=0 |

since there are 9 cases for how the crane should move, as shown in table 4.2.

The sequence of operations for this function is then as follows:

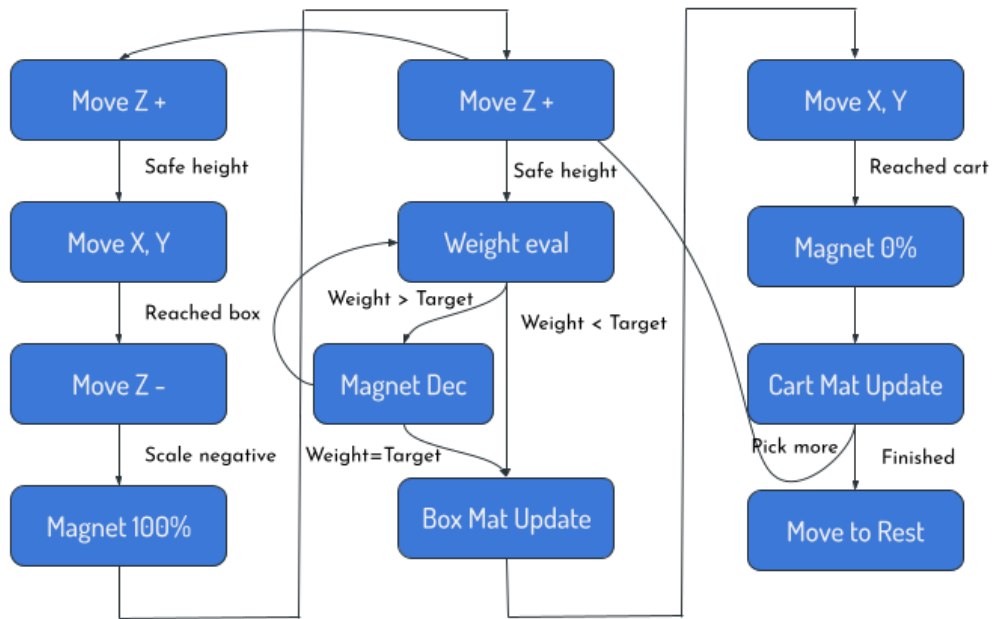
1. Activate X motor in the correct direction (simultaneous with next step)
2. Activate Y motor in the correct direction (simultaneous with previous step)
3. Stop X motor when reached coordinate.
4. Stop Y motor when reached coordinate.

#### 4.4.4 Pick & Place

This function is initiated by the HMI operator or the recipe function. Inputs for Pick&Place (P&P) are; where to take material from, how much, and where to deposit it. It also takes a boolean input declaring if the P&P targets are from box to cart or box to box. Eligible inputs for the picking and placing locations are both boxes and carts. The P&P (Pick & Place) function moves the material and outputs a boolean called P&PComplete as true when finished. Values of material stored in the relevant cart and box are updated as material is moved. At the end of the function, it is checked whether the right amount of material has been delivered or not. If it has been, then the function ends. If not, it begins again until the correct amount of material has been delivered. See figure 4.8. The SOP for the P&P function is as follows:

1. Raise electromagnet to transport height.
2. Call the *Move X, Y* function and move to the box that it should take material from.
3. Lower the electromagnet until it contacts material, IE when the scale registers a negative value.
4. Activate the electromagnet.
5. Raise electromagnet to transport height.
6. Check the target delivery amount and compare to how much material is currently on the electromagnet. If the electromagnets weight is larger than the target, reduce the magnetic force until the scale registers within a given weight interval

7. Update how much material is in the box by subtracting the current material on the electromagnet.
8. Call the *Move X,Y* function and move to the cart that it should deposit material into.
9. Deactivate the electromagnet.
10. Update how much material is in the cart by adding material delivered by the electromagnet.
11. If all material has been delivered - move to rest position. Else, start from step 1.



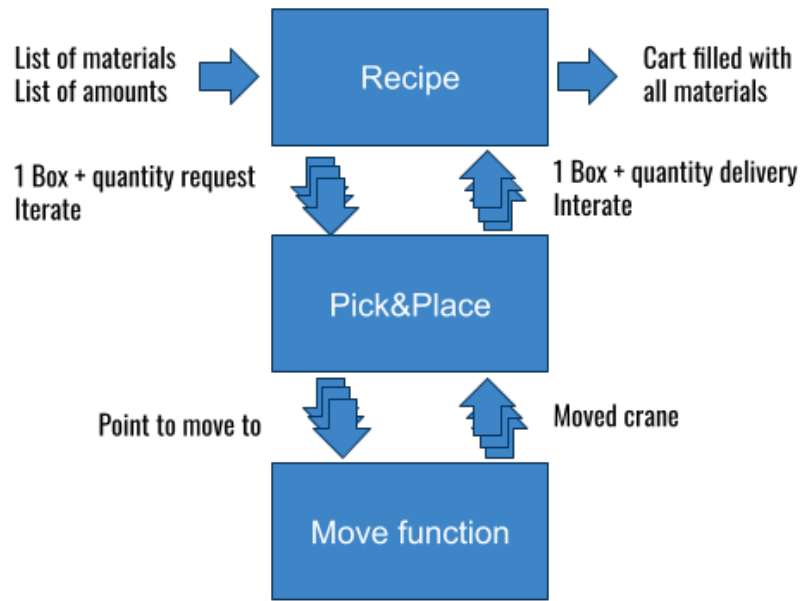
**Figure 4.8:** Visualized PickPlace sequence

### 4.4.5 Recipe gathering

This function is initiated by an operator starting the procedure through the HMI. The recipe function takes four inputs, an integer of how many materials are in the recipe, two lists, one of box numbers and another of quantities for each box and lastly, to which cart it should deliver. It then verifies that the sufficient amount and right type of material are in the material hall and that a material cart is in a loadable position using a light sensor. Then it calls the P&P function for each type of material that should be collected from each specified box. The SOP for the recipe function is as follows:

1. Utilize the P&P function to move from specified box to cart, repeat for how many materials there are in the recipe.
2. Send the cart out to the melting furnaces.

For an overview of the functions called and data passed from the recipe function, see figure 4.9.



**Figure 4.9:** Figure detailing the recipe function.

#### 4.4.6 Reshuffling

This function is automatically started after completing a recipe sequence or after loading new material. The reshuffling sequence is set to resolve the objective of re-organizing material for efficient storage detailed in section 1.1.3. The reshuffle procedure suggests moves between boxes since some will be blocked during construction and can not be directly loaded externally. Furthermore, while moving material, the inventory can be controlled.

In the reshuffle code, the boxes are split into two categories, ones that can be loaded from the outside, called loadable boxes, boxes 7 through 12, and ones that can not be loaded from the outside, called unloadable boxes, boxes 1 to 7 and 13.

The box comparison works by first looking at the unloadable boxes and comparing the material type in each with the material type in the loadable box. If it finds a match between two boxes that share material, it will call the *P&P function* and move all material from the loadable box to the unloadable. If no boxes share the same material, it will instead find the first empty unloadable box and move material from the furthest away loadable box. This logic evaluates boxes in rising order, prioritizing placing material closest to the carts and picking material from the boxes furthest away. This solution will stack the material close to the output, which will reduce the crane's travel time when the material is supposed to be delivered.

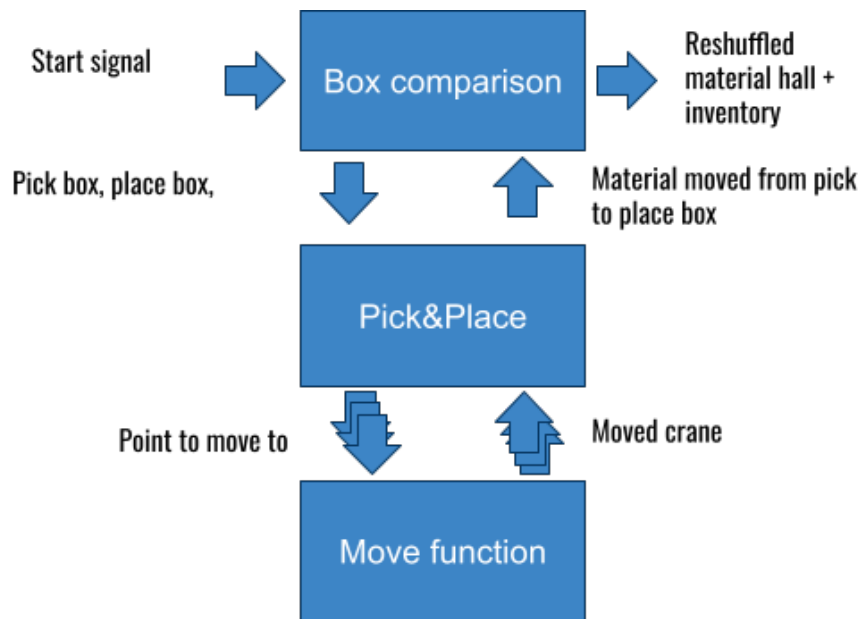
##### Special cases:

- The program is written so that boxes 10, 11, and 12 should not have their

material redistributed to other boxes, and they are also not eligible to be loaded for any other material. These boxes have material returns constantly coming and are frequently in use.

- The reshuffle will not move from one box to another if the box that should accept the moving material does not have enough room to fit it, with regards to the defined capacity of boxes from section 4.2.2.

For a figure detailing the reshuffle process, see figure 4.10



**Figure 4.10:** Figure detailing the reshuffle function.

### 4.4.7 Smaller functions

Some smaller functions were required for specific cases. These are described in this section.

#### **Magnet change**

This function changes the power on the magnet. The magnet's power is currently defined in 10 steps between 10% to 100% of the voltage applied to the electromagnet. An existing PLC currently controls this process. Making more accurate deliveries requires smaller steps. Therefore the step size was reduced to 1%, making for 100 steps. The functionality of the existing PLC for the magnet should be implemented in the main PLC that controls the entire automation to have all control sequences gathered in one place. The smaller steps, alongside the P&P sequence's iteration to hit specified target weights, allows for the objective of accurate deliveries described in section 1.1.3. This function allows for increasing or decreasing the power by one level, turning it off or turning it to its highest level.

#### **Weight change**

This function is called when material amounts in boxes or carts have to be changed.



It adds or subtracts material taken using the electromagnet to the box or cart that it is taken from or deposited into.

#### 4.4.8 HMI

##### Conceptual design

The results from the conceptual design are listed in the following table, 4.3. The security levels are given as a recommendation.

**Table 4.3:** Conceptual Design Contents.

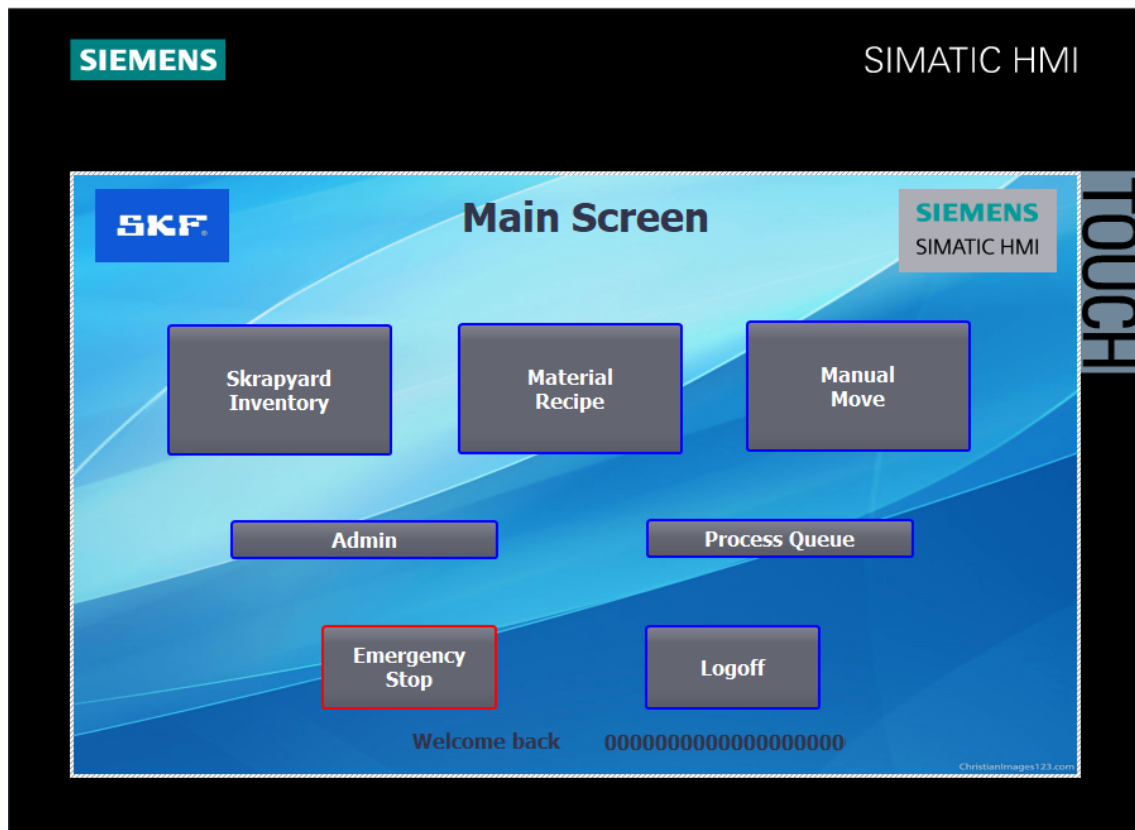
| HMI Page            | Main Function   | Security Level  |
|---------------------|---|---|
| Scrapyard Inventory | Inventory levels and material type for each box                     | Monitoring access granted to all staff. Unrestricted page.                              |
| Material Recipe     | Order new material composition from multiple boxes to the furnaces. | Access to operators and Admin.  |
| Manual Move         | Moving the materials between boxes.                                 | Access to operators and Admin.  |
| Admin               | Modify the materials and amounts in the boxes manually.             | Access is restricted to be used by Admin only who could be a programmer or an engineer. |
| History             | Showing the last few records of material gathering and moving.      | Monitoring access granted to all staff. Unrestricted page.                              |

### Crane HMI Functions

The HMI complete design is added to Appendix E, and the following is a description of the HMI design and its different functions:

#### 1. Main screen:

The main screen contains buttons to all other screens on the HMI. Upon clicking one button a login is prompted and the user is only allowed to access the desired page if the user has sufficient security clearance. An image of the main screen can be seen in figure 4.11.



**Figure 4.11:** HMI main screen.

#### 2. Inventory Monitoring Screen:

The scrapyard consists of thirteen boxes, so a custom design photo is made and used in the HMI, showing the thirteen boxes for better visualization, this can be seen in figure 4.12. The amounts and types of box materials are displayed on the inventory screen, and the page is accessible by all the staff (even non-specialized staff). The Tags used for the amounts and types of the materials are taken as HMI tags and connected to the associated PLC tags, and the tags are set to be only in the output format. The measurement unit (KG) is posted beside the amount following the SKF standard [30].

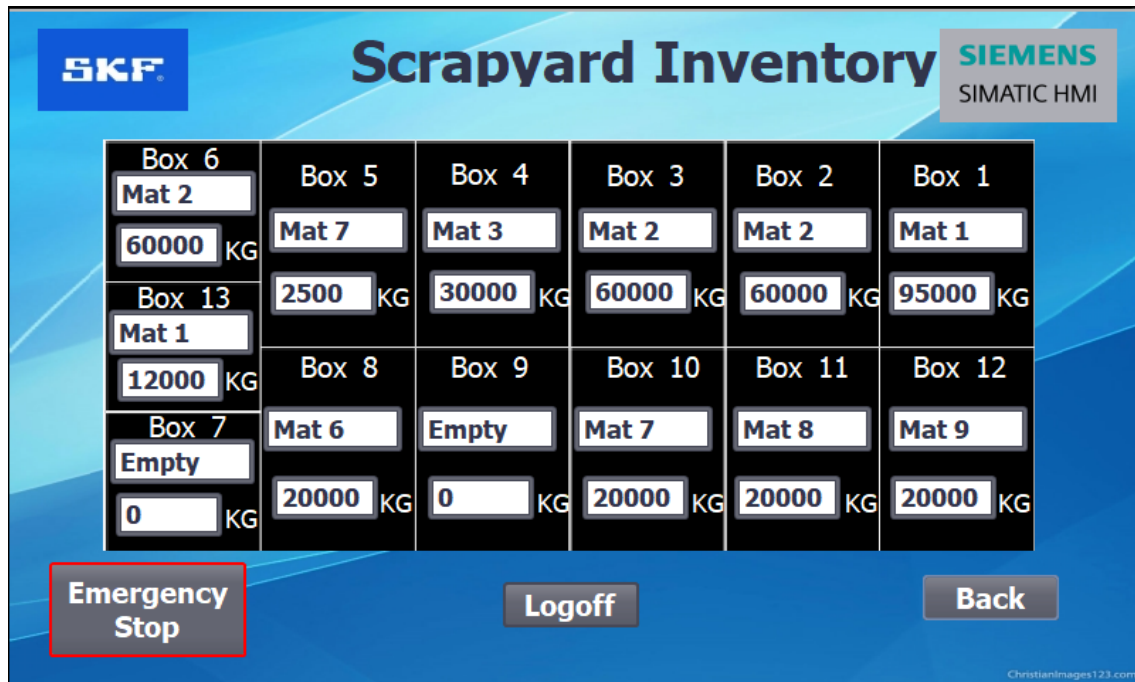


Figure 4.12: HMI inventory screen.

### 3. Material Recipe Screen:

The operator sets the material recipe at the furnaces area when the material level is low in the furnaces. When the operator opens the screen, the scrapyard with the thirteen boxes will appear so he can make sure what he wants to order. Then he will press the "Start Recipe" button to move to the next page to order the materials combination he desires. This screen can be seen in appendix E.3. The inputs for the recipe include

- The box numbers: IO fields are limited from 1 to 13, and an alarm will appear if the limits are crossed.
- The material amounts: IO fields are limited from 500 to 150000 KG, and an alarm will appear if the limits are crossed.
- Which cart is required to be filled by the crane: two buttons, Cart 1 or Cart 2
- Start Recipe button: this will validate the combination. However, a pop-up screen will appear to confirm the process, and it could be cancelled or approved, so the crane will start.

Once the operator prepares the recipe and presses the start button, the crane will gather the materials from each box until it fills the required amount of material in the assigned cart. A data record has been added to the screen so the operator can make and save a new recipe or use previously saved ones, for example, housings or bearings recipes.

### 4. Manual Move Screen

Reshuffling the materials from box to box is an automatic process and will be a second priority after the furnaces orders. However, the Manual move function was added to the required tasks because of the construction works that often occur in the scrapyard area, which require closing new gates and opening new ones. Seeking more flexibility at the scrapyard, the operator can initiate a manual move from box to box to empty a loadable box to an unloadable box. This screen can be seen in appendix E.6. The inputs for the Manual move include

- (a) Pick and place box numbers: IO fields are limited from 1 to 13, and an alarm will appear if the limits are crossed.
- (b) The material amounts: IO fields are limited from 500 to 150000 KG, and an alarm will appear if the limits are crossed.
- (c) Start Move button: this will validate the material move. And a pop-up screen will appear to confirm the process, and the crane will start moving material between the assigned boxes.

A data record has been added to the screen so the operator can make and save a new move or use previously saved ones. Notably, in both material recipe and manual move screens, the operator will be able to see the material types once he inputs the box number so that no mistakes will happen during the process.

## 5. Admin Screen:

This screen is made to update the box material types and amounts manually. Once you press the Admin button on the main screen, the scrapyard custom design photo used for the "scrapyard inventory" screen shows the thirteen boxes. The amounts and types of box materials are displayed on the inventory screen, and it's in input format so that the admin can modify the material types and quantities. This screen can be seen in appendix E.9. The Tags used for the amounts and types of the materials are taken as HMI tags and connected to the associated PLC tags. The measurement unit (KG) is posted beside the quantity following the SKF standard [30].

## 6. General Aspects

- (a) The text font and layouts are taken by the authors and don't follow the mentioned SKF standard because of short notice.
- (b) There are general buttons used on each screen in the HMI, such as "Back", "Logoff", and "Emergency stop".
- (c) SKF logo is taken as per SKF standard, and it exists on all pages.
- (d) Confirmation Pop-ups are connected directly to the PLC.
- (e) Testing and simulation of each function are completed using PLCSIM advanced, which is approved to be optimal for validation and verification purposes.

**Gate HMI Functions** The Gate HMIs are presented to be used by the truck driver

to provide the exact quantity of material. In most factories, the truck driver will carry a delivery note for the truckload, which contains the precise amount of materials in the truck. Moreover, the material type loaded in the truck is also important input, and the driver will have the same delivery note he has all the time. Therefore, the authors decided to make the truck driver part of the automation procedure.

The authors adopt a straightforward design. Considering the time consumed by the driver should be as short as possible. So there are two main screens: the main screen where he chooses the material type that the truck carries. Once entered, a pop-up window will appear where he will provide the material quantity. The “Open Gate” button will be viable. Once it’s pressed, a signal will reach the PLC to open the gate and then unload the materials.

#### **4.4.9 Connection of PLC and HMI**

The created PLC and the HMI were connected to ensure the proper functionality was present in the coupling. Both the HMI and PLC were put in the same TIA Portal project. The HMI’s and the PLC were coupled using a PROFINET industrial ethernet (PN/IE) connection in TIA Portal in the devices & networks window to enable communication between them. Data blocks (DBs) were created in the PLC to hold the signals sent from the HMI for the PLC code. Every output from the HMI is coupled to a variable of the correct type in a DB in the PLC.

The connection was simulated by utilizing TIA Portal, PLCSIM Advanced and WinCC. Firstly, an instanced virtual PLC was created in PLCSIM Advanced, to which the PLC code from TIA portal was downloaded. Now the simulated PLC contains the code. Then the connection between TIA Portal and PLCSIM Advanced can be made, this is required to monitor the code in real-time. Going online TIA Portal connects to the PLC that was downloaded and started the simulated PLC in PLCSIM Advanced. Then the HMI can be simulated through TIA Portal by right-clicking on an HMI and then selecting start simulation. WinCC is then opened, and the HMI is shown. Due to the PLC being online and connected with the HMI, inputs can be given to the PLC, for example, recipe instructions to gather material, [34].

#### **4.4.10 Alarm system and eliminating faulty inputs**

The HMI is designed so that the operator cannot make invalid orders. When giving values as inputs limits are set in the so that faulty values can not be given which would produce errors in the PLC code and fault alarm will pop-up immediately. For example this is done when specifying which boxes to order from, only values from 1 to 13 are valid for input. Moreover, different alarms and supervision systems are created and visualized as cognitive support tools. The alarms and error popups are coloured, lights are flashing, and even sounds will occur in the control room and on the HMI screen in case of errors. The correcting actions should be clear to the user, and the emergency option stop for the whole system should be accessible on

all of the HMI pages as an I/O field button [13].

### 4.5 Logical device modelling and virtual commissioning

Although virtual commissioning and modeling of the logical device were not performed due to delimitations, the automation procedure was visualized using animations in CATIA v5.

### 4.6 Hardware

The following section recommends or declares the chosen hardware for the thesis. If relevant, choices are discussed regarding reasoning for specific models and how and where they should be used.

#### 4.6.1 PLC hardware

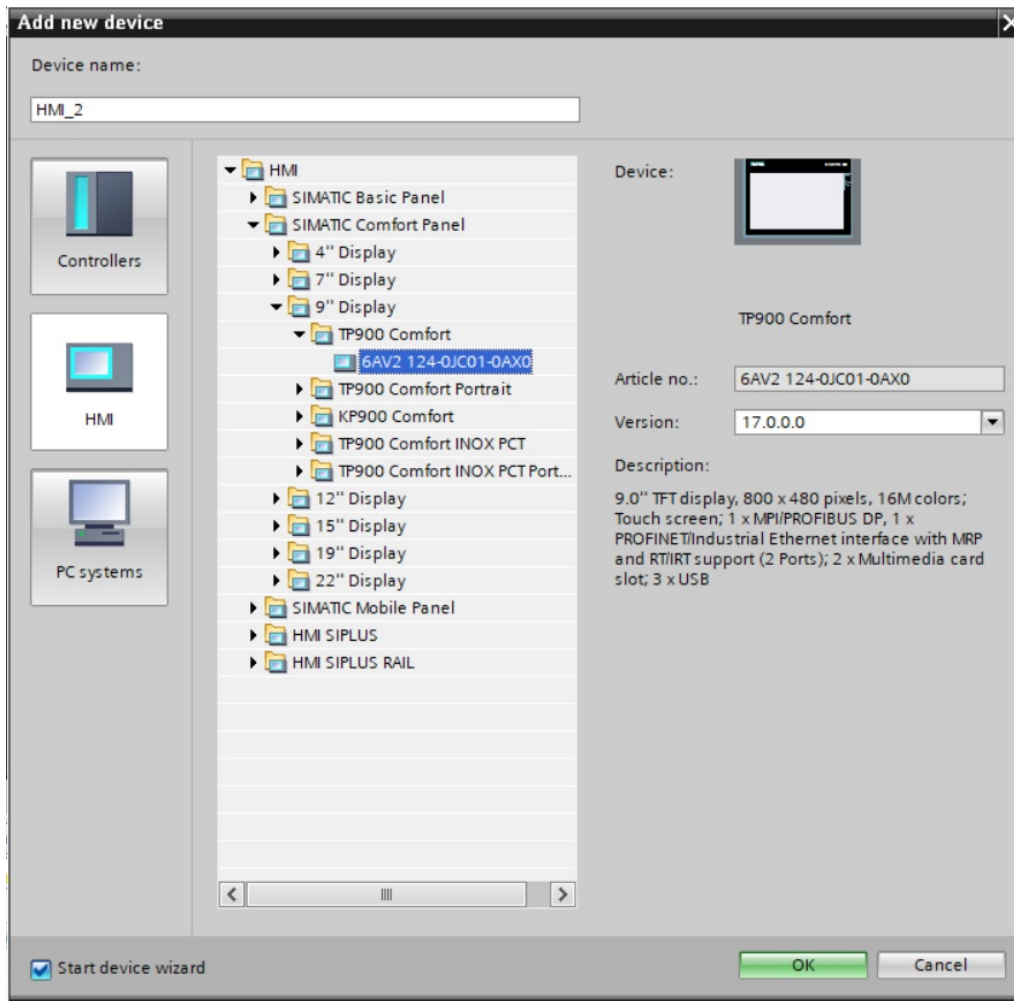
The PLC to be used needs to be of Siemens brand due to the software being developed in Siemens software alongside SKF using Siemens PLCs as standard in their automation processes. More specifically, the functions required by the process to be automated can be best supported by an S7-1500 series PLC. This is because it is modular, supporting more I/O's, being the fastest model that futureproofs it for later updates and additions, and can utilize controllers like PIDs, which may be required later in the stabilization work of the crane's swing.

Regarding the specific model number for the PLC CPU, it is difficult to conclude what will be necessary since the final requirements on the PLC can not be made until the code is ready for real-world use, which is not the goal of the thesis. Therefore, it is left as a recommendation to SKF employees to decide on the exact CPU version for an S7-1500 PLC. However, SKF standards specify that the type can not be a compact PLC since this is not allowed due to the restricted expansion of modules.

#### 4.6.2 Crane HMI hardware

The chosen HMI type for performing the central task in this project is the 9" SIMATIC HMI TP900 Comfort Panel, see figure 4.13, which is embedded in the TIA Portal through WinCC runtime. The screen lets the operator effectively monitor and fully control the crane's tasks from A to Z. while choosing the required device. The tricky part was exploring a universal and future proof application that can handle a high level of connectivity, a 5G network, for example. Moreover, something should always be in mind that the chosen solution should be as transparent as possible.

Worth mentioning that the 9" HMI is in the furnaces area in the existing control room and should be controlled by the furnace's operator. The operator should



**Figure 4.13:** Features of the selected 9" comfort panel.

initiate the signal so the crane will start gathering materials when the material level in the furnaces is low.

### 4.6.3 Gates HMI hardware

Those HMIs controlling and monitoring the truck's gates use the same process of transferring data between the gate and the central PLC.

The choice was a set of small 4.3" KTP 400 comfort HMIs located at the truck unloading gates of the foundry (at gates 7, 8, 9, 10, 11, 12). We choose to implement this solution to provide a complete automation solution without the need for the operator to visit the foundry. So, we designed that low-cost HMIs to be used by truck drivers for inventory control purposes. Figure 4.14 shows the main features of the selected comfort panels for the task.

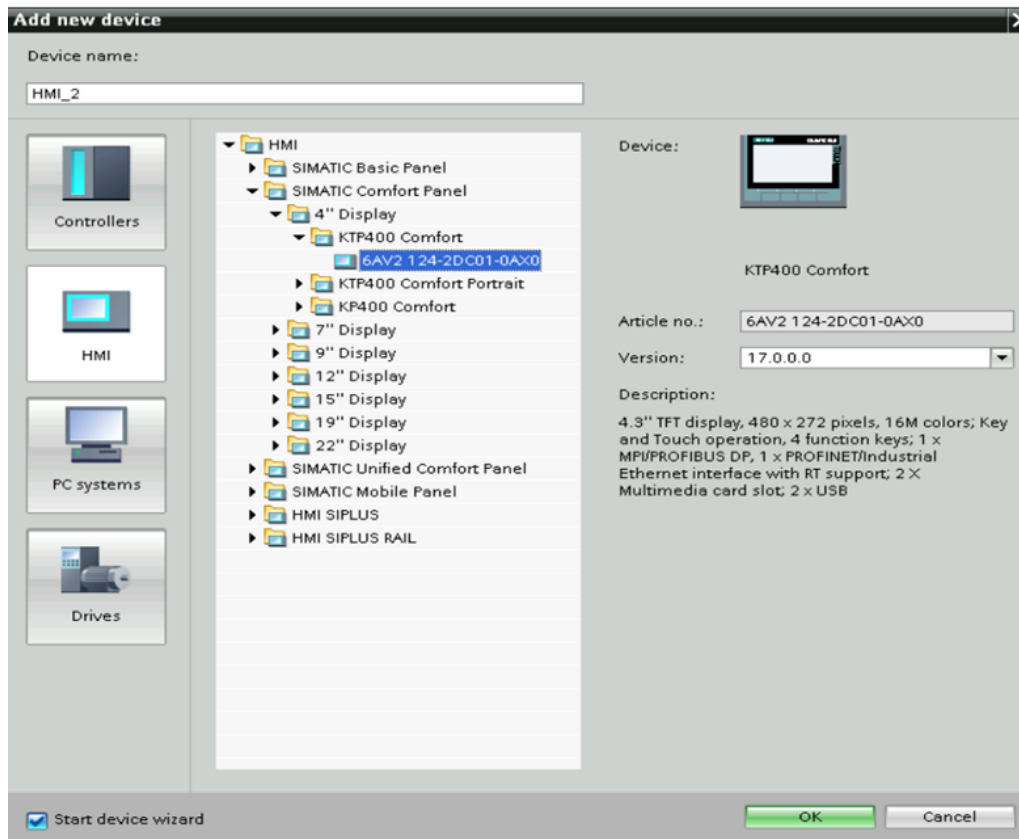


Figure 4.14: Features of the selected 4.3” comfort panel.

### 4.6.4 Sensors

Some additional components will have to be acquired for the full functionality of the automation procedure.

#### Light sensors

In order to be able to detect whether a cart is in a loadable position within the material hall, light sensors should be installed where the light is broken when the cart is in the loadable position. One light sensor should be installed for each cart. These should be given as inputs to the PLC.

#### Coordinate system

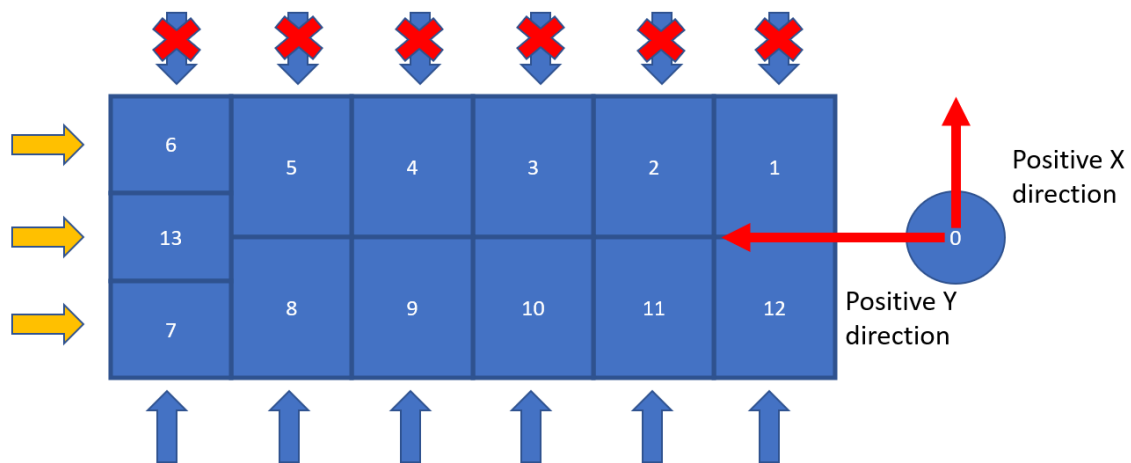
For the automation to be possible, the PLC program needs to know the crane’s location at any given time. There are approaches for creating systems that deliver this coordinate data. Accelerators could be attached to all moving parts to use the acceleration to calculate a speed and distance over time. A grid of light sensors could be mounted around the crane giving points where the PLC would know the crane’s location. Lastly, multi-turn absolute encoders could be implemented to measure the wheels’ rotation that induces the movement in the crane and calculate the distance from the angular change. Upon advising the company supervisor, a decision was made to assume that a coordinate system would be implemented that could give the exact current location of the crane at any given time, so something in line with the



multi-turn absolute encoders would be implemented. What should be implemented and how is not something that is further explored in this thesis.

A coordinate system was defined in the material hall to clearly define where the crane is at all times, as shown in image 4.15. The coordinate system's origin is defined on the floor in front of the boxes. This position is the origin since when the crane is not in use, it should be on the floor in a resting position, so the crane often starts from this position. Relative to the walls, the origin position is 6730 mm from the side walls (centre) and 9320 mm from the entry gates of the scrapyard 4.15.

The Z coordinate, being the height, is 0 when the bottom of the electromagnet is 1575 mm below the bottom of the crossbeam. Down is positive, and up is negative. This origin is also what is referred to as safe transporting height. It is considered safe since when at the Z origin, the magnet bottom is 3300 mm above the side railings, 2450 above the cart sides (highest point) and 4500 mm above rest position, same for box walls. This provides a reasonable margin of safety not to hit obstacles while moving material that hangs under the electromagnet. It is also a safe distance from the crossbeam and trolley so that the magnet does not hit the crossbeam if it were to swing while moving.



**Figure 4.15:** Coordinate system in the scrapyard.

#### 4.6.5 Implemented safety measures

In the case of the overhead crane, the safety analysis looked at different hazards and included functions in the PLC code to avoid them. Functions are used in the PLC code to represent the safety measures and measures recommended to be considered at the construction time are as follows:

1. Emergency stop function is used heavily in this project allowing the user to stop the crane operations and override the HMI commands once the user observes the hazard.
2. While the gates are open for truck unloading activities, the crane will be idle and will not be activated until the gate is closed.

3. Utilizing the existing light fence (sensors fence) to detect any unexpected movement beyond the carts area will immediately trigger the emergency stop.
4. Electromagnet power is a sensitive device that could cause significant hazards to personnel and properties at the workplace in case of power loss or unexpected behaviours. Therefore, it is recommended that cognitive support devices such as flashing lights or unique sounds be installed and activated once the electromagnet power is on.

# 5

## Discussion

The following chapter elaborates on the acquired results and gives insight into why certain decisions were made.

### 5.1 Error sources

This section outlines the causes for errors in the thesis work and their potential consequences, and what caused the errors. Actions to amend these errors are discussed in section 5.2.

#### 5.1.1 Omitted & assumed CAD details

When constructing the CAD files, some objects in the provided drawings were either ambiguous or hidden behind other parts, so their dimensions could not be obtained. Regarding the ambiguous elements, these were sections on the crossbeam that, if made of solid steel as the drawing indicated, would add a substantial amount of weight to the beam. The company supervisor was queried about this and advised disregarding these elements or making valid assumptions if hidden parts were crucial. Removing these objects and making assumptions for certain geometry will somewhat differentiate the CAD drawings of the crane from the actual crane. Additionally, for some components, such as the carts, no drawings were provided. Therefore, a basic assumptive shape was constructed instead.

#### 5.1.2 Picking material from box centers

Currently, the PLC program is ordered to move to a box's centre coordinates, go down, pick material, go up, move to a cart, and deliver the material. There is an assumption in this logic that the material will be in the centre of the box. From the visit made to Katrineholm and seeing the material hall in person, it can be verified that this assumption is inaccurate. The material is very often distributed along the sides of the boxes. An algorithm would have to be implemented within the PLC program to find the local high points and take material from there instead. If this is not implemented, the crane will attempt to take material from the centre of each box and eventually, there will be no material to take from it and then it will be marked as empty. In reality, there remains much material around the sides of the box. This remaining material could cause the box to be filled with another type of material, mixing them and causing severe issues upon delivery.

### 5.2 Recommendations for further work

Due to the large scope of this thesis, much work is still to be done if a virtual commissioning procedure is desired. The remaining work would primarily be in verifying the accuracy of the work made and ensuring that internal SKF Standards are followed throughout.

#### 5.2.1 CAD verification

It is recommended that SKF Mekan verify the constructed CAD geometry's accuracy compared to the actual material hall before performing virtual commissioning. Ways to do this are to attempt to receive original CAD models from the OEMs of the equipment or to order a 3D scan of the material hall, including its components. A 3D scan generates a point cloud, which is a data set composed of discrete points in space with X, Y and Z coordinates alongside RGB values, [35]. The point cloud can then be imported into a CAD program where the shape and measurements of the constructed CAD files can be directly compared to the real-life measurements in a virtual environment, [36]. The measurements from 3D scanning are accurate up to two mm. Furthermore, the carts should be accurately modelled since no drawings were provided from SKF, and the carts were given a rough and approximate design.

#### 5.2.2 Additional safety measures

A failsafe should be programmed for when the coordinate system gives inaccurate information. All edge heights are known, and the scale registers a negative value when the crane contacts an object from beneath. When lowering the electromagnet, the code can inspect if the height is roughly that of an edge and if the scale registers a negative value. If both are true simultaneously, an error should be sent requesting recalibration of the coordinate system. The distance to the box walls from the crane's safe transport height (0 position) on Z-axis is 4500 mm, and to the cart sides, it is 2450 mm.

In order to stop the crane from moving into walls if the coordinate system and navigation were to fail, limit sensors should be implemented as an added safety level to stop this extreme case.

As per SKF, the risk assessment fulfilment shall be completed and documented during the project's design stage. This unfinished activity should be addressed and completed before implementing the actual automated solution.

#### 5.2.3 Manual steering override

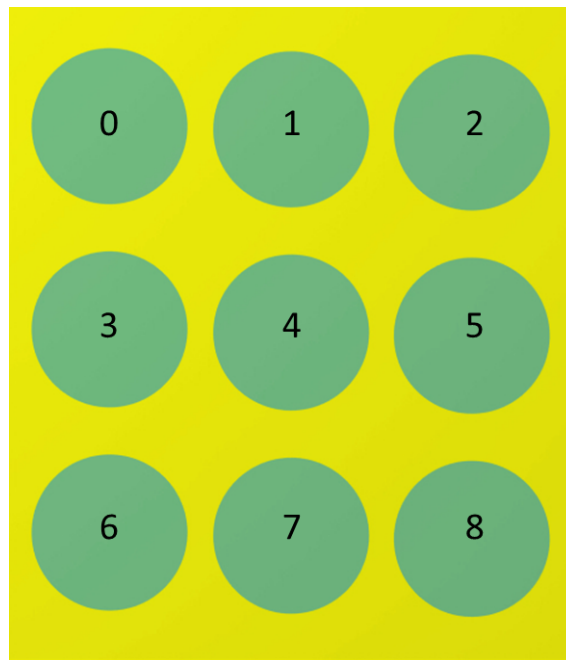
The crane in its current state is being controlled manually by an operator. If the crane were automated, this manual steering should not be removed but instead implemented as a safety feature for the crane if manual steering is required. So an

admin could put the crane in manual mode by interfacing with the HMI. This could be useful if systems such as the coordinates are malfunctioning.

### 5.2.4 Box screening mechanism

To ensure that material is picked evenly throughout the whole box, there needs to be a function that finds the highest point of material when taking material from a box. Although this was not implemented into the PLC program, a concept for solving the issue had been generated. The most convenient implementation of this procedure would be to use the sensors that are already existing. Naturally, a vision-based system would work, but the given concept only uses existing sensors.

If a box is examined to see how many times the electromagnet can fit into it, it will be apparent that the electromagnet can fit nine times in the regular-sized boxes, see figure 5.1. This figure has the correct dimensions for the boxes and electromagnet. A function that examines these points should be written while lowering the magnet. If the scale on the magnet registers, a negative value material has been reached. If the maximum depth of the box is reached in all nine locations, then the box shall be listed as empty. However, if the bottom is reached in only one location, the others should be tested in a given order to find local high points of material.



**Figure 5.1:** Spacing of electromagnet placements in box.

Since these changes have not been implemented, it is difficult to say if they would be fully functional as suggested. However, hopefully, the main principles of the process could be implemented similarly.

### 5.2.5 Utilize virtual commissioning for investment proposition

As SKF aims to conduct an investment proposition for implementing an automation sequence on the overhead crane, the authors propose utilizing the strength and detail of virtual commissioning to achieve this.

When properly performing a virtual commissioning project all required components for the automation will be implemented into the virtual system. This final virtual version of the automated system can then be compared to the current state to find the different components that are required for the automation to work as intended. The cost of these components can then be utilized in an investment proposition to find the cost of the implementation. Although, the cost of components is not a fully descriptive of the total cost for the investment. There will be indirect costs in regards to the project and engineering required that can not be calculated from the virtual commissioning alone. The authors have provided a direct and indirect costs table (table 5.1) that SKF Mekan can use to calculate the investment feasibility.

**Table 5.1:** Investment Analysis Direct/Indirect Costs.

| Direct Costs   | Indirect Costs    |
|--|-------------------|
| Hardware Costs (PLC, Central HMI, Gates HMIs, Sensors, Cables, etc.) | Project costs     |
| Labour costs   | Engineering costs |
| Energy costs   | Maintenance costs |
| Quality costs (Alloys consumption reduction)                         |                   |
| Logistics costs  |                   |

# 6

## Conclusion

In this section summarizing areas are covered for clarity such as the solutions to objectives set in the beginning of the report as well as answers to research questions. The thesis concludes with visualization and validation using virtual commissioning which outlines why the methodology was chosen and what was not completed in time.

### 6.1 Solutions to objectives

The five objectives defined in section 1.1.3 were all completed in the following manner.

#### 1. Accurate deliveries

The issue was that deliveries from the crane were inaccurate towards the given target. To solve this issue, the magnet's power changed its step size from 10% change per step, resulting in 10 steps, to 1% change per step, resulting in 100 steps. Furthermore, the weight evaluating logic is done in an iterative manner where the weight is evaluated, and then the power is reduced by 1%. This iterative evaluation and smaller step-size results in a much more accurate delivery.

#### 2. Collision avoidance

The crane should not collide with boxes or carts while automated. Each location that the crane might travel to was predefined according to a coordinate system to resolve this issue. This solution was chosen because the crane only travels to 16 different locations, boxes 1-13, carts 1 and 2, and a resting position. The crane should have a coordinate system implemented where the crane's location is constantly known. Since the carts can move in and out of the scrapyard, their correct position is ensured using light sensors to tell the system that a cart is in place.

#### 3. Safety assurance

When the material is being loaded into the scrapyard, personnel can be present in the crane's working area, which is the scrapyard. Safety must be of high regard while personnel load material into the scrapyard. This is solved by connecting the PLC with light sensors at each gate. When a gate is opened, all movement is stopped until the gate has been closed. Additionally, when re-initiating the crane, cognitive support tools will be activated to warn any potential personnel still in the active area.

### 4. Crane automation and priorities

This objective regards the crane's general automation of gathering material and executing automation sequences in priority order. The priority order is solved by allowing the operator at the central HMI to decide between gathering a recipe order or moving material between boxes. The reshuffle procedure is automatically executed only after loading material into a box or after delivering a recipe. The detailed automation of all procedures can be seen in section 4.4.

### 5. Re-organize material for efficient storage

Due to construction projects at SKF Mekan, only half of the storage boxes that could be loaded are still eligible for direct loading, and the rest are obstructed. Therefore material has to travel through the gates open for external loading and then be re-organized, or reshuffled, internally by the crane to the boxes with their gates blocked. This was done by creating a reshuffling logic that can be seen in 4.4.6. The main principle is to move material between boxes with the same material, from loadable boxes to non-loadable ones. If not possible, the material is moved to an empty, unloadable box from a loadable box.

## 6.2 Answers to research questions

1. How can an automation project for an existing process be evaluated without interfering with the operational process?

A PLC being developed to automate a process can have its code developed and tested towards a virtual PLC to ensure its functionality. Although by only testing towards a PLC, it is only possible to see how the logic itself works, not how it will act on the process that is to be automated. There might be faulty assumptions made in the programming that are apparent first when the PLC code is controlling the process, [31].

Real commissioning evaluates the PLC code connected to the machine; however, this requires the machinery to be removed from active operations, [31]. Instead, a virtual method can be utilized where the physical device is modelled virtually and connected to a virtual PLC. The simulation is then made complete by including physics and kinematics. This process is referred to as virtual commissioning, [18].

One benefit of virtual commissioning, according to [5] is that it allows parallel execution alongside production and assembly processes. It is discussed by [20] that an advantage of virtual commissioning is that solutions can be tested and verified virtually. Further support for this method can be found in [37] that suggests Virtual commissioning can be defined as the investigation of a PLC integration.



2. What are the different tools and requirements needed for evaluating an automation project virtually?

For an automation project that is conducted using PLC to automate the procedure at hand, several tools are required to develop and evaluate the automation virtually. By using a methodology such as the one provided by [27], see figure 3.2, six steps need to be addressed with specific tools and techniques;

- **Process design**

If the process to be automated is already existing, meaning it is a brown-field investment. There must be a detailed and fundamental understanding of how the current process works, [20]. The following should be found: its purpose, all tasks, current issues or shortcomings, safety standards, and hardware. For this, the authors recommend a qualitative data gathering approach of firstly receiving internal documents of the process that could be technical documentation of the hardware or current practices. Then a visit can be made where visual observations are made of the process in action, preferably of it performing all the tasks. This should be documented in some manner, preferably by filming or taking extensive notes for future reference. In conjunction with a visit, semi-structured interviews with operators and managers of the process should be held firstly to answer any questions that arose during the visit and reviewing of documents and secondly, to explore the topic further, [26].

When the process has been detailed and thoroughly understood, its inputs and outputs should be defined, and then the SOP should be defined for each sequence the process should be able to perform.

- **Physical device modeling**

By utilizing the documentation acquired in the previous step, the device should have a physical model represented as 3D CAD geometry. It is recommended to receive this directly from the OEM since it is the most accurate representation, [28, 27]. However, if this is not possible, the physical model should be created using CAD software in conjunction with drawings, preferably digital drawings. Regardless of the chosen approach, it is vital to ensure compatibility between the format of the CAD files with the program that has been chosen to conduct the virtual device and the virtual commissioning. The authors chose Catia V5 to construct the physical device from drawings because it can produce files compatible with NX MCD, [17].

- **Logical device modeling**

A program must be used to make the logical device modelling detailing the electrical connections between sensors and the PLC. The authors chose SIMIT for this task.

- **Virtual device**

In order to connect the physical device and the logical device, there is a requirement for a program that can connect a CAD assembly with signals so that, for example, motors move when prompted by the logical device.

- **System control modeling**

Three main tools are required if the automation sequence is to be tested with an HMI. Firstly the automation sequence must be developed within a program that supports PLC coding. For this, the authors chose TIA Portal. Then the HMI must be modelled, this was also done in TIA Portal, but then to simulate and connect the HMI to the PLC, a simulating software is required. For this, WinCC was chosen since it is integrated with TIA Portal. Lastly, to be able to have the PLC code run and evaluated, there must be a PLC connected to the program where the logic has been developed. This should be done for a truly virtual evaluation using SiL [38]. This was done using PLCSIM Advanced.

- **Virtual commissioning**

Finally, software that can connect the virtual device to the created PLC code in the system control modelling stage is required. For this, the authors chose NX MCD.

Furthermore, to evaluate the created automation sequence, information regarding the performance of the current state of the sequence should be gathered to compare the two.

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# A

## Gantt schedule

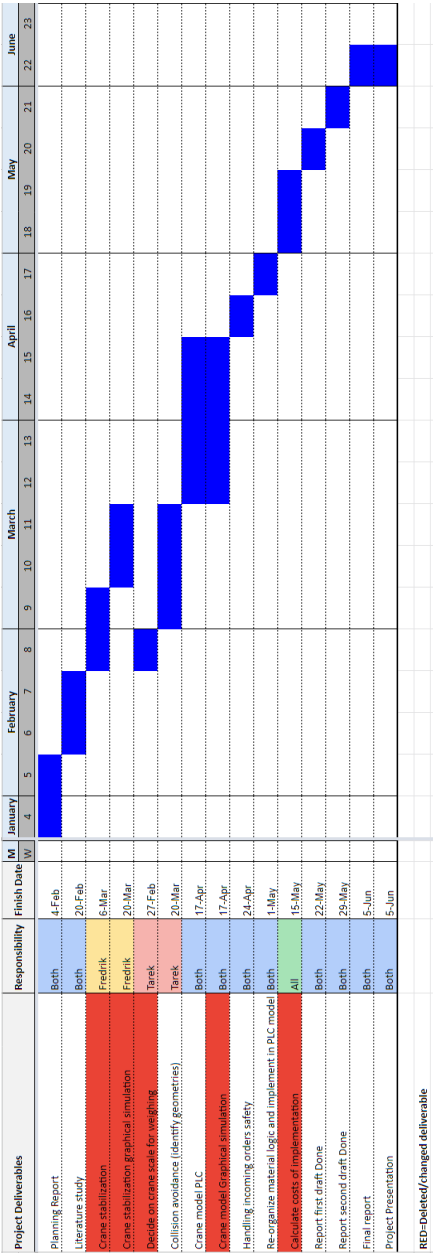


Figure A.1: Gantt schedule.





# B

## Interview questions and observations

### **Interview with crane operator:**

1. What are the steps for the whole process? From placed order to delivered material.
2. What is the standard procedure after delivering material?
3. Safety procedures around the crane? What is the procedure like when loading material etc?
4. How do you pick up a fraction of a load, say  $\frac{1}{2}$  of the crane's max pickup weight for example?

### **List of observations to be made:**

1. Crane lifting, moving, and delivering material (Video).
2. Unloading station with the carts, with and without carts on it.
3. The material in the storage boxes.
4. Control room with instruments - What values are presented to the operator? Speed, position, depth, etc?

### **Stakeholders interview:**

1. What type of materials are loaded into the boxes in the scrapyard and which ones are added later?
2. Do you know the quantity of each load when you receive it? Is it accurate or an estimate?
3. Which materials should be closest, and which are most frequently used?
4. If considering the material that takes up the most volume, how much can each box hold of that material?

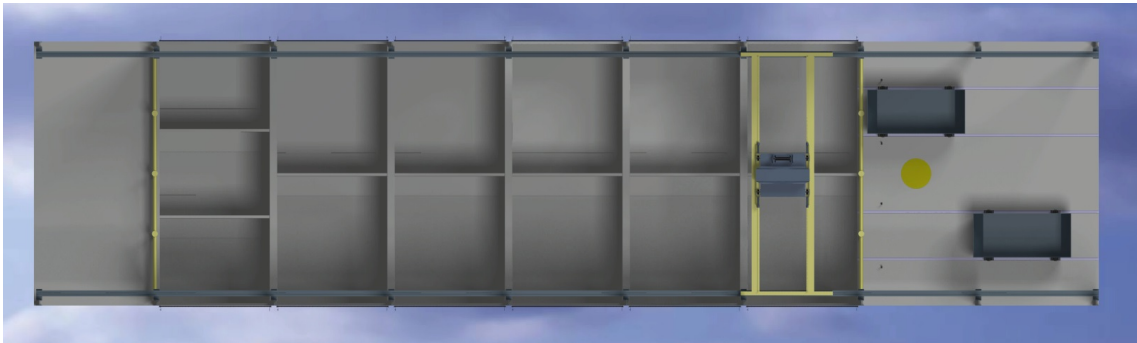
### **Automation engineer interview:**

1. What safety precautions should be implemented for the crane's automation?
2. How are automation projects structured at SKF?
3. What PLC would you chose for the automation in the thesis and why?
4. Do you have any other suggestions for conducting the automation that we have not discussed?



# C

## Additional CAD images



**Figure C.1:** Rendered CAD image the full assembly from a top view.



**Figure C.2:** Lightsensor on bracket.



**Figure C.3:** Reflex for lightsensor on bracket.



# D

## PLC code and fuctions

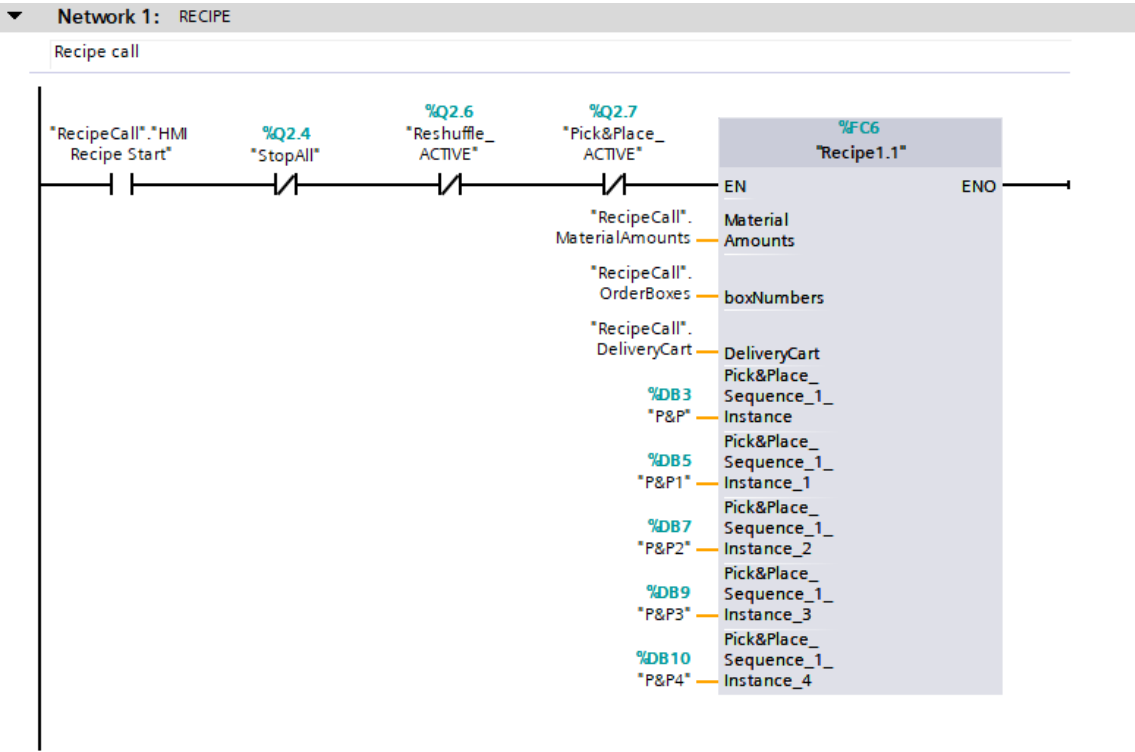


Figure D.1: Main code figure 1.

D. PLC code and fuctions

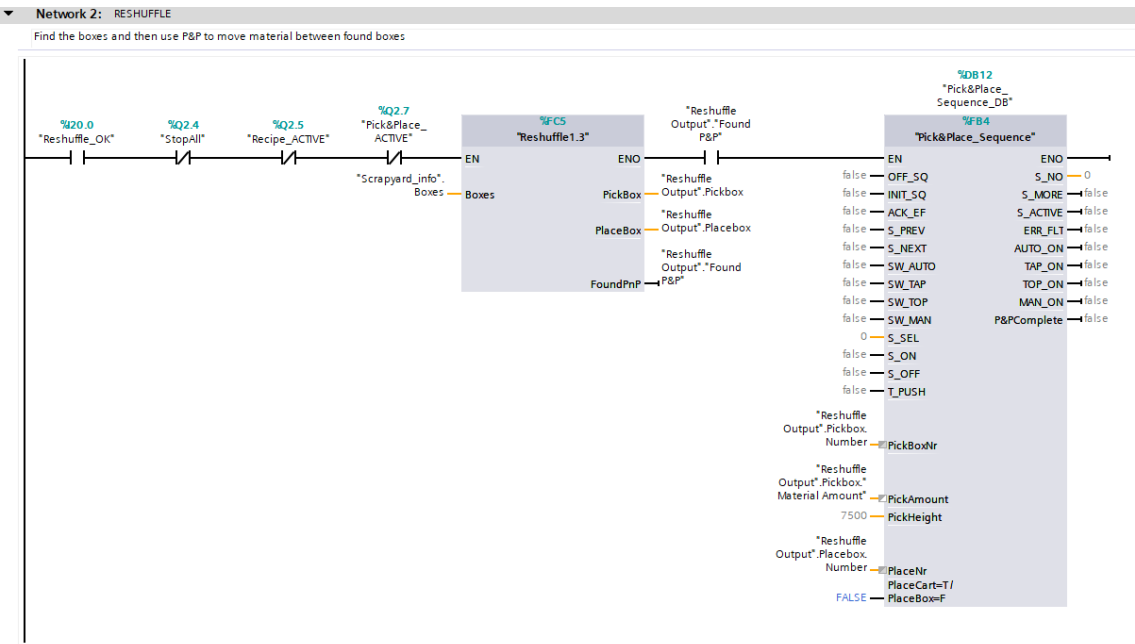


Figure D.2: Main code figure 2.

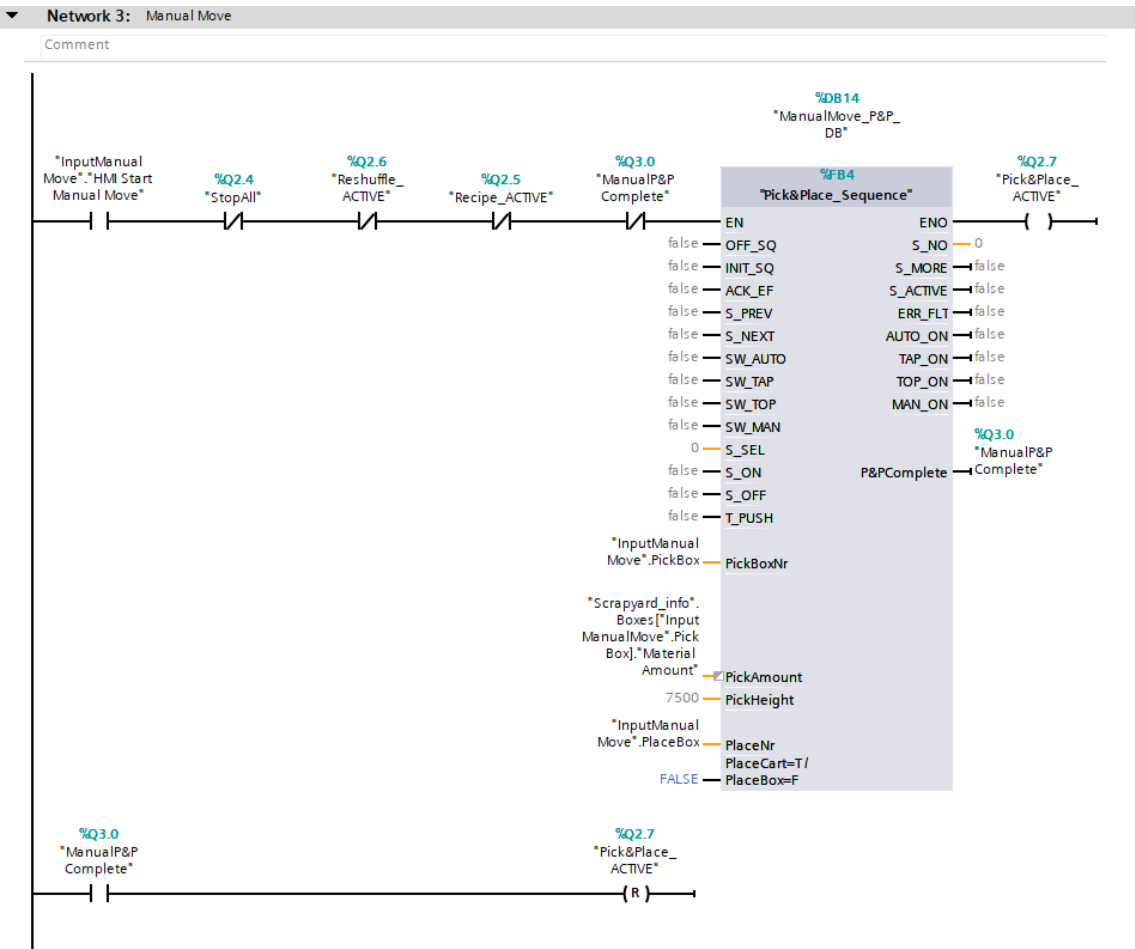
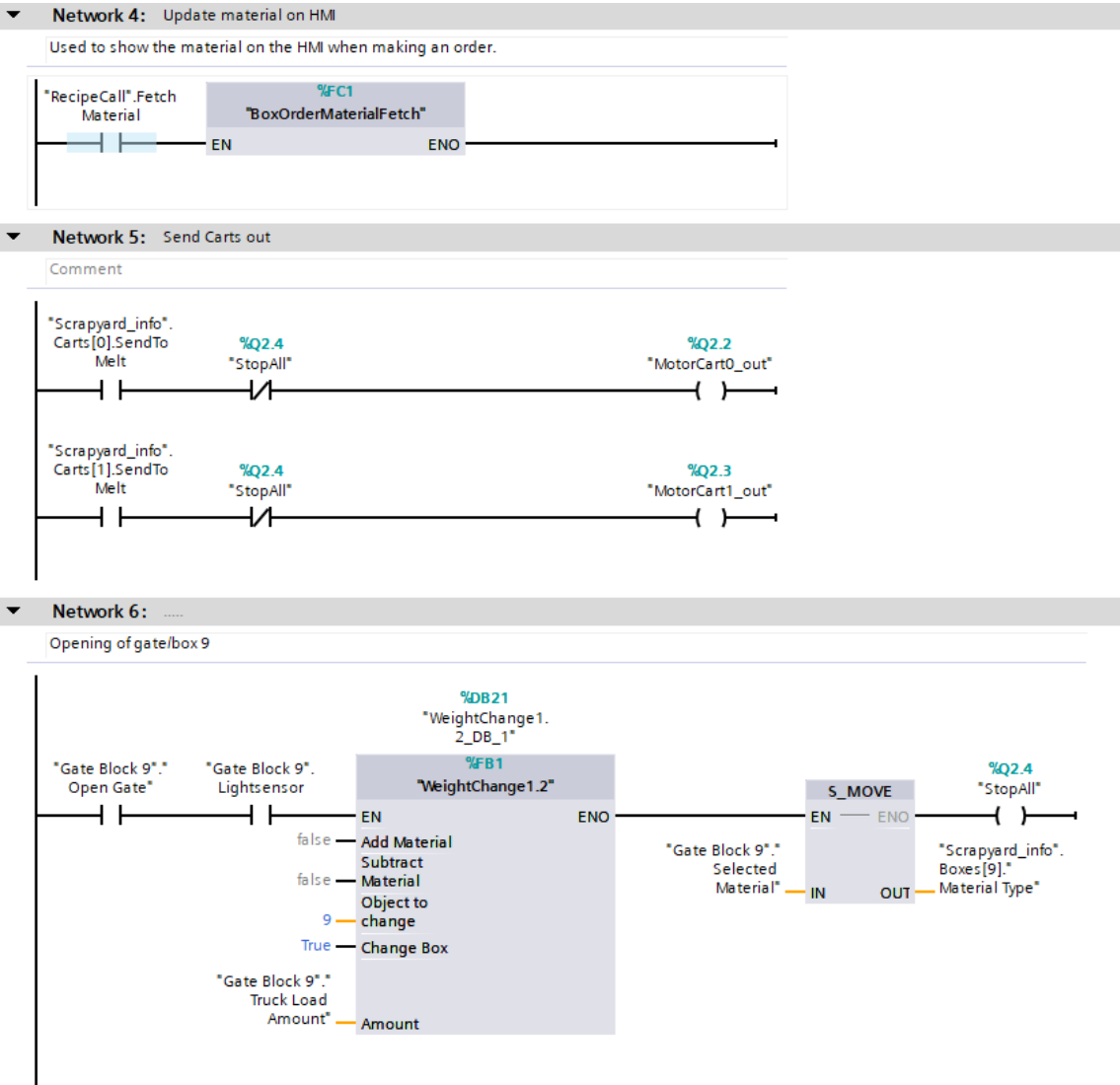


Figure D.3: Main code figure 3.



D. PLC code and fuctions

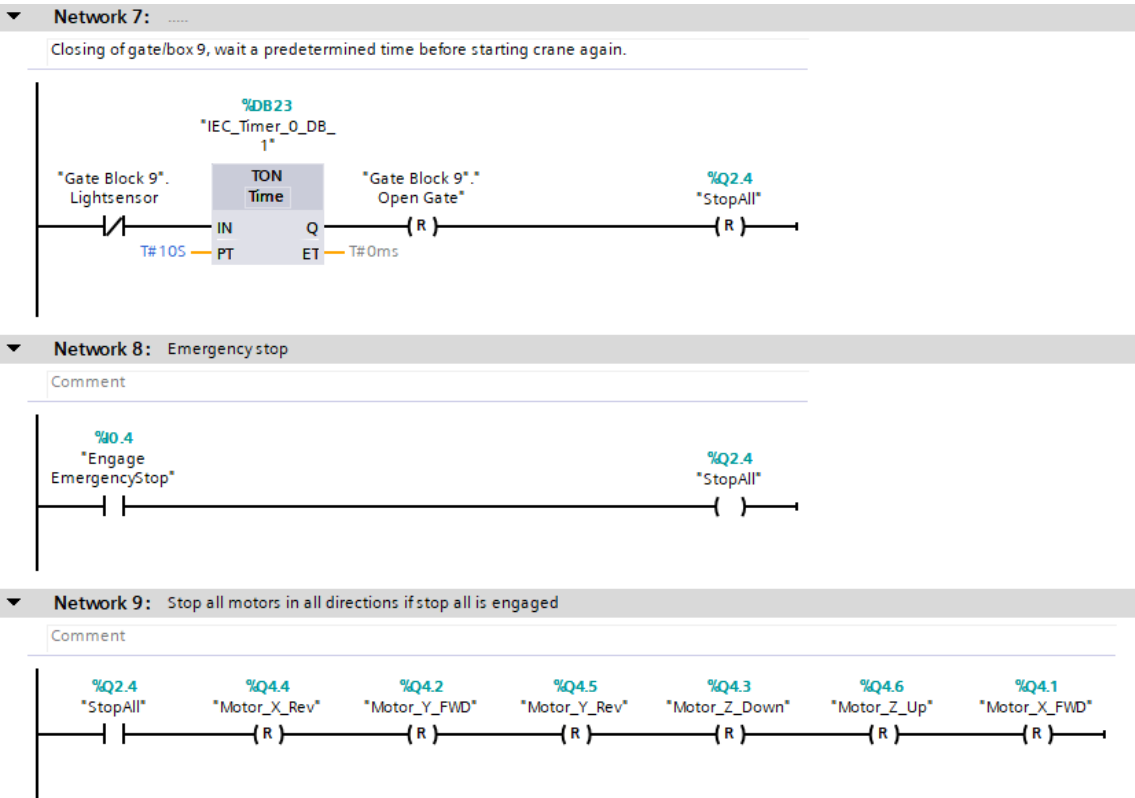


Figure D.5: Main code figure 5.

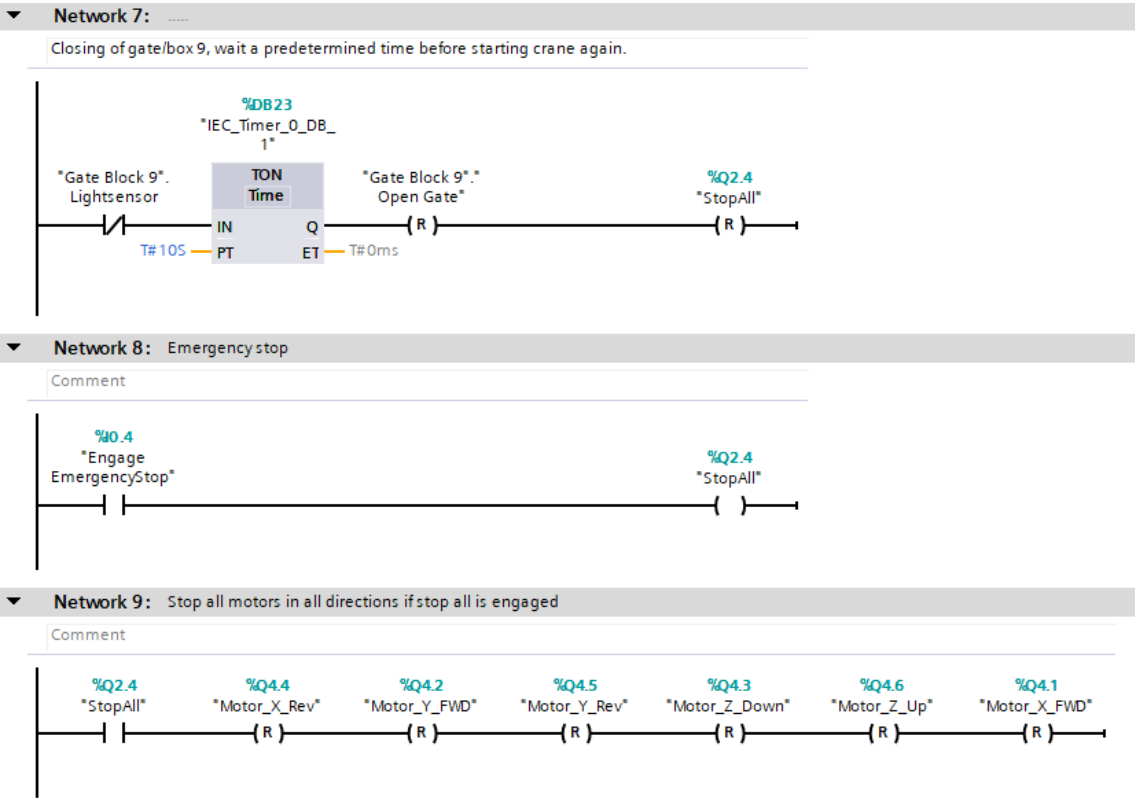


Figure D.6: Main code figure 6.



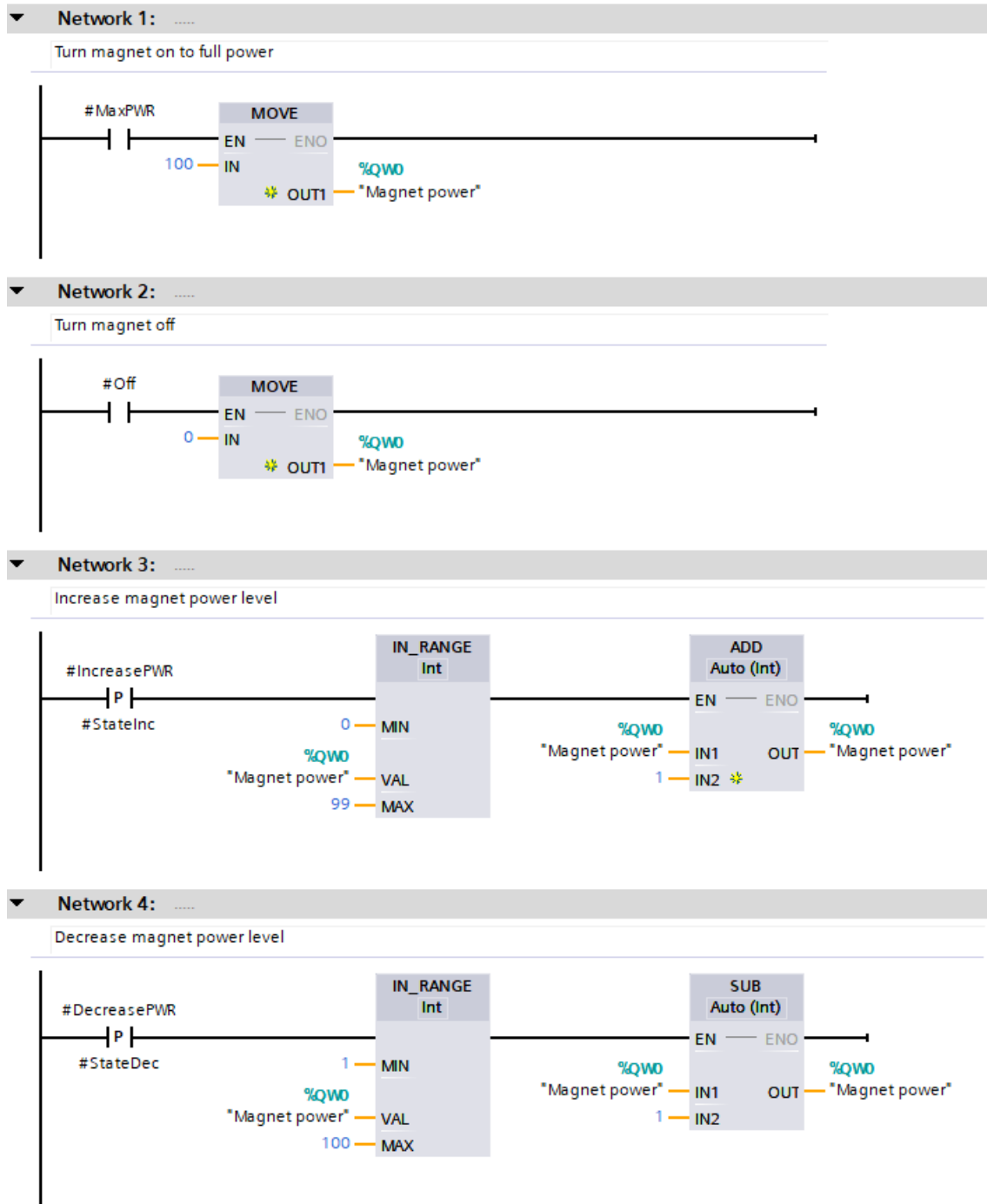


Figure D.7: Magnet change function.

```

1  #FoundPnP := FALSE;
2  FOR #PickCtr := 8 TO 10 DO // index is pushed from 7 --> 8 due to box 13 having index 7
3  IF #FoundPnP = TRUE THEN //do not continue looping if boxes have been found
4      EXIT;
5  END_IF;
6  IF #Boxes[#PickCtr].Material Type = 'Empty' THEN
7      //Will not pick from an empty box
8      CONTINUE;
9  END_IF;
10
11
12  FOR #PlaceCtr := 1 TO 7 DO
13  IF #Boxes[#PlaceCtr].Capacity >= #Boxes[#PlaceCtr].Material Amount + #Boxes[#PickCtr].Material Amount
14      AND #Boxes[#PickCtr].Material Type = #Boxes[#PlaceCtr].Material Type THEN
15          // Same material and placebox can hold all of pickbox's material, found boxes
16
17          #PickBox := #Boxes[#PickCtr];
18          #PlaceBox := #Boxes[#PlaceCtr];
19          #FoundPnP := TRUE;
20          EXIT;
21      ELSE
22          CONTINUE;
23
24      END_IF;
25  END_FOR;
26  END_FOR;
27
28  IF #FoundPnP = FALSE THEN //Only go in here if we have not found PnP
29  FOR #PickCtr := 8 TO 10 DO
30  IF #FoundPnP = TRUE THEN
31      EXIT;
32  END_IF;
33  IF #Boxes[#PickCtr].Material Type = 'Empty' THEN
34      //Will not pick from an empty box
35      CONTINUE;
36  END_IF;
37
38  FOR #PlaceCtr := 1 TO 7 DO
39  IF #Boxes[#PlaceCtr].Material Type = 'Empty' THEN
40  IF (#Boxes[#PickCtr].Material Amount + #Boxes[#PickCtr].Material Amount <= #Boxes[#PlaceCtr].Capacity) THEN
41      // Placebox empty and placebox can hold all of pickbox's material
42      #PickBox := #Boxes[#PickCtr];
43      #PlaceBox := #Boxes[#PlaceCtr];
44      #FoundPnP := TRUE;
45      EXIT;
46  ELSE
47      CONTINUE;
48  END_IF;
49  END_IF;
50  END_FOR;
51  END_FOR;
52  END_IF;
53
54  "Reshuffle_OK" := FALSE; //Resets the approval for reshuffle, needs to be approved from elsewhere

```

Figure D.8: Reshuffle function.

```

1  #Move complete := False;
2  IF #MoveToBox THEN //moving to box
3  |
4  | IF "Current X" > (#TargetBox.X_coordinate + #IntervalConstant) AND NOT "Motor_X_FWD" AND NOT #X_off THEN
5  |   "Motor_X_Rev" := TRUE; //
6  | ELSIF "Current X" <= #TargetBox.X_coordinate + #IntervalConstant
7  |   AND "Current X" >= #TargetBox.X_coordinate - #IntervalConstant THEN
8  |   "Motor_X_Rev" := FALSE;
9  |   #X_off := TRUE;
10 | END_IF;
11 |
12 | IF "Current X" < (#TargetBox.X_coordinate - #IntervalConstant) AND NOT "Motor_X_Rev" AND NOT #X_off THEN
13 |   "Motor_X_FWD" := TRUE;
14 | ELSIF "Current X" >= #TargetBox.X_coordinate - #IntervalConstant
15 |   AND "Current X" <= #TargetBox.X_coordinate + #IntervalConstant THEN
16 |   "Motor_X_FWD" := FALSE;
17 |   #X_off := TRUE;
18 | END_IF;
19 |
20 | IF "Current Y" > (#TargetBox.Y_coordinate + #IntervalConstant) AND NOT "Motor_Y_FWD" AND NOT #Y_off THEN
21 |   "Motor_Y_Rev" := TRUE; //Current Y is larger than the target, must reduce Y coord - reverse Y
22 | ELSIF "Current Y" <= #TargetBox.Y_coordinate + #IntervalConstant
23 |   AND "Current Y" >= #TargetBox.Y_coordinate THEN
24 |   //Not subtracting interval from target since its ULInt and in reverse it can go to y=0 and ULInt should not go below 0
25 |   "Motor_Y_Rev" := FALSE;
26 |   #Y_off := TRUE;
27 | END_IF;
28 |
29 | IF "Current Y" < (#TargetBox.Y_coordinate - #IntervalConstant) AND NOT "Motor_Y_Rev" AND NOT #Y_off THEN
30 |   "Motor_Y_FWD" := TRUE;
31 | ELSIF "Current Y" <= #TargetBox.Y_coordinate + #IntervalConstant
32 |   AND "Current Y" >= #TargetBox.Y_coordinate - #IntervalConstant THEN
33 |   "Motor_Y_FWD" := FALSE;
34 |   #Y_off := TRUE;
35 | END_IF;
36 |
37 | ELSE //move to cart
38 | IF "Current X" > (#TargetCart.X_Coordinate + #IntervalConstant) AND NOT "Motor_X_FWD" AND NOT #X_off THEN
39 |   "Motor_X_Rev" := TRUE; //
40 | ELSIF "Current X" <= #TargetCart.X_Coordinate + #IntervalConstant
41 |   AND "Current X" >= #TargetCart.X_Coordinate - #IntervalConstant THEN
42 |   "Motor_X_Rev" := FALSE;
43 |   #X_off := TRUE;
44 | END_IF;
45 |
46 | IF "Current X" < (#TargetCart.X_Coordinate - #IntervalConstant) AND NOT "Motor_X_Rev" AND NOT #X_off THEN
47 |   "Motor_X_FWD" := TRUE;
48 | ELSIF "Current X" >= #TargetCart.X_Coordinate - #IntervalConstant
49 |   AND "Current X" <= #TargetCart.X_Coordinate + #IntervalConstant THEN
50 |   "Motor_X_FWD" := FALSE;
51 |   #X_off := TRUE;
52 | END_IF;
53 |

```

Figure D.9: Move X,Y function figure 1.

```

54 |
55 | IF "Current Y" > (#TargetCart.Y_Coordinate + #IntervalConstant) AND NOT "Motor_Y_FWD" AND NOT #Y_off THEN
56 |   "Motor_Y_Rev" := TRUE; //Current Y is larger than the target, must reduce Y coord - reverse Y
57 | ELSIF "Current Y" <= #TargetCart.Y_Coordinate + #IntervalConstant
58 |   AND "Current Y" >= #TargetCart.Y_Coordinate THEN
59 |   //Not subtracting interval from target since its ULInt and in reverse it can go to y=0 and ULInt should not go below 0
60 |   "Motor_Y_Rev" := FALSE;
61 |   #Y_off := TRUE;
62 | END_IF;
63 |
64 | IF "Current Y" < (#TargetCart.Y_Coordinate - #IntervalConstant) AND NOT "Motor_Y_Rev" AND NOT #Y_off THEN
65 |   "Motor_Y_FWD" := TRUE;
66 | ELSIF "Current Y" <= #TargetCart.Y_Coordinate + #IntervalConstant
67 |   AND "Current Y" >= #TargetCart.Y_Coordinate - #IntervalConstant THEN
68 |   "Motor_Y_FWD" := FALSE;
69 |   #Y_off := TRUE;
70 | END_IF;
71 |
72 | END_IF;
73 |
74 |
75 | IF NOT "Motor_X_FWD" AND NOT "Motor_X_Rev" AND NOT "Motor_Y_FWD" AND NOT "Motor_Y_Rev" THEN // in the case that the target pos is current pos
76 |   #Y_off := TRUE;
77 |   #X_off := TRUE;
78 | END_IF;
79 |
80 | IF #X_off AND #Y_off THEN // Verifying output of the move being complete.
81 |   #Move complete := TRUE;
82 | END_IF;

```

Figure D.10: Move X,Y function figure 2.

```

1  "Recipe_ACTIVE" := TRUE;
2
3  FOR #i := 0 TO 4 DO //Five boxes, 0-4
4  IF #i = 0 THEN
5  "Pick&Place_Sequence_1_Instance"(PickBoxNr := #boxNumbers[#i],
6                                     PickAmount := #MaterialAmounts[#i],
7                                     PickHeight := 7500,
8                                     PlaceNr := #DeliveryCart,
9                                     "PlaceCart=T / PlaceBox=F" := TRUE,
10                                    "P&PComplete" => #"CompleteP&P_1"[#i] );
11
12  ELSIF #i = 1 AND #"CompleteP&P_1"[#i-1] THEN //Previous call must be complete
13  "Pick&Place_Sequence_1_Instance_1"(PickBoxNr := #boxNumbers[#i],
14                                     PickAmount := #MaterialAmounts[#i],
15                                     PickHeight := 7500,
16                                     PlaceNr := #DeliveryCart,
17                                     "PlaceCart=T / PlaceBox=F" := TRUE,
18                                     "P&PComplete" => #"CompleteP&P_1"[#i]);
19  ELSIF #i = 2 AND #"CompleteP&P_1"[#i-1] THEN //Previous call must be complete
20  "Pick&Place_Sequence_1_Instance_2"(
21                                     PickBoxNr := #boxNumbers[#i],
22                                     PickAmount := #MaterialAmounts[#i],
23                                     PickHeight := 7500,
24                                     PlaceNr := #DeliveryCart,
25                                     "PlaceCart=T / PlaceBox=F" := TRUE,
26                                     "P&PComplete" => #"CompleteP&P_1"[#i]);
27  ELSIF #i = 3 AND #"CompleteP&P_1"[#i-1] THEN //Previous call must be complete
28  "Pick&Place_Sequence_1_Instance_3"(PickBoxNr := #boxNumbers[#i],
29                                     PickAmount := #MaterialAmounts[#i],
30                                     PickHeight := 7500,
31                                     PlaceNr := #DeliveryCart,
32                                     "PlaceCart=T / PlaceBox=F" := TRUE,
33                                     "P&PComplete" => #"CompleteP&P_1"[#i]);
34  ELSIF #i = 4 AND #"CompleteP&P_1"[#i-1] THEN //Previous call must be complete
35  "Pick&Place_Sequence_1_Instance_4"(PickBoxNr := #boxNumbers[#i],
36                                     PickAmount := #MaterialAmounts[#i],
37                                     PickHeight := 7500,
38                                     PlaceNr := #DeliveryCart,
39                                     "PlaceCart=T / PlaceBox=F" := TRUE,
40                                     "P&PComplete" => #"CompleteP&P_1"[#i]);
41
42  END_IF;
43
44  END_FOR;
45  IF #"CompleteP&P_1"[4]=TRUE THEN
46  "Reshuffle_OK" := TRUE; //Reshuffle after delivering a recipe order
47  "Recipe_ACTIVE" := FALSE;
48  "Scrapyard_info".Carts[#DeliveryCart].SendToMelt := TRUE;
49
50
51
52  END_IF;
53

```

Figure D.11: Recipe function.

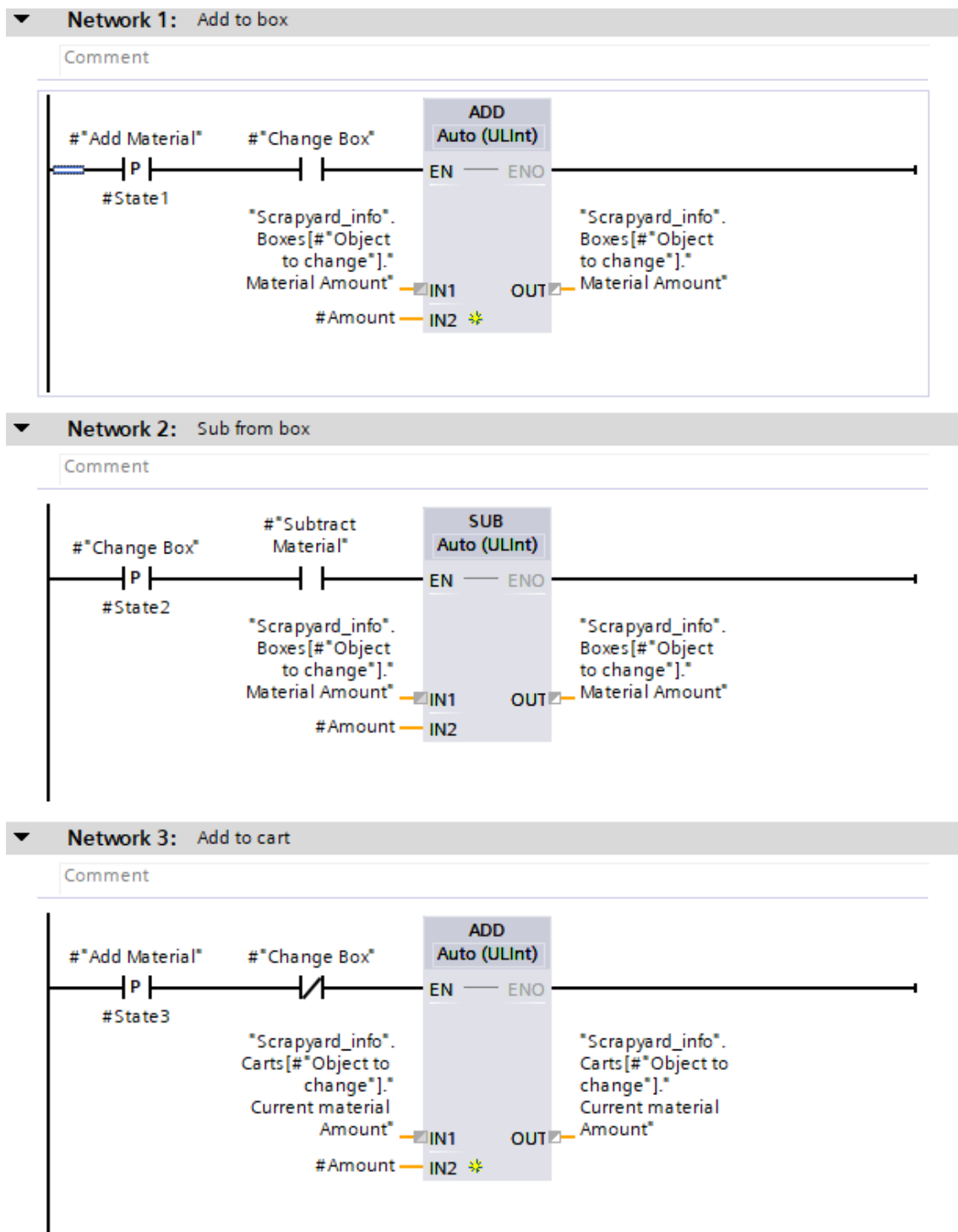


Figure D.12: Weight change function figure 1.

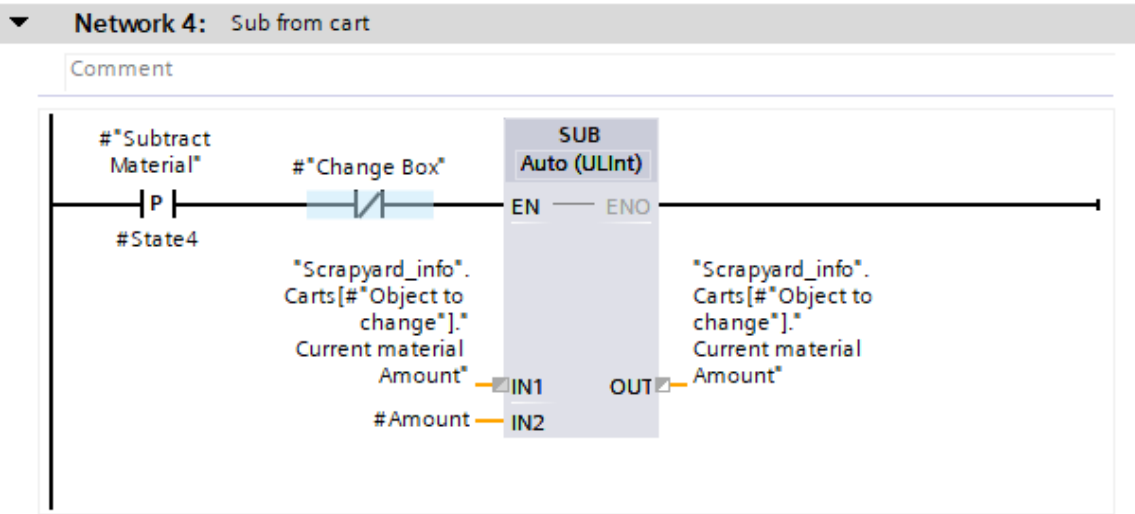


Figure D.13: Weight change function figure 2.

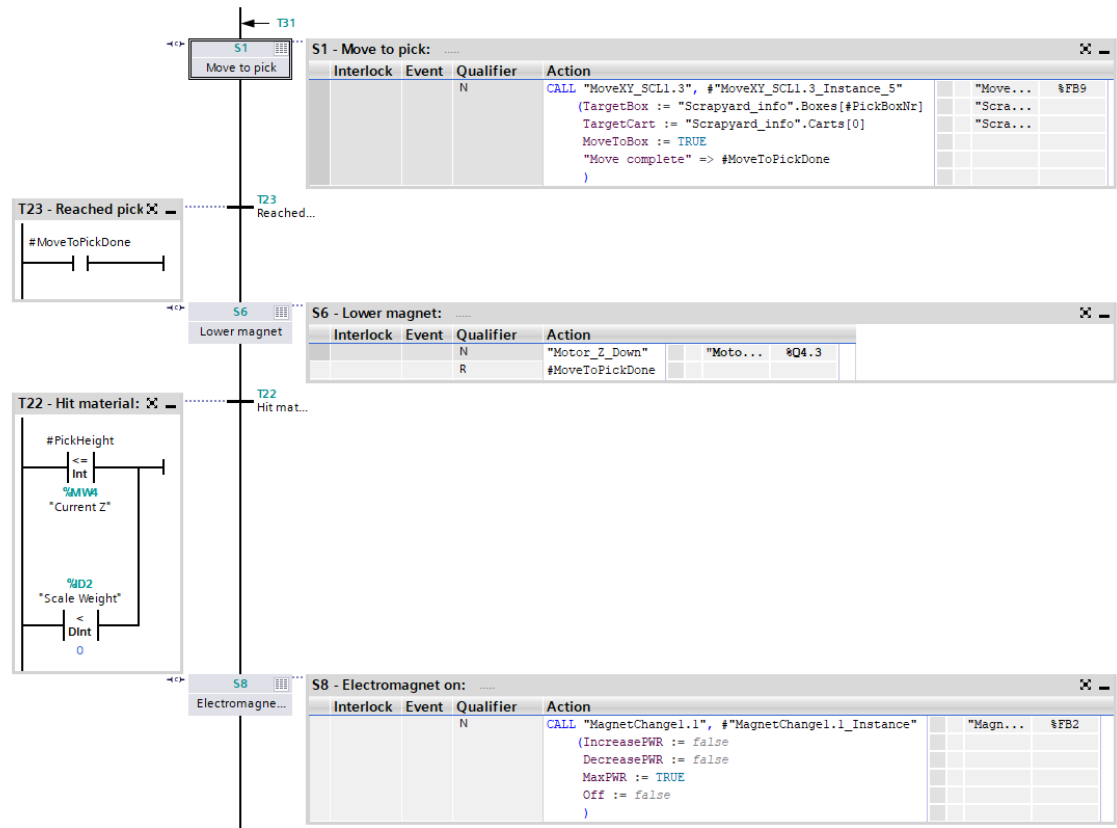


Figure D.14: Pick & Place function figure 1.

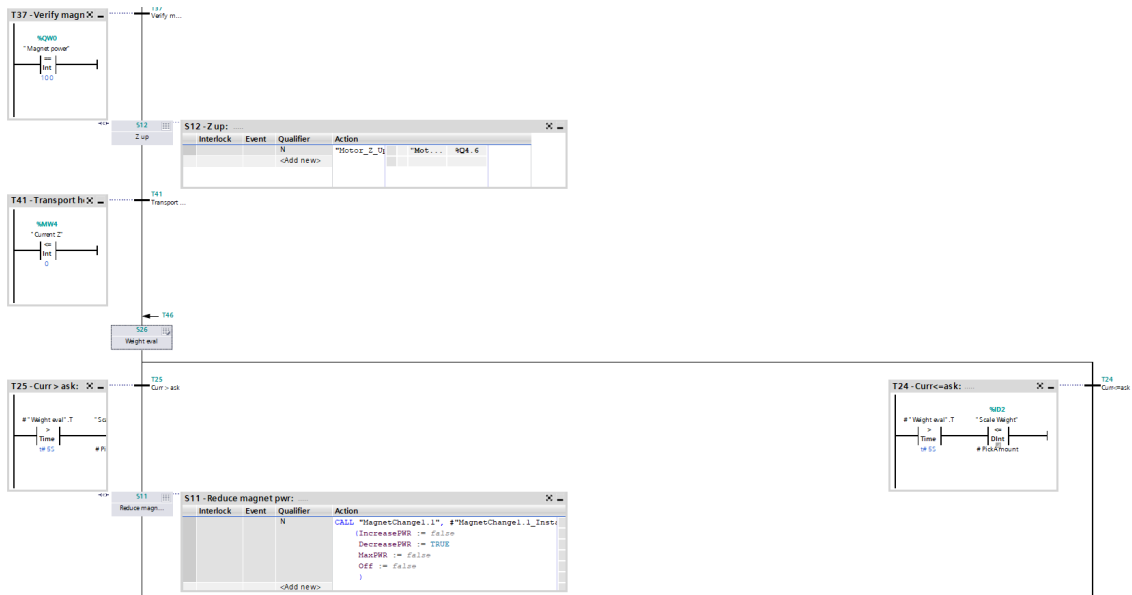


Figure D.15: Pick &amp; Place function figure 2.

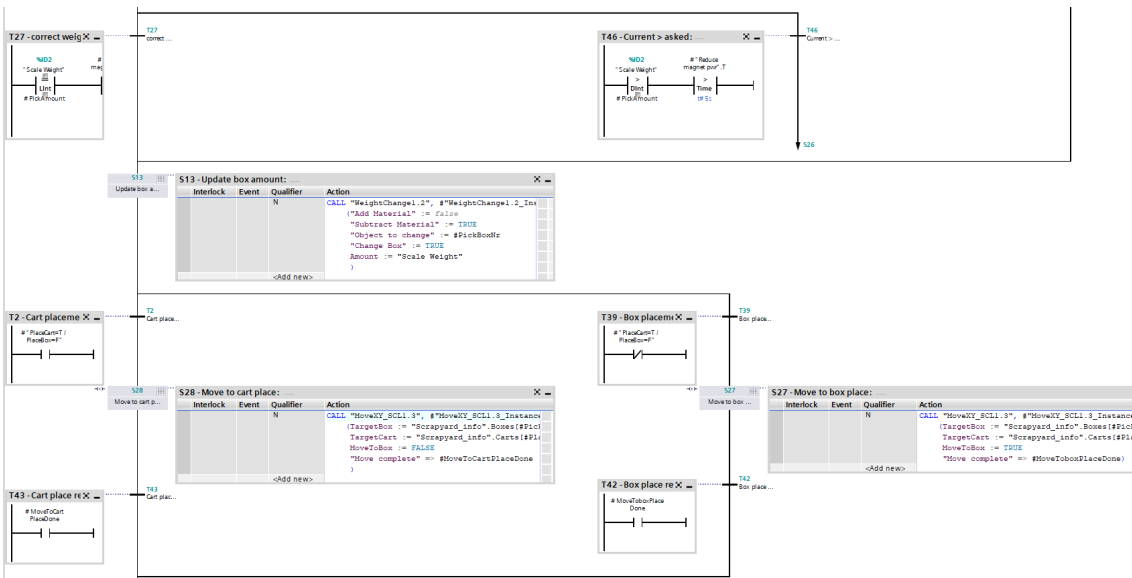


Figure D.16: Pick &amp; Place function figure 3.

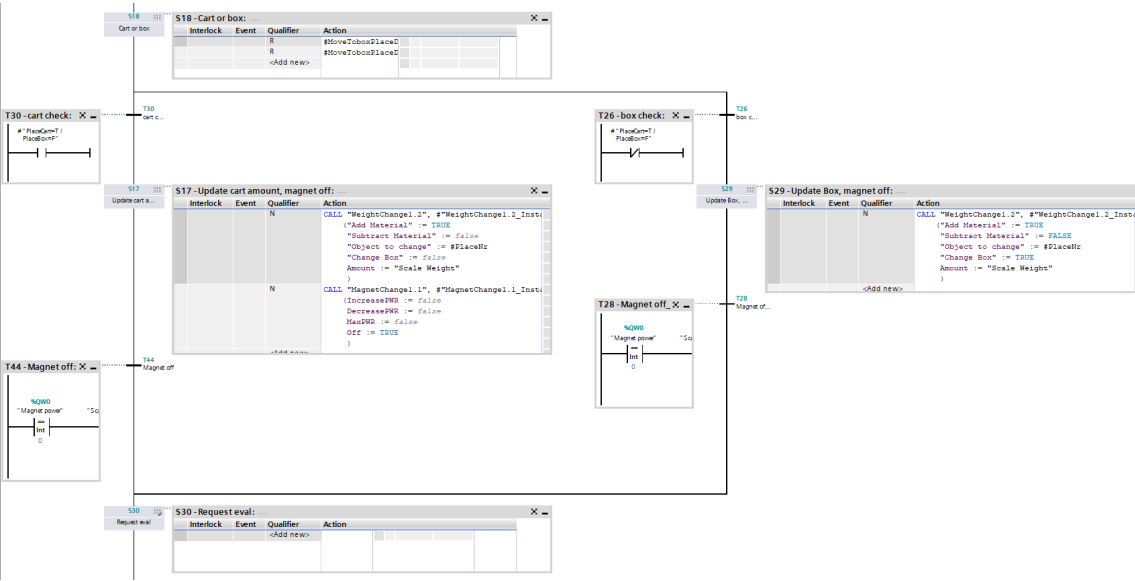


Figure D.17: Pick & Place function figure 4.

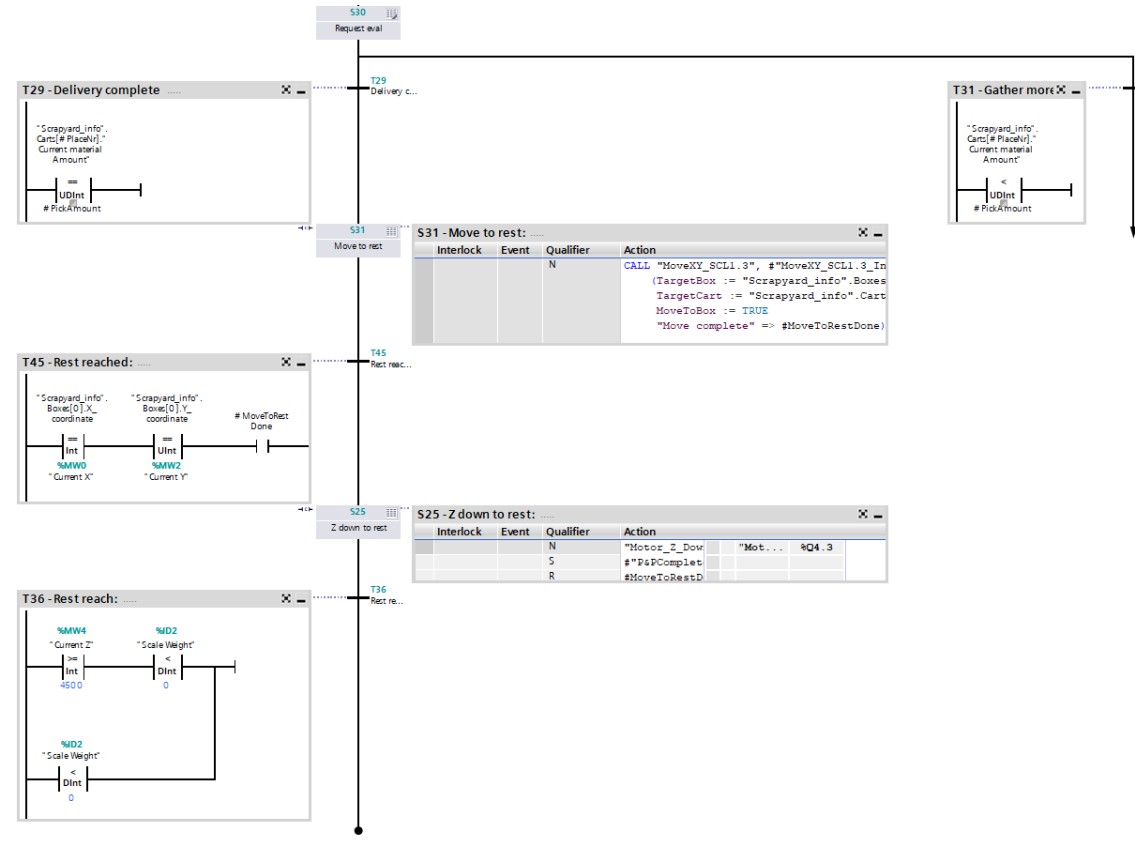


Figure D.18: Pick & Place function figure 5.



# E

## HMI screens

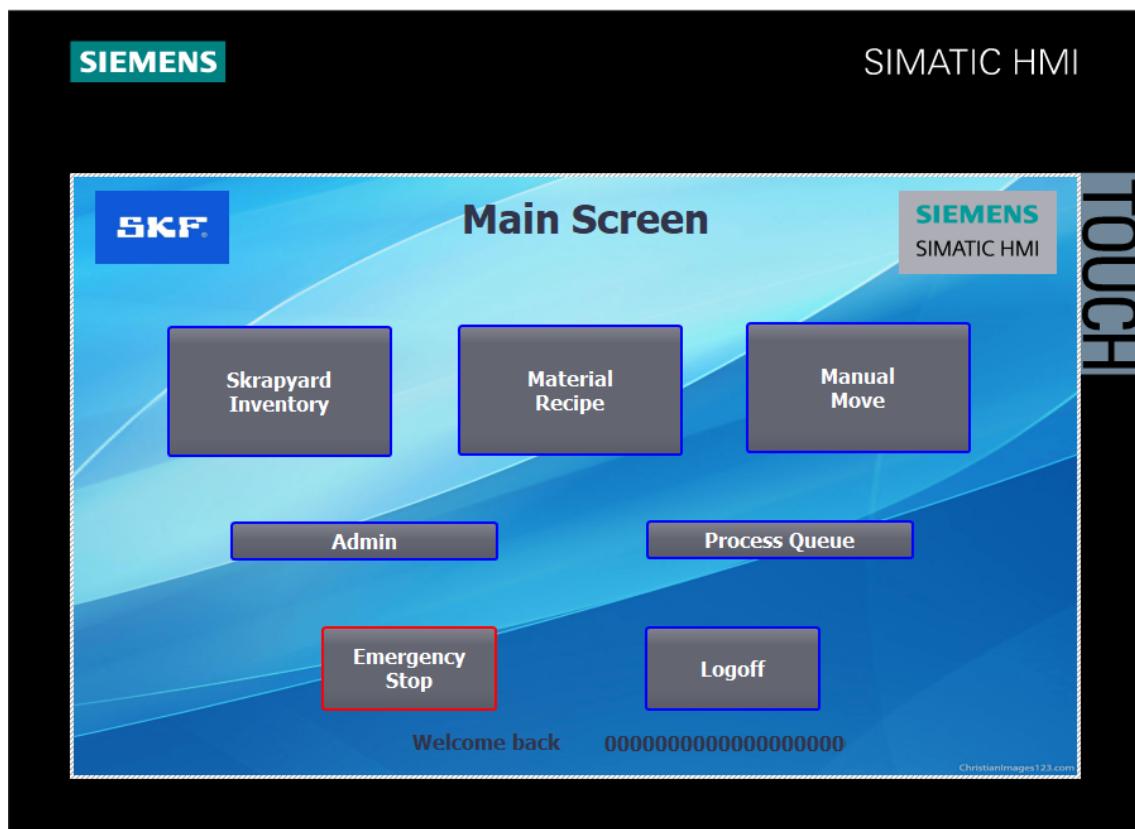


Figure E.1: HMI main screen.

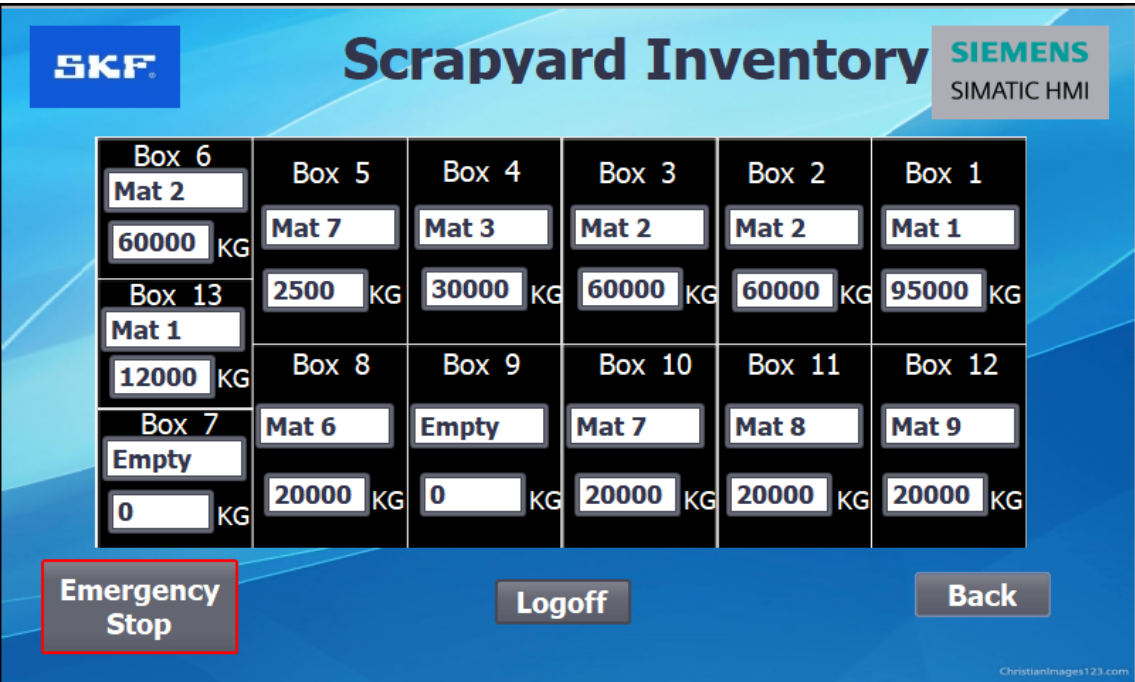


Figure E.2: HMI inventory screen.

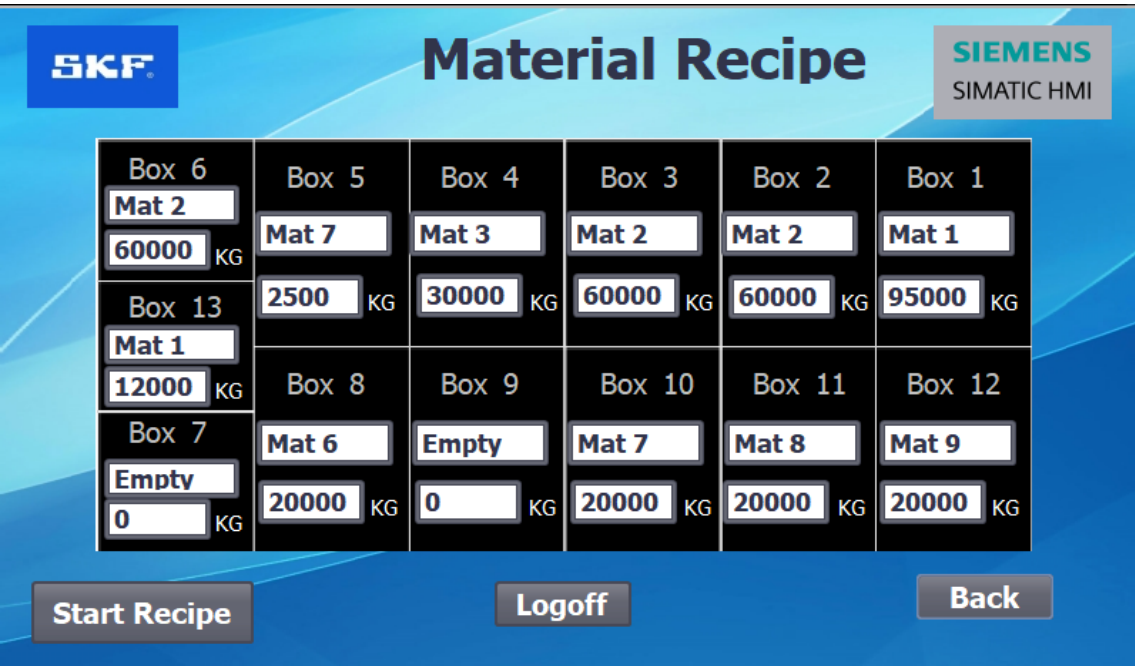


Figure E.3: HMI Material recipe screen.

Box Nr.

5

Material Amounts (KG)

6000

Material type

Mat 7

4

3500

Mat 3

10

5000

Empty

13

2500

Mat 9

0

0

N.A.

Please Choose Cart!

Cart\_1

Cart\_2

Start Recipe

Cancel

Data Records

Data Record Name:

Housings

No.:

1

Entry Name

Value

Box Order[0]

5

Box Order[1]

4

Box Order[2]

10

Box Order[3]

13

Box Order[4]

0

Target Amount[0]

6000

Transfer completed

Emergency Stop

Figure E.4: HMI Material recipe popup screen.

Are You Sure?

Yes

Cancel

Figure E.5: HMI Material recipe confirmation popup.

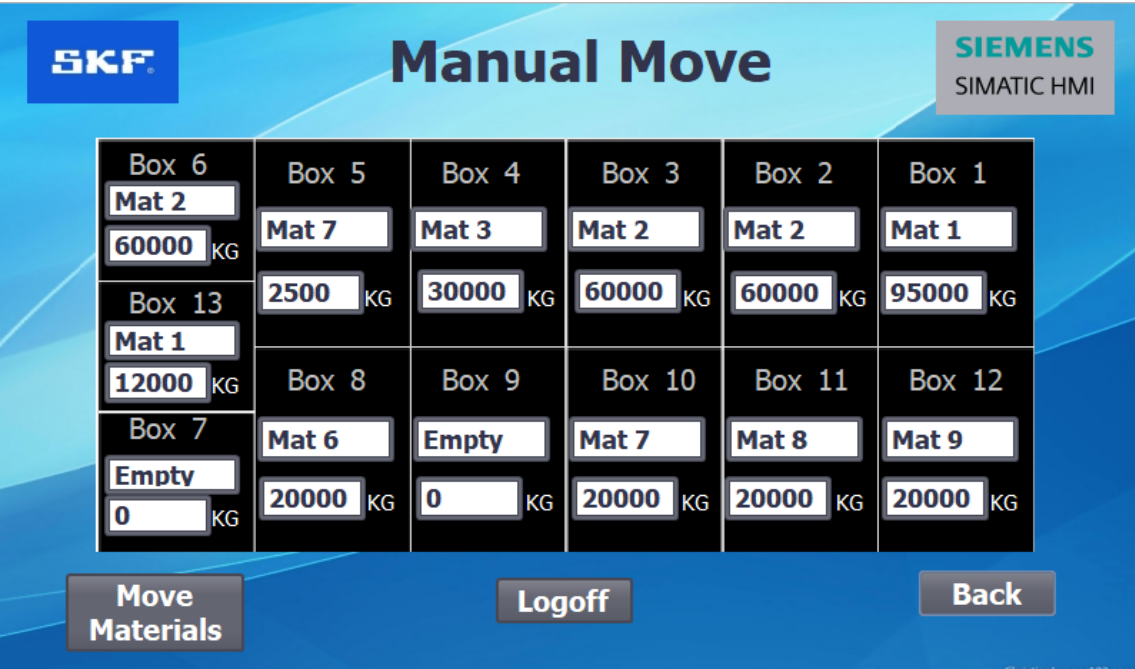


Figure E.6: HMI Material manual move screen.

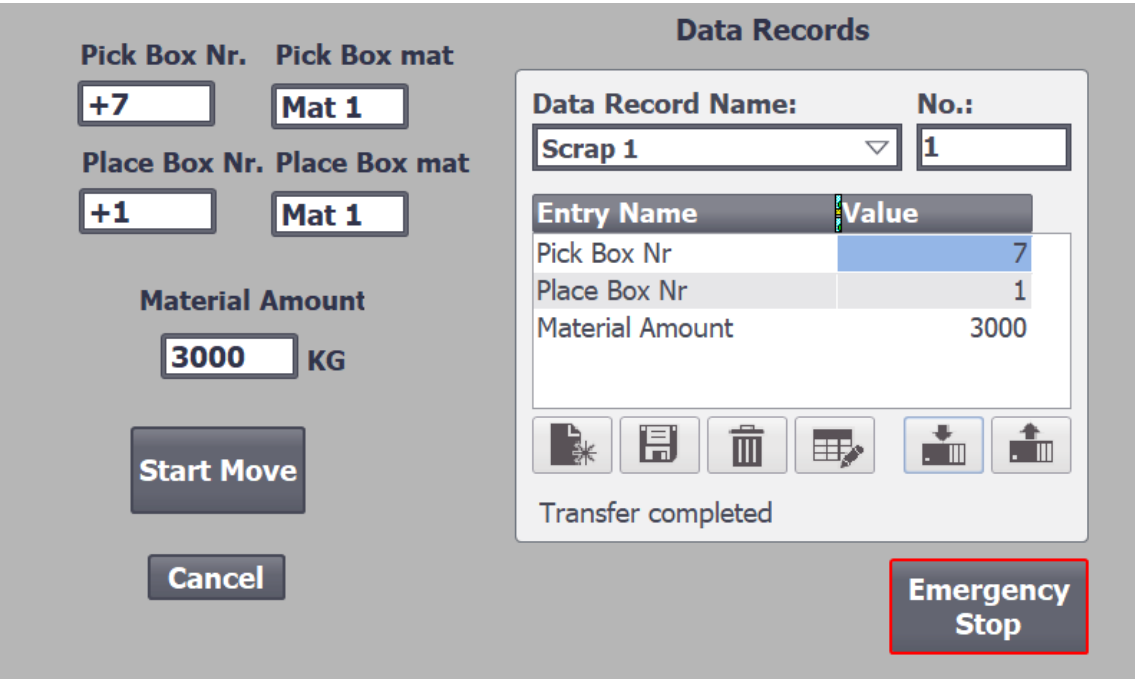


Figure E.7: HMI Material manual move popup screen.

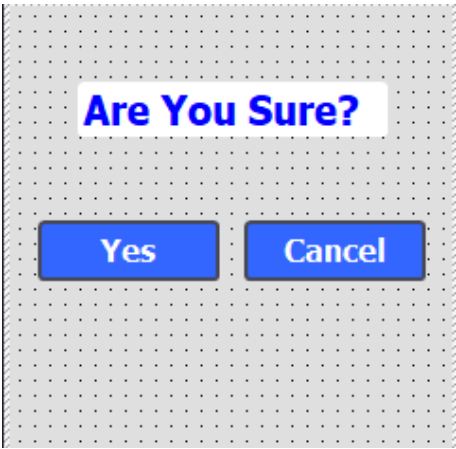


Figure E.8: HMI manual move confirmation popup.

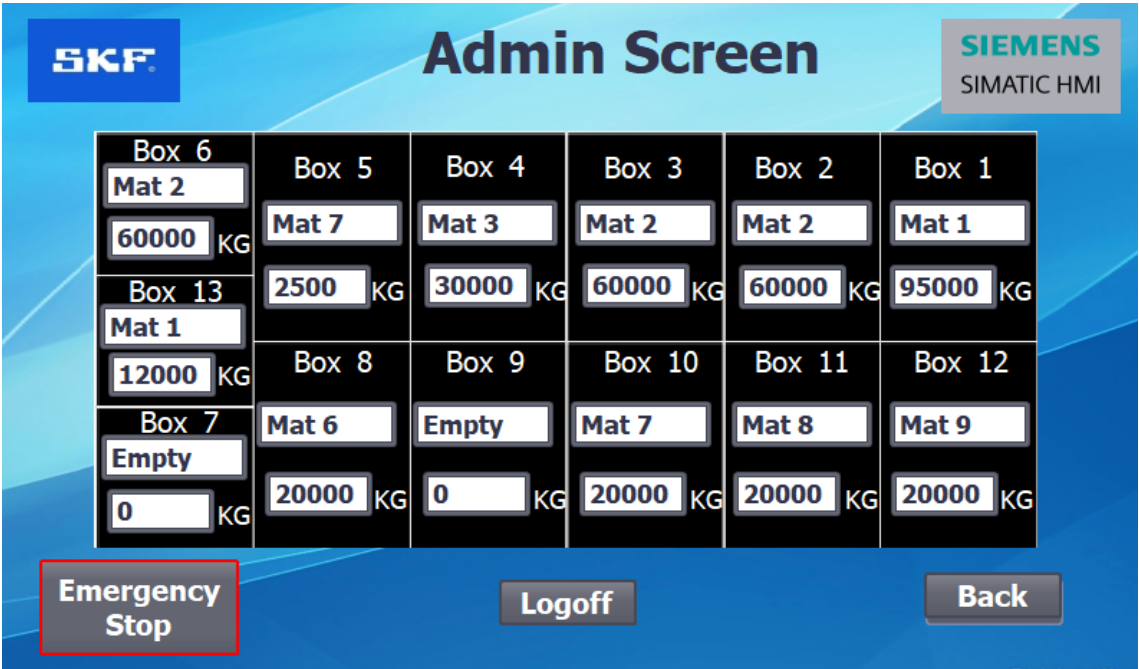


Figure E.9: HMI Admin screen.



Figure E.10: HMI process records screen.

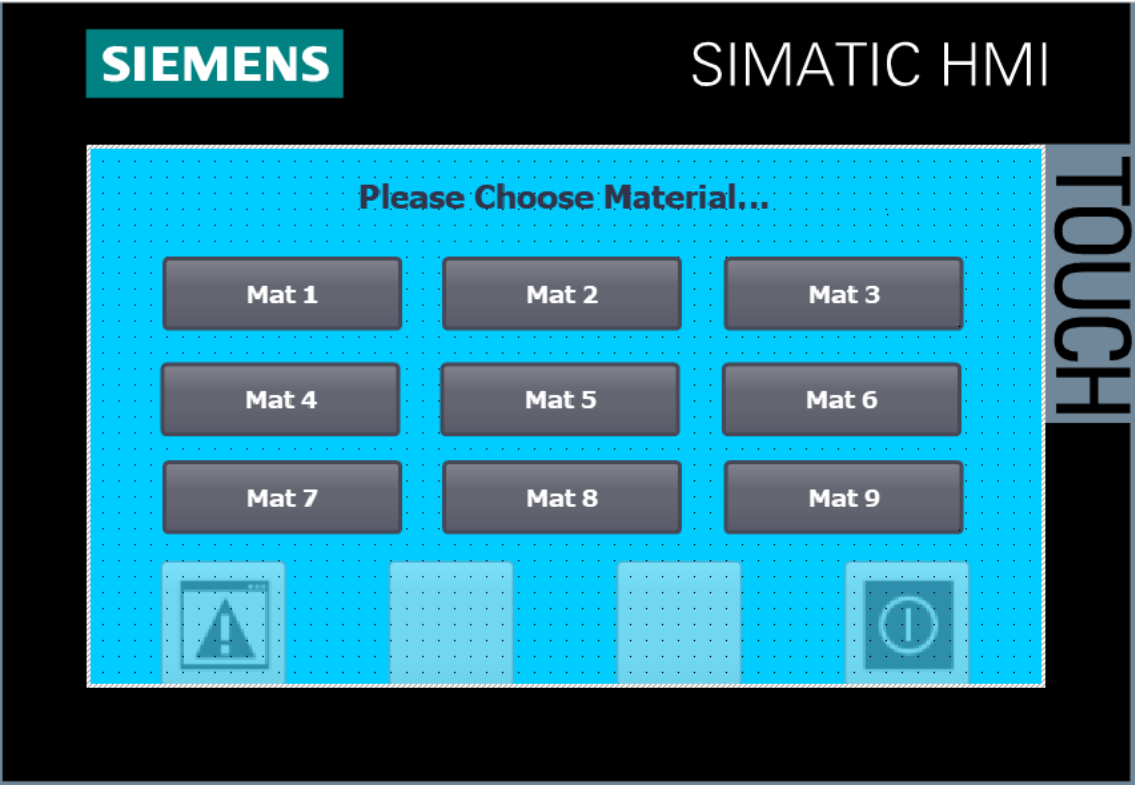


Figure E.11: Gate HMI start screen.

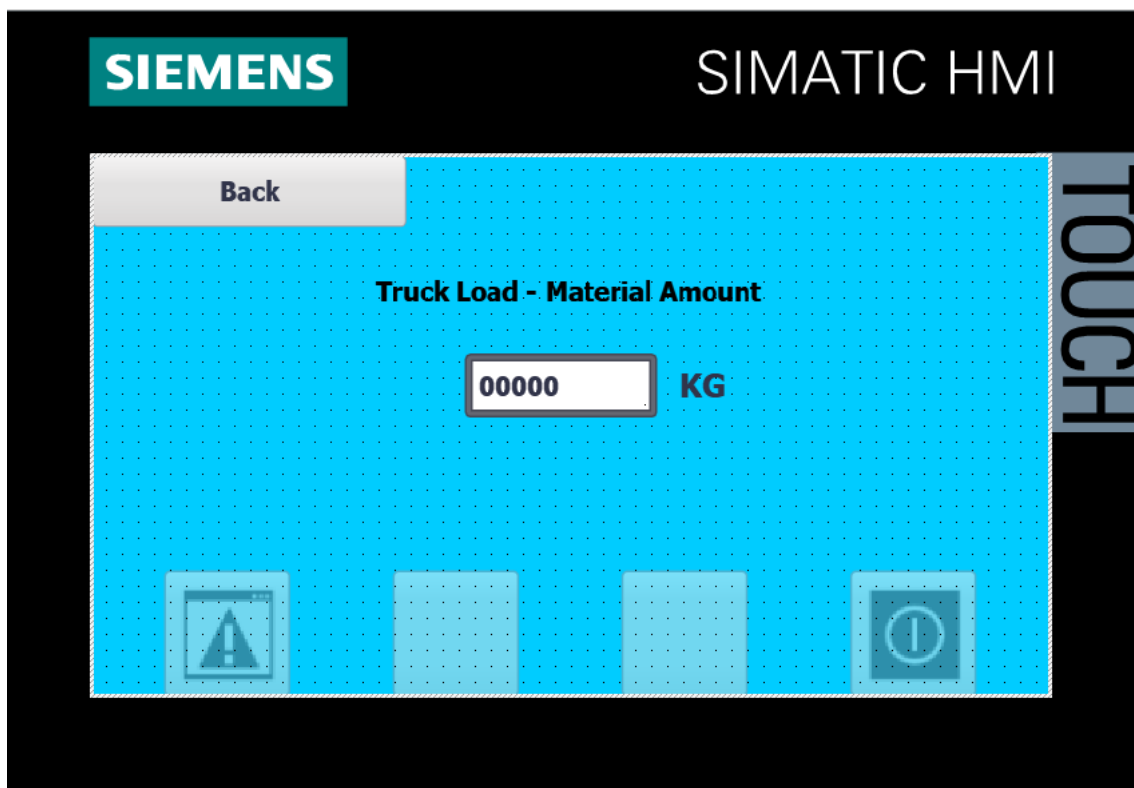


Figure E.12: Gate HMI material amount selection.

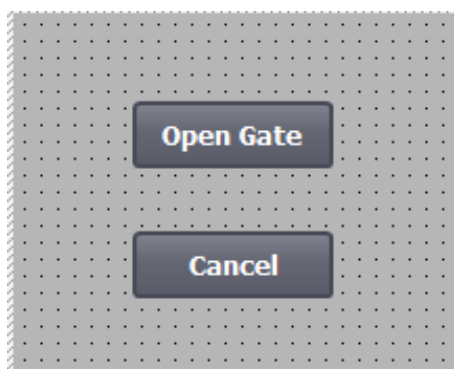


Figure E.13: Gate HMI popup confirmation screen.





Department of Industrial and Materials Science  
**CHALMERS UNIVERSITY OF TECHNOLOGY**  
Gothenburg, Sweden  
[www.chalmers.se](http://www.chalmers.se)



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