New era of automation in Scania’s manufacturing systems

- A method to automate a manual assembly process

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Foreword

We would like to thank all the employees at Scania's Smart Factory Lab in Södertälje, who were involved in the study and contributed to solving any questions and concerns, and for their pleasant treatment and support. This period has been instructive and will give us great benefit in our future working lives. Above all, we would like to thank Juan Luis Jiménez Sánchez and Lars Hanson, our supervisors at Scania, for giving us this assignment, encouraging, and guiding us. Special thanks are extended to our supervisors Anders Robertsson and Charlotta Johnsson at the Faculty of Engineering, Lund University, for their support and help during the thesis project. Finally, we would like to thank our families and friends who are behind the scenes, for their guidance and motivation through this and upcoming projects. Thank you for a very inspiring, developing, and fun collaboration over the time that has passed.

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Sammanfattning

Dagens bil- och lastbilsindustri upplevs ha komplexa produktionssystem med relativt höga tillverkningskostnader, varav en stor del kan kopplas till arbetskostnader vars arbetsmoment utgörs av komplexa och icke ergonomiska monteringsuppgifter. Genom att automatisera sådana uppgifter kan produktiviteten öka samtidigt som arbetskostnader och sjukfrånvaro minskar.

Många produkter och monteringsoperationer är utformade för att utföras manuellt, vilket skapar ytterligare utmaningar när det kommer till att omforma dessa till automatiserade lösningar. Men, framtiden är här, och det som brukade vara manuellt, repetitivt och ineffektivt kan nu automatiseras. Denna uppsats föreslår en potentiell lösning för en helautomatiserad monteringslinje för ratt och framhjul på en trampbil; utvecklad, testad, utvärderad och implementerad i Scanias Smart Factory Lab.

Studien kan ses som en potentiell bas och fysisk demonstrator för att implementera ett sådant system i en verklig monteringslinje. Studien har även visat att produkter som är utformade för manuell montering kan automatiseras utan att behöva anpassa dem för automatisering. Studien föreslår en metod för att omvandla manuell montering till en automatiserad process, metoden är flexibel och kan tillämpas vid andra typer av manuella monteringsprocesser. Därefter följer en beskrivning av design, test och implementering på några av de viktigaste automatisering-systemkomponenterna, inklusive de fysiska resurserna i produktionslinjen för trampbilen. Slutligen kommer en sammanfattning av de upplevda utmaningarna gällande systemets automation komponenter.

Nyckelord: Montering, Industri 4.0, Automation, Robot, Produktion.

Abstract

Today's car and truck industries are perceived as having complex production systems and relatively high manufacturing expenses, such as labour cost, which is usually combined with complex and unergonomic assembling tasks. A shift towards automation is one solution to eliminate such tasks while increasing productivity and lowering labour costs.

Many products and assembly operations are designed to be performed manually, which creates additional challenges to re-shape these operations so that machines can carry them. The future is here, and what used to be manual, repetitive, and inefficient can now be automated. This master’s thesis suggests a potential solution of a fully automated assembly line of a steering wheel and front wheel on a pedal car; developed, tested, evaluated, and finally implemented in Scania's Smart Factory Lab.

The study can be seen as a potential base and a physical demonstrator for implementing such a system in an actual assembly line. It has proven that even manually designed assembly tasks can be automated without a need for redesigning the process or the components involved. The study suggests a method to transform manual assembly operations into automated ones, the method is flexible and can be modified and applied for other types of manual assembly processes. Thereafter, the developing, testing, and implementation of some of the main automation system components, including the physical resources within the production line for the pedal car. Finally, the experienced challenges regarding the automation system components are summarised.

Keywords: Assembly, Industry 4.0, Automation, Robot, Production.

List of abbreviations

SFL	Smart Factory Lab
IFR	International Federation of Robotics
SME	Small and Medium-sized Enterprise
AGV	Automated Guided Vehicle
AMR	Autonomous Mobile Robot
PLC	Programmable Logic Controller
HMI	Human Machine Interface
I/O	Input/Output
CAD	Computer-Aided Design
PDCA	Plan, Do, Check, and Act
DFX	Design For X
DFM	Design For Manufacturing
DFA	Design For Assembly
DFMA	Design For Manufacturing and Assembly
DFAA	Design For Automatic Assembly
HTA	Hierarchical task analysis
CXI	Complexity Index
MTM	Methods-Time Measurement
LOA	Level Of Automation
LOA_P	Level Of Automation Physical
LOA_C	Level Of Automation Cognitive
KPI	Key Performance Indicator
IP	Ingress Protection
SOP	Sequence Of Operations
UR	Universal Robots

Table of Content

1. Introduction

The following chapter gives an introduction on this master's thesis, and consists of background on the targeted area, problem definition, objectives, research questions, delimitations, and disposition of the project.

1.1. Background

A research team at the management consulting firm McKinsey & Company has conducted a study on manufacturing systems, this was in both developed and developing regions of the world in a total of 46 countries. As of the year 2015, the study has shown that more than a half of the total working hours, or more precisely 64%, have been spent on manufacturing-related tasks that can be automated with today's technology. This means that there is a huge automation potential within manufacturing [1].

The McKinsey research has also shown that the manufacturing sector is in second place compared to other sectors with regard to automation potential. Figure 1 below illustrates how automation potential varies among sectors by their activity type, where manufacturing is in the second place behind only accommodation and food service; Figure 1 shows that the ability to automate manufacturing sector for predictable physical tasks is almost at its highest [1].

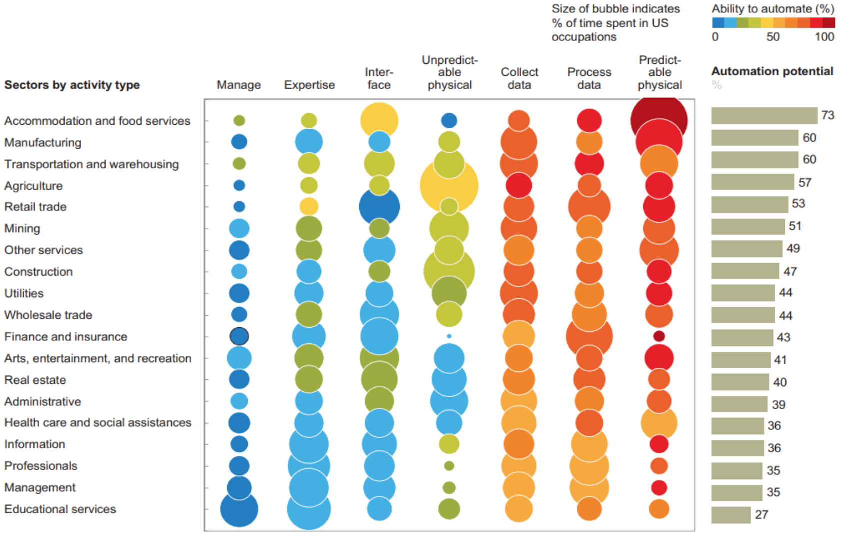


***Figure 1**. Automation potential among sectors and their activity type [1]*

The global competition in production is continuously changing. Until recently, developing nation's main advantage was low wages competing against highly technologically developed nations. During the past ten years, they have begun to catch up in innovation and research in this field, putting more significant pressure on developed nations such as Sweden to keep innovating [2]. Sweden has a long history of ranking as one of the top innovative countries in the world, and according to the World Economic Forum, Sweden came in eighth place in the global competitiveness index 4.0 in 2019 [3]. While this is comforting news, it is of no assurance that Sweden will keep its place. Therefore, continuous effort and development is a necessity to maintain Sweden's competitive advantage in technology, such as developing technologies for the future of Industry 4.0.

1.2.Scania

Scania is one of the world's leading suppliers of transportation solutions such as trucks and buses and has a workforce of 51,000 employees in more than 100 countries. The company's purpose is to shift today's transportation solutions towards a sustainable transport system that enables mobilities that are better for the environment, society, and businesses [4],[5].

Smart Factory Lab (SFL) is an innovative department at one of Scania's leading factories in Södertälje; where new sustainable and creative ideas and concepts are adapted, evaluated, and demonstrated. The proven concepts and emerging technologies are then implemented in the manufacturing processes [6]. Figure 2 below shows the development process at Scania, starting with idea management at SFL, to test and study ideas, concepts, and technologies. Proven successful concepts are then fully developed and implemented in Scania's production system (SPS) [6].

Figure 2. *SFL and SPS processes [6]*

1.3. Problem definition

Today's car and truck industries are perceived as having complex production systems and relatively high manufacturing expenses, such as labour costs which are usually combined with complex and unergonomic assembling tasks. Unergonomic and repetitive tasks are one of the main reasons behind injuries such as musculoskeletal disorders. Injuries related to this disorder are estimated to cost the European Union around 240 billion euros per year in productivity loss and sick leave [7]. Musculoskeletal disorders related to repetitive motions in assembly lines within the automotive industry are a common problem. According to a study conducted in an automotive plant in Germany, 92.5% of patients seeking medical attention at the companies' medical service units were diagnosed with an underlying musculoskeletal disorder related to work tasks, of which 86% were blue-collar workers employed in the assembly line [8]. Automation is one solution to eliminate such unergonomic and repetitive tasks and therefore achieve a safer factory while increasing productivity [9].

Efficiency and flexibility have been a common discussion topic within manufacturing systems; automated solutions are one example among other concepts that have been developed to enable the combinations of efficiency and flexibility within manufacturing systems [10]. With the advent of Industry 4.0, new technologies, more flexible and collaborative robots, new ways of solving these problems are now possible [11]. Many products and assembly operations are designed to be done manually, which creates additional challenges to re-shape these operations so that machines can carry them. Safe, efficient, and smart are three words that would describe a perfect future factory; therefore, Scania is now looking to see if it is possible to fully automate one of their production lines which has mainly used manual labour up to now. The future is here, and what used to be manual, repetitive, and inefficient can now be automated. This master thesis suggests a potential solution of a fully automated assembly line for a pedal car; developed, tested, evaluated, and finally implemented in Scania's SFL.

1.4. Thesis goals and research questions

A shift towards automation is necessary to increase productivity and lower labour costs by reduce or repurpose working hours. This study aimed to design and develop a fully automated and unmanned assembly line of a steering wheel and front wheel on a pedal car. Additional objectives were to investigate the approaches to automate an assembly process, the automation system components required, and their challenges. Additionally, the study has an objective to prove that even manually designed tasks can be automated without redesigning the process or the components involved. The study can be seen as a potential base and a physical demonstrator for implementing such a system in an existing assembly line, which verifies that a similar solution in Scania's manufacturing system is possible. To achieve the goals of the thesis, three research questions were stated according to the following:

- How to proceed with transforming manual assembly operations into automated ones?
- How to proceed with automating the assembly of a steering wheel and front wheel on a pedal car?
- What are the automation system components required? Moreover, what are the challenges regarding these?

1.5. Delimitations

This study has been intertwined with a larger project in the SFL about Industry 4.0, meaning that some objectives are sub-objectives for the larger project and are therefore not be covered by this study. The focus in this study has been on selected sub-assemblies of the complete assembly for the pedal car, mainly driven by the company supervisor. The areas being investigated are assembly parts, automation system components, and solution development methods. Economy and product design issues are not taken into account in the case study. Designing for manufacturing or automation methods are not included in the study but briefly discussed, partly to prove that manual operations can be automated without redesigning the parts involved. In an actual production case, redesigning could be essential to ensure an optimal solution.

Scania previously determined the manufacturing system layout to be a line assembly layout, serving as a physical demonstrator of an actual automotive production system, where a line is one the most common and suitable production layouts.

Not all of the recommendations and concepts for the assembly line of the pedal car can be implemented in an actual truck manufacturing system since the assembly line is used as a demonstrator of available technologies and automation concepts rather than solutions for the actual production. There may be variations in the study's results and future recommendations between the demonstrator and actual production.

1.6. Disposition

This master's thesis report has the following disposition:

- Chapter 1, introduction to the subject and the problem investigated, the research questions, purpose and delimitations.
- Chapter 2, theoretical framework: deals with the theory that is relevant to create and develop an automated industrial process.
- Chapter 3, methodology: describes the scientific methods chosen to perform the study and to collect the relevant data.
- Chapter 4, system analysis: maps the current situation in the manual pedal car assembly and analyse the product specification. The chapter also includes the selection and design process of the automation system components involved.
- Chapter 5, results: here the study's results are presented, and the research questions are answered.
- Chapter 6, discussion: the analysis and the results of the study are discussed.
- Chapter 7, conclusions: the study's results and suggestions for improvement are summarised. Recommended future studies are presented.
- Chapter 8, sources: source reference.
- Chapter 9, appendices: appendices that report research materials, flowcharts, programming scripts, and empirical data in more detail.

2. Theoretical Framework

The industrial revolution is shaping the future and rapidly shifting today's factories towards more automated, flexible, efficient and smart plants. This chapter covers the theoretical framework that has been used in the study, this framework has been the foundation for the thesis. The chapter covers related literature areas that were used during the study, starting from an introduction to industrial robots, their configuration, production and product design principles, to finally describe, the most common automation system components and automation solution development.

2.1. Link between research questions and theory

Based on the master's thesis research questions, a theoretical framework has been formulated and used to provide a theoretical basis for the research questions and analyse the results of the study. The following theories are described in the framework according to Table 1. The first and the second research questions have used the same theory framework, section 2.6 and 2.7 were lastly introduced in the theoretical framework section to structure the content of the framework, yet were used earlier during the study to define an approach for the project.

Table 1. *Link between research questions and theory*

Research questions	Heading in theory
How to proceed with transforming manual assembly operations into automated ones? How to proceed with automating the assembly of a steering wheel and front wheel on a pedal car?	2.2 Introduction to industrial automation
	2.6 Solutions development
	2.7 Integrated control logic design
What are the automation system components that are required? Moreover, what are the challenges regarding these?	2.3 Industrial robot configurations
	2.4 Production and product design principles
	2.5 Automation system Components

2.2. Introduction to industrial robots

Robots have been used in industry since the mid-1950s; this chapter covers a brief history of their development, applications, benefits, and impact on employment.

2.2.1. History of industrial robots

Robots come in many shapes and sizes and are mainly categorized into service and industrial robots. Service robots vary from unmanned military aircraft, cow milking machines, and robot surgeons to robotic vacuum cleaners and toys. The primary purpose of industrial robots is to meet the needs of industry and therefore come in a more standardized format. Unimate developed the first industrial robot in 1956. It had hydraulically driven arms and was used for stacking die-cast parts at General Motors plant in Trenton, New Jersey. In 1969 General Motors did the first central installation of industrial robots, where they used them to spot weld cars. The Olivetti Sigma, developed in 1975, was the first assembly robot and was based on a cartesian design. With the advent of microprocessors and electrical motors in the late 1970s and ’80s, performance and reliability increased with Unimation developing the first universal programmable robot in 1978. Today the application of industrial robots ranges from aerospace to food. However, throughout industrial robot’s history, the primary driver of development has been the automotive sector, as can be seen in Figure 3 below, it still remains the most prominent user, with the electronics business rating second. The application of robots in the automotive industry mainly occurred in body shops with processes such as welding, painting, and sheet handling between stamping stations. Their implementation in the final assembly was slower due to more complex parts and fittings where humans had a more significant advantage [12].

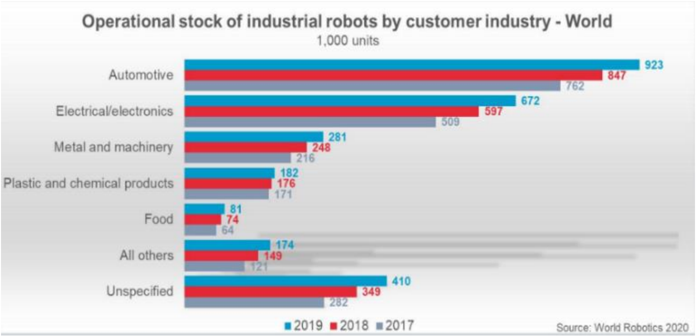


__Figure 3.__ Operational stock of industrial robots by customer industry [13]

2.2.2. Typical industrial robot applications

Industrial robots have a wide range of applications; among which welding is prevalent in automotive industries. Examples of other application areas are dispensing, palletizing, machine tool tending, material handling operations, measurement, inspection, testing, picking, and packing [12].

2.2.2.1. Measurement, inspection and testing

Inspection applications within manufacturing systems are essential to ensure quality and decrease risks; robots enable measurement devices to reach, test, and inspect different locations or points in a system or product. Another application area within the inspection field is mechanical test rigs, where robots can provide motion to test rig systems. Robots enable different kinds of inspection and testing applications while reducing the overall cost for these systems; it is important to consider that some inspection systems require a high level of accuracy. Robots may not achieve that desired level, therefore, the user for such applications have to consider that robots are not accurate [12].

2.2.2.2. Packing and picking

Applying robots as a means of picking and packing increases throughput, labour savings and consistency, and leads to improved quality. Vision systems are commonly used to detect the position of the parts to be picked while providing a means of quality control. Another aspect of using robots for picking and packing is health and safety regulations; if the parts are heavy or the movements are monotonous, robots can alleviate some of the manual strain. The type of robot can vary depending on the task being performed; if the process is high speed with light products, the flex picker would be a good choice. For packing procedures where the products are placed in boxes, the 6-axis articulated arm could be a better choice. It offers more orientation capabilities and a better configuration for reaching into boxes [12].

2.2.2.3. Assembly

Robot applications in the assembly have grown significantly thanks to the flexibility, consistency, speed, and precision that robots provide. SCARA robots are very common in assembly applications, mainly in electronic products. Six-axis robots are increasingly employed in assembly due to their high flexibility and capability compared to other types of robots [12].

Speed is a significant factor in using robots in this field; along with the payload, which is the load that a robot can lift and includes the weight of the tool or gripper attached to the robot. Other criteria such as reach, and size may need to be considered since most assembly systems have a limited area and need to be compact. Mechanical assembly applications may have other specifications, such as motions and forces, that are necessary to attach or press two components together. Such motions require mechanical capability from the robot in terms of force to execute such a task. In addition to the above specifications, some assembly systems may require joining functions with the help of additional fixings, it is possible to automate such operations, but the level of variation may be high, adding too much complexity to the process. Joining methods and product design remarkably influence the complexity and reliability of the final automation solution that may be provided [12].

Accuracy and positional repeatability are two of the most critical assembly application issues in robotics; accuracy is the difference between the obtained and the requested task, while repeatability means the ability of a robot to perform the same task repeatably. Accuracy is how close the robot can position itself at the desired target, while repeatability is how close the robot will hit a taught target over many cycles [14].

Assembly parts need to be located within specific tolerances that permit the joining method to be performed; other requirements may need to be considered, such as the part locations, chamfer, or a guide that position the part in place. The components themselves need to be repeatable, i.e., the design needs to enable the execution of such tasks; for example, electrical components like capacitors have legs that have to be undamaged and straight to be mounted into circuit boards. Feeding of parts is another issue to be considered, which can be solved using some type of assembly feeding system such as bowl feeders [12].

2.2.3. Benefits of robots

At early stage of industrial robot implementation robots were not used for beneficial or financial attributes. Instead, they were chosen based on the idea that robot technology is a necessity for future production development. As the functionality and ease of use increased, the interest in robots changed, offering financial savings and higher utilization of manufacturing systems [12]. IFR believes that higher level of competitiveness and an increase of productivity can be achieved with robot applications, primarily for Small to Medium-sized Enterprises (SME). Large businesses can achieve these benefits through faster product development and shorter delivery time [15].

Companies in high-cost countries are now able to bring home or ‘re-shore’ their businesses thanks to the implementation of robots, mostly since cheaper labour costs have been one of the main drivers to outsource their businesses in the first place. The inability of businesses to stay competitive is the most significant risk for unemployment, while automation offers a way to stay competitive and create jobs. Robots complement and may substitute labour tasks, but they do not replace jobs. According to IFR, fewer than 10% of jobs are fully automatable [15].

2.2.4. Robot versus employment

One of the most common misunderstanding concerning robots is that they reduce the number of job positions. A specific robot installation may lead to a loss of certain jobs, but these positions are usually recreated elsewhere. In other words, automation solutions generally result in more business growth and an increased level of competitiveness for a business, leading to new higher-skilled professions becoming more available. Furthermore, robots replace repetitive, dangerous or highly manual tasks, with higher paying tasks that are more suited to humans, such as monitoring, controlling, and maintaining robot systems [12].

Successful companies always seek to grow and become more competitive by streamlining their processes. Automated solutions offer significant advantages in this aspect. Even more so in the 21st century with its international free trade agreements and globalization where the focus has shifted from mundane tasks to highly skilled and value-adding tasks. Finally, health and safety requirements are constantly evolving, which means that it is even more important now than ever to replace those dangerous, repetitive and intensive tasks with the use of automation and robots [12].

2.3. Industrial robot configurations

This section covers the most common structures for industrial robots, their performance, selection criteria, and describes the next generation of industrial robots, collaborative robots.

2.3.1. Robot structures

Industrial robots are typically a combination of joints that can come in different configurations; the most common have been classified into five different groups: Articulated arm, SCARA, Cartesian, Parallel, and Cylindrical. In Figure 4 below different robot models can be seen [12].

Figure 4. *Top left: ABB 140 6-axis articulated arm robot, top right: 4-axis ABB 910 SC Scara robot, bottom left: robot with cartesian configuration, bottom right: ABB IRB 360 FlexPicker, parallel configuration [16], [17],[18],[19]*

2.3.1.1. Articulated arm

This is the most common type and is known for its arm-like configuration, which normally has 6-axis rotation. The number of axes allows it to reach a set point with various configurations and tool orientation with uses ranging from welding, painting, packing, picking, and material handling. They can vary in height from 0.5 to 4.5 m with a payload capacity of 3 to 1000 kg [12]. A commonly used model is the *ABB IRB 140*, which can be seen in Figure 4 [16].

2.3.1.2. SCARA

SCARA robots are defined as four-axis robots consisting of 3 revolute joints and one linear joint in the vertical direction. The Robots were initially developed for assembly but are also used in packing, small press tending, and adhesive dispensing, their configuration provides them with high speed and precision. The advantage of SCARA robots is their speed, outperforming 6-axis arms on specific goalpost tests. What keeps them back is their restriction to the four-axis, limiting their range of motion and low carrying capacity and small reach [12]. *ABB*'s largest SCARA robot is the model *910 SC* which can be seen in Figure 4 [17].

2.3.1.3. Cartesian

Cartesian comes from the cartesian coordinate system and can be seen in Figure 4. It is built upon a 3-axis configuration moving linearly in x, y, and z with some special variants having additional rotary axes on the last linear axis. Their size can vary from under 1 m to over 10 meters and a payload capacity measuring tons. Some applications can be palletizing, plastic moulding, 3D printing, assembly, and machine tending [12].

2.3.1.4. Parallel

The parallel or delta robot has a configuration of the concurrent prismatic or rotary joint. They were developed as an overhead mounted robot with a base drive and linked arms that manipulate the tool position. With this approach, the weight of the moving arms can be kept low, giving excellent acceleration, speed, and precision with cycle times competing with the SCARA. One disadvantage is their payload capability which is usually under 8 kg. Their main applications are picking and packing in the food industry [12]. A model provided by ABB is the IRB 360 flexpicker which can be seen in Figure 4, it comes with an integrated vision system, and a wash proof body [18].

2.3.1.5. Cylindrical

This robot consists of a 3-axis configuration with one rotary axis base and two linear axes moving horizontally and vertically. Their advantage is a rigid structure, easy to program, and ability to reach into cavities. The linear horizontal axis which produces on the back side of the robot, creates the disadvantage that the robot needs to have space behind it to avoid collisions. Its main applications are in the electronics industry [12].

2.3.2. Collaborative robots

Traditional industrial robots have the advantage of speed, repeatability, and accuracy, although, they cannot work safely in a collaborative environment with humans. To solve this limitation, wide range of collaborative robots have been developed with different levels of collaboration between robots and humans in the production environment. The most basic application of collaboration is that of traditional industrial robots, which operate in a separate workspace while detecting when workers enter. This causes the robot to either slow down or stop completely while the worker is in the designated space. This method can save time on shut down procedures, resulting in less overall downtime [9].

At the more advanced levels of collaboration, the robots, also called ‘cobots’ are specifically designed to collaborate alongside humans within the same workspace. The cobots are equipped with various technical features that ensure that collisions do not cause any harm to workers when they accidentally or deliberately come in direct contact with the robot. These features can be lightweight materials, soft contours, padding, ‘skins’, which contain embedded sensors that detect contact and sensors within the robot joints that measure and regulate speed and force according to defined thresholds. The most common types of collaboration levels are shared workspaces where robots work side by side with humans, completing tasks sequentially. In these cases, the robot is often used to perform tedious and unergonomic tasks, such as heavy lifting and repetitive motions [9].

For the automotive industry, collaborative robots offer new ways of automating the final assembly process. Collaborative robots make it possible to automate parts of the line with minimal changes while relieving humans from repetitive, tedious, and unergonomic tasks, such as fetching parts, feeding machines, lifting, and quality inspection [9].

2.3.3. Robot performance

The robot's performance is highly dependent on its structure, configuration, and number of axes. Different robot models all have their advantages and disadvantages depending on the application. Besides structure, configuration, and axes, the main performance features are defined as payload/weight-carrying capacity, repeatability, reach or working range, and speed. The weight carrying capacity is defined as the maximum load applied at the tool-mounting flange of the robot wrist without affecting other specifications such as speed, reach, and repeatability. In the robot manuals, the position of this parameter is specified as the load centre of gravity with a certain distance in x, y, and z from the tool mounting flange [12].

Repeatability defines how accurately the robot can position itself in a certain XYZ point or perform a defined path with the same precision over many cycles. The reach and working range define the volume in which the robot can reach; the volume is often divided into a side and planar view in the robot specification. Figure 5 below shows a working range for a six-axis robot [12].

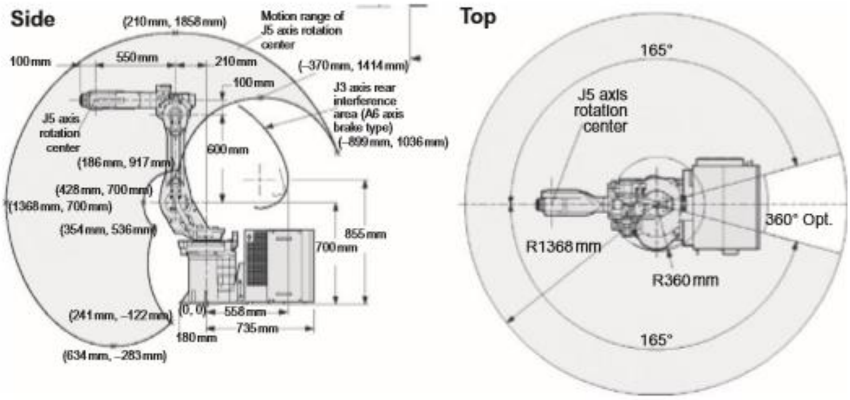


__Figure 5.__ An example of a robot working envelope [12]

The robot's speed is often defined as the maximum speed for each joint. However, since the joints do not operate independently, these speed measurements give a limited understanding of the actual speed. For a more general value on the robot's speed, a so-called goalpost test has been developed, which provides a reliable way to compare speeds of different robots and help engineers assess cycle times [12].

2.3.4. Robot selection

Capabilities and performance are two, among other essential requirement areas, that drive the robot selection process. The application area and system concept need to be defined before investigating what characteristics and robots are suitable. since different approaches require different capabilities in the robots, it is essential to understand the application area. For example, a robot carrying a tool to a fixed part or a robot carrying a part to a fixed tool is one important aspect of defining carrying capacity. Determining which approach to choose may be driven by other factors such as total cost for a system. Capability and performance characteristics required for the robot can be defined once a system concept is obtained. Datasheets are typically issued when defining such requirements. Reach is one of the first paraments that are usually checked in datasheets, in combination with other parameters such as weight capacity and repeatability being as crucial in many cases, overall cost and solution complexity are crucial factors and usually have a significant impact on the decision process as well. Datasheets vary depending on the objectives and specification for a system solution, the most common of which are addressed below [12]:

- Reach, different robot models have different reach capabilities and in some robot applications, a specific reach is crucial. Therefore, it is common to state such information in a datasheet.
- Payload, robot variations result in different load capacities; datasheets often specify the payload intervals.
- Number of axes commonly mentioned in datasheets among the speed for each axis and the working range.
- Robot configuration, for example, delta, SCARA, or articulated.
- Work envelope: usually a plan view that illustrates a robot's range of movements when an arm reaches up, down, forward and backward. This information is commonly stated in datasheets.
- Weight and dimensions are most likely stated in datasheets.
- Repeatability in both path and position.
- Mounting capabilities; robots can be mounted in different orientations.
- Electrical requirements such as power usage.
- Environmental capabilities and protection. Ingress protection (IP) rating is often stated.

2.3.5. Homogeneous transformations

One of the robot’s primary purposes is to manipulate parts and tools in a chosen space. From this, a need arises to represent these positions and orientations in mathematical terms, using coordinate systems and developed conventions for representation. When a coordinate system has been established, a point can be located with a 3x1 position vector containing the values for the x, y, and z positions. The position vector has to be tagged with information to identify which coordinate system it is defined in. For example, position vector ${}^{A}P$ is tagged with the letter A, meaning that it is defined in coordinate system {A}. A point gives a position to which the manipulator hand should move. However, it does not define the orientation it should have. To give the orientation, a second coordinate system {B} at the point has to be created. The rotation of this in relation to system {A} is defined in a 3x3 matrix denoted as ${}^{A}_{B}R$. The combination of a point and its orientation is called a frame. Figure 6 below illustrates a general transformation view of a vector [20].

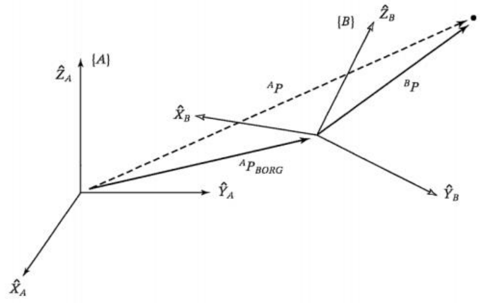


Figure 6. *General transform of a vector [20]*

To map the position of a vector which is known in frame {B} and wants to be defined with respect to frame {A} the following transformation equation can be used [20].

$$ {}^{A}P = {}^{A}_{B}T\,{}^{B}P $$

Equation 1

where:

- ${}^{A}_{B}T$ is a 4x4 matrix containing the rotation and translation of {B} with regards to {A}.
- ${}^{B}P$ is the position vector of point P with regards to {B}.
- ${}^{A}P$ is the position vector of point P with regards to {A}.

2.4. Production and product design principles

Production and product design principles are essential to ensure a well-developed and efficient production system [21], the section below describes the most common production layouts, followed by a summary of some standard product design principles.

2.4.1. Production layouts

Selecting the proper manufacturing layout for a specific system can be challenging. High flexibility, short lead time, and high-capacity utilization are three important factors that should be taken into account during the development process of a manufacturing system. Product type and properties also influence the choice of the manufacturing layout. Different production layouts can be combined to achieve the desired goals; the five basic types are described below [21].

Fixed position: Resources in the form of personnel and equipment are transferred to a fixed place where the production occurs; this layout is most common in the construction and power industry, where products are few, and the tied-up capital is high [21].

Functional workshop: It can be seen as a resource-oriented layout, where the machines that perform the same type of operation are gathered in one place. This layout is flexible in terms of product mix flexibility; the trade-off is the limited volume of products that can be processed due to the high rate of transport and movement of the material, which prolongs the lead time [21].

Flow group: The product-oriented layout is often associated with short transport routes; this layout is designed based on the product properties and the manufacturing equipment which form a flow group. Usually, there is a controlling machine which the flow group is designed around, and in many cases, this machine is the bottleneck for the sub-process [21].

Line: High volumes and standardized products are the starting point in the designing process of a line layout. Usually, the machines are arranged sequentially in a continuous line according to the sequence of operations [21].

Continuous production: This production layout is used at high volume production, where the products are often measured in tonnes, litres, or metres, for example, in a nuclear power plant or a paper mill [21].

2.4.2. Design for Manufacturing and Assembly (DFMA)

Several methods have been developed to design products that are easy to manufacture and assemble. These methods are known as design for X (DFX), where X stands for what the method is used for [22]. One of the most famous DFX methods is known as Design For Manufacturing and Assembly (DFMA), which is an engineering methodology that focuses on simplifying the design of a product, efficient manufacturing, and configuration of smaller parts so that they can be planned and manufactured faster resulting into lower overall production cost and time-to-market. DFMA used to be divided into two different methods before it became a singular philosophy as it is known today. These two methods are Design For Manufacturing (DFM) and Design For Assembly (DFA) [23]. DFM and DFA are two of the most popular and common DFX tools since they allow more exact assessment of how the downstream product lifecycle impacts of design choices made upstream at early stages [24].

DFM methods focus on minimizing the complexity and the cost of manufacturing operations and raw materials. This is usually performed at an early stage during the product design phase. Manufacturing term is often associated with processes such as machining, where these operations are required to produce and assemble the final product. Manufacturing operations usually require high technical capabilities to ensure high quality, like, for example, good tolerances and surface finish. On the other hand, DFA focuses on minimizing the number of parts or assembly steps to reduce the assembly complexity, time, and cost. Assembling commonly refers to the joining or addition of parts produced during manufacturing [23],[25].

2.4.3. Design for Automated Assembly (DFAA)

DFAA is a similar design method for manual assembly (DFMA), built upon the methods-mime measurement analysis (MTM), where the focus is to design products to reduce the cycle time during manual assembly. What differs between the two methods is that DFAA is used to design the parts as friendly for automated assembly. The method itself should execute continuous improvements in the production and is not made to find solutions for one specific problem. The method can be condensed into the following thirteen steps which needs to be applied to create a product that is better suited for automated assembly [22]:

1. Minimize the number of components to be assembled.
2. Decrease the number of fasteners.

3. Choose a suitable base component.
4. Mount the base component so that no further changes have to be made in its orientation.
5. Choose an effective mounting fixture.
6. Facilitate the reach of subcomponents.
7. Adjust the components so that they are suitable for the assembly task at hand.
8. Strive to design symmetrical components.
9. Strive to design components that are symmetric in the mounting direction.
10. If asymmetric components exist, make these as asymmetric as possible so there is no mistaking the direction they should be mounted.
11. Strive to assemble the components from the same attack direction and in a linear fashion.
12. Take advantage of chamfers, guides, and elasticity to simplify integration.
13. Maximize the available space during assembly.

The DFAA method works by analysing the product on two different levels, first at a product level and then on a more detailed level. The product level analyses the following [22]:

- Reduce the number of components.
- Have as few unique components as possible.
- Choose one base component that the rest are mounted on to.
- Angles of assembly.
- Parallel operations.
- Tolerance chains.

The detailed level seeks to further investigate each subcomponent and its different characteristics. It can be divided into three subcategories [22]:

- The component's functions: Can the component be integrated with other components to make a more significant component which does not need to be pre-assembled, what orientation does the component have, fastening methods, is it a fragile component.
- Its characteristics: weight, shape, length.
- The component relates to other components when assembled: movements during assembly, tolerances, integration, fastening method etc.

2.4.4. Level Of Automation (LOA)

The strive for automated solutions in the industry has been a critical path to mitigate the high wage cost in Europe and the US, enabling them to compete with low-wage countries. The 20th century was marked with efforts to increase efficiency and quality through automated production solutions, with the idea of “lights out factory’’ going back to the 1980s, a factory that in theory could operate in the dark without any operators present. Due to the complexities of different tasks and increased product customization. Most manufacturing systems remain a combination of automated and manual solutions to this day. Highly automated solutions to increase flexibility or efficiency may at first seem to be the superior solution but can instead result in poor system performance and vulnerability to disturbances [22].

One recent example of this was the case of the company Tesla in 2017, where the idea was to build a “lights out factory’’ to produce their model 3. The over-automated production process could not deal with the complexity and variation, resulting in a less efficient production with inferior quality. Ultimately, Tesla had to redesign its process, introducing humans who are better at detecting errors and dealing with variations [26].

To subjugate the mistakes of high LOA, it is crucial to find the balance between automation and human solutions. One method developed for this purpose is Dynamo++, which gathers information about the current system and thorough analysis determines the level of mechanized and cognitive automation most suitable for the specific production task [22].

2.4.5. Dynamo++

Dynamo++ is a method developed to analyse an existing production setup and find possible automation solutions. The method works by determining the cognitive and physical LOA needed for the task, giving guidelines into what type of automation solution is suitable. The analysis is carried out in 4 phases beginning with a current situation analysis. Here data is collected with the help of DFAA, competence matrices, hierarchical task analysis (HTA), and Complexity Index (CXI). With this analysis, a general understanding of the current production is formed, built upon in the following phases. In phase 2, measurements are taken to determine the LOA within the two categories, physical (LOA_P) and cognitive (LOA_C). These levels are plotted on a scale from 1 to 7. With a score of 1, the task is entirely manual without any tools needed, and the fitter performs the task using his own experience [22].

With a score of 7, the task is completely automated, the machine can switch between different products by itself and makes all the decisions, with no operator guidance required. Phase 3 consists of analysing and presenting the data collected from phases 1 and 2. Since this will be the foundation for further improvements in the upcoming phases it is important that the analysis is agreed upon, If not, one should go back to phases 1 and 2 to check if the data is valid. When the analysis is deemed correct, the analysis of each task can be carried out. This is done by examining each task and setting a min- and maximum value on the physical and cognitive automation possible in the respective task. When several tasks have been analysed, and a SOPI matrix has been made for each task, the tasks are overlaid into a single SOPI matrix to see which possible LOA they have in common. An example of this can be seen in Figure 7 below. From this matrix, decisions can be made into which tasks can be improved and which ones can stay as they are [22].

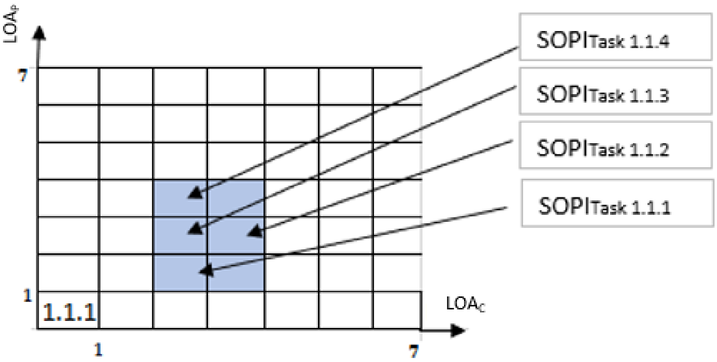


Figure 7. *Possible LOA for all analysed tasks [22]*

Phase 4 is the implementation stage; here, the solutions are implemented and tested, KPIs are measured, and interviews with operators are conducted. It is essential to get a complete overview of how the solution performs and if there are any drawbacks or further improvements to be made [22].

2.5. Automation system components

This chapter outlines various types of handling equipment for material transport to and from an automated production system. The chapter includes a general description of conveyors, automated guided vehicles (AGVs), autonomous mobile robots (AMRs), and part feeding equipment.

2.5.1. Handling equipment

One crucial part of manufacturing is the material handling to and from workstations. This is not a value-adding task, and a poorly designed system may result in excess work in progress and handling, disorganized storage, damaged products, and idle machines. Therefore, the aim should be to streamline the process so that the correct parts get transported to the right place, at the right time with the quantity required. There are many different types of equipment to achieve this, such as forklifts, conveyors, and cranes. The three central handling systems for automation are conveyors, discrete vehicles, and part feeding equipment [12].

2.5.1.1. Conveyors

Conveyor systems provide a fixed movement between two points with a set path; this can be between automation systems or within them. They offer great benefit when moving high volumes of products through a factory and can be mounted on the floor, above it, or in the ceiling, as well as providing temporary storage and buffers between the workstations. There are many conveyor systems; standard types are belt, chain, and roller conveyors, each having its advantage depending on the product being transported [12].

2.5.1.2. Discrete vehicles

Automated guided vehicle

AGV is an unmanned vehicle guided automatically through the factory, often by wires on the floor. They provide a flexible alternative to conveyors. They can move around the factory, transporting material where needed, and are not dependent on other workstations to complete their task. However, they do not provide the same level of high-volume throughput as conveyors, no intermediate buffers, and are more expensive. They are also limited in size and the weight they can carry, and the fact that implementation where wires are buried in the floor makes any changes to their path inflexible and expensive [12].

Autonomous mobile robot

If AGVs were a train then the AMR would be the automobile. While AGVs follow a set path and use simple sensors to avoid a collision, the AMR is packed with sensors and a powerful onboard computer that helps it understand the environment in which it operates. This gives it the ability to navigate dynamically using a map to plan the most efficient path to travel to their destination while being smart enough to avoid collisions with personnel, forklifts, and other objects. Their flexibility makes them both cheaper and more efficient than AGVs. While all the extra computers and sensors at first glance may seem more expensive, they can be as much as 40% cheaper than AGVs [27].

2.5.1.3. Part feeding equipment

All automation systems need to feed individual parts into the system, and the method of doing so can vary greatly depending on the product being produced. As mentioned previously, one solution could be a conveyor system. Another could be a manual loading of sheet metal components into fixtures. For assembly, there is a necessity to feed individual components in high volumes with a frequency that matches the assembly speed [12].

These components can range from parts to be assembled to joining tools such as screws or rivets. The task of the feeder is to orientate parts that can be delivered loosely in boxes or crates and continuously feed the system with as little interruption as possible. There are several types of feeding systems available. Some common designs include the bowl, linear, blow, bandoleer, and magazine feeders, with the most common solution being the bowl feeder, which makes up about 80% of all installations [12].

Kitting is a method used to group different components together into a single assembly kit according to their future assembly schedule. These are then stored close to the assembly line and supplied through different logistical means. Based on the assembly schedule derived from cycle times or takt times, the kits are continuously supplied, providing the line with the parts necessary for the operations [28].

2.5.2. Vision systems

Machine vision means using optical sensors to send and receive information to automatically interact, monitor or control a certain process. Vision systems have a wide range of applications within automation areas, such as product or tool inspection, pick and place procedures, etc. Recent technological developments have resulted in a significant reduction in the cost of vision systems while their capability has improved tremendously, enabling their usage in automated manufacturing systems [12].

Machine vision is not yet as accurate as human capability; for instance, human vision has much higher resolution and analyse complex situations rapidly. Thus, the application of machine vision needs to consider these facts. Although, unlike humans, machine vision can operate in almost any environment, or even outside the visible light spectrum, these systems can be characterized as tireless, consistent, and can perform the pre-programmed task with great precision [12].

Measurements, part identification, and inspection are some major areas where machine vision can be applied within the automation field. For instance, an inspection can be used in mass production lines or even in microscopic inspection areas for different kind of small parts, where sizes at the nanoscale matter in term of measurements. When it comes to robot applications, robot guidance is one important area, i.e., a robot needs to be able to navigate and find itself in the space with the help of vision systems. Such applications are picking and tracking applications, or even parts detecting, barcode reading and scanning [12].

The main components of a typical machine vision system are a camera, lighting, a processing device, and software. Furthermore, there are three principal tasks within a vision system. The first one is to get an image, secondly to modify or process this image, lastly to extract the needed information. The system software supports, coordinates, and performs the analysis needed to perform these three main tasks [12].

2.5.3. Grippers and tool changers

Grippers are defined as an active link between the workpiece and handling equipment. They have a wide range of applications in automated solutions; some common areas are industrial robots, automated solutions for assembling and packing, tool changing in CNC machines, and load-carrying equipment. In robotics, the functionality of grippers varies greatly, and they are usually designed to serve a certain need for a specific application. Grippers can use different grasping techniques and are not limited to prehension methods alone, hence the generic name "end effector" in robotic applications. In broad terms, gripper types can be classified into four categories [12],[29]:

- Impactive: a mechanical force is applied in two or more directions to the workpiece. Can be applied with chucks, internal or external fingers and tongs.
- Ingressive: the gripper permeates the object surface to achieve prehension of the workpiece.
- Astrictive: a binding force is applied to the workpiece in one direction through vacuum, electromagnetic fields, or electro adhesion.
- Contigutive: grips the workpiece through adhesive methods.

Impactive mechanical grippers are standard and have a wide range of applications. This gripper type is mainly suitable for picking components that are not easily damaged by forces from the gripper. They can be either electric, pneumatic, or hydraulic driven. Pneumatic grippers are suitable for lighter use cases; their simple mechanism makes them low weight with high speed at a low cost. Hydraulic grippers are usually used for high load cases that require higher forces. However, they come with drawbacks in maintenance and reliability. Electric grippers are used when more precise control is needed and can be equipped with servo motors, allowing the robot to accurately control the gripper's yaw position. However, they come with penalties in weight and cost. Mechanical grippers come in a variety of shapes and numbers of fingers, where the most common being between 2-4 fingers [12].A significant part of the impactive gripper is its finger design, as this is the active part creating contact between the gripper and the object to be manipulated. An essential feature of the fingers is to provide enough stability while gripping so that no misalignment of the object can occur. This can be ensured by applying an effective gripping force at the contact points or active surfaces [29].

The type of contact and number of contact points influence the required gripping force and retention stability. Overall, there is several categories in which the finger can create contact with the object. An illustration of these can be seen in Figure 8 where the contact types are described as: A - single point contact, B - line contact, C - surface contact, D - circular contact and E - double line contact. The best retention stability is achieved by matching the finger profile to the object surface, hence creating a uniform fit with multiple points of contact [29].

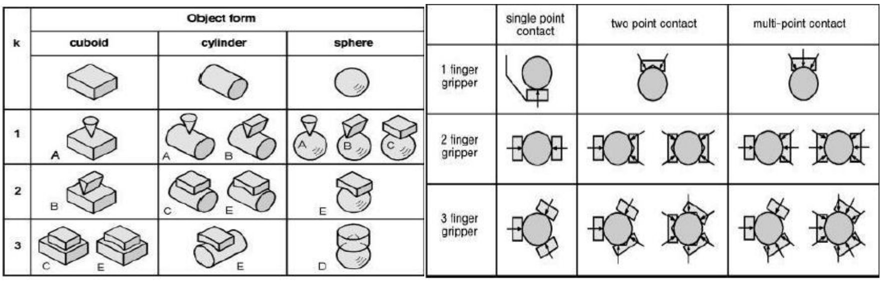


Figure 8. *Number of contact points between the gripped object and the gripper jaw, right: gripping methods depending on number of fingers [30]*

Vacuum cup grippers fall into the category of astrictive grippers. They are commonly used for handling flat parts, boxes, and similar objects. They provide excellent efficiency, speed, and have a soft rubber cup, making them ideal for handling scratch-sensitive parts. However, they can have problems working on varied surfaces with curvy or uneven structures. Designers can mitigate the problem by implementing high-flow vacuum generators or altering the cup size. They also need to operate on clean surfaces as dirt and dust can get clogged in their vacuum system. Magnetic grippers can be used to lift ferrous materials and work by engaging an electromagnet to create a magnetic field around the gripper. They provide great reliability with low maintenance [12],[29],[30].

2.5.4. **Nutrunner**

A significant part of assembly operations is to join two parts together with the help of fasteners. A widely used tool in industry is the nutrunner which uses either hydraulic, electric, or pneumatic systems to tighten threaded fasteners where the correct torque is crucial for the application. The mechanism in the tool uses a torque multiplier with an absorption platform which reduces the impact on the operator without impacting the capability of tightening industrial bolts. The multipliers are used to control the amount of torque necessary to meet the application's specification [31].

2.5.5. Tooling and fixating

Fixtures are used to hold and locate a part to be processed in an accessible and stable position to enable a robot to perform its motions in a repeatable manner that provide the required results. Fixtures are mainly categorized into two different variates: dedicated and reconfigurable. A dedicated fixture is designed for one specific product or geometry and is usually most suitable for mass production applications where their cost can be distributed over the high volume of products produced. In a lower volume production with higher flexibility demands, a reconfigurable fixture is more advantageous. Since it is designed for a family of different product geometries it offers greater flexibility and reduces set-up times between product switches in production [32].

A common way to fixate a part in a fixture is through clamping systems, which should be easy to mount and remove, to enable simple load and unload procedures. Different clamp types can be used depending on the application area and the process environment. Manual on/off clamps are the most common type, due to their low cost and simple functionality; one drawback is that they depend on the operators to close them correctly. Manual on clamps with air backup and automatic off is another type of clamp that is used in industries. These are manually closed but they are pushed closed when the system sends a signal to apply air pressure to the clamps. These types of clamps can even automictically open once the cycle is complete, the main benefits of using such clamps are that they provide greater certainty of closing, allow for quick unloading of the parts and reduce time for releasing the clamped part [12].

Using auto on/off clamps is another solution that can be applied. A part can be loaded into the fixture and once the signal is initiated the clamps close. These types of clamps save time both during loading and unloading, yet they require a high design standard to ensure faultless function, while manual clamps can operate even if the design is poor. Sensors can be added to the fixtures, either as part-present sensors that detect if the parts are loaded correctly, or sensors to make sure the clamps are working correctly.

Clamps and vacuum can be used to hold parts in place, additionally in some other applications, clamps need to tolerate the forces applied to the parts during the process. Other types of tooling can be used when no force is applied to the part to hold a part in position [12].

Tooling material is important, considering the heat generated during welding, a heat resistant material should consider for such application, while plastic is suitable for other applications such as mounting and material handling. Robot cells will always perform as good as the parts are presented, for that reason an investigation on the clamping, tooling or fixturing method to be used is desired to ensure the planned output [12]. One way to design and construct a clamping fixture is to use the following four steps [32]:

- Fixture setup planning: in this step the number of setups to be used, orientation of the product or workpieces are defined.
- Fixture configuration planning: determine the points where the product is to be located and clamped to achieve full retention.
- Fixture construction: select fixture elements and position them in their final configuration. Locate and clamp the product.
- Fixture assembly: assemble the fixture according to the previous stage.

In the setup planning stage, the number of different setups required for the fixture and the orientation of these are defined. In the configuration planning stage, the points that locate, clamp and restrain the workpiece are determined [32]. A method used in this stage to achieve geometric control is the *Axiomatic design* technique. The technique builds upon that a workpiece has six degrees of freedom and twelve directions of motion which are restricted by locators and clamping forces. One locator restricts movement in one direction, so for a full restriction of motion, six locators are needed while the remaining six will be restricted with the help of clamping tools. The placement of the locators and how they restrict motion can be seen in Figure 9 below. The function of each locator is as follows [33]:

- Δ1 blocks any motion in the -z direction.
- Δ2 blocks the rotation along negative y-axis direction.
- Δ3 blocks the rotation along negative x-axis direction.
- Δ4 blocks any motion in the -x direction.
- Δ5 blocks the rotation along negative z-axis direction.
- Δ6 blocks any motion in the -y direction.

The method consists of the following six axioms which are used as a rule to place the locator positions [33]:

- Axiom 1: to sufficiently locate any workpiece no more than six locators are necessary. More than six will result in redundancy and uncertainty in location.
- Axiom 2: to define a plane three locators are needed.
- Axiom3: on each degree of freedom only one direction is located.
- Axiom 4: there only one locator for each degree of freedom.
- Axiom 5: In order to provide the maximum stability and avoid workpiece irregularity the six locators should be spaced as widely as possible.
- Axiom 6: to locate a cylinder only five locaters are required.

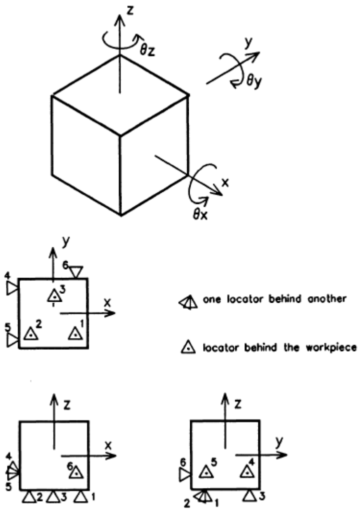


Figure 9. *The six locators to locate a cube [33]*

The five first axioms are combined to give the 3-2-1 location system where the locators restrict the workpiece motion by placing them in an order of three on the largest plane, two on the second axis perpendicular to the first and one on the third axis. When all the clamping and location points are defined the final configuration of the fixture can be determined and constructed in the fixture construction stage. When this is complete the fixture is assembled in accordance with the previously defined configuration from the construction stage [32],[33].

2.5.6. System control

A control system is crucial for the operation of an automated system; it provides essential vital functions, such as controlling the elements of the system, ensuring that they all operate in the sequence that was intended, presenting data that is easy to understand for both operators and supervisors, an error system that assists maintenance personnel with information in the event of faults and safety functions to ensure that the system is operated and maintained in compliance to safety regulations [12].

2.5.6.1. Programmable logic controller

Before the invention of the programmable logic controller (PLC) in the 1960s, these functions were carried out by banks of hardwired relays, that offered low flexibility and often high complexity. Through ladder logic programming in the PLC, the relays could be replaced with software allowing greater flexibility and ease of use. At the basic level, the PLC works by getting inputs from sensors in the equipment, that will activate specific inputs in the PLC module, which results in the PLC giving an output that activates an actuator. This could be a conveyor belt that is waiting for a box to be placed on it; that when placed, activates a sensor that provides an input to the PLC, which gives the output to actuate the motor, and the conveyor starts moving. In safety aspects, the PLC can be programmed so that doors must be closed for the system to run [12].

PLCs are still widely used today in system control, with their programming and capability developed over the years. They can come in a wide range of system applications from microunits with a few digital inputs and outputs (I/O) to larger units that control hundreds of I/Os, analogue functions, and interfaces with networks such as Profibus and Ethernet. In a robot application, the PLC can provide the overall control and interface with a Human Machine Interface (HMI) system that provides the operator, maintenance, and other personnel with information about the system and process and control functions such as start, stop, and reset [12].

2.5.7. Safety and guarding

The main goal of safety and guarding is personal safety by ensuring that no person can harm themselves during an operation or maintenance of a system. Some standards describe guidelines and require assessing the different risks within an automation system; such standards are commonly provided by the suppliers, while companies often have additional internal standards. These standards state assessments of all potential risks to be minimized or eliminated by applying the guarding and safety systems [12].

Safety measurements are strongly dependent on two different main factors. The first one is factory-specific requirements; many factories have internal standards where the controls and safety issues are addressed and standardized. The second factor that control and safety are dependent on is legislation for a specific country, which varies in different regions of the world. The basic idea for control and safety is that a person cannot be exposed to danger, which means that the automation system needs to be secured to prevent access into the working area of an automated machine; this does not need to be the case for all types of automation systems. Many automation companies such as *ABB* are investing and developing collaborative robots, where humans and machines can integrate with each other in a safe environment and these robots are designed with inherent safety to ensure that humans can work alongside [34]. However, the majority of automation systems are not there yet, which means the systems need to have safety measurements in order to prevent human access to working automation environments, except in some controlled circumstances, which could be needed for maintenance and control purposes [12].

Safety should be considered at the early stages of automation solution development to ensure the system can perform its task effectively and safely. PLC is one tool that can be used to integrate and control every element of an automation system. HMI can be based on the PLC where humans can interact, control and maintain the system. HMI has considerable importance since it provides information on what has failed in the system and effectively guides maintenance personnel in the right direction. Concept designs need to address other issues such as housing the PLC, location of the control panel, the location and number of HMI systems [12].

2.6. Solution development

The following chapter outlines essential steps that can be used when developing an automation solution. Determining the application parameters for the automation project is one of the first steps to developing a successful system.

2.6.1. Determining application parameters

The development of a successful project starts with obtaining a detailed understanding of the project and its application. It may seem like an obvious step, yet its importance should not be overlooked as missed details at this stage may lead to failures or costly changes at commissioning.
Firstly, all the drawings and documentation on the parts being produced and process details should be obtained [12].

One other important thing is to check the actual part for variations in dimensionality, surface finish, cleanliness, and part presentation. If a system is built entirely from drawing the parts, these real-world variations may cause problems further into the project. Operators can also be an excellent resource for information regarding the process and parts. They may work in specific ways or use methods that make the process easier, which may not be detailed in any work plans and process documentation. This can be things like solving part-fit problems or production problems that have not been further communicated to other parts of the organization. After the groundwork is done, the next step is to define the production rate and capacity, which can then be used to determine a suitable cycle time that meets these numbers. Metrics such as downtime due to breakdowns, planned maintenance, and replenishment of consumables should all be included [12].

2.6.2. Initial concept design

Previous experience often assists when designing an initial concept; together with a detailed case study of the application, an engineer may suggest a possible solution based on previous experience. However, each application has its circumstances. The concept design process can be seen as an iterative process yet having preceding insights can facilitate the development and understanding of the project. The coming section explains one of the main robot application areas and some significant issues related to developing a solution [12].

2.6.2.1. Assembly

Assembly operations can typically be divided into two types of procedures: adding new parts to the product and the other being the attachment of fixturing parts such as screws and glue. A first step to automate such procedures is to break down the process and find how many operations it consists of and its sequence. The automation system design is often dependent on the number of procedures; for a process with a small amount, it may be possible to carry out all operations within one robot cell. It is more beneficial for more complex and more extensive assemblies to divide the process into subassembly tasks with a transport system such as conveyors or AGV/AMR that carry the product to the next assembly station [12].

Once the number of operations and subassemblies have been determined, it is time to look at what type of automation equipment should be used for each stage. A part of this development stage is to assess the cycle times for each operation; the slowest operation will determine the system's output. Therefore, it is essential to balance all the cycle times to not differ too much from each other [12].

2.6.3. Testing and simulation

A big part of concept development is testing a proposed solution to see whether the solution can achieve the desired results. This can be done through both physical testing and using a digital twin to simulate the process. While physical testing is a sure way to test if a solution works, it can also be costly to test everything on the actual system; certain things must be tested in the physical world, such as gripper functionality. For instance, if the robot is picking and placing fragile components such as biscuits, it can be hard to simulate this in a digital environment [12].

Simulation with digital twins allows the engineer to test the system's performance on a detailed level with a relatively low cost and risk. Things like the kinematics of the robot and surrounding equipment are ideal for testing in a virtual environment. The kinematic simulation is carried out using digital models of robots, parts, and equipment to build a virtual environment of the robot cell. Here things like collisions, configurations, and cycle time can be determined. Different types of robots can also be tested and compared with each other. One other advantage is that it provides a presentable simulation shown to supervisors, giving a better foundation for decision making [12].

2.7. Integrated control logic design

A frequent mistake when developing a new automation system is to design the control logic too late in the process; this can affect both the efficiency of designing the control logic and the quality of the completed automation system. Also, suppose the control logic requirements are not defined at an early stage in the process. In that case, it may lead to significant redesigns of the product or the mechanical resource later in the project, which can lead to unnecessary expenses and delays. By defining requirements and specifying how the logic should work, the information of the control logic design can be handled in a unified way, increasing efficiency during the whole development process and reducing time spent on finding information from different sources late in the project. Defining essential properties and the relation between the product and its manufacturing system can be seen as a crucial step to obtain an integrated control logic design from an early product design stage to a production-ready stage. This step needs to be carried out before anything else since it can be seen as the basis for the operation-oriented approach for developing an integrated control logic. The operation-oriented approach appraises operations as the basis for manufacturing design and even for the control logic specification since they state the logic to execute each task. Therefore, operations need to be studied in detail where the product parts are specified, and the relations are fairly described, the process is investigated, and finally, the resources to perform the operation are explored. This is to accomplish and realize the connections and design an optimal integrated logic control [35].

A. Product specification

A product is made up of parts and features; these two elements can be defined as entities, that interface with entities from other parts and features; this interface is called liaisons; a liaison interface may contain information about a location, orientation, or a connection. Liaisons, in turn, are executed by one or more operations. Lastly, an operation is performed using one or more resources [35]. Figure 10 below illustrates an example of the relations between a product and manufacturing. Part entities can be seen as standalone entities that are assembled in a manufacturing system, parts are physical entities, while features in some extents are harder to specify and can contrail logical and abstract product entities since the extent of features are much more extensive. For example, a feature from a feature-design perspective can be seen as a property that specifies what will be removed by a machine, like a slot or a hole. In contrast, in other cases a feature could define other types of information such as reference points and spot welds [35],[36].

B. Process specification

One or more operations are usually performed in order to manufacture a product at a process level. Therefore, the connection between the product and the process design is crucial for an optimal process design. Liaisons are carried out by a set of operations in a manufacturing system based on the product design and the assembling methods. Therefore, this basis should be investigated as early as possible during the process design phase.

In many cases, manufacturing operations cannot all be carried out simultaneously or in parallel; some operations may have sequence or order restrictions. An operation should wait for the previous operation to be completed, and then the next operation can begin [35].

C. Resource specification

Each operation specified in the manufacturing process uses one or more resources to be actualized or performed. This results in a strong connection between the design of the process and its resources. An example of this could be drilling a hole; the process would define the drilling operation while the resource would define the type of tool to use. Resources can be physical types of equipment such as conveyors, fixtures, robots, and other tools or virtual instruments in the manner of variables and communication interfaces [35],[36].

D. Accomplish and realize connections

From the previously mentioned definitions, it has been concluded that one or more operations accomplish a liaison between two products. These operations are in turn realized with the use of one or more resources. The definition of these bi-directional connections is the accomplish connection and realize the connection. The accomplished connection illustrates that an operation partakes in accomplishing a liaison; in other words, it will accomplish the liaison at a certain point in the operation sequence. This connection is used to define constraints in the product design and manufacturing design, where product constraints can be things like tolerances, geometry constraints, and opposite directions. Manufacturing constraints can be things like changing liaisons due to problems with manufacturing functionality or new tolerance requirements. The realize connection defines that a resource is involved in realizing an operation. The resource is chosen for the operation if its capabilities correspond to the operation requirements [35].

E. Control logic design

In the control logic design, the connection between resources and operations is described in more detail. This stage focuses on specifying things like electrical cabinets, I/Os, safety, and sensors in a more detailed manner than the resource specification stage. Every resource has defined variables that represent input and output signals; for example, if a robot has a function block designed for its communication, the inputs and outputs would belong to this resource. The operations will then use the variables at the resource to control and communicate with it [35].

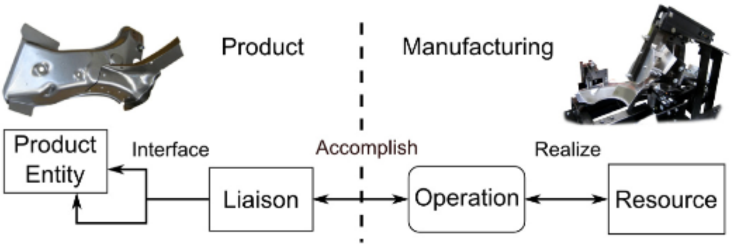


Figure 10. *An example of the relation between a product and manufacturing [36]*

2.7.1. Operations planning

The relations among manufacturing operations can in many cases be described as complex, mainly when designing a new automation system or developing an existing one. This is because these operations constantly change their relations throughout the development process. Therefore, it is necessary to use some form of a method or standard to plan and coordinate the sequence of these operations. Sequence planning can be used when designing an automation system; it is mainly used to determine how operations should be carried out. Sequence planning combines both high- and low-level requirements. The Sequence Of Operations (SOP) is another method that can express the order of operations and understand the relations between the mechanical design and the cell control, and even between the product design and the total system behaviour [37].

This method improves the understanding of the sequential behaviour, visualizes the operations, and contributes to developing manufacturing systems by optimizing and verifying operations sequences [37].

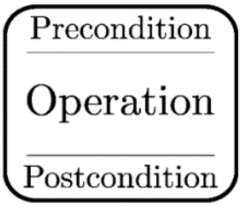


Figure 11. *Example of an operation in SOP [37]*

Figure 11 illustrates how an operation is visualized in SOP language, where each operation contains a set of conditions, describing how and when an operation should be performed. The first field is called “Precondition”; an operation can have one or more preconditions that need to be fulfilled to execute the operation. These preconditions define when an operation can begin, safety interlocking and guard expressions that are in connection to other operations can be included in the preconditions. Additionally, preconditions can cover actions expressing the output of an operation. In the second field, “Operation,” the actions to be performed during the operation are stated. Finally, the third field, “postcondition,” can define when an operation is completed. An operation will continue the execution of the operation until the postconditions are fulfilled. Similar to preconditions, postconditions may contain both actions and guards [37].

In summary, operations are the foundations for an integrated control logic design. Therefore, the product, process, and resources need to be integrated via the operations to obtain an optimal manufacturing system design. Entities are the parts and features that build up a product, which interfaces with entities from other parts and features; these interfaces are called liaisons. One or more operations execute liaisons. In turn, an operation is performed using one or more resources. To operate, one or more preconditions need to be fulfilled; additionally, one or more postconditions can define when the operation is completed. This set of conditions determine in what order the operations can be carried out for the manufacturing control system to produce a product [36].

2.7.2. Flow charts

In the planning phase of program development, a flow chart is often created after the initial written description has been defined. The flow chart translates the written text into a more easily understood graphical representation of the program logic and sequence, that records, analyses and communicates information. As shown in Figure 12 below, the flowchart is made up of boxes of different shapes and sizes that follow a path where each box represents an operation ranging from input/output, decision, or data process [38].

The flowchart brings forward the relationship between broad concepts and minor details that makes them appear in a way that is hard to achieve through a general description. As shown in Figure 12, there are different flowchart symbols with specific meaning that helps with the interpretation of the system. An important aspect to think about when making a flow chart is its complexity. If a system is extensive, it is better to make one main flowchart that shows primary functions and then make smaller flowcharts that describe each subfunction in detail [38].

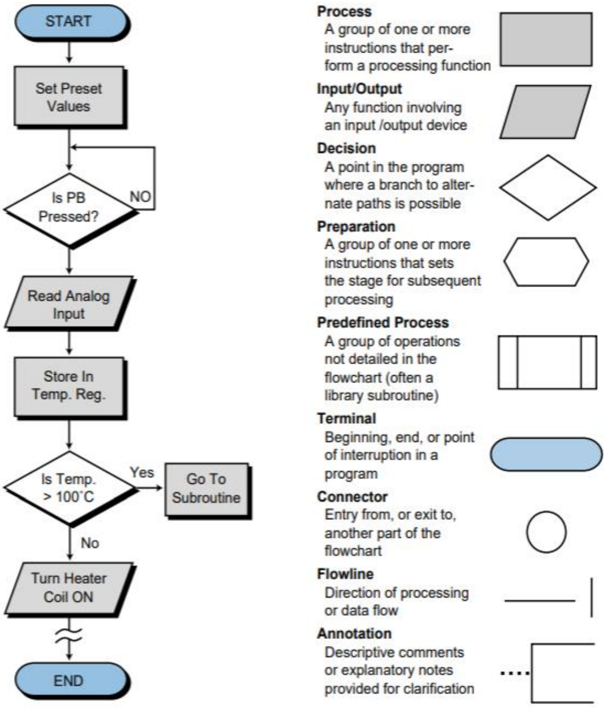


Figure 12. *Left: flow chart, right: Flowchart symbols [38]*

2.7.3. Operation optimization

A manufacturing system can consist of hundreds of operations at different levels. These operations can be reorganized and optimized in order to increase overall productivity and reduce the cycle time. There are some common ways to optimize a robot cycle time regarding operations in an automated production unit. One way is by making the robot trajectories more efficient by adjusting the speed of individual motions and targets/waypoints. Another way is to reduce the stop time of the robot, by, for example, adding special move instructions or zone data [39].

When the robot moves between waypoints, it usually makes small stops to change direction, this results in the robot slowing down. Adding blend radius/radiuses is one solution to this issue when it comes to *Universal Robots* (UR). Blend radius/radiuses enables a trajectory path to reduce the travel time between the waypoints, which results in the robot moving around the waypoint and not through it. In this way, the robot does not need to accelerate and deaccelerate its motors around the waypoint every time. Figure 13 below illustrates a trajectory path for an UR robot where waypoint 2 has an additional blend radius instruction [39].

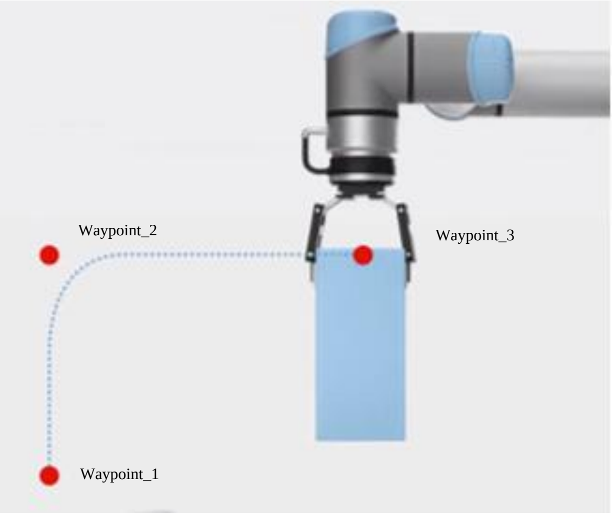
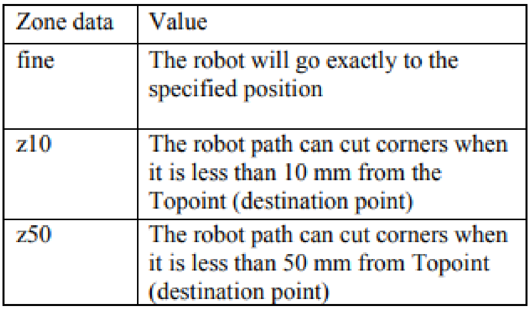


Figure 13. *Waypoint with blend radius for UR [39]*

The same approach can be applied to other types of robots, but the syntax may vary depending on the manufacturer. For example, *ABB* robots instead use “zone data” to define whether the robot needs to go precisely to the specific positions zone “fine” or if the robot can cut corners and not stop at the exact point. Table 2 below illustrates three different examples of zone data [40].

Table 2. *Zone data for ABB robots [40]*



Zone data	Value
fine	The robot will go exactly to the specified position
z10	The robot path can cut corners when it is less than 10 mm from the Topoint (destination point)
z50	The robot path can cut corners when it is less than 50 mm from Topoint (destination point)

Yaskawa robots use position level, which technically fulfils the same purpose as *UR*’s blend radius or *ABB*’s zone data. These position levels can be added to a move instruction and result in a reduced stop time of the *Yaskawa* robots. Figure 14 illustrates an example of the different position levels for Yaskawa robots [41].

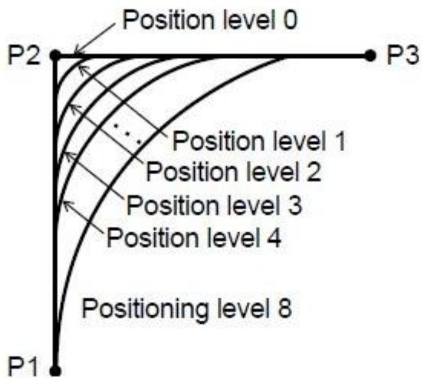


Figure 14. *Example of different position levels for Yaskawa robots [41]*

Robots’ operations can be optimized by increasing the speed and the acceleration, this can be achieved for almost any type of robot. However, lower speed increases safety, and lower acceleration values can potentially increase the lifecycle of the robot joints [39].

3. Methodology

This section describes the methodology that has been used to fulfil the purpose of this master’s thesis and answer the research questions. The section mainly discusses the research designs that have been used in this study, the approach, data collection, validity, reliability, and finally, source criticism.

3.1. Research designs

The choice of method is governed by the type of phenomenon studied and the empirical data to be collected, which can be mainly characterized as quantitative or qualitative data. The main research methods are Survey, Case Study, Experiment, System Development, and Action Research [42].

3.1.1. Case study

This method is chosen when a smaller limited group such as one, a group of individuals or an organization wants to be studied. The study is done with a holistic approach that collects information about the big picture as precisely as possible. A combination of data collection methods, such as interviews, surveys, and observation, can be used to achieve this. It is common in a case study to use both qualitative and quantitative data collection to get an as comprehensive overall picture as possible [42].

3.1.2. Action research

Some systems can be studied and developed at the same time. In such cases, an action research method design can be presented, where the objective is to improve and study a case simultaneously. This method is valuable for studies that can be characterized as problem-solving studies. Action research methodology starts with an observation of an existing situation, to identify and clarify the problem. The next step is to develop a possible solution and implement it. After that, an evaluation phase takes the place of the implemented possible solution. This can be done by analysing and reflecting on how the solution has been applied. This process can be described as an iterative process that can be repeated frequently until an optimal solution is obtained. The action research process is based on a similar concept used in continuous improvement models such as the Shewhart cycle, which usually referred to as the Plan, do, check, and act (PDCA) cycle [43].

This concept has a strong presence and multiple application fields to control and continuously improve processes and products. Action research aims to influence, affect, and evaluate a process at the same time. This could be problematic in some cases since it is hard to be critical to a solution that one has been involved in executing and implementing previously. This can be avoided by deciding a fixed list of criteria to have an objective assessment [43].

3.2. Approach

The research method used in this study consisted of two methods, firstly as for the overall project a case study method in the selected company, where a limited department is under investigation, in this case, Scania, is the selected company, and the SFL is the limited department which is under investigation. Collection and verifying of data have occurred continuously, based on a similar approach as action research, a method to study and develop a system simultaneously [43].

The study has been conducted by combining quantitative and qualitative approaches, common in a case study, to get one comprehensive picture. Finally, a comparison of the final evaluated solution has been made with the theoretical framework and the system analysis, including manual assembly procedure to conclude the study. The comparison aims to get a greater overview of the available technologies for the automated and unmanned assembly production lines and arrive at solution proposals and recommendations for the investigated company. Additionally, a simplified method that describes the steps needed to transform a manually fashioned assembly line into an automated one has been obtained, based on the procedure that has been carried out through this project and the obtained results.

The project started with a pre-study phase that consisted of a literature study, which covered general topics, including different approaches of how to proceed with automating a manufacturing system and the typical requirements and components for a traditional automation system. This was done to give a background on the project area and provide enough information for both the reader and researchers on the targeted fields. The next phase in the study was to investigate the manual assembly process and its components as it was, and the next step was to explore the potential automation solutions available and select the necessary based on the literature study, current situation analysis, and market research.

The following step was the designing and developing phase for the automation system components. After suitable solutions were developed, the next step was to test and verify these solutions in order to evaluate and improve them so that they could be tested again. These four last-mentioned steps can be seen as an iterative process, where the steps are repeated over and over again until an optimal solution is obtained as in an action research methodology fashion. Figure 15 below summarises the course of action for the study.

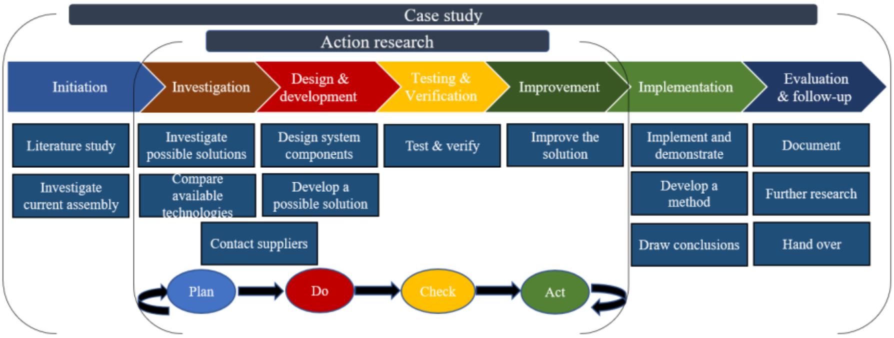


Figure 15. *Overall thesis methodology*

Finally, the implementation phase represented the step where the final solution was implemented, and the summarising conclusions were drawn. In this phase, the research questions have been answered, and the purpose of the thesis is fulfilled. Additionally, the evaluation and follow-up phase for the project will be carried out from Scania's side. Further research has been recommended in order to sustain the cycle of continuous improvements.

3.3. Data collection

3.3.1. Primary data

Primary data is the information that the researchers collect for analysis from main sources. Here the investigator has good control over the research process and can ensure that the validity of the empiric data is reliable [44].

For this study relevant primary data was collected, firstly through current system analysis, which describes the manual assembly procedure to be automated as it is today. Secondly through serial experiments and testing of different ideas, as in an iterative process where different ideas were implemented, tested and evaluated repeatedly to obtain optimal automation solutions, this has been enabled in the SFL environment.

Other type of primary data was used in this study, such as different data sheets that were obtained from a variety of suppliers within the automation field, and technical interviews that were carried out with various industrial automation suppliers. These data sheets were used as a basis to make various comparisons for the technical criteria of the obtained automation system components, such as for the robot and gripper selection. Compilation of the data sheets can be found in Appendix B.

3.3.2. Secondary data

For this study relevant secondary empirical data in the form of theoretical framework have been collected. The theory is primarily about the investigated subject in general to get a picture of the investigated area, which is automation solutions as a concept and the possible automation solutions that exist and can be implemented in order to execute this project. This was in order to later perform an in-depth study of different automation solutions that enable the project aim which is transforming a manually operated assembly line of a pedal car into unmanned and fully automated line.

To supplement the current situation analysis more empirical data has been collected from Scania’s resources, which include both quantitative and qualitative data that describe the manual assembly tasks, CAD models, and simulation and programming software.

3.3.3. Quantitative

A quantitative method is an approach where the researcher uses different measurements methods to collect numerical data as well as processing and analysing methods that are of a statistical nature [42]. Today's SFL layout has also been investigated using a 3D simulation program (IPS). Different variables of a quantitative approach have been performed in the form of time measurements and calculations on various performance measures. Finally, a comparison of different quantitative data represented as evaluation criteria, such as cycle time and repeatability between the manual and automated solution has been performed.

3.3.4. Qualitative

Qualitative methods focus on collecting so-called "soft" data that consists of an analysis, where the starting point is to interpret verbal data and interviews of a qualitative nature [43]. Part of this study has been conducted with a qualitative approach in the form of interviews, which have been structured and based on a non-random sample. Interviewees were chosen in advance based on their connection to the studied area, primarily suppliers working on automation system components. Other meetings have been carried out with people at the examined department. The interviews have been unstructured, with a low degree of standardization where the questions have been open, and the sequence of questions decided to some extent depending on the answers. The interviews have also had a low degree of structuring where open responses largely guided the interview [42].

3.4. Validity

The validity of a measurement is how well the selected measuring instrument measures what the investigator wants to measure. It is possible to ensure good validity by analysing the content of the measuring instrument based on the theoretical framework and then to compare if the instrument measures the same thing on another selected group. Good validity is essential for survey results so they can be generalized to other cases outside the sample selected in the study [42]. In this study a calliper was used to measure the dimensions of the parts involved, robot controllers have in some cases been used as timers to measure the cycle time for the operations, they were also used to check the robot positions and verify that with the camera vision systems. Both instruments are considered to have high validity when it comes to providing accurate data if used correctly.

3.5. Reliability

Reliability shows how well an instrument resists random influence to give a correct picture. In a survey with experiments and interviews, a lot depends on the reliability of the person performing them [42]. To ensure the reliability of the observation and measurements, two researchers participated and performed observations and data collection simultaneously.

3.6. Source criticism

An essential part of the research work is being source-critical, that is, to seek out where, when, and who published a document. This is in order to critically ensure the validity of an information source, the intentions of the author, and the circumstances behind it [42]. This study has primarily used scholarly literature sources in the field of automation. The sources, mainly literature books, are well tested in the industry and can be considered reliable.

4. System Analysis

This chapter covers an overall system analysis where the first part covers a brief description of the manual assembly procedure as it is performed at Scania's training facility. The second part includes a detailed description of the components involved, their liaisons, and the process and resources necessary to assemble them, followed by the selection and design process for the automation system components and description of the operations planning. Finally, a summary of the testing and improvement phases is introduced.

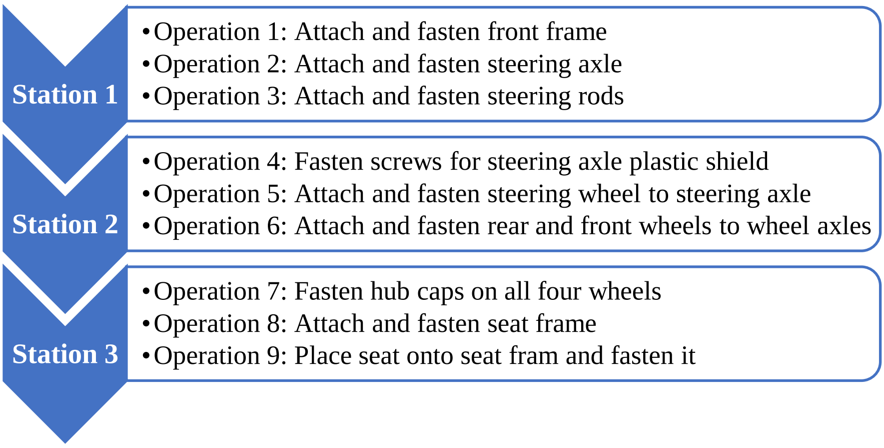
After the literature study, the project continued with a pre-study of the manual assembly tasks, where two main sub-assemblies were investigated. The first being the assembly of the steering wheel for the pedal car and the second the assembly of the front wheel. The objectives of the pre-study were to investigate different possible automation solutions that could be used to execute these manual assembly tasks. One of the main objectives was to prove that manually designed tasks can be automated without a need for redesigning the process or the components involved.

4.1. Manual assembly procedure

A successful project starts with getting a detailed understanding of the process and its components [12]. The first two steps in the method DYNAMO++ is to gather information about the current state and evaluate the LOA currently present within the process [22]. An analysis of the manual assembly procedure was carried out with the help of data previously collected by Scania.

As part of hiring new personnel for the final assembly line, assemblers are trained by assembling a pedal car in a dedicated training facility. The line consists of three separate stations with different sub-assemblies, shown in Figure 16 below. The back frame of the pedal car rolls into Station 1 on a fixture with wheels. Here the front frame is attached, followed by the steering axle with a pre-mounted plastic shield, and lastly, the steering rods. After the assembly of these parts, the pedal car is manually rolled to Station 2. The first operation in this station consists of tightening screws for the steering axle plastic shield. Thereafter the steering wheel is placed on the steering axle and fastened. The last operation consists of attaching back and front wheels and fastening them to the axles. Once the operations in Station 2 are completed, the pedal car is moved to Station 3.

This station starts with the operation of attaching hub caps on all four wheels, followed by attaching the seat frame to the pedal car frame, and lastly, assembling the seat on top of it. The pedal car is now complete.



Station 1
- Operation 1: Attach and fasten front frame
- Operation 2: Attach and fasten steering axle
- Operation 3: Attach and fasten steering rods

Station 2
- Operation 4: Fasten screws for steering axle plastic shield
- Operation 5: Attach and fasten steering wheel to steering axle
- Operation 6: Attach and fasten rear and front wheels to wheel axles

Station 3
- Operation 7: Fasten hub caps on all four wheels
- Operation 8: Attach and fasten seat frame
- Operation 9: Place seat onto seat fram and fasten it

Figure 16. *Workflow of manual pedal car assembly*

This report focuses on automating the assembly of the steering wheel in operation five and the left front wheel in Operation 6. The pedal car before and after the assembly can be seen in Figure 17 below.

Figure 17. *Left: Pedal car before assembly, right: after assembly*

In Table 3 below, the procedure of the steering wheel assembly can be seen. The first task consists of fetching the steering wheel together with a screw and washer. In Subtask 2, the assembler places the steering wheel on the steering axle, and hand-tightens the screw onto the steering wheel. In Subtask 3, the assembler fetches a torque wrench and tightens the screw to the desired torque in Subtask 4.

The last procedure is to return the torque wrench, and the steering wheel assembly is complete. In total, the steering wheel assembly has a cycle time of 32 seconds. The LOA_p consisted of 80% level 1 tasks, where the operator only used muscle power and 20% using a flexible hand tool giving it level 3. LOA_c, the operator had the help of work instructions but did not use them, giving a LOA_c of 2 on all tasks.

Table 3. *Subtasks for the assembly of the steering wheel*

Subtask	Procedure	Time (s)	LOA_p	LOA_c
1	Fetch steering wheel, washer and screw	5	1	2
2	Place steering wheel on steering axle and fix washer and screw	15	1	2
3	Fetch torque wrench	1	1	2
4	Tighten screw to desired torque	10	3	2
5	Return torque wrench	1	1	2

The working procedure of the left front wheel assembly can be seen in Table 4 below. All in all, it consists of one tyre with a screw and washer that keeps the wheels in place. The total cycle time of the assembly was 16 seconds. The LOA_p consisted of 86% level 1 tasks and 14% level 4 where the operator used an electrical nutrunner. LOA_c had a level 2 on all tasks.

Table 4. *Subtasks for the wheel assembly*

Subtask	Procedure	Time (s)	LOA_p	LOA_c
1	Fetch left front wheel	1	1	2
2	Place left front wheel on axle	2	1	2
5	Fetch screw and washer	4	1	2
8	Place screw on left axle	3	1	2
9	Fetch torque wrench	4	1	2
10	Tighten left screw to specific torque	1	4	2
13	Return torque wrench	1	1	2

The study’s goal for the automated assembly was to showcase a solution which was to be fully automated with no human intervention except for the order of a new product or acknowledge alarms, giving it a LOA of 6 in both the physical and cognitive category. Therefore, Phase 3 in DYNAMO++ of analysing and determining a suitable LOA was not included in this study [22].

4.2. Product specification

In this section, a detailed product specification is covered, including product description of the parts involved, product entities and interfaces, and finally liaison description, which covers the interfaces between the parts.

4.2.1. Parts description

An essential step before automating the pedal car process was to develop a thorough understanding of the product's dimensions, properties, variations, surface finish, and part presentation. This could have been achieved by gathering both dimensional drawings and inspecting the physical product [12]. However, for the pedal car case, no physical drawings were available; instead, a physical inspection was carried out to gather information about these specifications. This information is described in the following section.

4.2.1.1. Steering wheel

The steering wheel was made from of a solid injection molded polycarbonate material and consisted of a circular cylinder with a diameter of 70 mm in the centre connected to the outer steering ring by three spokes. The total diameter of the steering wheel was 270 mm. As shown in Figure 18 below, a triangular extruded cut on the bottom side was used to fit the steering wheel to the triangular bracket on the steering axle seen in Figure 20 below. The extrusion on the steering wheel had a horizontal length of 92 mm and vertical of 61 mm. The circular centre hole was used to fasten the screw into the steering axle. The surface finish of the outer ring consisted of a rough plastic leather pattern. There were no significant variations between the steering wheels in terms of shape, tolerances, size, or surface finish.

Figure 18. *The steering wheel*

The steering wheel was fastened to the steering axle using a 30 mm long *M8* hex screw. A washer was fitted in between the screw and the steering wheel.

4.2.1.2. Front wheel

The front wheel, as seen in Figure 19 below, was an assembly of three different parts; a rim comprised of solid injection moulded plastic with a central hub of 55 mm and an inner hole of 41mm, which was connected to the outer rim by five spokes. The centre hub had two ferrous steel bearings, each with a rubber sealant and was placed in the inner hole of 41 mm. On the front, the bearing was positioned 13 mm inside of the hole. The hole where the axle was to be fitted had a diameter of 20mm. A rubber tyre with a patterned surface was mounted on the outer part of the rim. The front wheel was fastened to the front axle using a 20 mm *M10* hex screw with integrated washer.

Figure 19. *The Front wheel*

4.2.1.3. Steering and wheel axles

As can be seen in Figure 20 the steering axle consisted of a painted triangular shaped plate with a horizontal length of 87 mm, vertical of 59 mm and a threaded hole for the M8 screw in the middle. The wheel axle consisted of a solid steel cylinder with a diameter of 19.9 mm and a threaded *M10* hole in the middle.

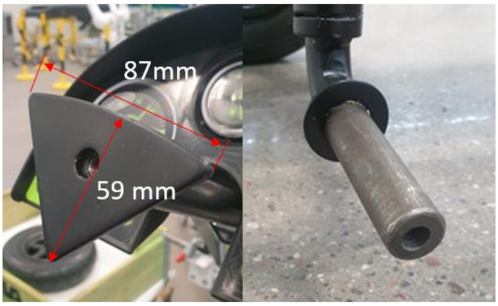


Figure 20. *Left: Steering axle, right: wheel axle*

4.2.2. Product entities and interfaces

The first step in the integrated control logic design process is to derive a product specification that is later used to define the process and resource specification and the control logic design behind the automated solution. A product can be broken down into two main categories, parts and features, also called product entities. The primary differentiation between parts and features is that parts are a physical entity assembled to form a product. In contrast, features are abstract virtual entities such as holes, reference points, and gripping surfaces [36]. In this section, the parts and features of the pedal car will be described. This study focuses on five different physical product entities of the pedal car assembly, as shown in Figure 21 below. The following part entities are defined as:

- *P0*: Pedal car frame.
- *P1*: Steering wheel.
- *P2*: *M8* hex screw.
- *P3: M8* washer.
- *P4*: Left front wheel.
- *P5*: *M10* hex screw with integrated washer.

Figure 21 below illustrates the feature entities of *P0* where the following two features were defined as follows:

- Reference point 1 (*Rp1*) is the triangular shape that the steering wheel was fitted on. This was used to locate the position of the pedal car in relation to the robots in Station 2 with the help of camera vision and to act as an orientation for the steering wheel assembly.
- Reference point 2 (*Rp2*) is the cylindrical/circular shape of the front wheel axle, this shape was detected by the camera vision system to determine the axles placement in the robots coordinate system.

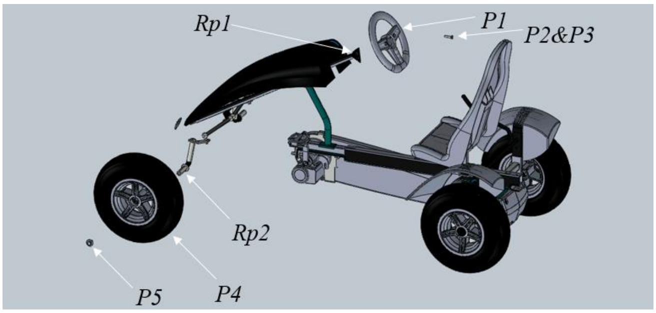


Figure 21. *Parts of the assembly process and Features of the pedal car (P0)*

Before entering the second assembly station the steering wheel was placed inside a foam fixture in a material box. This foam was designed specifically to position the steering wheel and the screw in a stable and pickable position. However, the material box could differ in position when entering the station. Therefore, the reference points *Rp3, Rp5 and Rp6* was set as a camera recognition feature, according to Figure 22 below. A gripping point for the robot to grip the steering wheel was defined as *Gp1*.

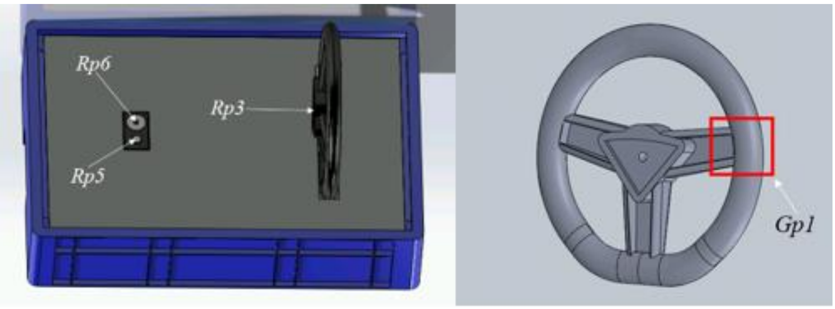


Figure 22. *Features in material box and steering wheel*

There were two features on the left front wheel which were crucial for the assembly procedure. First one was *Rp4* which is the reference position of the centre hole of the hub that was located using the camera vision system. The second was *Gp2* which is the spokes that the gripper used to grip the wheel, marked by the red square in Figure 23.

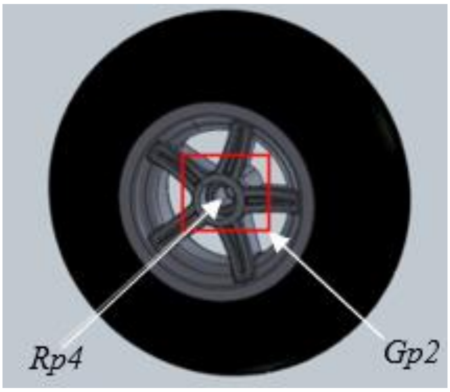


Figure 23. *Features on left front wheel*

In Table 5 below a summary of the parts and their features can be seen:

Table 5. *Summary of parts and features of the pedal car assembly*

Parts	Features
P0	Reference position Steering axle (*Rp1*)
	Reference position left front wheel axle (*Rp2*)
P1	Reference steering wheel (*Rp3*)
	Feature where gripper holds the steering wheel (*Gp1)*
P2	Reference point M8 screw (*Rp5*)
P3	Reference point M8 Washer (*Rp6*)
P4	Reference point front wheel hub centre hole (*Rp4*)
	Feature where gripper holds wheel (*Gp2*)
P5	Reference point *M10* screw (*Rp7)*

4.2.3. Product liaisons

Liaisons are used to define the interface between the different entities described in the product specification. Most commonly, they are used to specify the connection between parts and features. They can, however, also include information about the location and orientation [36]. In the pedal car assembly process, sixteen liaisons were identified and are described in more details below.

The liaison *P0P1* specifies that the steering wheel *P1* is placed on the pedal car frame *P0*. Before the liaison *P0P1* can be performed, liaisons *P0Rp1* and *P1G1* must be realized. In practical terms, this consists of the gripper *G1* gripping *P1* at the feature *Gp1* and using the camera vision to find *P1* with the reference position *Rp1*. Before *P1G1* can be achieved, *P1Rp3* must be realized. Liaison *P0/1P2/3* is the attachment of the *M8* screw and washer to the pedal car, and steering wheel. The primary liaison for this is *P0P1* and liaisons *P2Nr1* and *P2P3* created between the nutrunner, washer, and screw when picking it. *P2Rp5* and *P3Rp6* are a precedence for *P2Nr1*, and this liaison is fulfilled when the camera vision locates *P2* and *P3* position in the material box.

Liaison *P0P4* specifies that the wheel is placed on the left front wheel axle. Like *P0P1*, the wheel must be gripped, creating the liaison *P4G2*, and the camera detects the front wheel axle with liaison *P0Rp2* before this liaison can be achieved. Before Liaison *P4G2* is achieved, the camera system must locate *P4* and fulfil the liaison *P4Rp4*. *P0/4P5* is the tightening of the *M10* screw to *P0* and *P4*, which has the precedence condition *P0P4* and *P5Nr2*. The precedence *P5Rp7* for this liaison is the location of the screw in a screw feeder. Table 6 below summarises the liaison between the part entities.

Table 6. *Liaison between part entities*

Liaison	**Precedence**	**Description**
P0P1	*P0Rp1∧P1G1*	Steering wheel placed on steering axle
P0/1P2/3	*P0P1∧P2P3*	*M8* screw tightened onto steering wheel/pedal car
P2P3	*P2Nr1∧P3Rp6*	*M8* washer picked by nutrunner and matched with screw
P0P4	*P0Rp2∧P4G2*	Left front wheel placed onto steering axle
P0/4P5	*P0P4∧P5Nr2*	*M10* screw fastened to front wheel/wheel axle
P1G1	*P1Rp3*	Steering wheel gripped using a gripper
P4G2	*P4Rp4*	Front wheel gripped using a gripper
P2Nr1	*P0P1∧P2Rp5*	*M8* screw picked using a magnetic socket attached to a nutrunner
P5Nr2	*P0P4∧P5Rp6*	*M10* screw picked using a magnetic socket attached to a nutrunner
P0Rp1		Location of steering axle
P0Rp2		Location of front wheel axle
P1Rp3		Location of steering wheel
P4Rp4		Location of front wheel
P2Rp5		Location of *M8* screw
P3Rp6		Location of *M8* washer
P5Rp7		Location of *M10* screw

4.3. Process specification

To accomplish the liaisons mentioned previously, several operations in the assembly system must be carried out [35]. Below is a description of the operations needed to achieve the liaisons between the pedal car parts. These operations consist of picking, placing, locating reference positions using camera vision, and transportation of the pedal car between stations. All operations stated as *A* are assembly operations, *Cr* camera vision operations, and *T* transport operations.

The process starts with the operation *Ti1,* where the pedal car is transported to Station 2. After that, the assembly procedure starts with operation *A1* which is the picking operation of the steering wheel. Before this can commence, operation *Cr1* must be executed. This operation locates the steering wheel's position with camera vision. Operation *A2* is the placement of the steering wheel onto the pedal car steering axle. Before this operation is carried out, the operation *Cr2* must be completed. *Cr2* is the operation where the location of the steering axle reference point on the pedal car is determined. After *A2* is performed the robot stays in position while holding the steering wheel, as it otherwise has the risk of falling off before it is tightened with the *M8* screw. Meanwhile *P2* and *P3* are picked with operation *A3* by a second robot.

After *P2* and *P3* are picked the placement and tightening operation *A4* can commence. The reference points for operations *A3* and *A4* are derived out of the coordinates from operation *Cr1* translated to the position of the robot with the nutrunner. After this, the robot holding the steering wheel releases its grip and moves to a predefined position with operation *A5*. Next, the pedal car is transferred out of Station 2 with operation *Ti2*. No release operation similar to *A5* is necessary in Station 3 as the parts does not risk altering their position when they have been released. In other words, the place and release actions take place within the same operation.

When the pedal car has arrived in Station 3 the operation *A6* can start. In this operation the picking of the left front wheel from the material pallet takes place. However, before this can be initiated, the camera detection operation *Cr3* which locates the front wheel position in the material pallet must be completed. When *A6* is finished, operation *Cr4* can be executed to find the front wheel axle. After operation *Cr4*, the liaison *P0P4* can be achieved with operation *A7*.

Next, the operations *A8* and *A9* of picking and tightening *P5* can be performed, however, first the screw feeding operation *Fe1* to create the liaison *P4Rp6* has to be performed and lastly the liaison *P0P5* is achieved with operation *A9* using the same camera coordinates from operation *Cr4*. After *A6*, *A7*, *A8*, and *A9* are completed the transport *To* out of Station 3 can start.

Table 7. *Summary of the assembly operations*

Operation	Liaison	Precondition	Description
Ti1			Transporting *P0* into Station 2
Cr1	*P1Rp3*	*Ti1*	Locating the steering wheel using camera vision
A1	*P1G1*	*Cr1*	Picking the steering wheel from the material box
Cr2	*P0Rp1*	*A1*	Locating the steering axle using camera vision
A2	*P0P1*	*Cr2*	Placing the steering wheel on the steering axle
A3	*P2Nr1∧ P2P3*	*Cr1*	Picking the *M8* screw and washer
A4	*P0/1P2/3*	*Cr2*	Tightening the *M8* screw and washer onto the steering wheel/pedal car
A5		*A4*	Releasing the steering wheel
Ti2		*A1∧A2∧A3∧A4*	Transporting *P0, P1, P2* and *P3* into Station 3
Cr3	*P4Rp4*	*Ti2*	Locating the front wheel using camera vision
A6	*P4G2*	*Cr3*	Picking the front wheel from the material pallet
Cr4	*P0Rp2*	*A6*	Locating the front wheel axle using camera vision
A7	*P0P4*	*Cr4*	Placing the front wheel onto the front wheel axle
Fe1	*P5Rp7*	*A7*	Placing the *M10* screw in pick-position by a screw feeder
A8	*P5Nr2*	*Fe1*	Picking the *M10* from a screw feeder
A9	*P0/4P5*	*A8*	Tightening the *M10* screw to the front wheel/wheel axle
To		*A6∧A7∧A8∧A9*	Transporting *P0-P5* out of Station 3

4.4. Resource specification

In the Control logic design, the connection between resources and operations is described in more detail. At this stage, automation system components such as robots, sensors, and actuators, including their I/Os, were specified and used in a more detailed manner than the resource specification stage.
Every operation that is performed needs one or more resources to be realized. The type of resources and the operations they perform are specified in the resource specification [35]. Scania previously determined the manufacturing system layout to be a line assembly layout, serving as a physical demonstrator of an actual automotive production system, where a line is one of the most common and suitable production layouts. For a typical line layout, the machines or equipment are arranged sequentially in a continuous line according to the sequence of operations [21]. For the automated assembly line, the resources can be seen in Appendix A, Table A. 1.

A detailed map of the resources and their location can be seen in Figure 24 below. The camera vision resources *C1* and *C2*, nutrunners *Nr1* and *Nr2,* and grippers *G1* and *G2* are not depicted in Figure 24. *C1* and *G1* are mounted on robot *Rb2* and *Nr1* on *Rb1*, while *C3, G2,* and *Nr2* are located on *Rb3.*

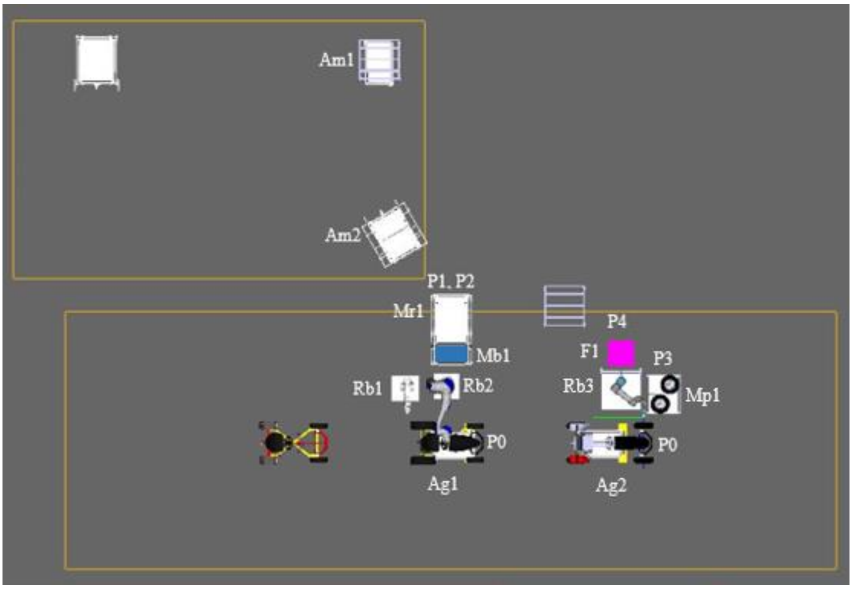


Figure 24. *Illustration of the resources in the automated assembly line*

The process is carried out using the resources according to below, (note that the assembly order of *Ag1* and *Ag2* could change depending on whether the customer ordered a hybrid or manual version of the pedal car):

- Operation *Ti1* starts with *Ag2* moving into Station 2 with pedal car *P0*.
- When *Ag2* is in position, operation *Cr1* starts using the resources *Rb2* and *C1*.
- *A1* starts, *P1* is picked from the material box *Mb1* using the resources *Rb2* and *G1*.
- Operation *Cr2* starts and is realized with *Rb2* and *C1*.
- The steering axle is located and operation *A2* starts, using the resources *Rb2* and *G1*.
- When the steering wheel is placed, operation *A3* will start by fetching *P2* and *P3* with *Nr1* and *Rb1*.
- Operation *A4* is then fulfilled with the resources *Rb1* and *Nr1*, the steering wheel is released with operation *A5*.
- The transportation operation *Ti2* is now initiated, transporting *P0, P1, P2, and P3* to Station 3. The resources and operations for *Ag1* will be the same as described for *Ag2*.
- After *Ag2* is in position, operation *Cr3* will start, using the resources *Rb3* and *C2*.
- Operation *A6* will use the resources *Rb3* and *G2* to pick the wheel from *Mp1*.
- When the wheel is picked, *Rb3* will move to locate the front wheel axle using *C2* with the operation *Cr4*.
- After *Cr4*, operation *A7* will start, using resources *Rb3* and *G2*.
- When the wheel is in place, the screw feeding operation Fe1 can be performed using the screw feeder F1 to feed the screw into the pick position.
- When the screw is in place, *Rb3* will use the nutrunner *N2* and fetch *P5* from the screw feeding system *F1* with operation A8 and tighten the *M10* screw with operation *A9* with the resources *Rb3* and *Nr2*.
- Operation *To* is now executed with the resource *Ag2*. Here all the parts *P0, P1, P2, P3, P4* and *P5* are transported out to Station 1 for quality inspection and disassembly.
- The operation and resources are the same for *Ag1* in Station 3.
- The AMR's *Am1* and *Am2* will continuously supply the line with components *P1, P2, P3,* and *P4*. The resources and control of these are not in the scope of this study.

4.5. Automation system components

After investigating the manual assembly procedure and analysing the assembly tasks, the next task was to look at the system components required to automate the manual assembly tasks. The design and selection process are explained in the coming subsections.

4.5.1. Handling equipment

A crucial aspect of production is the material handling to and from workstations. Common types of equipment used for this purpose are conveyors, forklifts, AGVs, AMRs, and part feeding equipment [12]. The selection of these were outside the scope of this study. However, a brief description of the equipment will be outlined below.

4.5.1.1. AMR

The AMRs task was to supply Station 2 and 3 with material needed for assembly. This consisted of the steering wheel and M8 screw for Station 2 and the front wheel for Station 3. The steering wheel and M8 screw came as a kit in a material box which was transported on a material rack on wheels that the AMRs could attach to. A stationary material rack was present at Station 2 which the AMR could dock to, and a mechanism released the box from the rack on the AMR onto the stationary one. At Station 3 the front wheels were supplied in half pallets placed upon carts which the AMRs could dock to and place at a given position.

4.5.1.1. AGV

Two *CEIT* AGVs *CEITRUCK 600LC-F* were chosen by SFL to transport the pedal cars between the three different stations. The AGVs were guided between the stations on a pre-determined path set by a magnetic strip taped to the floor and communicated wirelessly to send and receive information on position, orders, and start/stop signals.

4.5.1.2. Material box kit

Kitting is a method where the precise number of components necessary for an assembly task are grouped together and supplied to the line in the form of a kit [28]. The steering wheel, screw, and washer would arrive at Station 2 in the form of a kit placed inside a standard material handling box. A solution was developed on the following objectives: the robot end effectors had to reach and pick the parts without any collision; in other words, the parts were to be positioned to not limit or block the robot end effectors.

The second objective was to fixture the parts in an exact position during the logistic and assembly operation; this was required partly due to that the material racket was negatively tilted, which made the material handling box hit the end of the racket while loading new material. This minor hit could affect the positioning of the material inside the material box and negatively affect the picking operation. As there was no practical way to design the foam in a CAD software, prototypes were cut out manually out of polyether foam and tested until the desired design was achieved. A 3D printed fixture to hold the screw and washer in place was designed and placed in the foam. The finished material box kit can be seen in Figure 25 below.

Figure 25. Material box with steering wheel kit

4.5.1.3. Screw feeder

In Station 3, SFL decided to place a screw feeder which supplied the robot with the M10 screws necessary to fasten the left front wheel. The feeder would keep the screw in place with a magnetic mechanism until the robot came into the picking position and send a signal for it to release. Due to long delivery times this resource did not arrive during the time span of this study. To circumvent this a CAD model was designed and 3D printed to hold the screw in the location where the screw feeder would later be positioned. The holder can be seen in Figure 26 below. Note that a washer was used in this setup as the screws with integrated washers would arrive with the screw feeder.

Figure 26. *Left: CAD Model of Screw holder, right: 3D printed screw holder that was used in the temporary setup*

4.5.2. Assembly robots

Many factors can influence the choice of robots, such as payload, reach, and power consumption [12]. Two robots have already been om use in SFL, and they were chosen to be placed in Station 2 for the steering wheel assembly, since they matched the requirements and fitted the application. The robots were an *ABB IRB 1200* and a *Yaskawa HC20*. One new robot was purchased and placed in Station 3, where it was equipped with a gripper, nutrunner and camera vision system to assemble the left front wheel. Before reaching out to the robot's suppliers a requirement list was created. The list was developed based on product specification analysis and the traditional robot selection criteria [12]. From the requirement list, a summarising table was made, where technical data on different robot models has been summarised and compared based on the interviews, information and datasheets received by the suppliers, this is shown in Table B. 1, Appendix B. The requirements list was based according to the following specification:

- **Configuration:** Articulated arm with 6-axes. The nature of the assembly task meant that a robot that could reach all the possible positions and orientations was needed. The best configuration for this task was the articulated arm with 6-axes.
- **Payload:** it should handle more than 10 kg. The combined weight of the nutrunner, gripper, dual fixture for robot end effectors, camera, and the front wheel would be approximately 8 kg. Therefore, the requirement was set above 10 kg to give a margin of error if additional equipment were to be needed.
- **Reach:** more than 0.7 m. The reach necessary was determined to be above 0.7 meters.
- **Mounting capabilities:** No floor mounting accepted. Drilling on the lab floor was not an option since the lab layout was flexible and could be shifted depending on what kind of project was tested and demonstrated. The robot thus needed to be mounted on a stand that could be moved around.
- **Position repeatability:** less than 0.1 mm. The assembly of almost all the parts involved had some tolerances; for example, the front wheel axle had a diameter of 19.9 mm, and the ball bearing hole was 20.0 mm. Therefore, the positioning repeatability should not deviate above the difference of 0.1 mm.
- **Weight:** No specific number, however as low as possible was preferable.

- **Power requirements:** low energy consumption was a plus but not a must.
- **IP rating:** not specified.
- **I/O:** not specified.
- **Program interface:** offline programming if possible; otherwise, the simpler, the better.
- **Collaborative:** preferable. Collaborative robots offer a greater degree of safety, for example, inbuilt torque sensors that detect collisions with humans or robots [9]. This was seen as a plus, as it would help avoid accidents or damage to the robot, the surrounding equipment, and personnel during the test phase.

The study started with a broad search on different robot models available from manufacturers. The manufacturers included in the study consisted of *Kuka, ABB, Yaskawa,* and *UR*. Robots from *ABB* were preferred due to their well know offline programming simulation software *RobotStudio,* which facilitates easier and faster programming with the ability to test work sequences and improvements in the digital world before applying them to the real system. However, *ABB* did not have any collaborative robots with a payload capacity above 10 kg. Therefore, industrial robots *IRB 2400-10* and *16* were included to see if they provided any advantage more than the simulation compatibility. They were quickly discarded due to their weight of 380 kg and the requirement that they had to be mounted on the floor for stability.

Kuka and *Yaskawa* had a wide range of industrial robots. However, all these had to be floor mounted. Kuka had the collaborative robot *LBR iiwa 14 R820*, which weighted 58 kg and the ability to be mounted on a stand with a payload capacity of 10 kg and a reach of 820 mm. Two collaborative robots from *Yaskawa* were also in the accepted range of the requirement list. These consisted of the models *HC10DT YRC1000* and *HC20DT YRC1000*. They both had a reach well above 700 mm with 1200 mm and 1700 mm, respectively. Both could be mounted on a stand with a weight of 58 and 140 kg and a 10 and 20 kg payload capacity. But one drawback was their outdated offline programming interface. One of the robots that SFL had was an *HC20DT* model which was planned to be placed om Station 2. Since the project focused on testing new technologies, this model was less interesting, and its weight of 140 kg was also a limiting factor.

At the point of the study, *UR* had two collaborative robots available that fulfilled all the requirements. These were the *UR10e* and *UR16e*. The reach for the two robots were 1300 and 900 mm respectively. They weighed 33.5 and 33.1 kg and could be mounted on a stand with a payload capacity of 10 and 16 kg. Their ease of use and programming interface was also a plus. *UR* also had a wide range of grippers, camera vision systems, and accessories which could be easily integrated with the robot.

An interview was carried out with a technical representative from *UR*. The purpose of which was to get their insight and thoughts on the robot equipment and specification for the application area, including what their robot could contribute to fulfilling the purposes of the project. Following a consultation with the supervisor at Scania's SFL and the technical comparisons carried out, it was concluded that the *UR16e* would be the best choice, providing a reach of 900 mm and a payload of 16 kg combined with the benefits mentioned previously made this the best candidate for the task. The comparisons can be seen in Appendix B, Table B. 1. After the selection process, the specifications of the chosen robots were summarised in Table 8 below.

Table 8. *Specification's list of selected robots*

Manufacture	Universal robots	*Yaskawa*	*ABB*
Robot name	*UR16e*	*HC20DT YRC1000*	*IRB 1200*
Reach	900 mm	1700 mm	900 mm
Payload	16 kg	20 kg	5 kg
Number of axes	6	6	6
Weight	33.1 kg	140 kg	54 kg
Mounting	Any Orientation, stand	Floor, ceiling wall, tilt, stand	Floor, ceiling, wall, stand
Position repeatability	Pose 0.05 mm	0.05 mm	0.025 mm
I/Os	Digital- in 16 /out 16	Specialized signals: 19 inputs and 6 outputs / General signals: 40 inputs and 40 outputs	Digital- in 16 /out 16
Protection	IP54	IP67	IP40
Power consumption	Moderate 0.35 kW, Max 0.585 kW	Average 1.5 kW	0.39 kW
Collaborative	Yes	Yes	No
Other	Pick-IT camera URCaps	Safe force/torque sensors in all 6 links	
Comment	Light, easy to use, many grippers' options	Safe, collaborative, poor simulation program	RobotStudio

4.5.3. Robot end effectors

In this section the process of choosing the gripper and torque wrench type and the design of the gripper fingers is described. In total four different end effectors were chosen: gripper for attachment of the steering wheel, torque wrench to attach and tighten the steering wheel screw, gripper to attach the wheels and a torque wrench to attach and tighten the wheel screws.

4.5.3.1. Gripper selection

The third area of the automation system components was the choice of grippers; there were some challenges surrounding this process; examples of such challenges were that the weight of the grippers limited the possible solutions due to payload, possibilities to have multi or dual grippers attached to one robot, communication with the controller of the robots and achieving the correct torque for the right task. For example, to tighten the screws on the steering wheel and left front wheel, a unique nutrunner tool was needed with a specific torque capacity, but not as much as an actual production application would require. The coming sections describe these challenges among other requirements that were used for the robot end effectors.

Two grippers were needed for the assembly procedures, one for the picking and placing the steering wheel in Station 2 and one for the picking and placing of the wheel in Station 3. The grippers had to grip the parts with enough force so that they maintained their position in the gripper during the whole assembly procedure while not inflicting damage or scratches on the part.

Steering wheel gripper

The selection process of the gripper for the steering wheel was straightforward. The part was made of solid plastic, was not to be damaged or get any adhesive residue left on its surface and had no surface suitable for pneumatic suction cups. This eliminated all but impactive mechanical grippers from the category list. The task of the steering wheel robot was to grip the wheel, place it on the steering wheel axle and hold it while the *ABB IRB 1200* tightened the *M8* hex screw. This limited the gripping points available due to the risk of the robots colliding. It was concluded that *Gp1*, as seen in Figure 22, would be the most suitable gripping point to grip the wheel. From this point, it was determined that a two-jaw gripper with more than 10 mm stroke per jaw would be enough to clear the outer ring when positioning itself in the gripping position.

A requirement list was developed for a two-jaw gripper based on the product specification analysis and common grippers requirements according to the following [12]:

- **Stroke per jaw:** minimum 10 mm.
- **Gripping force:** Enough force to ensure correct gripping.
- **Workpiece weight**: more than 1.2 kg.
- **Weight:** not specified but as low as possible.
- **Mechanism:** electric was preferable due to less tubing and equipment required.

Table B. 2 was made based on the requirement list to compare different gripper types; this can be seen in Appendix B. Technical data on five different grippers from the supplier *Schunk* were summarised and compared. *PGB 80* was deemed unsuitable due to the stroke per jaw of 6 mm. *EGP- 64* had a recommended workpiece weight of 1.25 kg, which made it a plausible choice. *PGB 125* had a pneumatic mechanism that excluded it. The *EGL 90 -PN* was a suitable gripper for the application; however, Scania already had a *PGN plus E-100* in stock, which made this the first gripper of choice.

Front wheel gripper

The first step in the gripper selection process was determining which of the four gripper categories, ingressive, contigutive, astrictive, and impactive, could be used. An ingressive gripper achieves prehension by permeating the object's surface. Since the wheel was not to be damaged during assembly, any type of ingressive gripper was determined to be unsuitable. Prehension through contigutive methods was also deemed unsuitable due to their use of adhesive chemicals. The chemicals used may have left marks on the wheel’s surface, and their reliability would also be questionable [29].

Astrictive methods such as vacuum cups and magnetic grippers were also investigated. With the first thought being that of suction cups gripping the surface of the rubber tyre, however, at a closer look, the tyre had small ribs along the surface, which would allow air the get through the suction cup. The rim was also looked at as a potential gripping surface. Nevertheless, the geometry of the rim made it unsuitable for vacuum grippers. Extra equipment such as vacuum pumps and extra hoses needed was also seen as a disadvantage. A magnetic gripper was determined to be a plausible solution. The wheel had a ball bearing in the wheel hub made of ferrous steel, which could be used as a magnetic gripping surface if the right kind of gripper could be found.

Impactive mechanical grippers were also seen as a plausible solution for the application. With the help of a 3D printer, customized fingers could be designed to fit the geometry of the rim, creating multiple points of contact, which increased the retention stability [29]. After this exclusion method, a more detailed analysis of available gripper solutions could be performed with the help of data from suppliers and a requirements list. The requirements for magnetic gripper were according to the following:

- Gripper diameter less than 41 mm. The gripper diameter was not to exceed 41 mm since the ball bearing was placed 10 mm inside the wheel hub in the 41 mm diameter hole.
- Electromagnetic gripping force more than 30 N. The wheel weighed 3 kg which exerted roughly 30 N in gravitational force, therefore, a magnetic gripper which provided a gripping force over this value was necessary.
- Mechanism should preferably be electric rather than pneumatic. Pneumatic required extra equipment such as vacuum tubes and compressors.
- Communication with robot must be possible.

An interview was conducted with one of Scania's gripper suppliers *Schunk* which recommended one type of magnetic gripper. Magnetic grippers from *UR* were also investigated. The quantitative data of specifications for the available grippers can be seen in Table 9 below.

Table 9. List of relevant specifications for magnetic grippers

Manufacture	*Schunk*			*Robotiq*
Model	*SGM-HP 40 G1/4-IG*	*GM-HP 30 G1/8-IG*	*EMH 036*	*MHM magnetic gripper*
Diameter [mm]	40	30	~50	~80
Holding force [N]	320	130	530	80
Weight [kg]	0,415	0,215	1	0,475
Mechanisms	Compressed air	Compressed air	Electrical	Compressed air

Models *EMH* and *MHM* were not suitable for the application due to the diameter of the gripping magnet being above 41 mm, meaning that they could not make contact with the bearing placed inside the wheel hub. The *SGM* models were suitable for the application. Their diameter was below 41 mm, and their gripping force of 320 N and 130 N was well above the force of the 30 N needed to counteract the gravitational force of the wheel. One drawback was their pneumatics-driven mechanism which was the reason why impactive mechanical grippers were investigated instead.

The concept of the impactive gripper was that it would grip the wheel around the inner hub using two or more fingers; this meant that the gripper fingers were required to go between the spokes of the rim before gripping. A five-finger gripper was first considered. However, it was quickly discovered that no standard five-finger grippers existed and had to be custom made. Grippers with three or four jaws were also investigated, but, due to the shape of the front wheel's spokes the gripper jaws had to be custom made in an unsymmetrical pattern, since the standard grippers with 3-4 jaws were symmetrical in their jaw positions and would not fit the application. After an interview with *Schunk*, they recommended using a two-jaw gripper with a double finger attached to the second jaw. This would give three surfaces of contact and effectively act as a three-finger gripper. After the number of jaws was decided, further studies were conducted into which 2-jaw grippers were available from the suppliers *Schunk* and *Robotiq*. Before the selection process could begin, the following requirement list was compiled:

- Stroke per jaw: minimum more than 15 mm, maximum less than 75 mm. For the fingers to pass freely between the spokes each jaw must open at least 15 mm.
- Gripping force: Not specified, but enough force to ensure the gripping.
- Workpiece weight: it should handle more than 3 kg.
- Weight: less than 2 kg. So, it would not exceed the robot's payload.
- Mechanism: electric was preferable due to less tubing and equipment required.

Three different grippers were deemed to be suitable for the application: *Schunk*'s *EGL 90-PN*, *Robotics- 2F-85* and *2F-140* grippers. *Schunk*'s gripper had a stroke per jaw of 42,1 mm, a workpiece weight of 3 kg, a weight of 1.8 kg, and an electric mechanism. One drawback was that it could only handle a workpiece weight of 3 kg. *Robotics 2F-140* gripper matched all the requirements except for the workpiece weight of 2.5 kg. The *2F-80* gripper fulfilled all the requirements, and the fact that it could be easily integrated with the *UR16e* made this gripper the best suitable candidate. The specification list for the *2F-80* gripper can be seen in Table B. 2 in Appendix B.

4.5.3.2. Gripper fingers design

After the gripper model had been chosen, the process of designing the fingers for the jaw could begin. The gripper fingers are the active parts that provide contact between the gripper and the workpiece. Therefore, the design must be strong enough to withstand the gripping forces while providing the right surface contact without damaging the part. To achieve the best possible retention stability, the aim was to design the fingers to match the finger profile to the surface of the objects, creating a uniform fit with multiple points of contact [29].

Steering wheel gripper finger design

The concept for the steering wheel fingers consisted of two fingers to grip the outer ring and use one of the spokes as extra points of stability. The geometry of the fingers was designed in such a way that the outer ring surface matched that of the fingers, giving multiple points of contact. In contrast, one part was matched to the geometry of the left spoke, aligning the steering wheel in the correct position when gripped. Extra chamfers can be seen on the tip of the bottom fingers in Figure 27, where it enters the extruded cut at the back of the spoke. This was to give extra guidance when closing the gripper in case that the steering wheel was not fully aligned with the gripper fingers.

During the testing phase, it turned out that the CAD model which the fingers were modelled around was not identical to that of the actual wheel, resulting in that the fingers had to be adjusted to the dimensions of the physical steering wheel. This was done in four iterations, where the dimensions were changed to achieve a better fit by either adding or subtracting geometries on various parts of the fingers. The final fingers can be seen in Figure 27 below.

Figure 27. *Left: final CAD design of steering wheel fingers, right: 3D printed fingers gripping steering wheel*

Front wheel gripper finger design

For the front wheel, the concept was to design a 3-finger gripper with multiple contact points while only having a two-jaw gripper. In the concept design phase, SolidWorks which is a CAD software, was used to design and simulate the fingers around a 3D model of the wheel rim; a CAD assembly and the final gripper fingers can be seen in Figure 28 below.

The fingers were designed to fit the contours of the inner hub and the bottom part of the spokes so that even if the camera vision system had a margin of error, the fingers would be self-guiding and centre the wheel in the correct position. However, at the first physical test, it was noted that the initial concept of the fingers gripping both the wheel hub and spokes added too much complexity to the geometry, resulting in the gripper not gripping the part correctly. Further tests showed that the spoke geometry gave the best retention ability. After this, some minor adjustments on dimensions and geometry were made to improve the fit in a total of four iterations.

Figure 28. *Top: CAD assembly of the front wheel gripper, bottom: the 3D printed fingers gripping the front wheel*

4.5.3.3. Torque wrench “nutrunner”

The operations to fasten the screws to the components required a tool that could pick up the screws, tighten them to a specific torque, and communicate I/O signals to the robot when to start and stop the procedure. The most common tool for this application is the nutrunner; it has a mechanism that allows for precise control of the applied torque [31]. The idea was that the nutrunner would be mounted to the robots as end effectors and equipped with a magnetic socket to pick up the screws from the material position. The robot would then move to the tightening position, and the nutrunner would get a signal from the robot when to start the tightening procedure and send a signal back when the specific torque was acquired. The torque to which the screws had to be tightened to was derived from Scania’s standards for torque and nutrunners, where the recommended torque for *M10* and *M8* screws was 40 Nm. However, a lower torque could be accepted due to the study taking place in a lab environment.

SFL's main supplier of nutrunners was Atlas Copco; therefore, the first step in the selection process was to interview them to determine what products they could offer that suited the application. Their recommendation was the nutrunner model *ETD-STR61-90-13-T25* together with the control box *PF6000*. The nutrunner had a torque range between 20-90 Nm and a weight of 2.4 kg. The design of the nutrunner was made so that a custom fixture could be fabricated that allowed it to be mounted on a robot as an end effector. The *PF6000* controller could connect eight different I/O's, Fieldbus communication and could be used with Atlas Copco's *toolsNet 8* software, a data collection, and production analytics software for Atlas Copco tools. The controller also had an HMI that allowed for different tightening programs, batch sequences, and settings. It was decided that this nutrunner would suit the application.

Nutrunner fixture

The nutrunner did not come with the capability to be attached to the robots directly, which meant that a fixture had to be designed and fabricated. In the design phase, a 3D model of the nutrunner and the robot was used to model the fixture. One challenge when designing the fixture was to restrict the counter-rotation caused by the tightening momentum of the nutrunner as there were only cylindrical surfaces to attach the fixture to. As there was no sure way to calculate the necessary clamping force to prevent this, the fixture had to be 3D printed and tested to verify that it would work.

The initial design of the fixtures was implemented and tested; the fixtures managed to secure the nutrunners and keep them from counterrotating when the specific torque was applied to tighten the screws. However, it was noticed that the fixture for the *UR16e* was too long, causing it to collide with the robot at certain positions. The fixture was shortened, and the nutrunner's position in the fixture was brought further out. The final fixture and CAD design can be seen in Figure 29 below.

Figure 29. *Top: nutrunner ETD-STR61-90-13-T25, bottom: 3D printed fixture for UR16e*

4.5.4. Pedal car fixture

The pedal car was supposed to be placed on an AGV with the help of a fixture. However, due to supplier time delays the AGVs would arrive to SFL after the study was conducted. Therefore, four detachable wheels were added to simulate an AGV during testing which could be taken off when it was time to mount it on the AGV. The wheels also added the ability to use the fixture in future projects at SFL where no AGV would be used. The design of the fixture followed the four-step model with the steps; setup planning, configuration planning, construction, and assembly [32].

4.5.4.1. Setup planning

The number of setups was determined to be two; one for the manual pedal car and another for the hybrid version. They were similar in frame design, except that the hybrid version had a battery, an electric motor, and a 100 mm longer frame. Therefore, the goal was to make a fixture that could be used for both models. The orientation of the pedal car would be the same as in the manual assembly except for the wheel axle that was fixated at a perpendicular angle to the pedal car frame; this was done to lock the steering axle in position and provide stability and precision while assembling the front wheel and steering wheel. As part of the setup stage, the following requirements list was compiled:

- The fixture must be attachable to the AGV while being restricted in all degrees of freedom to ensure the quality of the assembly procedure.
- The fixture must ensure that the back frame, front frame, and steering axle are locked in all degrees of freedom.
- The fixture should allow the pedal car to be attached and detached easily when required; in other words, the fixture should have a flexible clamping system that facilitates the attachment and detachment without damaging the pedal car. Toggle clamps are the most commonly used due to their low cost and simple functionality; one drawback is that they depend on operators to close them correctly [12].
- The fixture should not block or limit the reach of the robots during the assembly operations.
- The fixture should position the wheel and steering axle at a 90-degree angle to the pedal car.

4.5.4.2. Configuration planning

After the orientation of the pedal car and the requirement had been listed, the configuration planning stage could be conducted. This stage defined the locators' points to be positioned to achieve full retention of the workpiece. The 3-2-1 model was followed to avoid redundancy of locators used [32],[33]. The pedal car frame consisted of an assembly of one front and one back frame, as seen in Figure 30 below. This meant that even if the back frame was fixed in all directions of motion, the front one could rotate about 20 degrees along the X-axis; as seen in the coordinate frame at the bottom left corner in Figure 30. Therefore, the frame was treated as two geometric bodies instead of one when defining the fixture points.

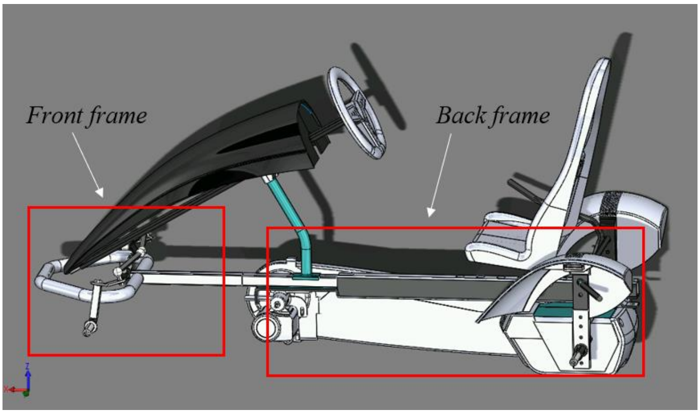


***Figure 30.** Pedal car front and back frame*

The procedure to define the right fixture points was a combination of the five axioms, the 3-2-1 rule, and the possibility of clamping without any obstructions [33]. The complex geometry of the pedal car and the independent rotation of the front frame introduced additional challenges when placing locators. The chosen fixturing points can be seen in Figure 31.

For the back frame, the three locators defining the X-Y plane according to the coordinate system in Figure 31; were placed in *Fx1*, *Fx2*, and *Fx3*/*Fx4*. According to the five axioms, no more than three locators are needed to define a plane [33]. However, *Fx3* and *Fx4* also served as locators for the front frame so were seen as one locator when defining the points for the rear frame. *Fx1* served as the first locator, restricting all motion in the -Z-axis direction. The second locator, limiting the rotation along the X-axis, was placed in *Fx2* with the two points *Fx3* and *Fx4*, serving as the third locator blocking rotation along the Y-axis.

Two locators were placed in *Fx1* and *Fx2* to achieve a defining line in the Y-axis. These acted as the fourth locator restricting motion in the X-axis direction placed in *Fx1* and the fifth-placed in *Fx2*, preventing any rotation along the Z-axis. The sixth point restricting motion in the +/- Y direction was placed in *Fx3* and *Fx4*.

The front frame was defined in the X-Y plane by locators in *Fx3*, *Fx4*, and *Fx1*/*Fx2*. To restrict motion in the -Z direction, the first locator was placed in *Fx3*. The second locator was placed in *Fx4*, preventing rotation along the X-axis and a third one was placed in *Fx1*/*Fx2* to restrict rotation along the Y-axis. In *Fx3* and *Fx4*, the two locators defining a line in the Y-axis were placed. These consisted of the fourth locator preventing any motion along the X-axis and the fifth preventing rotation along the Z-axis. *Fx3* and *Fx4* also served as the locator points restricting motion in the Y direction.

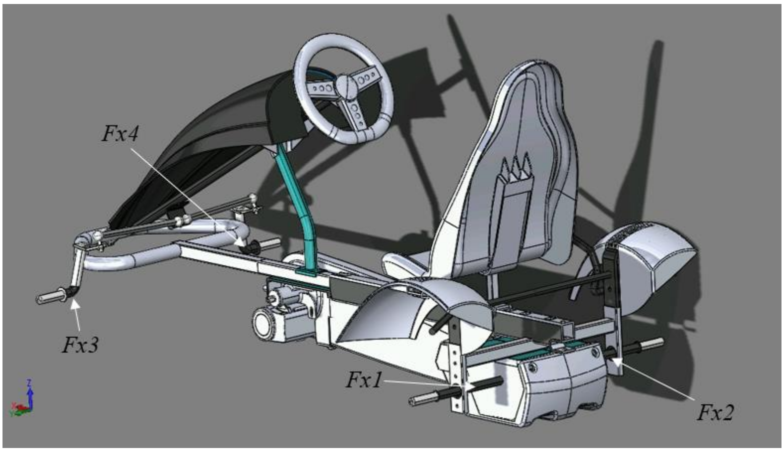


Figure 31. *Fixture points pedal car frame*

4.5.4.3. Fixture construction and assembly

After the configuration stage, the initial construction of the fixture could start. This was done digitally with the help of a CAD model of the pedal car and SolidWorks. As shown in Figure 32 below, the fixture was constructed out of aluminium profiles due to their low weight, modular design capabilities, and ease of modification. It consisted of four fixturing points with one toggle clamp to lock the pedal car in place in the -Z direction. The toggle clamps enabled quick and easy attachment/detachment. To lock the pedal car in the X- and Y position, 3D printed guides were designed, which had the same geometric shape as the axle of the pedal car.

The main reason behind this was that there was no plausible way to use toggle clamps in these directions without adding additional fixture points, which would result in an increased redundancy of locators.

Two clamp levers were added to the rear axle fixture profile to make the fixture adaptable for both the hybrid and manual versions; these could easily be adjusted by untightening the clamp levers and moving the profile to the desired position. After the construction phase the drawings and specifications were sent to an external supplier for fixtures where it was assembled and delivered to SFL. The fixture successfully locked the car in all degrees of freedom, aligned the steering wheel and front wheel axles and ensured that no movement could take place during the assembly operations. The fixture can be seen in Figure 32 below, equipped with wheels to simulate the transportation on top of an AGV.

Figure 32. *Physical fixture with wheels and CAD fixture design mounted on AGV*

4.5.5. Camera vision

Many factors could affect the positioning of an automation system components solution, like the AMRs and AGVs. Repeatability could also have been affected by AMRs and AGVs; negatively affecting the overall repeatability leading to insufficient precision or an inaccurate position of the grippers during the assembly operations. Therefore, a need for a camera vision system was necessary to guide and facilitate the navigation of the robots around space. SFL already had a camera vision system called "*Pickit3d M*" designed for shape identification and robot guidance, with the main applications being picking and placing. The main benefits of this camera system were that it could easily be integrated with the *UR* system. They offered an easy user interface which meant that there was no need for previous experience with camera vision systems. It was decided that this camera was to be placed in Station 3 with the *UR16e* robot.

Another camera vision system was required for Station 2, mainly for robot guidance and parts identification; similar to the robot selection, a comparison between different camera vision systems was made, based on a fixed specifications criterion listed up under the project pre-study of the system [12], primarily based on the application parameters and the product entities and interfaces that needed recognition during the operations to guide the robots. The main requirements of the camera were as follows:

- Must be able to be mounted on a robot. The camera was to record two different positions, so the best way to move it was to mount it on the robot.
- Must be applicable for both picking and placing operations.
- Working distance: Between 400-1000 mm. The distance which the robot was positioned when using the camera could range between these numbers.
- Type of vision system: 2-Dimensional(2D) or 3-Dimensional(3D). The height of the pedal car and material box from the floor was a fixed position, therefore no Z coordinate had to be determined by the camera and a 2D camera would be sufficient for the task.
- Detection accuracy: less than 1 mm. The tolerance between the steering wheel and steering axle was less than 1 mm.
- Weight: less than 1 kg.
- User friendliness was an additional requirement which meant that the camera required little setup time and expertise.

After the requirements had been determined, a broad study on different suppliers and the camera systems they offered was conducted. After the study, three different camera systems were selected as potential candidates, and interviews were held with the suppliers on how their camera systems could contribute to the project; these can be seen in Table 10 below.

***Table 10**. Specification list of selected camera systems*

Manufacturer	Onrobot	Pickit	SICK
Model name	Eyes	Picki M-HD	PLOC2D
Type of vision system	2.5D	3D	2D
Working distance (mm)	400-1000	617-2000	<3000
Minimum part size (mm)	10x10	10x10x5	
Supports pick and place	yes	yes	yes
Able to be mounted on robot	yes	yes	yes
Detection accuracy (mm)	< 2 mm	0.1 mm	<1 mm
Weight (kg)	0.8	2	~ 0.5

Onrobot offered an easily integrated camera system with 2.5D vision, meaning that it could get X and Y coordinates with height information. Overall, it fulfilled all the criteria except for the detection accuracy, which was above the required value of less than 1 mm. *Pickit M-HD* offered the best accuracy of 0.1 mm; however, the minimum working range of 617 mm and the weight of 2 kg made it less suitable for the application. *PLOC2D* was the camera that was finally chosen. It offered a working distance of up to 3000mm, had an intuitive HMI system, and low weight. The 2D system offered the ability to locate the parts in the X-Y plane and rotation along the Z-axis.

4.5.6. Other resources

Magnetic socket: Magnetic sockets were necessary to pick up the screws using the nutrunners. To test if it was a plausible solution, two ordinary sockets were equipped with neodymium magnets, fastened with glue on the inside. The sockets were tested and proved to work and SFL plans to obtain custom made magnetic sockets that fits the application.

Safety and guarding: Safety should be considered at the early stages of automation solution development to ensure the system can perform its task effectively and safely. The main goal of safety and guarding is personal safety by ensuring that no person can harm themselves during an operation or maintenance of a system. Risk assessments can be used to define all potential risks to be minimized or eliminated by applying the guarding and safety systems [12]. Safety measures are essential and a must in any automation system, as for this project took place as a part of a bigger project, safety measures and risk assessments were taken care by other project participants. Additionally, both the *Yaskawa* and *UR16E* are collaborative robots and can be run in a collaborative mode, where they slow down or even stop once they detect a human or an external force.

System controllers: Many controllers were involved in this project, starting from the robot controllers that control the logic and the movement of the robots, their sensors, and actuators. Additional controllers were also used to control the camera vision system at Station 3 and the nutrunners in both stations, and these controllers where directly communicating with the robots' controllers. The central control system used in the project was a PLC and was responsible for sending and receiving the triggering signals from and to the automation system components [12], mainly to the robots, AMRs, and various sensors. AGVs were also planned to be connected to the PLC, although they did not arrive within the thesis duration.

A *Siemens* PLC (*CPU 1518F-4*) was used to control the logic that triggers the stations, robots, and actuators; the PLC was mainly used since there were different manufacturers and controllers of the automation system components involved. Each of these had its standard of communication; therefore, a need for a mastermind, in this case, a robust traditional PLC, was required. A handshake communication link was developed between the robots and the PLC to communicate and trigger the signals.

4.6. Operations planning (sequence planning)

The relations among assembly operations can be described as complex because they constantly change their relations throughout the development process [37]. Operations in the automated assembly line were planned according to the pedal car entities, features, liaisons, and the available resources and then optimized to reduce the cycle time and the non-value adding wait time during the operations. Since there were three different types of robots in the line, different optimization approaches were used depending on the manufacturing specifications of the robots. However, the same objectives were maintained.

The operations were developed in a hierarchical tree-structured way, where some operations consisted of alternative or parallel execution. In contrast, some operations had to wait until a precondition was fulfilled or a previous operation was completed [35]. The results summarises the flow of operations obtained and implemented, which are based on the operations described previously, translated into flowcharts, and configured according to the Table 11 below, the flowcharts were drawn according to traditional symbols and can be seen in Appendix D [38].

Table 11. *Connection between operations, flowcharts and subprograms*

Station	**Operation**	**Flowchart and sequence**	**Subprogram**
Station 2	*Ti1*	-	-
	Cr1	*PickSteeringWheel*	*104*
	A1		
	Cr2	*PlaceSteeringWheel*	*105*
	A2		
	A3	*PickM8Screw*	*204*
	A4	*TightenM8Screw*	*205*
		ReleaseM8	*206*
	A5	*ReleaseSteeringWheel*	*106*
Station 3	*Ti2*	-	-
	Cr3	*PickFrontWheel*	*304*
	A6		
	Cr4	*PlaceFrontWheel*	*305*
	A7		
	Fe1	-	-
	A8	*PickM10Screw*	*306*
	A9	*TightenM10Screw*	*307*
	To	-	-

4.6.1. Homogenous transformation

In Station 2, the camera was mounted on the *Yaskawa* robot. This meant that the detected position vector and orientation of the part were in relation to *Yaskawa's* base coordinate system. To make these usable for the *ABB* robot, a homogenous transformation was applied [20]. Figure 33 illustrates the coordinate system for the *Yaskawa* and *ABB* robots with the position vectors ${}^{Y}P$, ${}^{A}P$, and $t^{A}{}_{Y}$. Where ${}^{Y}P$ is the position vector with regards to the *Yaskawa* for point *P* generated by the camera, ${}^{A}P$ is the unknown position vector for point *P* with regards to the *ABB*, and $t^{A}{}_{Y}$ the position vector of the *Yaskawa's* coordinate system with regards to the *ABB's*. $t^{A}{}_{Y}$ was determined by measuring the distance in x, y, and z from the *ABB's* base frame to the *Yaskawa's*.

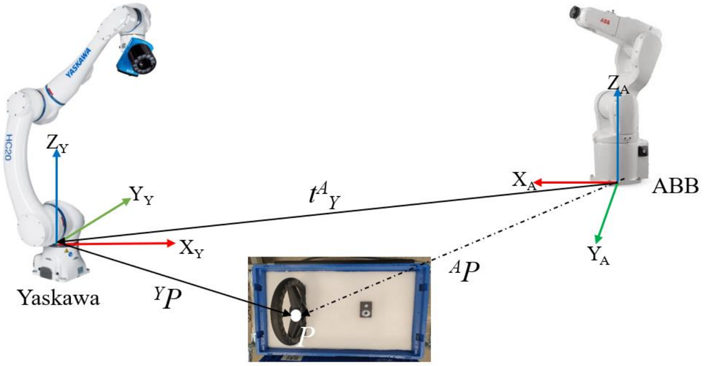


Figure 33. *Illustration of vectors and coordinate frames in Station 2 for picking of the steering wheel*

To calculate ${}^{A}P$ following equation was derived using Equation 1 [20]:

$$ {}^{A}P = {}^{A}{}_{Y}T\,{}^{Y}P = \begin{bmatrix} \boldsymbol{R^{A}_{Y}} & \boldsymbol{t^{A}_{Y}} \\ \mathbf{0\ 0\ 0} & \mathbf{1} \end{bmatrix} \begin{bmatrix} \boldsymbol{X^{Y}_{P}} \\ \boldsymbol{Y^{Y}_{P}} \\ \boldsymbol{Z^{Y}_{P}} \\ \mathbf{1} \end{bmatrix} = \begin{bmatrix} \mathbf{-1} & \mathbf{0} & \mathbf{0} & \mathbf{1461.1} \\ \mathbf{0} & \mathbf{-1} & \mathbf{0} & \mathbf{246.9} \\ \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{-75,5} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} \end{bmatrix} \begin{bmatrix} \boldsymbol{X^{Y}_{P}} \\ \boldsymbol{Y^{Y}_{P}} \\ \boldsymbol{Z^{Y}_{P}} \\ \mathbf{1} \end{bmatrix} \qquad \textbf{\textit{Equation 2}} $$

where:

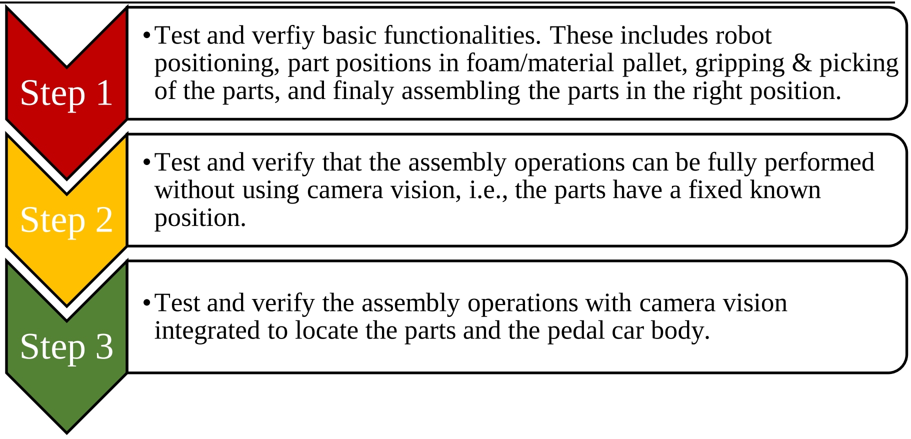
- $R^{A}{}_{Y}$ is the 3x3 rotation matrix of the *Yaskawa's* coordinate frame in relation to the *ABB*. In this case the *Yaskawa* was rotated 180° around the z-axis.
- $t^{A}{}_{Y}$ values are given by the camera vision.

The camera vision system did not get fully installed at Station 2 due to the missing robot communication code, which enabled the communication between the *Yaskawa* controller and the camera system. The homogenous transformation had to be validated in another way, and that was achieved by jogging the *Yaskawa* to a certain point and storing these coordinates as ${}^{Y}P$, and then jogging the *ABB* to the same point, checking its x, y, and z coordinates at the point and compare them to the calculated results in ${}^{A}P$. The results were accurate with ±2 mm deviations; this can be related difference in precision between the two robot controllers. The results could also get further improved once the installation and calibration of the camera system are completed. During the assembly operations, the *ABB* robot was programmed to move to an "offset" pick position with a specific orientation. The idea was then to use the obtained homogenous transformation coordinates for the targeted object, although, this was not fully implemented during the thesis project due the previously mentioned issue regarding the camera vision system.

4.7. Testing and improvement

Almost all the automation system components involved were tested, evaluated, and further developed as in an iterative process. Testing the robot end effectors was done in a multi-step process, starting from the CAD-design of the fingers and other components which were firstly tested offline using various simulation software, such as SolidWorks and IPS [12]. Then the fingers were 3D printed and tested physically to ensure the right gripping contact area between the grippers and the parts. The robot programs were tested and optimized using two main optimization methods: using blend radius points and by increasing the speed and acceleration of the robot joints [39].

The cycle time could have been further optimized, yet due the time limit of this project that was not an objective. Additionally, both *Yaskawa* and *UR* robots were planned to run in default collaborative speeds during the demonstration, and a comparison with a manual operated cycle time was not relevant in this case. A summary of the testing iterations is shown in Appendix C. Testing of the operation sequence and robot programs was done according to the procedure illustrated in Figure 34 below:



- Test and verfiy basic functionalities. These includes robot positioning, part positions in foam/material pallet, gripping & picking of the parts, and finaly assembling the parts in the right position.
- Test and verify that the assembly operations can be fully performed without using camera vision, i.e., the parts have a fixed known position.
- Test and verify the assembly operations with camera vision integrated to locate the parts and the pedal car body.

Figure 34. *Test approach*

After the programming and testing were complete the cycle time and LOA of the automated assembly were determined. The total cycle time in Station 3 was 80 seconds for the assembly of the wheel, of which 80% was robot movement, and 20% was camera recognition. It was observed that the wheel recognition was three times longer than that of the left front wheel axle; this was mainly due to the more complex geometry of the wheel compared to the wheel axle.

As station 3 was tested before the entire assembly line was complete, specific tasks had to be performed manually, such as pushing the pedal car to the station, placing the screw in a fixture that substituted the screw feeder, and transporting the material pallet or carrying the front wheel to the station. Since these tasks were planned to be automated outside of the project's time span, they were not considered when determining the LOA for this station. In practical terms, after the camera was calibrated and the materials were in place, the robot got initiated with a triggering signal from the PLC and did the entire assembly operation without any intervention from an operator.

The robot had been programmed to perform the assembly of the front wheel, and the setup time for programming a new task could be long, giving it a LOA$_p$ of 5, however, if programmed to do other tasks, it could get more flexible and quickly switch between different product assemblies reaching a LOA$_p$ of 6. Therefore, a LOA$_p$ of 5.5 was set as the robot itself was not only built for one purpose and could be programmed for greater flexibility [22].

The camera vision system gave the robot the ability to determine if the front wheel or pedal car was placed in the region of interest for the specific task and alter its configuration with regards to their location. However, certain errors could occur, such as the camera not finding the wheel or axle after three attempts or the nutrunner failing to tighten the screw to the specific torque after two attempts. Requiring an operator to acknowledge them and start the process again resulting in a LOA_c of 6 [22].

5. Results

In this chapter, the study results are presented based on the pre-literature study, the system analysis, and the iterative action research process that had taken place during the entire project duration. This chapter consists mainly of three parts. the first part covers a summarising method that was developed based on the results and lessons learned; this method describes how to transform manual assembly tasks into automated ones. The second part describes the implementation results of the final solution obtained, followed by a description of the challenges regarding automation system components.

5.1. A method to automate a manual assembly process

The initiation phase of this master's thesis project started with a literature study, which covered general topics, including different approaches to automate a manufacturing system and the typical requirements and components for a traditional automation system. However, no appropriate method has been found that could fulfil the needs of this project, which was mainly to design and develop an automation solution, more specifically to transform a manual assembly process into an automated one. The literature study could not find any complete relevant method that could fulfil the needs of this project. Therefore, a research question was added to the project, and a method has been developed. As a result, this method can be seen as a general guideline on transforming several manual assembly operations into automated ones. Figure 35 below illustrates an overview of the method to automate a manual assembly process.

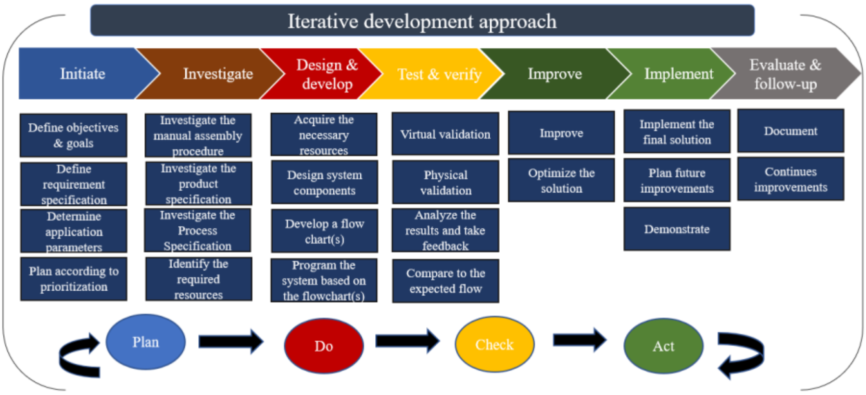


Figure 35. *Overview of the method to automate a manual assembly process*

This method can be seen as a further development of the methodology approach used to perform this thesis project, it was further developed based on two primary resources; the literature study and the experiences obtained during the project duration. The method is flexible and can be applied on other types of manual assembly processes, it could also be modified and fitted for other types of automation applications. The method consists of 7 phases, where phases 3-5 can be seen as an iterative process where the automation solution is evaluated and further developed until the desirable results are achieved. The method can be summarised according to the following:

1. **Initiation phase:**

In this phase, the objectives and goals for the automation project should be specified. A pre-study of the proper LOA at a system level should be the starting point; this is to clarify how much automation is required to achieve the project's goals. It is essential to understand that highly automated solutions may at first seem to be the superior solution that may increase flexibility or efficiency, but this can instead result in poor system performance and vulnerability to disturbances. In other words, realistic and well-defined goals should depend upon the product and the quantity to be produced. An automation solution of a fully automated line would require specific conditions, such as high-volume production, resulting in lower flexibility. The requirement specification for the automation project should be defined, and a determination of application parameters for the automation system is required. Finally, an overall plan according to prioritization should be developed in this stage, which shall be followed and carried out throughout the project.

2. **Investigation phase:**

Investigating the existing or current manual procedure is the optimal way to start with the automation project; this is essential to understand the studied process and its operations. The process specification should include a detailed description of the manual assembly operation. The operations should be divided into smaller groups (sub-assemblies) depending on their function as a group or at what order these tasks shall be performed. Different flows or procedures can be developed and compared based on, for example, the cycle time for each flow, which can be measured.

The most efficient scenario for each sub-assembly can then be chosen for further development. Precedence diagram can be used, the idea here is that each sub-assembly has its flow of execution. This may not be needed to manufacture a product with a low number of components. However, some complex designs require a higher number of components. The following action is to investigate the current and the desired task LOA for all the tasks. This action aims to gather information about the current system. Through analysis, it determines the level of mechanized and cognitive automation most suitable for the specific production task. Dynamo++ is one method that can be used here, which has been developed to investigate the type of automation solution suitable at a task level and find the balance between automation and human solutions.

The next step is where the assembly bill of materials needs to be identified, the parts, components, and materials used during the assembly process should be specified, including the quantity and weight for each (where weight is essential for the payload of the robots). The next step is to develop the product specification, where the product, including its parts, features, and the interfaces between the parts, needs to be specified, starting from detailed parts descriptions, product entities, interfaces, and finally liaisons. In this step, some other engineering methods can be used regarding the design, for example, DFMA and DFAA. A question could be asked: “Are there other ways of designing this part to facilitate the assembly while maintaining its function and manufacturing cost?”. The final action in this stage is to specify the resources required to perform the operations based on the previous gathered information; a list of the required system components to execute the operations should be obtained.

3. Design & development phase:

The design and development phase is where the system components required for the operations can be procured or obtained, based on the process, resource- and technical specifications; below is a list of the main system components for a standard automation solution:

- Handling equipment, such as conveyers, AGVs, AMRs and part feeders.
- Robots.
- Robots end effectors, grippers, and tool changers.
- Fixtures and tooling.

- Camera and computer visions systems.
- System controllers.
- Safety and guarding components, such as light sensors etc.

The operations can be sequenced and planned in a hierarchical tree-structured way, based on the relations between the operations, where some operations may include alternative or parallel execution.

Product entities, features, liaisons, and resources should be used as a foundation for operation planning. The next step is to develop logical flow charts for each sub-assembly by transforming the planned operations into structural flow charts. After that, the automation components can be programmed based on the flow diagrams in a relevant programming software. A standard programming procedure should be followed to ensure the quality and safety of the program and its environments. Safety measures should be added, such as a safety program, sensors and system guarding. This step and the further coming steps can be seen as an iterative process. These steps shall be performed and repeated for each sub-assembly until the desired objectives for the automation project are fulfilled.

4. Testing, verification, and validation phase:

Virtual validation can be the first way of testing, where the system can be tested and verified offline using simulation software. Next is the Physical validation, where the solution is tested online. Based on the feedback from the tests, the system can be further developed, and the cycle time can be optimized, an example of optimization method when using industrial robots is adding blend radius stops or increasing the speed and acceleration of the robot joints, where accuracy is not as required. The requirement specification developed at the early stages can be used as a checklist to ensure that the requirements are fulfilled. The solution should also be evaluated and compared to the manual flow considering essential parameters such as cycle time, accuracy, repeatability, and safety.

5. Development and improvement phase:

The solution can be further improved based on the requirements specifications and the feedback gathered, going back to the design and development phase or directly to the testing may be needed.

Phases 3, 4, and 5 can be seen as an iterative process repeated until the desirable solution is achieved.

6. Implementation phase:

In this phase the final solution should be implemented, future improvements and further developments shall be planned. Documentation of the final automation solution design and all its components is essential for traceability and future development.

7. Evaluation & follow-up phase:

The automation system should be evaluated and followed up continuously. Continuous improvements should be a core ideology. Congratulate yourself and your team.

5.2. Automated assembly line

This section describes the layout and process flow for the steering and front wheel's automated assembly for the pedal car. The flow is based on the planned operations and flow chart described in the previous chapter. The line consists of three stations: Station 1 for quality and manual disassembly, Station 2 for the assembly of the steering wheel, and Station 3 for the assembly of the front wheel. The pedal car is to be transported between the stations using an AGV with a custom-designed fixture for the pedal car. Two AMR robots handle the material flow from and to the stations at the line, Figure 36 below illustrates the layout for the final design of the assembly line, where the blue lines indicate the process flow direction.

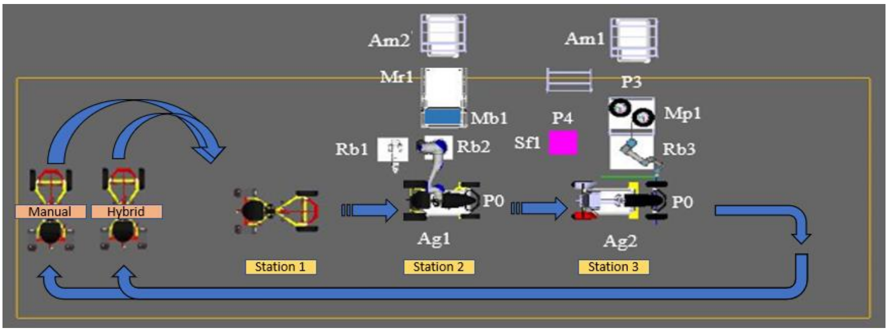


Figure 36. *Layout for the Automated assembly line*

Due to supplier delays, three of the main automation system components were not present during the implementation phase, namely the AGVs, the nutrunner that was planned to be attached to the *ABB* robot at Station 2, and the screw feeder for Station 3. Four wheels were attached to the pedal car fixture to enable movement to and from stations, a 3D printed fixture replaced the position of the screw feeder, and a nutrunner dummy was used to mimic the position of the nutrunner. The authors programmed the robots and cameras at both the stations, and the nutrunner at Station 3 according to planned operations. SFL planned to update the layout with the missing components once they arrived. A third party did the PLC installation with an extensive cooperation with this project. Additionally, the camera vision system at Station 2 had an extended delivery time, and when it arrived, it could not be directly connected to the *Yaskawa* controller and required a robot communication code for this matter; therefore, the camera vision system was programmed to detect the components but was not fully integrated with assembly equipment at Station 2 and instead the operations were carried out without camera vision for this thesis project.

5.2.1. Station 2 process flow description

Figure 37 illustrates the finished installation of Station 2; including the *ABB* robot equipped with a nutrunner dummy, the *Yaskawa* robot equipped with the *Schunk* gripper, and the *Sick* camera vision system. A video illustrating the flow can be seen on *YouTube* [45].

Figure 37. *Station 2 final installation*

The process starts with the *Yaskawa* robot in home position waiting for the triggering signal from the PLC to initiate the execution of the operations; after receiving the signal, the robot moves to an "offset" position of the material box where it can enable the camera vision system to locate the steering wheel. Now the robot waits for the sensor in the upper part of the material-rack to be false, which in turn indicates that there is a box in position. Once the sensor signal is true, the robot sends a signal to the camera asking for the location of the steering wheel; after locating the part, the camera communicates back to the *Yaskawa* robot, sending the coordinates of the steering wheel. In this stage, the robot will wait until the AGV is in place; once the signal is received, the robot can start the picking operation of the steering wheel.

Now the robot can move to an offset of the location of the pedal car steering axle; the *Yaskawa* robot triggers the camera to locate the pedal car steering axle; once it is located, the camera communicates the coordinates of the steering axle back to the robot, these are then used by the robot to move and place the steering wheel in position. Now the *Yaskawa* robot will send a signal to the PLC indicating that the steering wheel is placed in the correct position; the *Yaskawa* robot stays in place, holding the steering wheel until the tightening operations are performed, then it moves back to the home position.

The tightening process starts with the *ABB* robot in home position waiting for a triggering signal from the PLC to start; after receiving the signal, the robot asks the PLC for the coordinates of the *M8* Screw and washer, which were previously derived by the *Yaskawa* robot and saved in the PLC memory and the PLC sends them back, these coordinates are then used to calculate the location of the *M8* screw and the washer in the material box using the pre-programmed homogenous transformation Equation 2, which transform the position of the *M8* screw and washer to the *ABB's* base frame. Before executing the picking operation of the *M8* screw, the robot checks again if the AGV is in place and the steering wheel is mounted. Now the robot is free to move and pick up the *M8* screw and the washer using a magnetic socket attached to the nutrunner.

The *ABB* robot can now move to an "offset" location of the pedal car steering axle; the robot asks the PLC for the coordinates of the pedal car steering axle, which was obtained previously and stored inside the PLC memory, the same pre-programmed homogenous transformation gets applied on the coordinates, and transforms these to the frame perspective of the *ABB*, now the PLC communicates the coordinates back to the robot, the robot can now move linearly and tighten the *M8* screw on the steering wheel, additional instructions are added to make sure that the tightening is done correctly using the inbuilt torque sensor in the nutrunner which sends a feedback signal to the robot controller. In case that no or low torque is achieved, loosening instructions will run, followed by tightening instructions. If the tightening is not performed correctly twice, the program will stop and send an error message indicating and explaining the matter. Once the tightening is performed correctly, the *ABB* robot sends a signal to the PLC scheduler indicating that the tightening is done, which in turn trigger a signal to the *Yaskawa* robot to release the steering wheel and go back to the home position, now that the assembly for Station 2 is finished the *ABB* robot moves back to the home position and all the signals are reset.

5.2.2. Station 3 process flow description

Figure 38 illustrates the finished installation of Station 3; including the *UR16e* equipped with *Robotiq* gripper, *AtlasCopco* nutrunner and camera vision system *Pickit*.

Figure 38. *Station 3 final installation*

The process starts with the *UR16E* robot in home position waiting for a signal from the PLC to execute the picking operations of the front wheel; after receiving the signal, the robot check if Sensor 3 is false, which indicates that there is a material pallet in position, now the robot asks the camera to locate and send the coordinates of the front wheel. If the part is detected and reachable, the coordinates are sent to the robot. In the case that no object is detected or detected but not reachable, the camera will try to locate the part one time; if the same condition(s) occurs, the camera will send an error indicating that no part has been detected or the part is not reachable. Before executing the picking operation, the robot checks whether the AGV is in place. Now the robot is free to move and pick up the front wheel using an active gripper; after the closing of the gripper is performed, the robot is programmed to question whether the front wheel is detected/picked or not; this is checked by an internal force sensor inside the gripper. If a part is detected, the gripper performs the opening and closing of its fingers one more time; this additional motion is added to ensure that the part is centred and picked correctly; else, the robot sends an error that indicates no object has been picked/detected.

Now the UR robot can move to an offset of the location of the pedal car left front axle; the robot triggers the camera asking it to locate the pedal car's left front wheel axle; once it is located, the camera communicates back with the robot, sending the coordinates of the axle. These coordinates are then used by the robot to move and place the front wheel in the correct position. Similarly, to the picking operation, an if statement is added, which checks if the part is detected and reachable. In case that no object has been detected or detected but not reachable, the camera will try to locate the part one more time; if the same problem occurs, the camera will send an error indicating no part has been detected, or the part is not reachable. If the front wheel is placed correctly, the robot will send a signal to the PLC that the front wheel is placed in position, the robot can now move to an offset position of the screw feeder.

This part of the process starts with the *UR16E* robot at an "offset" position of the screw feeder while waiting for a PLC signal to start; after receiving the signal, the robot checks if the screw feeder is ready and whether the AGV is in place. After confirming the pre-conditions, the robot is free to move and pick up the *M10* screw, the picking operation is done by firstly moving the robot downwards linearly towards the nut while rotating the nutrunner, where a magnetic socket is attached to the nutrunner to enable the picking. Now the *UR* robot can move to an offset of the location of the pedal car front wheel axle; the robot re-uses the coordinates of the front wheel axle to move in front of the hole with some offset. The robot can now move linearly and tighten the *M10* screw on the front wheel axle using the nutrunner. The program has an additional statement which ensures that the tightening is done correctly, which is done using an inbuilt torque sensor inside the nutrunner which sends a feedback signal to the robot controller. In case of low or no torque achieved, loosening instructions will run, followed by tightening instructions. If the tightening is not correctly performed at the second attempt, the program will stop and send an error message explaining the matter. Once the tightening operations are completed, the robot will send a signal to the main program that the front wheel screw is tightened; the robot can now move back to the home position, and the process is finished.

5.3. Challenges regarding automation system components

Generally, the study has concluded that precision can negatively get affected in a cumulative way. In other words, all of the automation system components have a specific accuracy and precision repeatably which they usually operate about. By using multiple automation components from different manufactures with differing accuracy and precision repeatably ranges adds complexity, and negatively affect the overall precision. Therefore, it is essential to decrease errors and failure proactively to maintain high precision in multiple cycles; it is beneficial if automation system components have the same range of accuracy, and repeatably.

Robots: One challenge with the robots was to deal with the programming interfaces from three different manufacturers. There was no relevant offline software that could be used to program and simulate a fully functioning code, which could be directly inserted into the robot controllers. Instead, each robot had to be programmed online. Since this was a lab environment, this could be accepted as there were no costs associated with downtimes. However, it limited the possibility to program and test the robots until all the system components had arrived on site.

Robot end effectors: The *Robotiq 2F-85* gripper was easily integrated with the *UR16e* robot, taking no more than an hour to fasten on the robot, calibrate and run. The gripper came with an inbuilt functionality called “active gripper” to detect when a part was gripped. At first, this was seen as an advantage to prevent any unwanted damage to the part, gripper, or fingers. However, at the testing phase, it was quickly discovered that this function prevented the gripper from achieving full prehension of the wheel, and there was no possibility to turn it off. The problem arose due to some edges of the gripper fingers touching the wheel during the closing action before full contact was achieved. This resulted in that enough force was exerted to signal the gripper that the part was gripped. This was solved by simplifying the geometry and designing the fingers to only grip the spokes.

The integration of the nutrunner with the robots was straightforward. The parameters for the nutrunner were programmed on its controller with one program for picking up the screw and another for tightening it. In contrast, the movements to the necessary point were programmed in the robot. The start and stop were determined by the robot's position and the status of the nutrunner through I/O signals.

One challenge was to sync the speed at which the screw was threaded into the hole with the robot; if the robot did not follow the screw threading speed, the screw would come to the end of the socket and loose contact with it, resulting in the nutrunner spinning without turning the screw. This was solved by trial and error until the right feed speed was achieved.

Camera Vision system: Regarding the camera vision system that was used in Station 3, the study has concluded that there were some common issues which affected the camera recognition; these are summarised below:

- After running the program multiple iterations, the precision of the camera recognition was negatively affected; in other words, repeatability and accuracy worsened with time. This was tremendously improved by running a calibration program, where the camera was calibrated using a calibration plate at the beginning of every working day. Therefore, a scheduled calibration before start should be added to the operations when using camera vision in an assembly process. Upgrading the camera system is also an option to decrease this setup time.
- The detection accuracy for *Pickit3D-M* of ~3-6 mm proved to be within the limits of what the application required, at least for the picking application of the front wheel, while the placing operation required higher precision to position the wheel on the steering axle, which was achieved but worsened after a certain number of iterations and a new calibration was required.
- The more complex shape of the front wheel meant that the picking operation could sometimes be a couple of millimeters off. To circumvent this, chamfers were added to the fingertip design to guide the fingers to the correct position between the wheel's spokes.
- As shown previously, the camera vision increased the cycle time, with 20% of the total time being dedicated to camera detection. This was mainly due to the camera processer requiring extra time to process the images and obtain the desired information.
- Other parameters, such as the background contrast and colours affect the cycle time for camera vision recognition; this was limited since the camera lens on the *pickit3D-M* could not be changed or upgraded to fit this specific application.
- Finally, the product shape and symmetry play a significant role in the camera vision's cycle time. It takes time for a camera vision system to recognize a part with a complex shape or numerous details.

Regarding the camera vision system that was used in Station 2, the study has concluded that there were some common challenges that should be considered; these are summarised below:

- Contrast and brightness settings had great influence on the cameras ability to detect parts. This was solved by trial and error until an optimal solution was achieved. The conclusion is that for 2D cameras such as the *SICK PLOC2D*, colours can add additional difficulties such as longer detecting time or poor detection abilities, therefore the part colour should differ from the background to facilitate camera recognition.
- Communication: A major challenge which arose during the installation of the *SICK PLOC2D* was that there was no robot communication code available. Therefore, compatibility is a crucial factor and one of the first requirements that should be checked when procuring a system component.

Many of the previously mentioned challenges could have been solved by using DFMA and DFAA methods at early stages, more precisely already during the product development stage. In the case of this study, the product and its components were decided at a previous stage, and the goal was to not redesign the components involved, partly to prove that automation is applicable for products that are designed to be mounted manually and another reason was the limitation of time and resources for this thesis project.

Control system: a Siemens PLC unit was used to control and trigger the system signals. The fact that the equipment such as the robot and camera vision systems came from different manufactures made the PLC installation phase take longer time than planned, which can be expressed in the form of establishing communication channels between the equipment and the PLC. As the conclusion mentioned previously, yet to emphasize the importance of the point, acquiring automation systems components from the same manufacture can be seen as a plus and would simplify and save time during the installation.

6. Discussion

This chapter includes a discussion of the study's method and results.

6.1. Method discussion

Combining a case study with action research proved to be an effective method to develop and implement an automation solution. The case study provided the groundwork to understand the product's specifications, processes, and resources required to assemble them. Based on the overall case study, clear goals were defined, which guided the action research in an iterative process until an optimal solution was achieved. The primary raw data for this thesis project consisted of two resources; firstly, the interviews that were carried out with technological suppliers and their equipment data sheets. The second source was the feedback results from the iterative process of testing and development. Other types of raw data could have been gathered to achieve the goals for this study; for example, different performance indicators could have been collected and analysed. However, that would expand the thesis projects scope and would have required an existing and fully developed automated solution.

The system components' performance indicators, such as accuracy and precision repeatability, could have been obtained using a precise instrument during the testing phase. In the case of this study, a calliper was used for this purpose, and its reliability could be questioned. Additionally, some of the automation system components already included data on their precision and accuracy from their manufacturers, and it was noticed that this data varied during the testing phase, which could be explained by the different application circumstances between the SFL and the manufacturer's test site, therefore, the validity and reliability of the datasheets were questionable.

6.2. Result discussion

The result has proven the possibility to automate assembly operations that are designed to be performed manually; this was followed by a summary of the experienced challenges regarding automation system components. The solution development process could have been carried out differently by redesigning the product and its components to facilitate the automated assembly, which could have led to different specification requirements and, therefore, a different selection process of the resources required.

This also meant that some of the challenges could have been solved using DFMA and DFAA methods at early stages, more precisely already during the product development stage. In the case of this study, the product and its components were decided at a previous step. The goal was not to redesign the components involved, partly to prove that automation is applicable for products that are designed to be mounted manually; another reason was the limitation of time and resources for this thesis project.

A fixed layout in the form of a line was decided at a previous stage by the SFL project group, as part of a larger project within Industry 4.0 to demonstrate a typical automotive production system. A pre-study of the proper production layout should be carried out, however, that was not an objective in this study.

Many components, including fixtures and gripper fingers, were designed using SolidWorks. As many of the parts were designed with the existing CAD model of the pedal car as a reference, its dimensions needed to represent that of the actual pedal car. However, it was quickly noted that this was not the case for any of the components such as the wheel, steering wheel, or pedal car frame. Instead, the CAD models were used as a rough template, and crucial dimensions were measured on the physical parts. This resulted in unnecessary additional iterations in the finger design process, including the 3D printing time to test whether the fingers matched the dimensions.

There have been time delays during this thesis project, mainly due to extended delivery times from the supplier's side; additionally, the purchasing process took much more time than planned, which is typical in a large organization such as Scania, where the purchasing process is complex, leading to longer processing times.

Finally, the method to automate a manual assembly process could have varied if a different product or production layout had been analysed; therefore, the method can be modified and fitted for other applications. Although the method is flexible; it should not be generalised for all types of automation applications.

7. Conclusions

The chapter summarises the study's conclusions and recommendations and concludes with suggestions for further research.

7.1. Conclusions and recommendations

The study investigated the approaches to develop an automation solution and concluded a method to automate a manual assembly process. The method is summarised in seven steps. Starting with the initialization phase, where the project goals and its system LOA are defined. The second phase covers an investigation phase of the current assembly and its product specification, followed by the third phase, where the designing and development process for the automation system components required occurs. The fourth phase is about testing and verifying the previously developed components, followed by the improvement and optimization phase. Finally, the implementation phase can occur, and continuous improvements shall be carried on.

The groundwork for developing an automation solution should consist of knowledge regarding the current state of the process, its products, and resources, which should later be built upon in an integrated logic design to define the relationship between the product and its assembly process, which is the foundation for the automated solution. The groundwork has proven to be crucial in the selection and design phase of various system components, as inaccurate primary data from the first stage would harm the results and cause unnecessary challenges during the design process.

The required automation system components for this project included handling equipment, assembly robots guided by camera vision systems, robot end effectors, positioning fixtures, and the central controlling unit. Unfortunately, most of the handling equipment, such as the AGVs and screwfeeder, did not arrive in time, and the challenges with these were not explored. As for the automation system components, it was concluded that the use of equipment from different manufacturers negatively affects accuracy, precision repeatability, compatibility, installation time, and offline programming, which makes an automation project costly and time detrimental.

The use of a camera vision system adds a greater degree of flexibility to a robot's navigation and guidance ability and decreases the need for positioning fixtures. However, equipment compatibility should be verified early in the selection process, and the additional cycle and setup times must be considered when selecting a camera vision system. As for the end effectors, their installation and integration with the robots were straightforward, although it was shown that the design process of the fingers is adversely affected by any inaccurately measured dimensions, either from the CAD models or the parts involved.

The study has proven that manually designed tasks can be automated without redesigning the process or the components involved. However, the DFAA method shall still be an essential tool for developing an efficient process or eliminating design details that would cause unnecessary assembly challenges. The study shall be seen as a potential base and a physical demonstrator for implementing such a system in an existing assembly line. The working model of the automated system verifies that a similar solution in Scania's manufacturing system is possible.

7.2. Further research

This study proved the possibility to automate the assembly of a part designed for a manual assembly. However, it did not touch upon how such a solution would affect specific key performance indicators within an existing production system. A future project at SFL could be to select an actual subassembly to be automated within the final assembly production line and investigate it to fulfil this missing gap.

SFL has plans to build upon the automated assembly of the pedal car to include more of its components in the process. As part of such a project, a potential research field would be the development of their own camera vision system for robot guidance. Another aspect that was noticed during the study was the impact that a part’s geometry, contour, and colour had on the effectiveness of the camera vision system. Technology is evolving rapidly, and such challenges may be gone within the near future. However, as part of DFAA, further research on this topic shall be conducted to include camera vision when designing an assembly process. Design For Computer vision (DFCV) should be introduced and considered as a new method for product design within the product development process. Additionally, investigating an existing product using automation methods such as DFAA shall be considered, including the positive and negative consequences on the production costs, including development costs. Finally, the summarising method for automating a manual assembly developed in this thesis can be seen as a potential base, and it can be further developed, refined, and standardized in Scania’s production systems.

References

[1] M. Chui, K. George, J. Manyika, and M. Miremadi, “Human + machine: A new era of automation in manufacturing,” Mckinsey.com, Sep. 7, 2017. [Online]. Available: https://www.mckinsey.com/business-functions/operations/our-insights/human-plus-machine-a-new-era-of-automation-in-manufacturing#. [Accessed: Dec. 9, 2020].

[2] Regeringskansliet, Näringsdepartementet, ”*Smart industri – en nyindustrialiseringsstrategi för Sverige*,” Näringsdepartementet, Stockholm, 2015. [Online]. Available: https://www.regeringen.se/informationsmaterial/2016/01/smart-industri---en-nyindustrialiseringsstrategi-for-sverige/. [Accessed: Dec. 10, 2021].

[3] K. Schwab, ”*The Global Competitiveness Report*,” World Economic Forum, Geneva, 2019.

[4] “Facts and figures,” *Scania Group*. [Online]. Available: https://www.scania.com/group/en/home/about-scania/scania-in-brief/facts-and-figures.html#:~:text=With%2051%2C000%20employees%20in%20about,no%20matter%20where%20they%20operate. [Accessed: Feb. 2, 2021].

[5] “Our purpose,” *Scania Group*. [Online]. Available: https://www.scania.com/group/en/home/about-scania/scania-in-brief/our-purpose.html.[Accessed: Feb. 2, 2021].

[6] “Smart factory lab,” *Scania Group*. [Online]. Available: https://www.scania.com/group/en/home/about-scania/innovation/research/smart-labs.html. [Accessed: Feb. 2, 2021].

[7] M. Spallek, W. Kuhn, S. Uibel, A. van Mark, and D. Quarcoo, “Work-related musculoskeletal disorders in the automotive industry due to repetitive work - implications for rehabilitation”. Journal of Occupational Medicine and Toxicology, vol. 5, pp. 1-6, Apr. 2010.

[8] Irastorza. X, Copsey. S, Schneider. E, “OSH in figures: Work-related muscoskeletal disorders in the EU - Facts and figures”, Luxembourg, 2010. [Online]. Available: https://osha.europa.eu/en/publications/osh-figures-work-related-musculoskeletal-disorders-eu-facts-and-figures/view. [Accessed: Feb. 24, 2021]

[9] International Federation of Robotics, *Demystifying Collaborative Industrial Robots*. Frankfurt: International Federation of Robotics, 2018. [Online]. Available: https://www.ppma.co.uk/uploads/assets/5e46c1b9-cd23-423e-a59650c216e54a0f/ifrdemystifyingcollaborativerobotsupdate2019.pdf. [Accessed: Feb. 28, 2021].

[10] M. Wiktorsson, A. Granlund, B. Södergren, and M. Lundin, "Automation and Flexibility: Exploring Contradictions in Manufacturing Operations," *23rd EurOMA conference*, EUROMA, 16-22 June 2016, Trondheim, Norway [Online]. Available DiVa: diva2:1157364. [Accessed: Mar. 17, 2021].

[11] A. Rojko, *"Industry 4.0 concept: Background and overview," Int. J. Interact. Mob. Technol*, vol. 11, no. 5, p.77, November 2017. [Online]. Availabe: IJIM, https://online-journals.org/index.php/i-jim/article/view/7072/0. [Accessed: Feb. 2, 2021].

[12] M. Wilson, *Implementation of robot systems: an introduction to robotics, automation, and successful systems integration in manufacturing*. London: Elsevier, 2015.

[13] IFR, "IFR Press Conference," *IFR Press Conference, 24 Sept 2020, Frankfurt, Germany* [Online]. Available: https://ifr.org/ifr-press-releases/news/record-2.7-million-robots-work-in-factories-around-the-globe [Accessed: Apr. 21, 2021].

[14] A. Joubair, *What are Accuracy and Repeatability in Industrial Robots?*. [Blog] Available: https://blog.robotiq.com/bid/72766/What-are-Accuracy-and-Repeatability-in-Industrial-Robots. [Accessed: Feb. 10, 2021].

[15] International Federation of Robotics, *The Impact of Robots on Productivity, Employment and Jobs*. Frankfurt: International Federation of Robotics, 2017. [Online]. Available: https://ifr.org/img/office/IFR_The_Impact_of_Robots_on_Employment.pdf. [Accessed: Feb. 10, 2021].

[16] "IRB 140: ABB Robotics - Industrial Robots: ABB Robotics," *ABB Robotics - Industrial Robots | ABB Robotics*. [Online]. Available: https://new.abb.com/products/robotics/industrial-robots/irb-140. [Accessed: Jan. 7, 2021].

[17] "IRB 910SC: ABB Robotics - Industrial Robots: ABB Robotics," *IRB 910SC | ABB Robotics - Industrial Robots | ABB Robotics*. [Online].

Available: https://new.abb.com/products/robotics/industrial-robots/irb-910sc. [Accessed: Jan. 7, 2021].

[18] "IRB 360: ABB Robotics - Industrial Robots: ABB Robotics," *IRB 360 | ABB Robotics - Industrial Robots | ABB Robotics*. [Online]. Available: https://new.abb.com/products/robotics/industrial-robots/irb-360. [Accessed: Jan. 7, 2021].

[19] D. Collins, "What is a Cartesian robot?," *Linear Motion Tips*, Oct. 8, 2018. [Online]. Available: https://www.linearmotiontips.com/what-is-a-cartesian-robot/. [Accessed: Jan. 7, 2021].

[20] J. J. Craig, *Introduction to Robotics*, 3rd ed. Upper Saddle River, NJ: Pearson Education, Inc, 2005.

[21] J. Olhager, *Produktionsekonomi: Principer och metoder för utformning, styrning och utveckling av industriell produktion*, 2nd ed. Lund: Studentlitteratur AB, 2017.

[22] Å. Fast-Berglund and S. Mattsson, *Smart automation: metoder för slutmontering*. Lund: Studentlitteratur, 2017.

[23] Siemens Digital Industries Software, "Design for Manufacturing and Assembly (DFMA)," *Siemens Digital Industries Software*, 2021. [Online]. Available: https://www.plm.automation.siemens.com/global/en/our-story/glossary/design-for-manufacturing-and-assembly-dfma/53982. [Accessed: Feb. 3, 2021].

[24] J. Cooper, C. C. Hayes, J. W. Herrmann, S. K. Gupta, K. Ishii, D. Kazmer, P. A. Sandborn, and W. H. Wood, "New Directions in Design for Manufacturing," *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, vol. 3d: 8th, September 28 – October 2, 2004, Salt Lake City, Utah, USA [Online]. Available: https://doi.org/10.1115/DETC2004-57770 [Accessed: Jun. 2, 2021].

[25] G. Boothroyd and P. Dewhurst, *Product Design for Manufacture and Assembly*. New York: Marcel Dekker, 2004.

[26] D. Edwards, and H. Edwards, "How Tesla "shot itself in the foot" by trying to hyper-automate its factory," *qz.com*, May. 1, 2018. [Online]. Available: https://qz.com/1261214/how-exactly-tesla-shot-itself-in-the-foot-by-trying-to-hyper-automate-its-factory/. [Accessed: Apr. 3, 2021].

[27] Fetch Robotics, "AMRs vs. AGVs: The Difference Between a Robot and a Guided Vehicle," *fetchrobotics.com*, 2018. [Online]. Available:

https://fetchrobotics.com/fetch-robotics-blog/amrs-vs-agvs-whats-the-difference/. [Accessed: Apr. 2, 2021].

[28] E. Aghezzaf, M. Goetshalckx, H. V. Landeghem, V. Limere, L. F. McGinnis, “Optimising part feeding in the automotive assembly industry: deciding between kitting and line stocking,” *International Journal of Production Research*, vol. 50, pp. 4046-4060, Aug. 2012. [Online]. Available: https://www.researchgate.net/publication/232831003_Optimising_Part_Feeding_in_the_Automotive_Assembly_Industry_Deciding_Between_Kitting_And_Line_Stocking. [Accessed: Jun. 2, 2021].

[29] S. Hesse, G. J. Monkman, H. Schunk, R. Steinmann, *Robot grippers*. Weinheim: Wiley-VCH, 2007.

[30] PNEUMATICTips “Vacuum cups: Key uses,” *pneumatictips.com*, Feb. 25, 2016. [Online]. Available: https://www.pneumatictips.com/how-are-vacuum-cups-used/. [Accessed: Apr. 2, 2021].

[31] Chicago Pneumatic, “When do you use a nutrunner versus an impact wrench,” *cp.com*, Aug. 21, 2017. [Online]. Available: https://www.cp.com/nordic/tools/expert-corner/blog/when-to-use-a-pneumatic-torque-wrench-versus-an-impact-wrench. [Accessed: Apr. 5, 2021].

[32] A. Y. C. Nee, A. Senthil Kumar, and A. K. Whybrew, *Advanced Fixture Design for FMS.* London*:* Springer-Verlag London Limited, 1995.

[33] H. Ding, C. Xiong, and Y. Xiong, *Fundamentals of Robotic Grasping and Fixturing.* Singapore: World Scientific, 2007.

[34] “Collaborative Robots”, *ABB Robotics*. [Online]. Available: https://new.abb.com/products/robotics/collaborative-robots. [Accessed Feb. 15, 2021].

[35] K. Bengtsson, S. Biller, B. Lennartson, P. Falkman, and C. Yuan, *“Operation-oriented specification for integrated control logic development”*, *5th Annual IEEE Conference on Automation Science and Engineering*, CASE 2009, pp. 183–90, 2009. [Online]. Available at: <https://doi.org/10.1016/j.ifacol.2017.08.536> [Accessed: Feb. 23, 2021].

[36] K. Bengtsson, B. Lennartson, and C. Yuan, *“The Origin of Operations: Interactions Between the Product and the Manufacturing Automation Control System”*, *IFAC Proceedings Volumes*, vol. 42, pp. 40-45, 2009.

[online]. Available: https://doi.org/10.3182/20090603-3-RU-2001.0148. [Accessed: Feb. 23, 2021].

[37] K. Bengtsson, P. Bergagård, P. Falkman, B. Lennartson, S. Miremadi, C. Thorstensson, C. Yuan and K. Åkesson. “Sequence planning using multiple and coordinated sequences of operations,” *IEEE Transactions on Automation Science and Engineering*, vol. 9, pp. 308–319, 2012. [Online]. Available: <doi: 10.1109/TASE.2011.2178068.> [Accessed: Feb. 23, 2021].

[38] Industrial text & video, “Introduction to PLC Programming and Implementation - from Relay Logic to PLC Logic”. Marietta, Industrial Text and Video Company, 1999.

[39] “Circular path using MoveP/MoveC,” *Collaborative robotic automation*. [Online]. Available: https://www.universal-robots.com/articles/ur/programming/circular-path-using-movepmovec/. [Accessed: Mar. 20, 2021].

[40] H. M. A. A. Al-Assadi, T. Faisal, M. Iwan, A. Izabo and H. Ramli, “Programming ABB Industrial Robot for an Accurate Handwriting”, *Latest Advances in Systems Science and Computational Intelligence*, 2012. [Online]. Available: https://www.semanticscholar.org/paper/Programming-ABB-Industrial-Robot-for-an-Accurate-Izabo-Faisal/d50033add5c8cc5a102172e791787e3542fea7ec. [Accessed: Mar. 19, 2021].

[41] “Robotics Glossary,” *Yaskawa*. [Online]. Available: https://www.motoman.com/en-us/about/company/robotics-glossary. [Accessed: Mar. 20, 2021].

[42] B. Davidson and R. Patel, *Forskningsmetodikens grunder: att planera, genomföra och rapportera en undersökning*, 4th ed. Lund: Studentlitteratur, 2017.

[43] M. Höst, B. Regnell, and P. Runeson, *Att genomföra examensarbete*. Lund: Studentlitteratur, 2006.

[44] A. Eliasson, *Kvantitativ metod från början*, 2nd ed. Lund: Studentlitteratur, 2010.

[45] New era of automation. "Automated Assembly Line at Scania’s Smart Factory Lab," *YouTube*, Jun. 3, 2021 [Video file]. Available: https://www.youtube.com/watch?v=SRy-5CtzV_4. [Accessed: Jun. 3, 2021].

Appendix A

Table A. 1 below summarises the list of the resource names, shortenings and descriptions. These resources were used in the automation system.

Table A. 1. *List of resources*

Name	**Abbreviation**	**Description**
Station 1	*St1*	Manual station
Station 2	*St2*	Steering wheel assembly
Station 3	*St3*	Front wheel assembly
Robot 1	*Rb1*	*ABB 1200*
Robot 2	*Rb2*	*Yaskawa HC20DT*
Robot 3	*Rb3*	*UR 16E*
Gripper 1	*G1*	Schunk *plus E100*
Gripper 2	*G2*	*Robotic 2F 85*
Nutrunner 1	*Nr1*	*AtlasCopco ETD STR61-90-13-T25*
Nutrunner 2	*Nr2*	*AtlasCopco ETD STR61-90-13-T25*
Part 0	*P0*	Pedalcar body
Part 1	*P1*	Steering wheel
Part 2	*P2*	*M8* screw
Part 3	*P3*	*M8* washer
Part 4	*P4*	Front wheel
Part 5	*P5*	*M10* screw with integrated washer
Fixture 1	*Fx1*	Pedal car fixture
Fixture 2	*Fx2*	Pedal car fixture
AMR 1	*Am1*	Automated guided vehicle 1
AMR 2	*Am2*	Automated guided vehicle 2
AGV 1	*Ag1*	Autonomous mobile robot 1
AGV 2	*Ag2*	Autonomous mobile robot 2
Screw feeder 1	*F1*	Screw feeder
Camera 1	*C1*	*Sick PLOC2D* camera
Camera 2	*C2*	*Pickit 3D* camera
Material rack 1	*Mr1*	Material rack for steering wheel and M8 screw
Material pallet 1	*Mp1*	Material pallet for front wheel and M10 screw
Material box 1	*Mb1*	Material box in material rack1
Linear actuator 1	*La1*	Linear actuator in material-rack
Sensor 1	*S1*	Sensor in the upper part of the material-rack, false when box in position
Sensor 2	*S2*	Sensor in lower part of the material-rack, false when an empty material box in position
Sensor 3	*S3*	Located in station 3, false when pallet in position

Appendix B

Table B. 1 below summarises the specification for the robot's selection process, where Specifications marked as green mean that it fulfils the requirements, orange means that it is plausible and red means that it does not fulfil the requirement.

Table B. 1. *Robot's selection criteria*

Manufacture	*ABB*		*Universal robots*		*KUKA*	*YASKAWA*	
Robot name	***IRB 2400-10***	***IRB 2400-16***	***UR10e***	***UR16e***	***LBR iiwa 14 R820***	***HC10DT YRC1000***	***HC20DT YRC1000***
Reach	1550 mm	1550 mm	1300 mm	900 mm	820 mm	1200 mm	1700 mm
Payload	10 kg	16 kg	10 kg	16 kg	14 kg	10 kg	20 kg
Number of axes	6	6	6	6	6	6	6
Weight	380 kg	380 kg	33.5 kg	33.1 kg	29.9 kg	58 kg	140 kg
Mounting	Floor mounted and inverted mounted for all versions. Wall mounted for IRB 2400/10	Floor mounted and inverted mounted for all versions. Wall mounted for IRB 2400/10	Any Orientation	Any Orientation	Any Orientation	Floor, ceiling wall, tilt	Floor, ceiling wall, tilt
Position repeatability	0.03 mm	0.03 mm	0.05 mm	Pose 0.05 mm	Position accuracy ±0.15 mm	±0.1 mm	±0.05 mm
I/Os	16 in, 16 out	16 in, 16 out	Digital- in 16/out 16	Digital- in 16 /out 16	Bus connection. Ethernet or Profinet	Specialized signals: 19 inputs and 6 outputs / General signals: 40 inputs and 40 outputs	Specialized signals: 19 inputs and 6 outputs / General signals: 40 inputs and 40 outputs
Protection	Foundryplus IP67, IP54	Foundryplus IP67, IP54	IP54	IP54	IP54	IP67	IP67
Power consumption	At max speed 0.67 kW	At max speed 0.67 kW	Moderate 0.35 kW, Max 0.615 kW	Moderate 0.35 kW, Max 0.585 kW	Missing information	Average 1 kW	Average 1.5 kW
Collaborative	No	No	Yes	Yes	Yes	Yes	Yes
Other			Pick-IT camera	Pick-IT camera		Safe force/torque sensors in all 6 links	Safe force/torque sensors in all 6 links
Comment	Heavy industrial robot, good simulation program	Heavy industrial robot, good simulation program	Light, easy to use, many gripper options	Light, easy to use, many grippers' options		Safe, collaborative, poor simulation program	Safe, collaborative, poor simulation program

🟥 Bad	🟨 Neutral	🟩 Good

Table B. 2 below summarises specification for the gripper selection process.

Table B. 2. *Gripper selction critera*

Grippers	*Schunk*					*Robotiq*		*OnRobot*
Model	*PGB 80*	*EGP-64*	*PGB 125*	*PGN Plus E-100*	*EGL 90-PN*	*2-finger 85 mm gripper*	*2-finger 140 mm gripper*	*RG2*
Stroke per jaw [mm]	6	10	10	10	42,1	42,5	70	55
Min/max gripping force[N]	230/260	75/300	590/640	200/810	50/600	20/235	10/125	3/40
Recommended workpiece weight [kg]	1,25	1,25	3,3	4,05	3	5	2,5	5
Max permissable finger length [mm]	80	80	125	160	165			
Max permissable mass per finger [kg]	0,35	0,24	1,1	1,1	0,5			
Repeat accuracy [mm]	0,01	0,02	0,01	0,01	0,05	Finger resolution = 0,4 mm	Finger resolution = 0,6 mm	0,1
Weight [kg]	0,46	0,8	1,32	1,73 -1,8	1,8	0,9	1	0.78
Mechanisms	Pneumatic	Electric	Pneumatic	Electric	Electric	Electric	Electric	Electric
Communication interface		Digital inputs		Digital inputs	Profinet	Modbus	Modbus	
Suitable application	Steering wheel	Steering wheel	Steering wheel	Steering wheel	Front wheel	Front wheel	Front wheel	
Comment	24 mm hole in the middle of gripper that can be used with nutrunner				Front wheel			

Appendix C

Table C. 1 summarises the iterations for the design of the steering wheel fingers, where each iteration was analysed and further improved based on the feedback until a desirable solution was obtained.

Table C. 1. *Summary of steering wheel's gripper finger designs, feedback and improvements*

Test	Feedback	Improvements
Design 1	Poor gripping, poor fit, and wrong geometry dimensions. The CAD model of the steering wheel was not the same as the actual one.	Physical measurements were taken to determine which dimensions that should be changed.
Design 2	Dimensions were still a bit off, resulting in a poor fit.	Small changes were made in certain dimensions.
Design 3	There was a small chance of fingers colliding with the steering wheel on gripping the part.	Extra chamfers were added that acted as a guide to solve any tolerance issues.
Design 4	Target was located and picked correctly with high precision repeatability and accuracy.	

Table C. 2 summarises the iterations for the design of the front wheel fingers, where each iteration was analysed and further improved based on the feedback until a desirable solution was obtained

Table C. 2. *Summary of front wheel's gripper finger designs, feedback and improvements*

Test	Feedback	Improvements
Design 1	Poor entry and low friction between the fingers and the front wheel. Fingers were too short and hit the front of the wheel.	The design required wider jaw opening and longer fingers.
Design 2	No contact with the inner hub of the front wheel and low friction.	Redesign was required to ensure better contact between the fingers and the wheel. The gripping of the hub was to complex, so it was decided that the gripper was only to grip the spokes.
Design 3	Better gripping, low friction, the movement in Z direction still not fixed due the complex shape of the wheel. The fingers sometimes hit the rim while entering between the spokes	Redesign of the fingers, a ribbed surface was added to ensure better gripping, chamfers were added to the top part of the fingers as a self-guiding design to correct or guide the fingers into the front wheel.
Design 4	A ribbed surface gave more friction, still some movement in Z. When positioning to assemble the wheel it slips into an angled position in the gripper, causing the wheel to misalign. The fingers were ductile and bend when gripping	The ribbed surfaces were made larger. To prevent the wheel from misaligning a small tap was added to the end of the finger which supported the wheel. The finger where made thicker and 3D printed with stiffer material (carbon fibre mix).
Design 5	Stiffer fingers, worked just fine	No further improvements were required

Table C. 3 summarises the iterations for the camera vision system used in station 2, where each iteration was analysed and further improved based on the feedback until a desirable solution was obtained.

Table C. 3. *Station 2 camera vision system tests, feedback, and improvements*

Test	Feedback	Improvements
Test 1	There were difficulties detecting part's contours (steering wheel), the background got labelled as a part. This was mainly due to the background being the same colour as the part. (Black material box foam was used).	The background/material box foam was replaced with a white one
Test 2	During the testing to detect the steering axle, the camera detected the parts and drew boundary lines, however they did not enclose the part fully. The camera also labelled certain background features as parts.	Different contrast and brightness were tested. To eliminate the problem with background features, exclusion areas were added
Test 3	With the right contrast and brightness settings the boundary lines enclosed the whole part. The camera did not label background features anymore.	No further improvements were required

Table C. 4 summarises the iterations for the camera vision system used in station 3, where each iteration was analysed and further improved based on the feedback until a desirable solution was obtained.

Table C. 4. *Station 3 camera vision system tests, feedback, and improvements*

Test	Feedback	Improvement
Test 1	Very off from the target, low precision and accuracy.	Multiple calibrations were carried out to ensure better precision.
Test 2	5 mm of the target, medium precision repeatability, low accuracy. Spokes orientation were not located.	White contrast to improve the recognition. Align objects coordinate system with TCP coordinate frame.
Test 3	3 mm of the target, high precision repeatability, low to medium accuracy.	The Distance was investigated, a decent distance from the camera where the lense gave the best details of the part where chosen.
Test 4	2 mm of the target, high precision repeatability, medium to high accuracy.	Improved filtering and threshold.
Test 5	Target is located and picked correctly with high precision repeatability and accuracy.	No further improvements were required.

Appendix D

Figure D. 1 illustrates the flowchart that was developed to translate the planned operations into a program, for picking the steering wheel from the material box in Station 2.

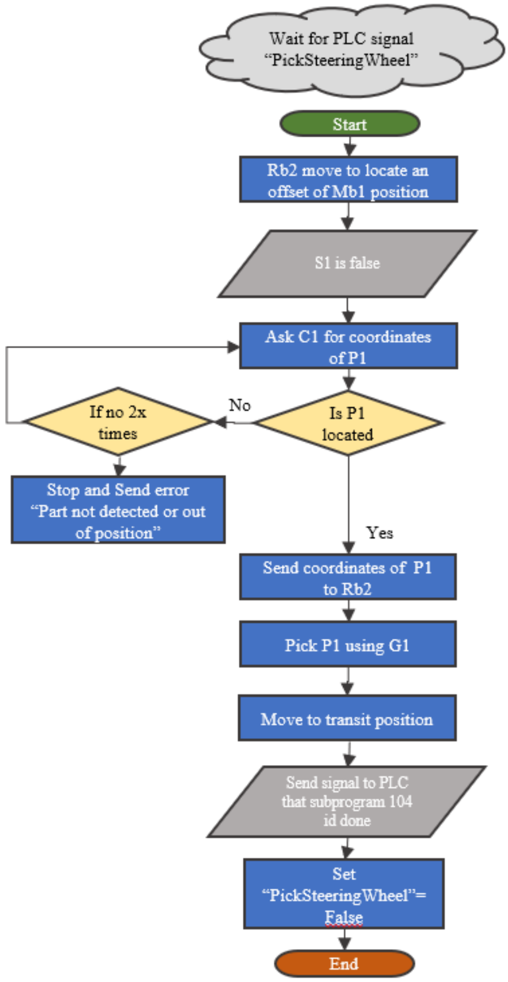


Figure D. 1. *Flowchart for subprogram 104, PickSteeringWheel*

Figure D. 2 illustrates the flowchart for placing the steering wheel onto the steering axle for Station 2.

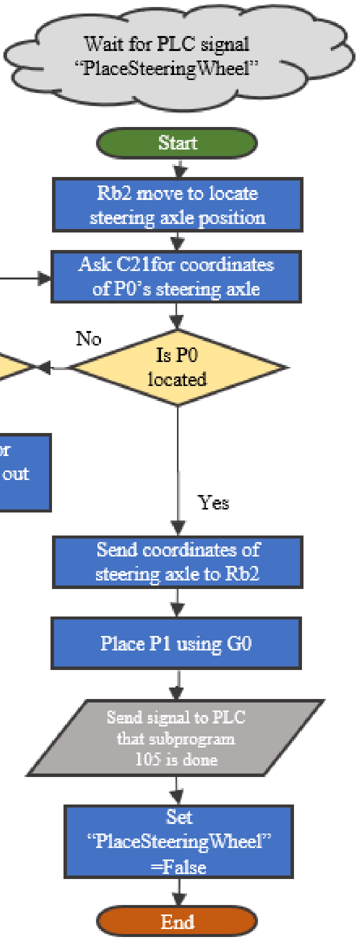


Figure D. 2. *Flowchart for subprogram 105, PlaceSteeringWheel*

Figure D. 3. illustrates the flowchart for the picking operations of the *M8* screw at Station 2.

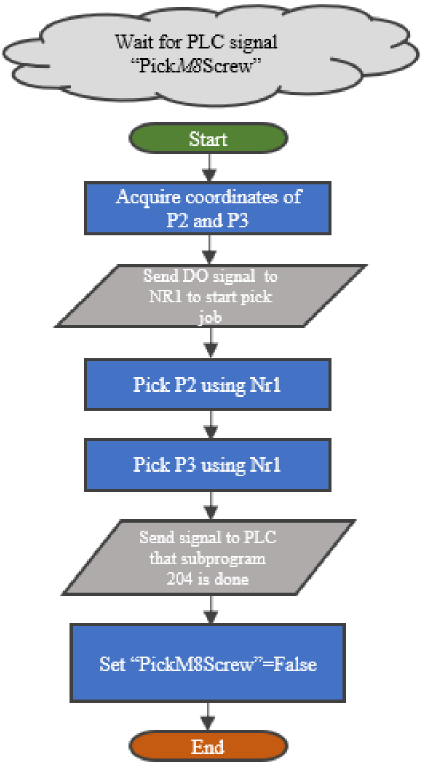


Figure D. 3. *Flowchart for subprogram 204, PickM8Screw*

Figure D. 4 illustrates the flowchart for the tightening operations of the *M8* screw at Station 2.

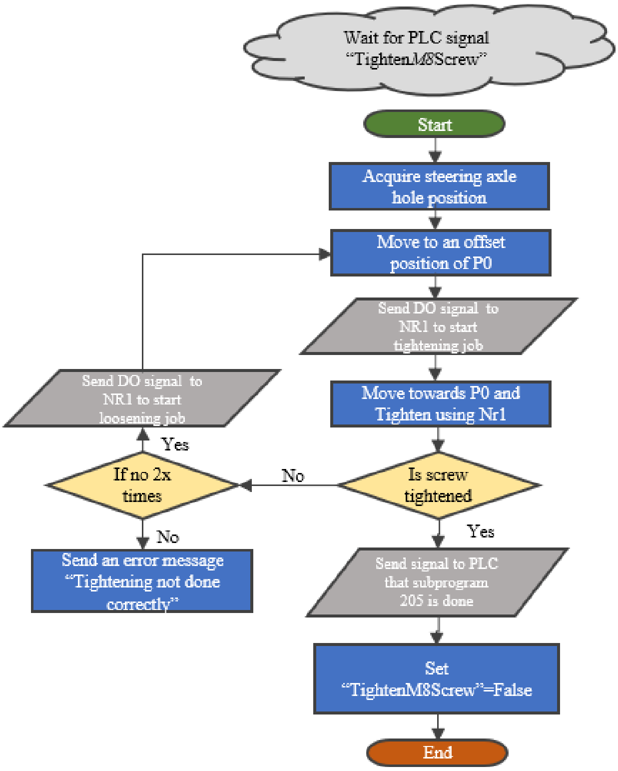


Figure D. 4. *Flowchart for subprogram 205, TightenM8Screw*

Figure D. 5 illustrates the flowchart for the releasing operations of the *M8* screw at Station 2.

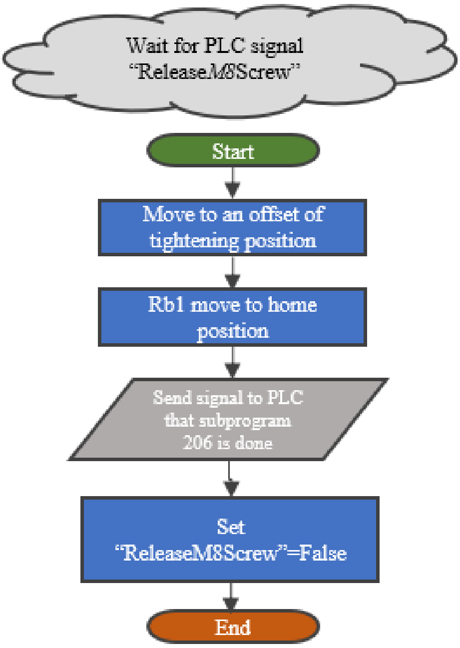


Figure D. 5. *Flowchart for subprogram 206, ReleaseM8Screw*

Figure D. 6 illustrates the flowchart for releasing operations of the steering wheel at Station 2.

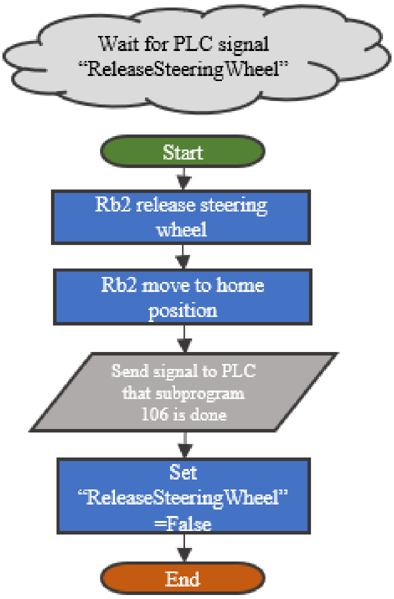


Figure D. 6. *Flowchart for subprogram 106, ReleaseSteeringWheel*

Figure D. 7 illustrates the flowchart for the picking operations of the front wheel at Station 3.

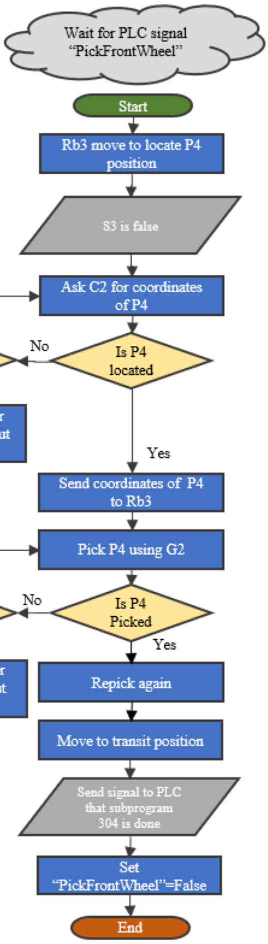


Figure D. 7. *Flowchart for subprogram 304, PickFrontWheel*

Figure D. 8 illustrates the flowchart that was developed to translate the planned operations into a program, for placing the front wheel onto the front axle at Station 3.

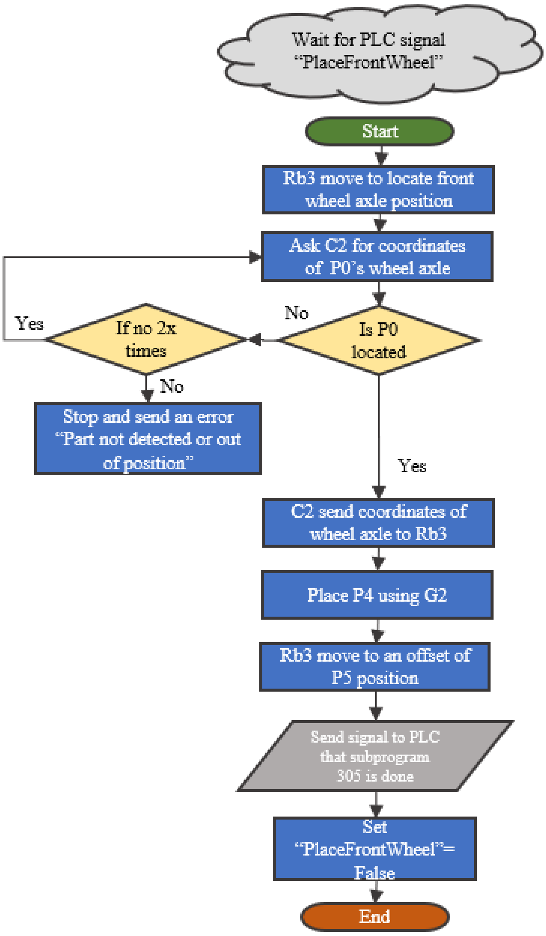


Figure D. 8. *Flowchart for subprogram 305, PlaceFrontWheel*

Figure D. 9 illustrates the flowchart for the picking operations of the tightening the *M10* screw at Station 3.

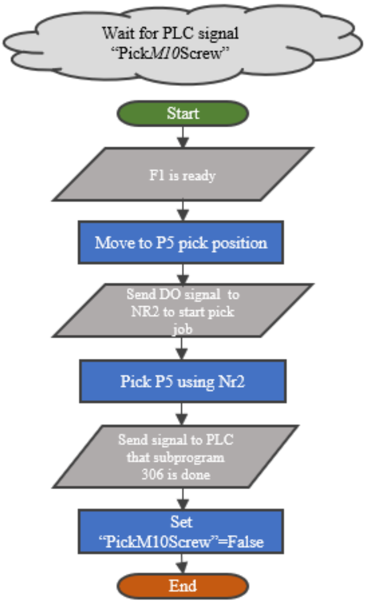


Figure D. 9. *Flowchart for subprogram 306, PickM10Screw*

Figure D. 10 illustrates the flowchart for the tightening operations of the *M10* screw at Station 3.

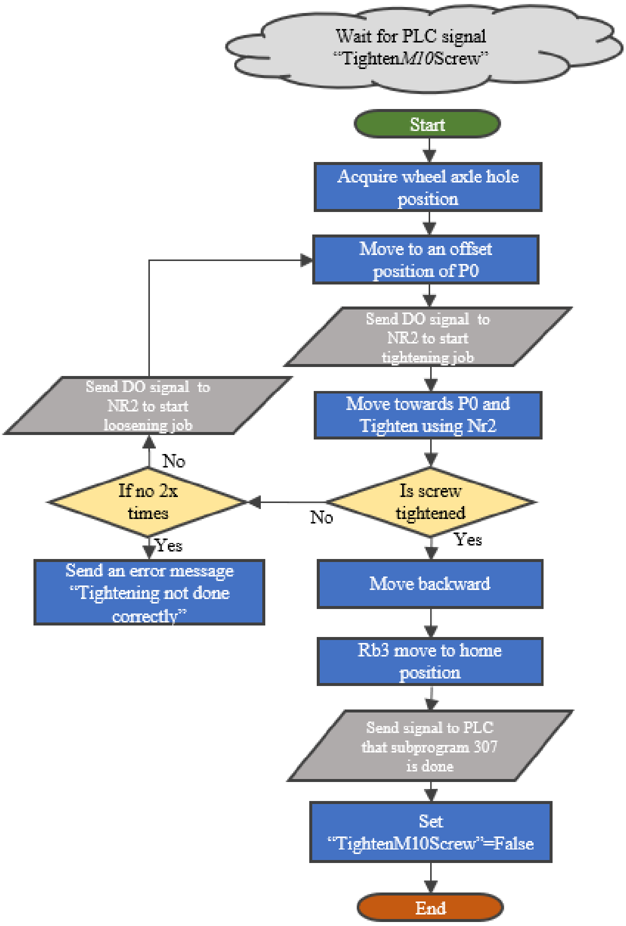


Figure D. 10. *Flowchart for subprogram 307, TightenM10Screw*