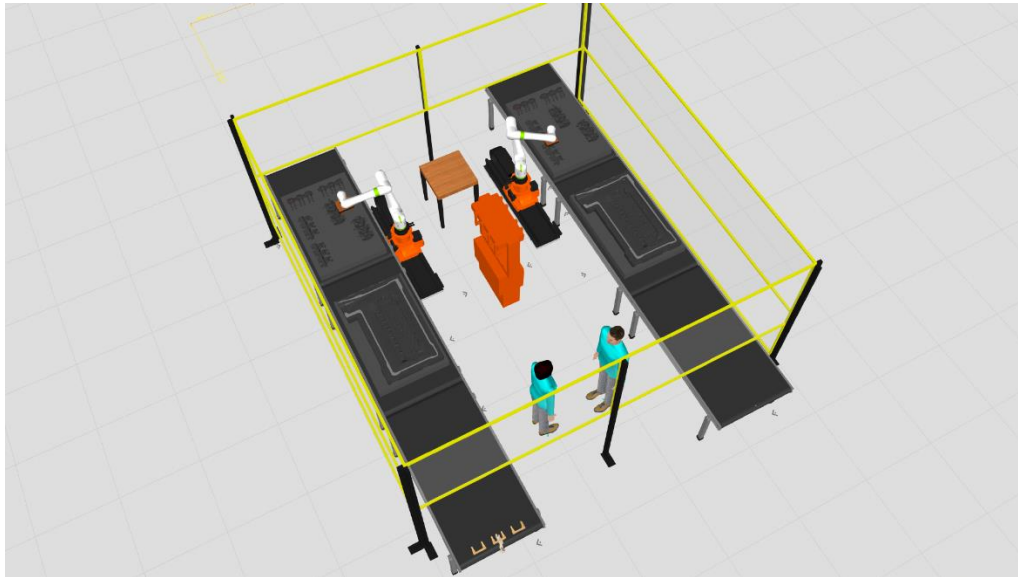




CHALMERS



# Collaborative Robot in sand core assembly

Are collaborative robots a good solution in sand cores assembly?

Bachelor thesis in mechanical engineering

Anton Andric  
Jens Danielsson

Bachelor's thesis 2022

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Jens Danielsson



**CHALMERS**

Department of Industrial and Materials Science  
CHALMERS UNIVERSITY OF TECHNOLOGY  
Gothenburg, Sweden 2022  
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Anton Andric, Jens Danielsson

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Cover: Visualization of simulation model in visual components

Typeset in LATEX

Printed by Chalmers Reproservice

Gothenburg, Sweden 2022

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### **Abstract**

At the Volvo site in Skövde they develop and manufacture engines and engine-related components. The main use of the engines is in trucks, but they are also manufactured for industrial use and marine use. Except for the assembly factory, there are three foundries and one machining factory on the site. Components from these factories are either sold separately or transported to the assembly factory for assemblage. With the help of Visual Components and the virtual commissioning approach, Fanuc CRX-10iA/L robots were implemented in a simulation in an attempt to automate the sand core assembly for smaller volumes.

To perform this project, the methodology was based on reviewing literature around the keywords of the project and learning the software through tutorials and guides with different exercises. The aim of the project was to simulate if there is a feasible way of implementing collaborative robots in the current assembly process whilst answering the research questions that had been given and are presented in the report. The results of the project are presented and concluded that it is possible to implement collaborative robots in the current assembly process although some adjustments need to be implemented to the current layout.

Keywords: Virtual commissioning, Visual Components, Collaborative robots, Simulation, Gripper, Computer aided manufacturing, Sand Cores

## **Acknowledgments**

We would like to dedicate this page to thank the people that made this thesis possible and helped us along the way. During the project, these people devoted time and energy to helping us face the challenges and technical difficulties throughout the entire project.

Foremost we would like to thank our academic supervisor Omkar Salunkhe, for his continuously magnificent support during this thesis. Providing us with great discussions and constructive feedback, he enabled us to keep our morale up even when faced with difficult obstacles. We would also like to thank our examiner Johan Stahre for his approval of this thesis.

We would like to thank Visual Components and especially Christer Ericsson for providing us with the software that was used throughout this project. Always being accessible and providing us with guidelines and tutorials when we were faced with technical difficulties.

Finally, we would like to thank Volvo Powertrain Sweden Skövde for granting us this opportunity for our thesis work. Especially to Nikos Valsamidis, Jesper Lundberg, Annika Carlsson, Marcus Gustafsson, Hampus Zell, and Marcus Gottschlich for providing us with continuous support and feedback to help us along with this project.

Anton Andric, Chalmers University of Technology, Gothenburg, May 2022

Jens Danielsson, Chalmers University of Technology, Gothenburg, May 2022

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# 1

## Introduction

### 1.1 Background

All companies today face a challenge of becoming more and more efficient to remain competitive. This can be done by identifying losses and non-value adding activities, which is an ongoing work at Volvo powertrain.

At Volvo Powertrain in Skövde, cylinder heads and cylinder blocks are molded for diesel engines. Depending on the volume size, the manufacturing is either automatized or built manually. Automation is becoming more common in the industry today and people's physical work is being replaced. Automation can reduce lead times, increase availability, reduce human errors and, in the long run, increase the cost efficiency. Is there a potential for collaborative robots to handle small and medium-sized volumes at Skövde and keep the whole production automatized or can there be a co-relation between manual assembly and the robots?

### 1.2 Purpose and aim

The goal of this thesis is to find a feasible solution for the utilization of collaborative robots in areas that are currently using manual labor, then present a simulation of how the robots will operate and if there is any point in implementing the concept in the production.

### 1.3 Deliverables

- The work will lead to a solution proposal that is implemented virtually in suitable software.
- Assess risks in collaboration between robots, humans, and other equipment.
- Present the advantages and disadvantages of collaborative robots in core manufacturing.

### 1.4 Project limitations

- There is no statement that the solution must make a profit. Means that we are free to work however we want to try to find a solution for implementing collaborative robots.
- There will be no special regard for a given budget frame. There has not been any discussion regarding a budget limit. Although we will provide different arguments for what we have found and why they are important.
- Time is a limitation. We only have around 20 weeks to complete this project.
- Limited knowledge and experience within this area.
- Limited resources, the workstations as of now have a very limited space.

# 2

## Theory

### 2.1 Current process

The current process consists of two assembly lines, three pallets on either side with components, three operators and a specialized lifting tool. Figure 1 illustrates the workspace.

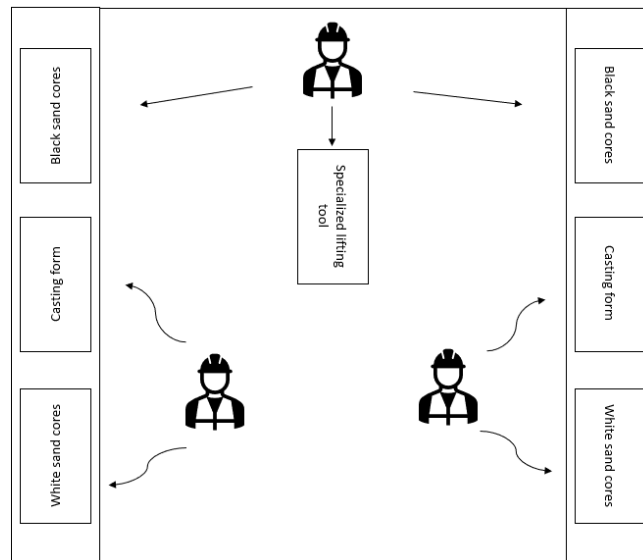


Figure 1: Current process

The breakdown of the process is the following (from the left side's point of view):

- The operator at the top only works with the heavier black sand cores and assembles them into the specialized lifting tool.
- While the top operator works, the operator to the left assembles the white and lighter sand cores to the casting form, in their specific order with a special glue that dries after 30 seconds.
- After the left operator has assembled a few of the white components, the top operator lifts the entire black sand core component with the assistance of the specialized lifting tool and assembles it to the casting form, where the left operator has prepared it with glue.
- After the black component has been assembled, the left operator finishes the assembly with the final white parts. While the left operator finishes the assembly, the top operator and the right one has started on the next assembly to the right.
- The process is then repeated.

## 2.2 Process Planning

The process planning includes planning and finding the best and the most feasible manufacturing processes for the specific project [1]. Process planning is getting more and more important, this is because of the competition and the strategy of the companies are changing to a shorter product lifecycle [2].

The process planning also includes which sequence the part should be manufactured according to the design documentation. Process planning can often be restricted to the resources that are available within the company. This can for example be the equipment and the technology that are available. It is often the production engineers that do the process planning. For the engineers or engineer that will perform the process planning it is important that they have good knowledge with all the manufacturing processes that occur in the company, it is also important that he or she is familiar with reading drawings. When working with the process this are some important steps to consider [1].

- Analyze the drawings
- Process sequence
- Which parts should be manufactured in house, and which parts should be outsourced.
- Tooling, fixtures, molds
- Analyze the method
- Tools and machining operations

The idea with parallel engineering is that the process planning, product design and process design are performed at the same time. An example of this can be seen in figure 2. The result of this will lead to that the manufacturing phase is working closer with the design phase, and this will probably result in shorter lead times. When working this way, it is easier to get good compromise between the products performance and the manufacturing process. The old or traditional way of working is by using sequential engineering. When working with sequential engineering the steps are done in sequence as seen in figure 3 [2].

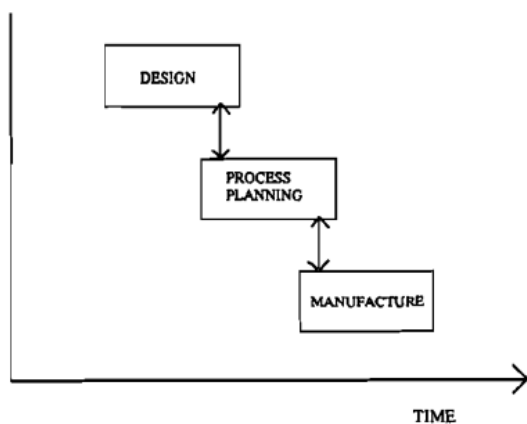


Figure 2 Parallel engineering [2]

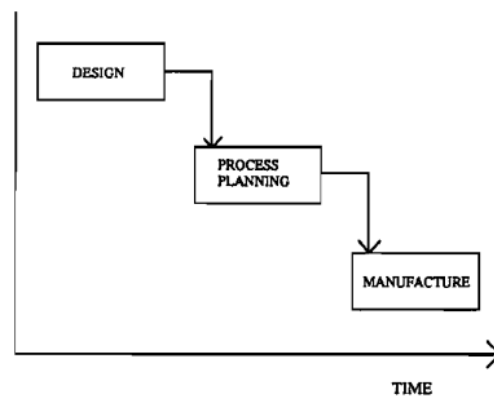


Figure 3 Sequential engineering [2]

## 2.3 Sand-casting

Sandcasting is widely used all over the world, and it is also one of the oldest way of casting parts. Sand casting are often being used on small and simple cheap products, but it can also be done for example to high-tech complex engines with cores that forms the interior of the casting. The reason that sand-casting is used to this wide extent are the possibility to cast many different metals. This is especially important for steel, iron and titanium which requires a very high melting point. The first step to performing sand-casting is to design the pattern equipment. The pattern equipment can be made of an assembly off different pieces, or it can be on a single piece. This of course depends on the complexity of the parts. The material that the pattern is made of depends on how many sandcasting forms that needs to be produced. If mass produced, the pattern needs to be durable, and the material of choice is often aluminum or cast iron. If it is small production volumes the pattern equipment can be made of wood or resin. The pattern equipment measurements are not the exact measurements of how the final part will look when it is finished. This is because shrinkage and distortion must be considered. To prevent that the sand form and sand cores don't break when removing them from the pattern equipment draft tape is applied to the surface [3].

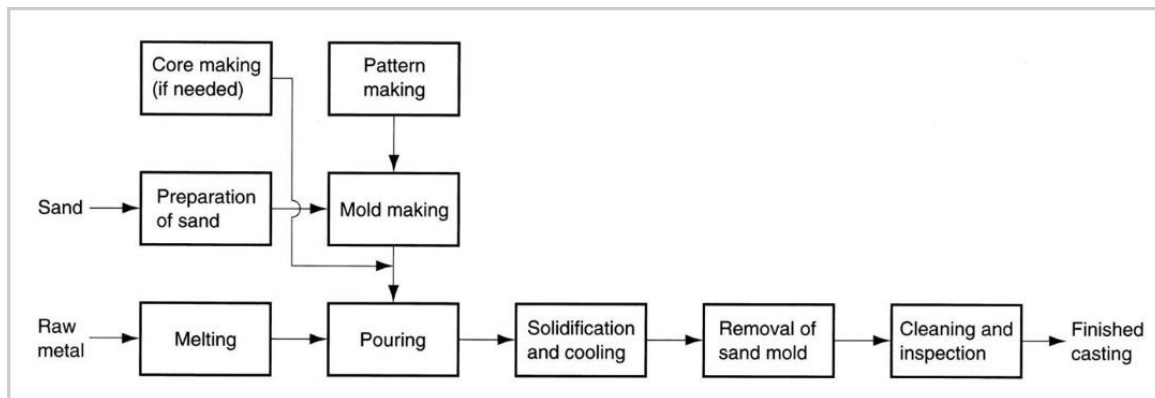
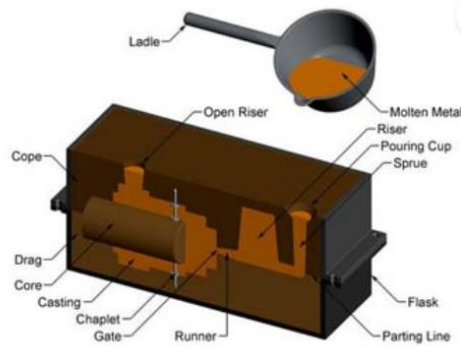


Figure 4: Sand casting [5]

The sand cores can either be solid or hollow depending on the design of the part. If it is a very complex casting it can involve multiple sand cores in one part. It is these parts that create and forms the hollow and the internal features of the finished part. The cores simply prevent the molten material from filling the space with molted material [4]. When the metal has melted it is thin and oxidates quickly. When it oxidates, it releases gases, this can then result in imperfections in the finished product. After the part is finished the sand-molds are destroyed and the cavities are cleaned [3].

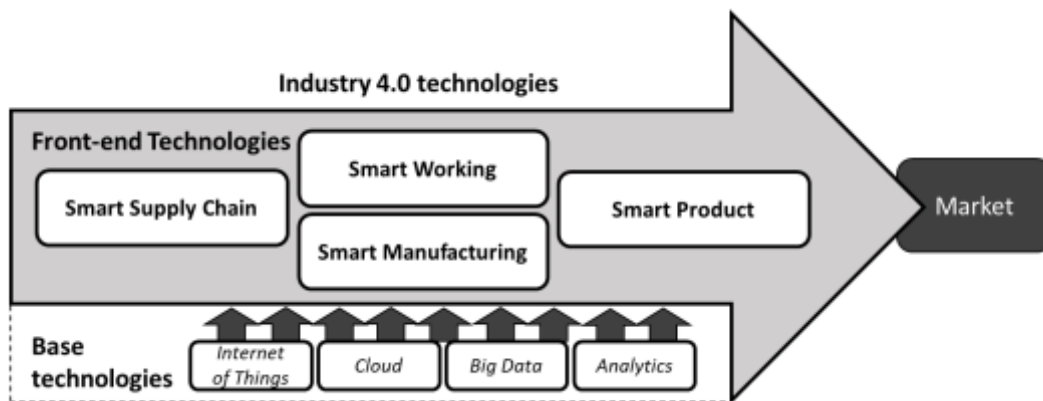


**Sand Mold - Closed**

*Figure 5: Casting procedure [5]*

## 2.4 Industry 4.0

With the purpose of increasing the national industry of Germany on a productive and efficient level, industry 4.0 was created with the help of advanced production systems. Industry 4.0 consists of two different layers according to figure 6, These are Front-end technologies and Base technologies. Front-end technologies consist of four topics, where each represent different technologies. Whilst base end technologies connect the Front-end [6].



*Figure 6: Industry 4.0 structure [6]*

## 2.5 Automation

Automation is used in many different industries nowadays, off course in manufacturing but also in industries like defense, IT (information technologies) and facilities. Automation has grown enormously in the last couple of years, this is because the availability of technology has grown and become accessible. Automation is usually used to minimize repetitive tasks and minimize none ergonomically tasks. This could for example be heavy lifting in bad positions. In manufacturing the most used automation is using robot lines, this could be for

welding, painting, or assembly. But the robots still need to be supervised and programmed for the specific task. Automation in software is also growing very fast, specifically in AI (artificial intelligence) and in ML (machine learning). One example for an automated software is when you can create a program that will test your software and when it is finished it will display a report of the errors in the program [7].

With automation there can be problems with people losing their jobs, this will specifically affect people with lower education. Because the easy jobs will probably be replaced with automation, this will not only happen in manufacturing but also more and more in other types of business. For companies to be competitive in today’s market there is a need for automation, but automation becomes more difficult because products today are becoming more and more customized for only one customer, and they need flexible automation [7].

Automation have now been discussed and this is how automation is defined according to groover 2001:

*Automation is the technology by which a process or procedure is accomplished without human assistance [8].*

Tasks that will be performed needs to be considered if they best fit a machine or a human [9]. The figure below shows the pros and cons of both machine and humans.

HUMANS SURPASS MACHINES IN THE:	MACHINES SURPASS HUMANS IN THE:
<ul style="list-style-type: none"> <li>▪ Ability to detecting small amounts of visual or acoustic energy</li> <li>▪ Ability to perceiving patterns of light or sound</li> <li>▪ Ability to improvise and use flexible procedures</li> <li>▪ Ability to store very large amounts of information for long periods and to recall relevant facts at the appropriate time</li> <li>▪ Ability to reason inductively</li> <li>▪ Ability to exercise judgment</li> </ul>	<ul style="list-style-type: none"> <li>▪ Ability to respond quickly to control signals, and to apply great force smoothly and precisely</li> <li>▪ Ability to perform repetitive, routine tasks</li> <li>▪ Ability to store information briefly and then to erase it completely</li> <li>▪ Ability to reason deductively, including computational ability</li> <li>▪ Ability to handle highly complex operations, i.e., to do many different things at once.</li> </ul>

*Figure 7: Fittings list [9]*

Automation can be divided into physical or cognitive automation. Physical automations are mechanical automation this includes tools and robots. While cognitive automation are information, instructions, and systems like pick to light [8].

2.5.1 Flexible automation

Fixed automation is when the equipment is specific to one product, this is the most common way to automate. This means that the company would spend a lot of money on automation equipment and use it for one specific product or product family and after that store it and try to use it in the future. In the electronics market the production runs are between 6-12 months

which is relative short compared to other productions. The reasoning behind using fixed automation is often that you as an engineer get a task to design a fixture and does not think or know about how the next product are going to be designed. Using fixed automation will also often be cheaper than using flexible automation in the short run [10].

This results in that for every new product that will be introduced more and more space and equipment is needed. This is also something that needs to be considered more and more now because the variant of the products tends to get more, and the volume gets lower per product. Therefore, flexible automation becomes more interesting. The concept of flexible automation is that the equipment can be reused. This will gain more space on the production floor and should reduce the amount of programming that needs to be done. The downside with flexible automation is that the initial investment is higher but in the long run it should be able to save money because of the space, equipment and time spent on setting up the new production lines. The figure below shows that fixed automation is best for low mix of different parts, but when it is a high mix of parts flexible automation is superior [10].

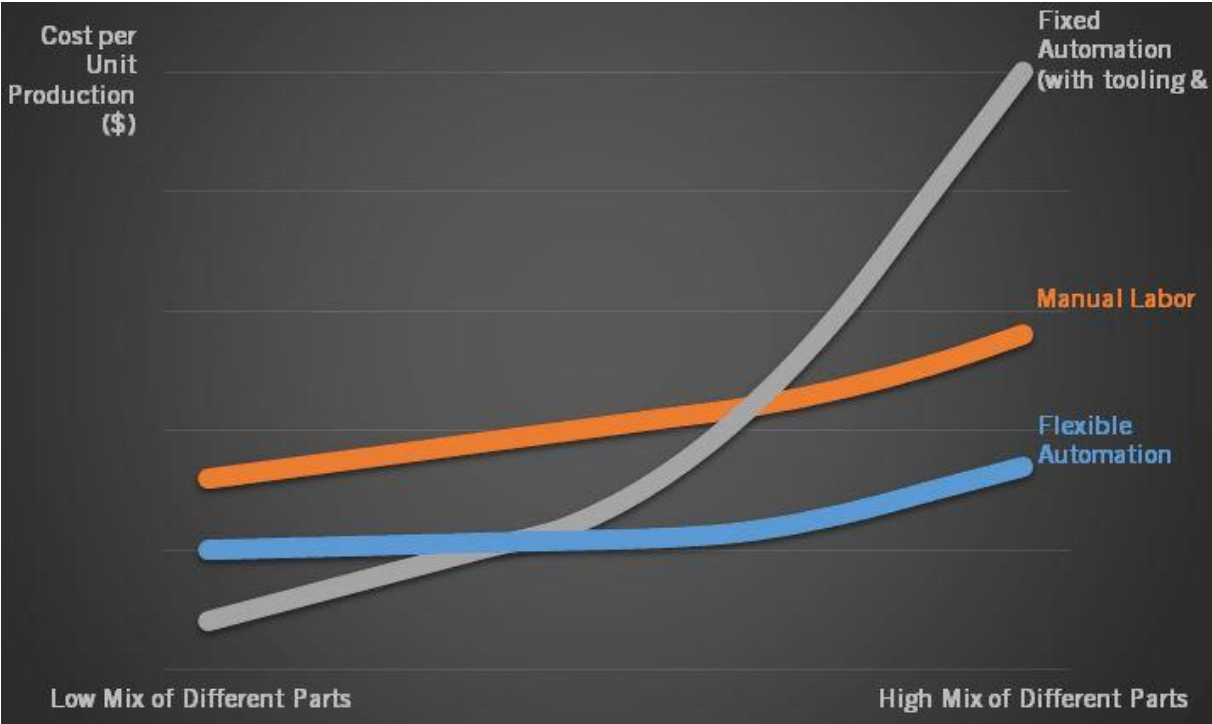


Figure 8: "Return of investment" [10]

There are three important components that are required in a flexible automation system compared to fixed automation, these are sense, think and act. Sense is how it gets the information, this can be through sensors, lasers, or other components. The think part uses information it has gotten from the sense and uses a computer program to process the information. The component that acts sends a signal to the robot, of what it should do, and the robot does the tasks. To define a flexible automation robot, a robot should have all these

attributes, sense, think and act. When a new product is being introduced the robot can be teched how to handle this product [10].

## 2.6 Collaborative robots compared to traditional robot automation

Robots are still not used to a wide extent in assembly when it comes to small and medium sizes production. This will collaborative robots solve because they don't need a cage around them and are easier to integrate. The goal with using collaborative robots is that they will minimize monotone tasks and avoid tasks with bad posture and while doing this increase the efficiency of the process.

Germany has high wages in comparison to many other countries but still lot of assembly jobs are done by humans. The companies choose to do this because there are many different products being assembled in the same line and some products are even specific to just one customer, this makes doing a traditional automation very expensive and the result is a long payback time. This is where collaborative robots come in, the most important contribution with collaborative robots are that they do not require a cage. This is very important because if the station is completely manual work now, and if you want to automate it with traditional automation, it will be very costly and take time, and often a lot of the station will need to be modified or a completely new station needs to be built. Whilst if you install a collaborative robot that does not require a cage it will be a smaller investment [11]. Collaborative robots can contribute to a variety of different factors, some of these are:

- Improving ergonomics
- Relieving the operator from repetitive tasks
- Gives help in high precision tasks
- Eases the workload on operator
- Minimizing working steps for the operator

### 2.6.1 Cost of implementing collaborative robots

When a traditional robot gets installed, the cost of the robot only stands for about one third of the total cost of the entire project. It seems that this estimation also follows when installing a collaborative robot. The main factors that contribute to this are the material and getting the right certification for the safety of the operator. When a company invest in a robot the time, they expect to get a return of investment depends on which industry they are involved in.

When working in automotive and the electronics industry the expected return of investment is about one year of a robot installation. The company seems to be accepting a longer return of investment time when it comes to installing collaborative robots. The reasoning behind this is the improvements collaborative robots can contribute with, see figure 9 [11].

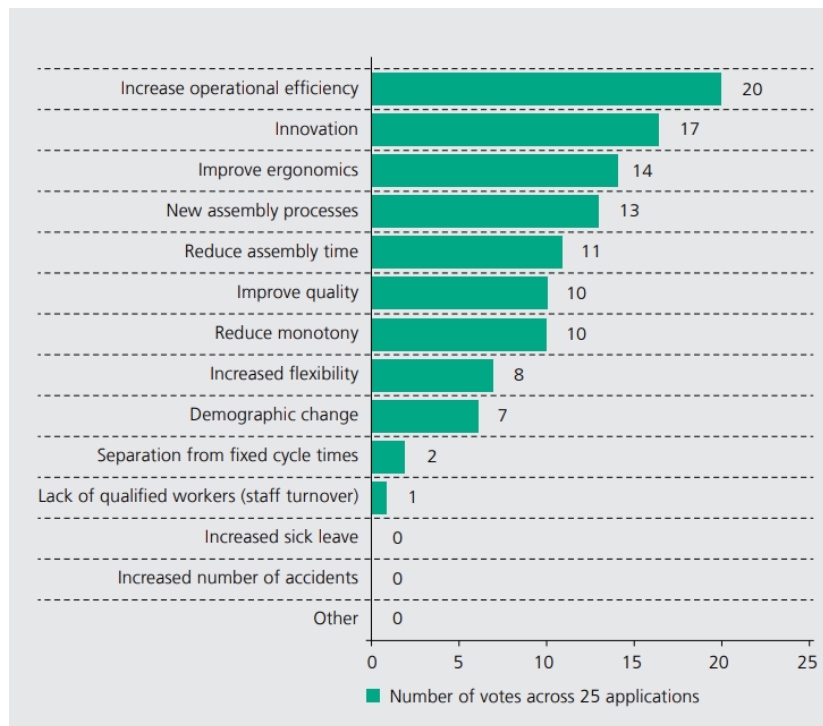


Figure 9: Benefits with collaborative robots [11]

### 2.6.2 Guidelines for implementing collaborative robots in a station

There are guidelines and recommendations before introducing and implementing a collaborative robot to a new workspace. A discussion between the operators and management will most likely need to be held before a robot is installed. Allowing the workers to give their thoughts on where, how and if they want a robot or not, also discussing the safety and training that needs to be done before implementing it [11]. The main points that need to be addressed are as follows:

- Operational efficiency
- Safety
- Ergonomics
- Development of the work content
- Acceptance

### 2.6.3 Levels of Collaboration

**Cell** – The robot operates inside of a cage and the operator outside of it, distancing the two.

**Coexistence** – In this scenario a cage-free robot and operator work alongside one another but they do not operate in the same space.

**Synchronized** – When there is a synchronized collaboration the robot and operator share the workspace, but they do not work at the same time.

**Cooperation** – When there is cooperation, the operator and robot work simultaneously in the same workspace, although not on the same product.

**Collaboration** – The highest level of collaboration between a robot and operator. They share the same workspace and both work on the same product simultaneously [11].

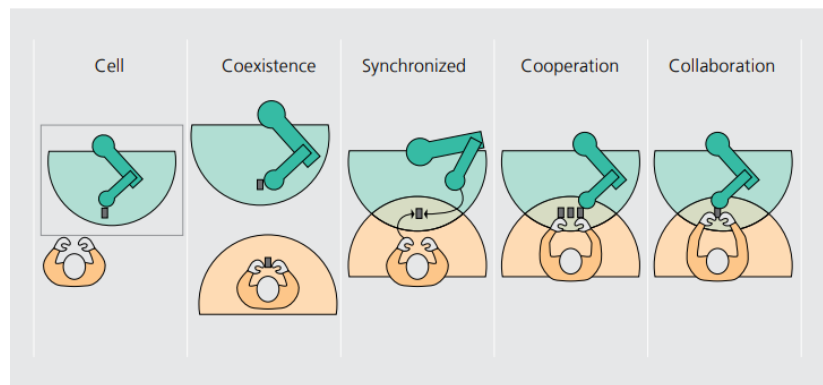


Figure 10: Levels of cooperation [11]

## 2.7 Robotics

The ISO standard 8373:2012 describes an industrial robot according to the following: “*automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes*”. Depending on the needs, the robot can either be stationary or mobile [12].

### 2.7.1 Robot anatomy

The three main components of a robot are the manipulator, control system, and the pendant. A manipulator is a mechanical structure which main purpose is to move and position the robot based on the work area it is capable of. The control system is a programmable computer which can control the engines of the manipulator, the I/O signals within the system, and the communication with the outside world. The pendant is a handheld item which is connected to the robots control system, an operator can retrieve and start finished programs, create new ones, or control the robot manually [13].

The manipulator consists of five parts, these are the wrist, arms, joints, links, and base. The wrist is linked with power driven joints for the positioning of the tool. Depending on the task,

a tool is connected to the wrist, these tools are grippers and processing tools. Like the wrist, the arms operate in the same manner, with the difference being instead of positioning the tool, it positions the wrist. The joints are power driven connections between two links and the links are rigid parts connecting the joints. A robot cannot have more than six degrees of freedom and it is the joints that provide them [13].

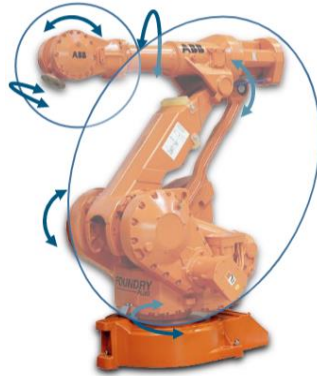


Figure 11: Robot movement [13]

### 2.7.2 Robot classification

There are differences in industrial robots' mechanical structure, and they are classified according to their structure [13].

- Cartesian: The construction and characteristic of these type of robots are that they coincide with the cartesian coordinate system and has three joints.
- Cylindrical: These robots have at least one linear joint and one rotary joint, the third one can be either. This enables it to move in a cylindrical coordinate system.
- SCARA: These robots are defined by their two parallel joints that can rotate and their third linear joint that enables change in its position.
- Delta: A fast paced, roof fixed robot meant for pick and place. It consists of three rotary joints all connected to the base.
- Articulated: A manipulator where the arms need to be connected in series. It needs to have at least three rotary joints.

### 2.7.3 Coordinate systems

The coordinate system is what determines the objects' location in space. There are different types of coordinate systems for an industrial robot, and each play a significant role, these are world, robot base, user, object, flange, and tool. The Cartesian system serves as the foundation for all of them [14].

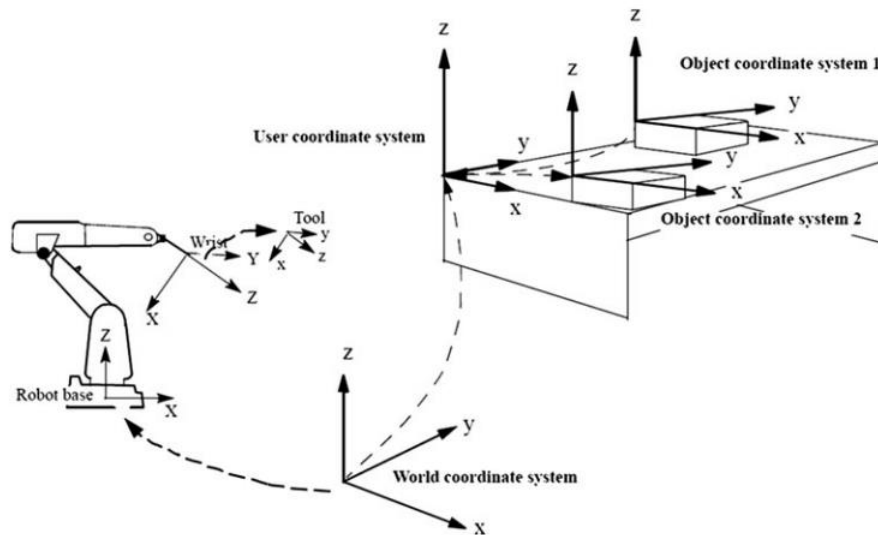


Figure 12: Coordinate system ABB [15]

#### 2.7.4 Fanuc CRX-10iA/L

The Fanuc CRX-10iA/L is a smaller robot that weighs 39 kilograms. Capable of cooperating with humans makes it easy to operate and allows it to be used in a variety of different environments. The manipulator, controller, table teach pendant, and connecting wires are the robot's fundamental components.

The CRX-10iA/L has a load capacity of 10 kilograms and a reachability of 1418 millimetres. As most of Fanuc's other robots it has a contact stop function thanks to its sensors and stops immediately at the contact of a human body. It is also capable with manual guided teaching, allowing the user to teach the motions of the robot by hand [16].



Figure 13: Fanuc CRX-10iA/L [16]

#### 2.7.5 Robot gripper (end effector)

Different tools can be attached to the wrist of a robot and the most used one is the gripper or also called the end effector. The grippers primary task is to manipulate objects, this includes moving, picking, and placing them at desired locations and can be used in many different environments and fields. There is a wide selection of grippers, and they all differ depending on what task they are going to be used for. There are mainly three types of grippers, the jaw

gripper which uses two or more fingers and apply force to an object to grasp and pick it up, it is also the most used type of gripper. There is also the vacuum and magnetic gripper. Due to more demanding tasks and the increase of customization over the years, grippers need to become more flexible and multifunctional [17].

#### **Pneumatic gripper:**

The concept behind pneumatic grippers is the use of compressed air and using it to its advantage for grasping objects with a jaw gripper. To regulate and control the air flow, pneumatic solenoids valves and cylinders are used. The main advantages with a pneumatic gripper compared to other types is the high clamping force and low price. The force and speed of the gripper can be regulated and adjusted depending on what is needed [17].



*Figure 14: Pneumatic gripper [18]*

#### **Hydraulic gripper:**

Like the pneumatic gripper, the hydraulic gripper functions in a similar manner, but uses oil instead. One of the sheer differences between the two is the clamping force, being up towards 25 times greater than the pneumatic gripper. Although there is a higher risk for contamination and more maintenance is needed [17].



*Figure 15: Hydraulic gripper [19]*

#### **Electric gripper:**

Electric grippers functions in a different way compared to the hydraulic and pneumatic gripper, instead they use servo motors to move the fingers. This allows the gripper to have a precise control and positioning when it operates. They are easily manageable to operate and have a lower operating cost than the previous two. Due to its advantages and their flexibility, they are becoming more popular in today's market [17].



*Figure 16: Electric gripper [17]*

#### **Vacuum gripper:**

Vacuum grippers are a popular choice when it comes to picking and placing. But a criterion that needs to be met when they are used is that the surface is smooth, meaning that there is not a wide selection of materials and properties that can be used, and they often need to be specially designed for their task [17].



*Figure 17: Vacuum gripper [17]*

### **2.7.6 Robot programming**

The main components of a robot are the motors, sensors, and the control unit of the robot. The control unit are often a combination of PLC, controllers and computers which makes the

decision based on the information from the sensors and the input from the pendant or the program from a computer. A robot can move in either a linear or in an angular movement. The movement of the joints are done by the motors and are controlled with a controller unit. The sensors give information about what position the motors are in and gives information about the environment around the robot [20]. See figure 18 for an illustration.

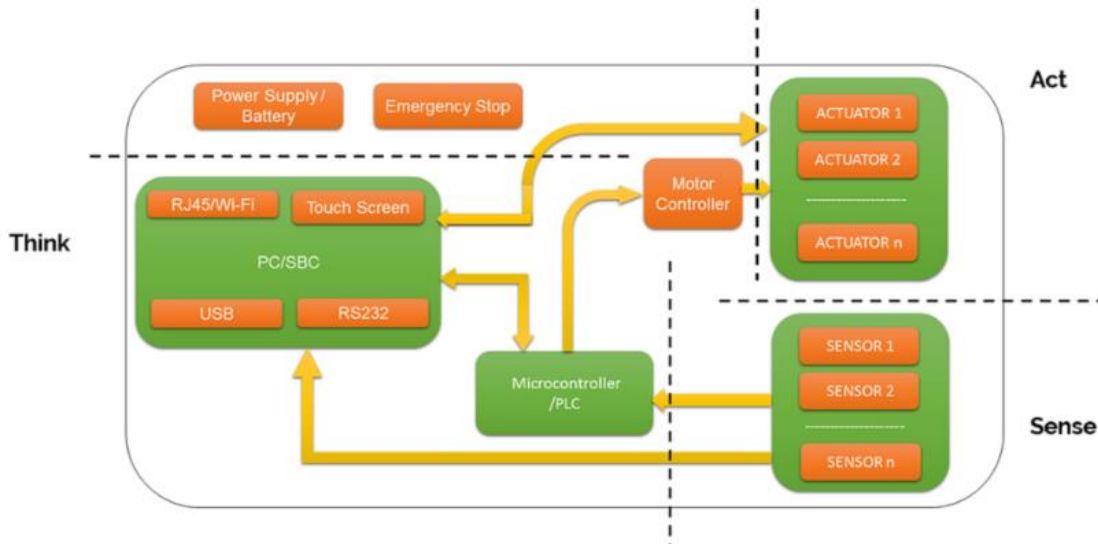


Figure 18: Robot diagram [20]

The robot can be programmed with several different languages for example RAPID, C/C++, java, python and many more [20].

When programming a robot you define a path from A to B, this can be done with many different methods. Either by using an offline simulation program, doing online simulation directly through the pendant or by utilizing walk through programming that are available in some of the robots.

### Online Programming:

When doing online programming the robot needs to be out of production, this will affect the downtime negatively. The programming is done by using the robot's pendant, it's possible to create new programs or modify existing programs. Using the robot's pendant are the most common way of programming a robot and stands for about 90% [21].

Advantages:

- No addition computer or simulation software is required
- Teach pendant are well known by technicians
- Good for small changes in programs, or create simple programs

Disadvantages:

- The robot cannot be in production when programmed
- When programming through a pendant, the language is often specific to the brand

### **Offline programming:**

When performing offline programming it is often done through a robot simulation software but can also be through a text-based software. Offline simulation requires training or experience in computers and the software. In the robot simulation software, a 3D-replica of the station are required to test the program for collision and test that the program works as desired. The main advantages are that when doing the preparation and programming the robot can still be in production. This will drastically reduce the setup time when introducing a new product or modifying an existing program in the production lines. When the program is done it needs to be tested in the station before it will go into production to evaluate it and make small adjustment [21].

Advantages:

- Less downtime and setup time because the program is done and only needs to be tested in the station
- Most time saved when doing complex programs
- Often very accurate

Disadvantages:

- Requires computers and software
- Requires training in computers and the simulation software

### **Walk-through programming:**

This programming method are mostly used for collaborative robots but can also be found on traditional robots. The main advantage with using walk-through programming is the ease of use for beginners who have not worked with robots before. The programming is performed by an operator who moves the robot to the desired location and then press a button. This is then repeated, and a robot programmed are created [21].

Advantages:

- There is no need for additional software
- Less errors if compared to typing instructions

Disadvantages:

- The robot cannot be in production when programmed
- It's not as precise as online programming or offline programming

### **2.7.7 Safety Methods**

The one groundbreaking rule of a collaborative robot and what sets it apart from the industrial robots, is the needed possibility of working alongside an operator. For this to be feasible and applied, they need to have safety features and methods. These features are set by the ISO standard 15066 and all collaborative robots are manufactured and designed following it. Collaborative robots are often designed with a lightweight frame and the material that it is made from is often softer than that of an industrial robot. There are many different types of

safety features that can be implemented into a collaborative robot, but some of the more common are Hand-guiding, Speed and Separation Monitoring, Power and Force Limitation, and Safety-rated monitored stop. Although all robots need to have safety features according to the different ISO standards, all safety measures must be considered before the installment of a collaborative robot is implemented [22].

### **Hand-guiding:**

A common feature for collaborative robots is the option of hand-guiding. Hand-guiding allows the operator to assist or guide the robot when a task need to be performed very precisely and the room of error is very miniscule. A handle is located close to the end effector and is there for the operator to use and steer the robot, this creates a collaboration between the robot and the operator. Hand-guiding equipment need to have access to an emergency stop option and other features that allows the user to control the tool that the robot has attached to it [23].

### **Speed and Separation Monitoring:**

This safety measure considers the distance between an operator and the robot. With the help of laser scanners, it can monitor the workspace of the robot and if this space gets intruded the robot will either stop or adjust its speed. This is an improved method of safety monitored stop. The area in which the robot operates can be adjusted according to what has been given, but it is often divided into three zones, a safe zone, a warning zone, and a stop zone. When the work area is not disturbed anymore, the robot will continue to operate again [24].

### **Power and Force Limitation:**

The concept behind Power and Force Limitation or shortened to PFL is to minimize the energy that is transferred into the operator from the robot in the event of a collision. In the case of a collision that exceeds the given parameters, the robot will stop its motion. A consideration when implementing a PFL is the application of the robot and what type of end effector it is going to have installed [24].

## **2.8 Computer Aided Design**

The concept behind Computer Aided Design (CAD) was to aid designers and engineers in their work before manufacturing components. Allowing the user to work in a 3D world and manipulating it, instead of drawing and making plans and adjustments by hand to every drawing. This system aids the user with creation, modification, analysis, and the optimization of a design. This makes CAD a very popular tool in many industries, for example automotive, shipbuilding, aerospace, and architectural design and many more [25].

There are many different CAD programs available, in this thesis Creo parametric 8.0.3.0 was used.

## 2.9 Virtual Commissioning

Being a part of industry 4.0 virtual commissioning is an approach that begins its steps early in the project to minimize errors and mistakes when the production finally begins. This allows errors to be dealt with early on so that a proper solution can be found. This approach can be used in many areas for example factory, cell, and machining level [26]. It is an approach that evaluates the design and decision making that has been done before it gets implemented into reality. Since its steps starts early in the process and are not prolonged, time for validation of software becomes less of a hindrance since that consumes most time and creates delays when commissioning new machines. Since this is a model circulating regarding preparation for a new instalment, the idea is to create the desired or imitated production system and that it will hopefully work as intended to the real station when it gets implemented without many adjustments [27].

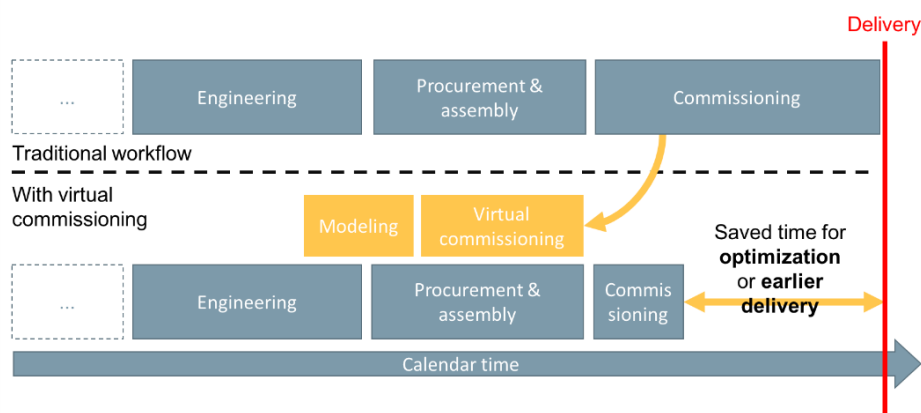


Figure 19: Project with and without virtual commissioning [27]

### 2.9.1 Virtual Commissioning Process

#### 1. Data collection

- Technical data
- Software selection

When starting a virtual commissioning process, the first action that needs to be done is to acquire data, this is done by literature review, collect data such as measurements and takt time and from there decide on the most suitable software depending on the task and simulation that is going to be performed [14].

#### 2. Process planning

During the process planning phase, the location and placement of the robot needs to be decided. Examining the different option of operation during the assembly, depending on the location that has been chosen and from there decide on the most suitable one [14].

#### 3. 3D-modelling

In some instances, 3D models will have to be created, the reasons being the lack of models in the software or having to compromise some parts and make changes to illustrate what needs and could be done for a solution. In this project a specialized gripper had to be designed due to complex components and a lifting tool had to be created and adjusted due to lack of workspace, this is further explained in the methodology [14].

#### 4. Simulation

- Visual components
- OLP programming

This step includes layout preparation and setups. Based on the data that has been acquired and depending on the task, what can be changed or what should be changed is the questions that should be asked. OLP or offline programming is being created to decide on the movements of the robot, trying to eliminate jerk movement, deciding on speed, and give precise commands on location to illustrate more effectively on how the robot could operate [14].

#### 5. Logical control programming

- PLC programming

The PLC program is being transferred to the virtual controller [14].

#### 6. Virtual commissioning

- SiL Method
- HiL Method
- Hybrid-simulation Method

The finalizing step in the process is to simulate with either SiL, HiL or a hybrid simulation method [28].

### 2.9.2 Virtual Commissioning Methods

- SiL method

SiL stands for Software in the Loop and is when an emulated PLC is being used instead of a real one [28].

- HiL method

Like the SiL method HiL method uses a real PLC and stands for Hardware in the Loop. The benefit with this method is that the production system will already have been evaluated and is ready for use in the PLC and other devices [28].

- Hybrid-simulation

When the manufacturers' developed virtual robot controller is being used it becomes a hybrid-simulation. This allows the simulation to be connected to a real PLC with RCS. This allows the exact configuration of the hardware to be determined and ready for use [28].

### 2.9.3 Benefits of Virtual Commissioning

The intent of using a virtual commissioning approach is to check so that the hardware and software work as predicted [27].

- If the faults are detected in early stages, it will be easier to remediate them. It will also be much cheaper to fix the problem before the equipment have been bought.
- If performing a virtual commissioning when preparing to install an automation process this can reduce the commissioning time by up to 75%.

- When performing virtual commissioning a 3D model of the station is required, this gives benefits to both the engineers working with the project and the stakeholders who has an interest in the project. When having meetings, the 3D model can be viewed and discussed without any misconceptions.
- Will reduce the setup time when introducing new products variants and when there are modifications to the current production.
- When having the 3D model of the station, there is a possibility to shorten the cycle time when simulating the model.
- Perform tests in beforehand to see if the PLC program works well with for example the robot programming.

#### 2.9.4 Drawbacks of Virtual Commissioning

Drawbacks with using the virtual commissioning approach [29].

- There is a need for 3D-models, and they take time and are costly to make.
- The workers require specific education within these software and generally within virtual commissioning.
- The outcome of the virtual commissioning relies on the quality of the 3D-models.

# 3

## Methodology

### 3.1 Data collection

The main purpose of this step was to collect the necessary information that would be needed for this project. This included literature research and software selection. Gather all the available information about the current process, measurements, and equipment to be able to recreate the current layout and later improve it. This section explains the procedures used.

#### 3.1.1 Literature research

Technical reports and articles were found with the help of Google Scholar and the Chalmers library website. To find the necessary articles for this project, keywords such as Virtual commissioning, collaborative robot, sand core and automation were used. Studying different tutorials on how to create different simulations and create ideal workflows that simulates the real process needed to be researched as well.

#### 3.1.2 Technical data

As mentioned in section 3.1, technical data about the current layout needed to be gathered. These were all physically acquired at Volvo Powertrain and included measurements on the entire workspace and work area between the conveyors. The size of the conveyors and the placement of the components on the conveyors. The precise location of the specialized lifting tool and its measurements. The takt time of the entire process and the takt time of every assembly procedure. The components themselves were provided by Volvo Powertrain and later implemented into the simulation software.

#### 3.1.3 Software selection

This step consisted of determining the simulation software that was going to be used for the project but also maintain a high standard. Four criteria were established, these were:

- Easy to understand
- Plenty of information and tutorials
- Good internal library
- Available from Chalmers

After investigating different options that were available, having an interview with our supervisor at Chalmers regarding different options and what we have prior experience working with. Having considerations what is mainly used in the automotive industry and especially what Volvo might work with, the different options became Robot studio, Technomatix and Visual components.

Being prepared that a CAD software might have to be implemented in the case that something would not be available from the simulation software, or a component would need to be created. These would be made with the use of Creo Parametric 8.0.3.0 due to prior experience and since Volvo uses the software.

### 3.2 Robot selection

The collaborative robot selection was done according to the requirements that were established.

These were:

- Payload – at least 10 kilograms.
- Reach – reachability must be at least 1300mm.
- Repeatability – as good as it can get if the payload and reach criteria are met.
- Weight – avoid unnecessarily big and heavy robots.
- Safety features.
- Well established manufacturer.

The selection of collaborative robots is quite few since collaborative robots are quite new, especially with the standard ISO 15066 released in 2016. ISO 15066 specifies safety requirements for collaborative robots and work environment. With the requirements that were established, the selection got narrowed down to Kassar Robots KR1410, Fanuc CRX-10iA/L and Siasun GCR14 1400.

### 3.3 Process Planning

At this stage the sequence of the assembly was planned, and different robot positions were tested. The study was based on the technical data that had been collected from Volvo powertrain that included documentation and interviews with the people working in the station and meetings with knowledgeable people working in the department. Also, information from the literature reviews. From figure 1 the activities were identified. From this different assembly orders were reviewed. The placement of the robot is extremely important. It needs to avoid collisions but also to be able to reach all the parts and the required equipment. To see if the robot could reach all the essential equipment and parts a reach test was performed. A couple of different positions were tried. The planning process that was used were parallel engineering, the philosophies and theory behind this are in section 2.2 in chapter 2. This method was repeated several times.

### 3.4 3D Modelling

The 3D modelling stage mainly consisted of creating a functional prototype of a gripper that could perform the tasks at hand. The main issue that had occurred was the different geometries of the components it was supposed to lift. At Volvo Powertrain all the components could be found in plastic to teach new employees the assembly operation. With this at hand, different variations and ideas were brainstormed and drawn on how the components could be grasped, later these ideas and different models were created in Creo Parametric 8.0. The

specialized tool used for lifting and stabilizing the sand cores had to be designed through own measurements on site.

As mentioned in section 3.1.2 all the CAD components of the sand core assembly were provided by Volvo powertrain and had to be implemented into the simulation software.

### 3.5 Simulation

A simulation was created to illustrate the assembly process of the sand cores with the implemented robots. The entire layout at Volvo Powertrain was recreated, including the entire conveyor system, specialized lifting tool, components, and operators. The robots were used to lift and place the heavier sand cores into the lifting tool and cooperate with the operators. The process is explained in the following section.

#### 3.5.1 Visual Components

##### **Model a component:**

As mentioned in section 3.4 a specialized gripper had to be designed and implemented into the simulation program. The same process had to be made regarding the specialized lifting tool. Appendix A, section A.1, describes the process for modelling the gripper and the configuration for it.

##### **Layout preparation:**

The layout of the sand core assembly station was recreated with the same scale as Volvo Powertrain. With all the data and measurements being gathered the entire workspace was created with the fence construction option in Visual Components. After the work area had been established, all the equipment such as robots and conveyors were implemented through the software online library and dropped into the 3D world with the drag and drop option and then placed in their correct location.

##### **Assembly process simulation:**

When the gripper was designed and the layout had been created, the robots were programmed for the new assembly process. The robot's focus was handling the black and heavier sand cores. The reasoning behind this was due to the lack of workspace, how the parts arrived, were assembled, and placed. The bad ergonomics for one of the operators were also removed due this task.

When the location and work task was established, the robots were programmed using the program tab in the software. Different movements and locations were saved using the jog option, and different signals, inputs and outputs were used depending on the task in the program tab. Flows had to be created to dictate which task and timing the operators were going to have and they were made through the statements option when creating the process. The procedure for programming the robots and operators for the assembly process is explained in Appendix A, section A.2 and A.3.

# 4

## Results

### 4.1 Technical data

The workstation layout information was obtained from Volvo powertrain and a simple illustration can be found in chapter 2.1 under current process figure 1.

### 4.2 Software simulation

The following simulation software was chosen after careful examination based on the criteria's that had been established.

- Visual components premium 4.4 by Visual components ®.

Based on prior experience with the software and discovering that the company had a lot of helpful tutorials and a FAQ-community the choice became simple. One big reason that this software was also chosen was thanks to one of our supervisors at Volvo who had previously worked with the application and had a contact with the Visual components head of sales in Sweden that was kind enough to provide the premium version of the software.

Creo Parametric 8.0.3.0 was used as the modelling program to create the gripper and the specialized lifting tool.

### 4.3 Process planning

In section 3 of chapter 3 the steps are explained that were used. Parallel engineering process planning were used as discussed in section 3 of chapter 3 and the theory behind it in section 2 of chapter 2 and worked well for our project. In our process planning the economic part were ignored. This was because we did not have any specific requirements on this. Our method was repeated several times to get the result of the robot position and the assembly order that the robot was going to use. The result of working with parallel engineering was that we got a good combination of the outcome and the manufacturing process, and all this leads to shorter lead times. When we worked, we took consideration to parallel engineering and worked closer with each other in the design phase and the manufacturing phase. Working this way, it leads to shorter lead times and a better outcome.

### 4.3.1 Component placement

The sand core components for the heavier black parts arrive at their location accordingly and no changes have been made to the current process.

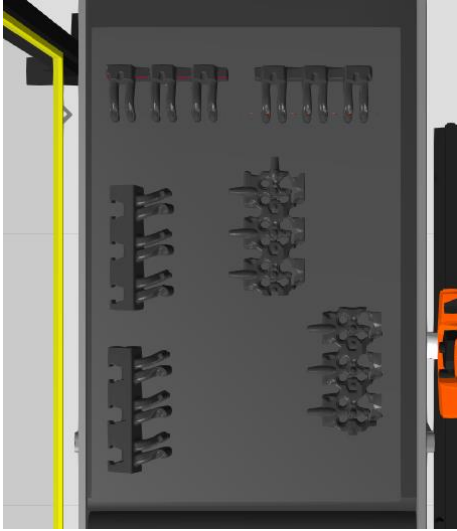


Figure 20: D6 engine

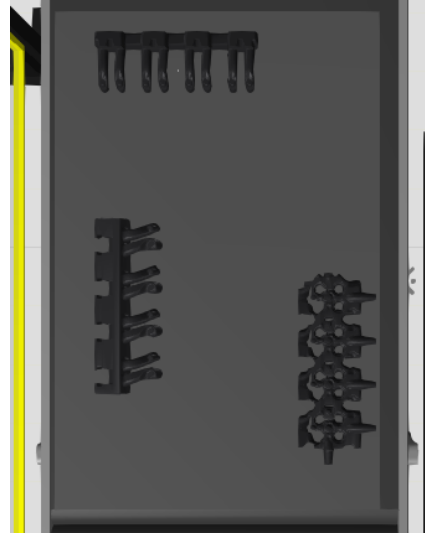


Figure 21: D4 engine

### 4.3.2 Robot selection

After analysing the different robot requirements and researching which robot manufacturer was available in Visual components the chosen robots became the Fanuc CRX-10iA/L. Information about the robot can be found in chapter 2.7.4 and the robot requirements in chapter 3.2.

### 4.3.3 Robot placement

The robots were decided to be placed next to the pallets where the black sand cores arrived, still being able to reach the specialized lifting tool and leave one of the components for the other robot to pick up with the help of a robot positioner.

A reach test on Visual Components was used to assess the robot's reachability, by selecting the 3D envelope option, as illustrated in figures 22 and 23.

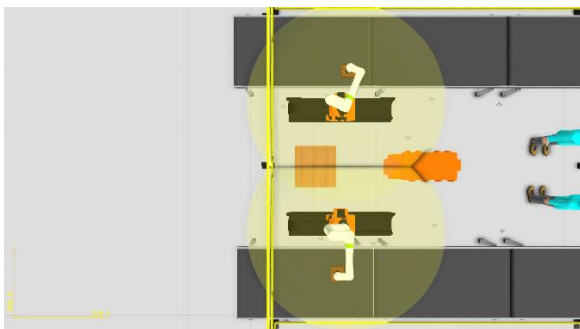


Figure 22: Envelope (home position)

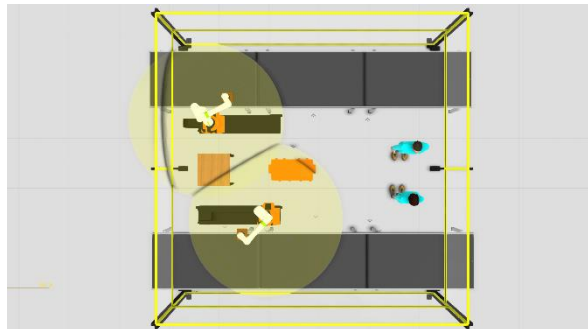


Figure 23: Envelope (either end)

#### 4.3.4 Robot assembly order sequence

The assembly order of the robot is presented in figure 27. The sequence will always begin with picking and placing the central black sand core in the specialized lifting tool, from either side. From there depending on which side is operating, the robot will always pick the next component closest to where it is going to assembled. The sequence describes from the closest robot from figure 22's point of view. If the robot from the top would start, sequence step three and forward would change to become figure 25.

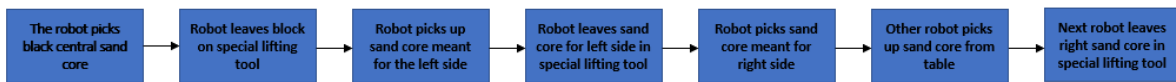


Figure 24: Left robot assembly order sequence

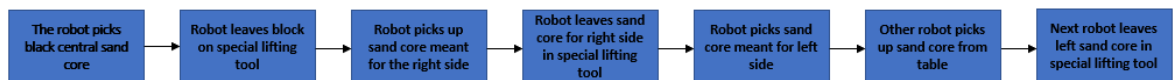


Figure 25: Right robot assembly order sequence

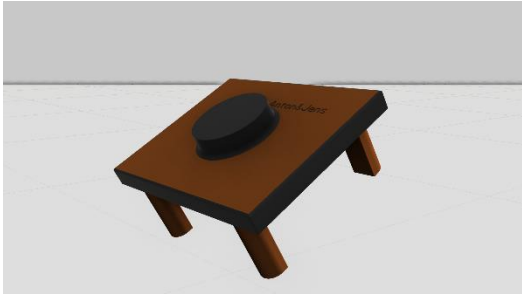
### 4.4 3D Modelling

The specialized gripper and lifting tool are provided in this section. The methodology followed is explained in section 3.4.

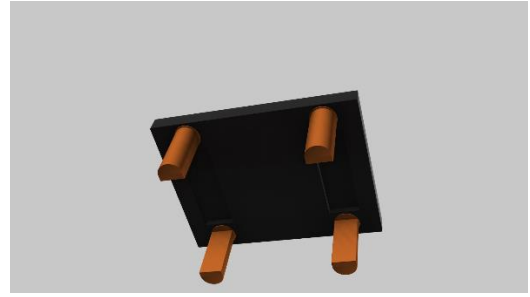
#### 4.4.1 Gripper Modelling

First, a choice had to be made on how the gripper was going to function and grab the components. After analyzing the components at Volvo, in particularly their shape and geometry, the decision was made to locate and grab them where they were most stable. Since sand cores are extremely fragile and could break if not handled properly.

A special consideration that had to be made was how the gripper was going to grab the sand cores since their design differed. They could not be gripped in the same way, therefore the fingers of the gripper had to be unique so it could grasp every part. The fingers were made with two distinct sides, one with a straight vertical side and the other with a cylindrical form. So, the fingers adjusted depending on which component the robot was going to pick up. Figures 26-30 illustrates the entire gripper as a whole and how it would look like when operating.



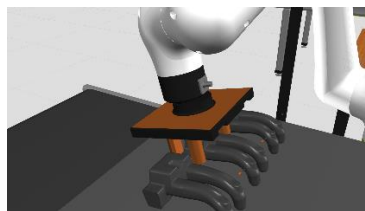
*Figure 26: Robot tool*



*Figure 27: Robot tool*



*Figure 28: Grab first component*



*Figure 29: Grab second component*

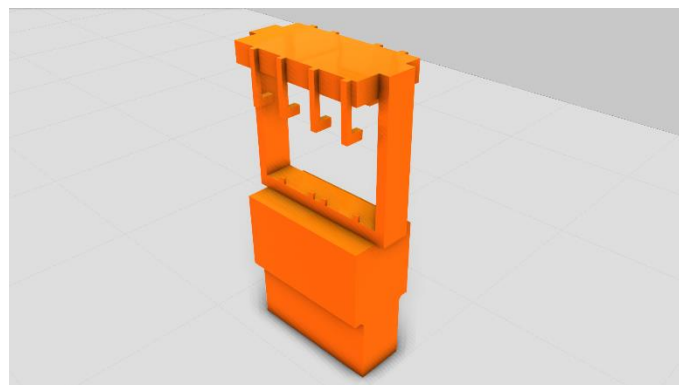


*Figure 30: Grab third component*

The gripper would therefore be pneumatic, that closes with enough force so that the part could be picked up without damaging it. The fingers themselves are controlled with a signal depending on which part the robot picks.

#### 4.4.2 Specialized lifting tool

The specialized lifting tool was a very complex tool which was hard to duplicate without the CAD files. Therefore, a similar model was created with modifications so that the simulation could be made.



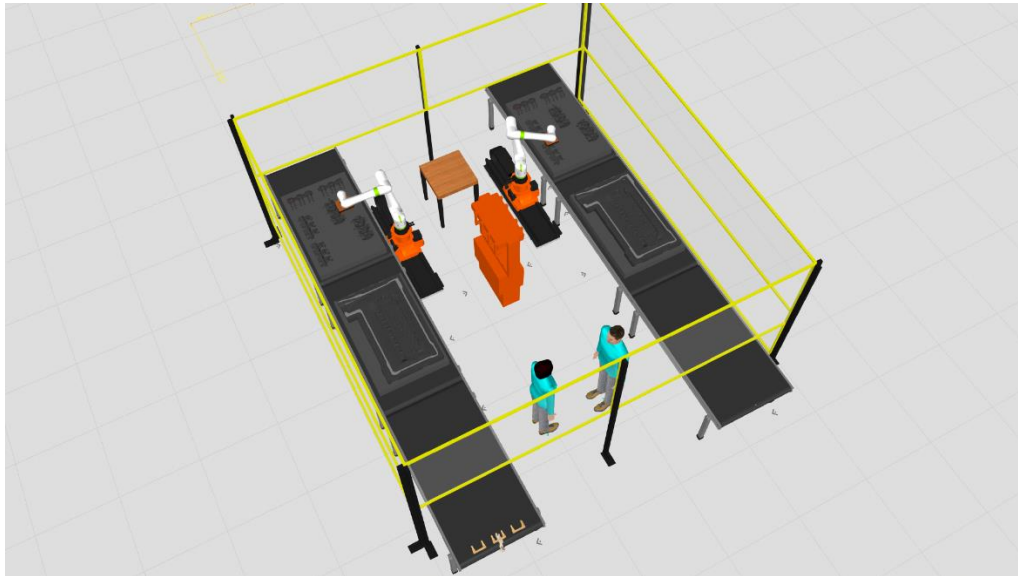
*Figure 31: Special lifting tool*

#### 4.5 Process flow and statements

The simulation can be created in many ways. This simulation mainly consisted of the use of process nodes and statements in each one of the nodes to make the simulation run smoothly and to create the proper takt time. This is illustrated and explained in Appendix B.

##### 4.5.1 The new layout

An illustration of the new layout is presented in the following figure 32.



*Figure 32: Finalized layout*

# 5

## Discussion

### 5.1 Discussing deliverable Question 2

The relationship between humans and robots' systems can be defined in many ways, these are described in the theory part, chapter 2.6. In this project the aim was to use synchronized cooperation between the human and the robot. This means that the robot and the human use the same workspace but only one is present at the time. This will reduce the risk of collision between the robot and the human.

The space available in this station is not from the beginning made for using automation, only manual assembly work. Therefore, the station is limited, and it can cause a problem when implementing a robot system. The safety systems we included in our research were speed and separation monitoring, hand-guiding and power and force limiting. These are described in the theory chapter 2.7.7.

From the simulation model figure 32 there were several risks that were identified that can possibly happened with the interaction between the robot system and humans. The risks that were identified are listed below in table 1:

No	Risk	Consequence	Operation	Carried out by	Safety system engaged
1	Robot drops the sandcore	Crushing	Pick and placing the sandcore	Robot	
2	The robot fails to perform an operation and operator wants to correct it	Collision	Pick and placing the sandcore	Robot and operator	SSM, PFL
3	Unaware of the system's status, the operator accidentally gets in the way of the robot	Collision	Pick and placing the sandcore	Robot and operator	SSM, PFL
4	The robot acts unexpected and collides with the operator	Collision	Pick and placing the sandcore	Robot	SSM, PFL

*Table 1: Identified risks*

Risk 1 is a risk that is hard to prevent, this is when a hardware fault or a control error will make the robot drop the sand core when in motion. This could hurt the operator; this risk does not have a safety system that can act in case of this.

Risk 2 This could occur when the robot is picking up the part and the parts is in the wrong position or location on the conveyor. This will result in collision due to the part is not within the tolerance and will collide with the main block when placing it. The operator may want to try and correct this without communicating with the robot system, this can result in a collision depending on how the safety system will act.

Risk 3 This could be a risk when the operator misreads the robot state, and the robot will start moving when the operator don't know it. But because SSM is in use the robot should not be moving when the human is in the robot's zone.

Risk 4 This could be a risk if the robots safety system fails, and the robot starts moving when there is someone in the robot's zone. This is minimized when using synchronized cooperation but is still possible.

#### 5.1.1 Quality of sand cores using collaborative robots vs manual assembly

The robot's movement when placing the sand core in the main block must be precise, as the tolerances are extremely small. Risk 2 could be the source of this issue, because if the cores are picked up in the wrong position, they will be in the wrong position in the gripper, causing the gripper to collide with the sand core main block and damage the cores. As a result, it is critical that the part arrive in the same location each time. One basic and straightforward solution is to draw the exact location of the object on the pallet. By doing so, the operator may quickly determine if the sand core is in the incorrect position and correct it.

The movements required to place the sand core in the main block must be precise, and we anticipate that doing so in an offline simulation model will be difficult. They will need to be touched up when tested the first time if done offline. Walk-through programming is another option for programming these movements and would probably work well depending on the precision that is possible with walk-through programming on this specific robot.

Because the cores are easily damaged if picked up too hard, the gripper must be set to the exact force required to pick it up without damaging it.

#### 5.2 Discussing deliverable question 3

There are both pros and cons with implementing collaborative robots to the current process. The biggest positive outcome that would occur is the bad ergonomically strain that is currently put on the operator's wrists while handling the black sand cores would be removed. With the implementation of collaborative robots this issue would be eliminated although other issues would rise in its place. For instance, the sand cores are very delicate, complex and could easily crack if not handled properly. Therefore, a specially designed gripper, with the objective to handle the different shapes would have to be created. Our solution seems to be feasible although not perfect in any way since there was not enough time to conduct proper research regarding this issue.

Another positive outcome through this thesis work was the discovery that one of the operators in the current process could be removed, since the robots would handle that operator's task from now on. This would not change the initial goal of completing 24 assemblies an hour for the D4 engine, but the D6 would only reach 19 assemblies an hour because there are more tasks for the robots. So, in terms of return on investment for this station, a robot would have been worthwhile after 14 months as illustrated in the graph below.

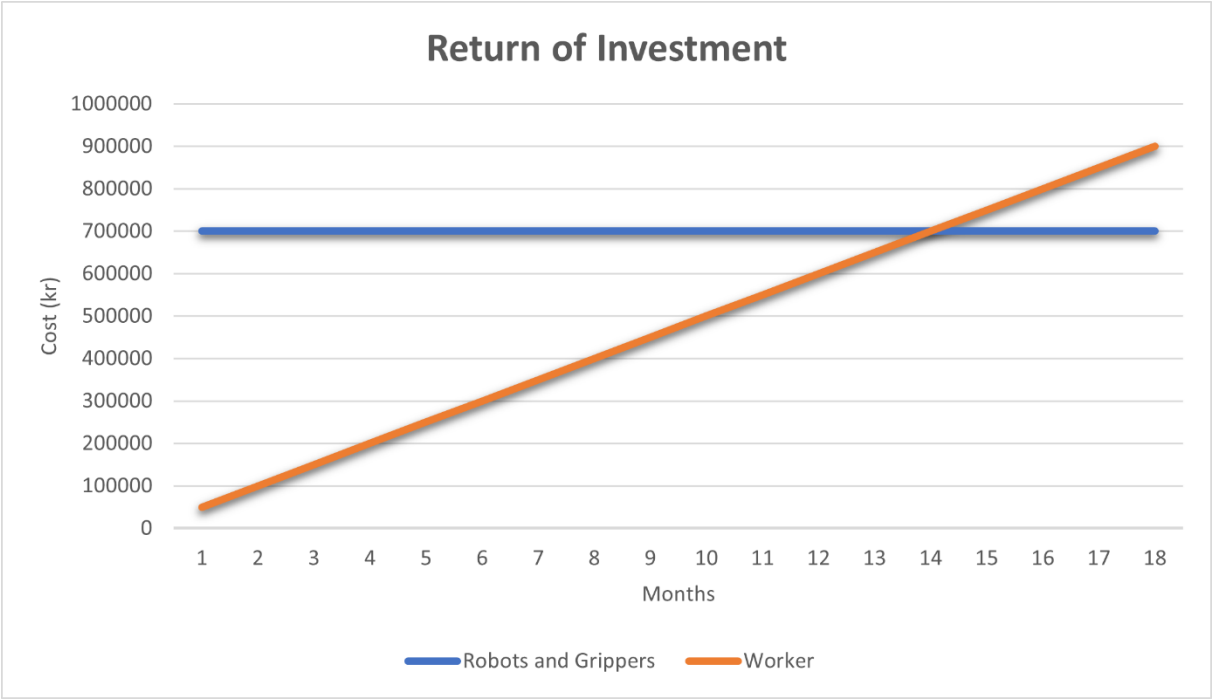


Figure 33: ROI

# 6

## Conclusions

The purpose of this bachelor's thesis was to find a feasible implementation of collaborative robots in an environment that was solely operated with manual labour. The robot's assembly procedure includes choosing and inserting sand cores into a specialised lifting tool, which relieves the operator of undesirable ergonomics. By developing a virtual model of the assembly station, we were able to discuss different ideas and implement them to the model for verification if they are feasible or not, saving a lot of time but also verify if they met the desired objectives of this project.

We believe that collaborative robots can be implemented within this process, this thesis work laid the foundation for this investigation although further studies need to be made before implementing collaborative robots to the process.

### 6.1 Further investigation

This bachelor thesis proposal provides a solid foundation for additional research into this issue.

The gripper should be researched further to see whether it can apply force to grasp the sand cores without damaging them. This needs to be tested physically with these exact sand cores. The gripper may require more support when gripping the cores, one possible solution is to provide some support beneath the cores if possible. Additional risk assessments of the entire station, including the robots, end effectors and equipment are required.

The lifting tool requires more research on how to make it perform well with collaborative robots while still being ergonomically sound for the operators. To allow the robot to position the component without colliding, the spacing between the bottom and top parts of the tool must be adjusted. The height of the entire instrument is another important characteristic that should be examined further.

The robot must be extremely exact while placing the parts in the main block. This programming step might be accomplished using walk through programming, as mentioned in the theory section. Another option for completing this work is to use hand guiding, in which the collaborative robots stops when it gets close to the intended location and hand guiding is performed.

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# A

## Appendix

### A.1 Procedure for modelling a gripper on Visual Components

1. Create the gripper in a computer aided design software, in our case Creo
2. Import the CAD file and find it in the library.
3. After importing, the part can be found in the e-catalog if placed in the right location on the computer, or you can use the import option.
4. Drag the part into the 3D “system” and the part will be placed at the world coordinate system.
5. Most of the work will be done in the modelling tab.
6. The axis may need to be re-defined, this can be caused because the definition of the coordinate systems can vary.
7. By creating a box as a reference and then doing some measures will solve this. The box needs be created in the component origin. Modelling tab → Geometry → Features → Box.
8. The offset can then be measured by clicking on Modelling tab → Tools → Measure.
9. To compensate for the offset the values can then be put in the gripper’s properties tab.
10. Right-click → collapse features. The gripper will now be at the world coordinate. The box that were created can now be deleted.
11. The gripper now needs to be split in different nods, this is done because we want individual parts to move not the entire gripper when for example closing or rotating.
12. Right click on the collapsed under ROOT (Gripper) and press explode
13. Press the control button and then press the parts you want to move at the same time, right click and press extract → Extract link. This can be repeated depending on the gripper’s features.
14. The parts are now defined as Link\_1
15. Degrees of freedom and the link joints now needs to be defined.
16. Press the link that will be defined, then define the joint type, for a linear motion choose (translational), then choose the right Axis.
17. For the specific gripper in this thesis the following joint characteristics were chosen.
18. For the transitional movement, a head node was created which all the other could follow, this axis was put to positive Z axis.
19. The other links were defined to transitional followers, following the head node.
20. In the four transitional links, one rotational link was made. Then three followers were made these were all in the positive X-axis.
21. Then a servo controller was added to the head nodes, in this case one in the transitional and one for rotation. This is needed for simulation of the gripper.

22. The gripper is later defined as an end effector, by pressing the wizards tab and selecting End Effector.
23. Under controls IO were chosen.
24. This feature will define a mount frame to mount the tool, a tool center point, and signals for activating the gripper (opening and rotations)
25. The gripper is now done and can be tested, mount is done using the PNP command.

## A.2 Procedure for building simulation model and robot programming on Visual Components

1. Start with using fence and wall builder to build up the work area.
2. From the e-catalog using drag and drop the right components can be placed out and then positioned.
3. From the PM Transport controllers two human transport controllers were put in an appropriate place. Then two humans were added from the PM resources option.
4. The collaborative robot Fanuc CRX-10iA/L and the robot positioner were picked from the e-library and placed on an appropriate place.
5. For creating the sand cores and the pallet PM flow components were used
6. For the white sand cores a single process node are created and placed on the conveyor. In this process node the definition of which sand cores and in which order to create them are defined. Then the transport out statement are created.
7. For every black sand core, a process node was created. A create and delete statement are created. This creates and deletes the sand cores accordingly.
8. The collaborative robot and robot positioner were place in the right place. Then a new sequence was made from the programming tab, several sequences were later added.
9. The programming was done by making via locations in the 3D-world easily, with either LIN or PTP movement at the appropriate place.
10. To control the gripper signals are used, for the action signal SET binary output were used, this controls opening and closing and rotation of the fingers in visual components. For controlling that the gripper is in the right position wait for binary input statement are used.
11. Depending on the gripper the values are then set to true or false.

### A.3 Procedure for creating process flow and statements on Visual Components

1. Appendix A section A.2 explains how the model was created.
2. The import can be done by either using import in the geometry tab or by dragging the file into the 3D-world, or by finding it in the e-catalog, if placed in the right spot.
3. Adjust all CenterPoint's for every component so that they will be in the middle. (This maybe are the case, then skip to step 8).
4. This is done by creating a box at the world reference coordinates. Modelling tab → Geometry → Features → Box.
5. By using the tool, measure the offset. Modelling tab → Tools → Measure.
6. To delete the offset, the measured values are calculated in the component properties tab.
7. Right-click → collapse features on the tools tab. The sand-cores now have a better CenterPoint.
8. Press process → products.
9. Press add product type, open the properties tab on the right side and choose pick components option and define every part.
10. Press process → products.
11. Press add assembly, create every step of the assemblies when placed in the mold.
12. Assemble the entire black sand core component to one part.
13. Right click one of the process nodes at the last, next to the robot. A new tab opens and press statements.
14. Statements can now be added to the chosen node. Press create statement. In the statement properties tab, find the correct product type for that node.
15. Repeat for every node in the last conveyor and change the product type based on what product that node is supposed to create.
16. Repeat step 13 and 14 for the central conveyor, now choose the assemblies for the mold and repeat until all assemblies have been added to the node in their right order.
17. For the first conveyor, right click the process node and press the statement tab, press create and chose the lighter sand cores. Add all the to the node in their right order of the assembly process.
18. Press the flow tab, press the process node for the first conveyor and connect it to the to conveyor process node on the same conveyor. Choose transport by conveyor.
19. Connect the to conveyor process node to the from conveyor process node on the same conveyor.
20. Connect the from conveyor process node to the process node in the second conveyor. Choose transportation by worker.
21. Choose the process node in the specialized lifting tool and connect it to the process node on the second conveyor. Choose transportation by worker.
22. Go back to the first process node on the first conveyor. Right click and add new statements. This time pick the transport out statement and pick the first light sand core as the product that is going to get transported out. It should be under the statement of

that product creation. Repeat for every product. The conveyor will now transport the products.

23. Choose the to conveyor process node on the first conveyor, add statements transport in, add the first light sand core as the product that is going to get accepted. Add the statement transport out and the same product again. Repeat this for every light component.
24. Choose the from conveyor process, right click and press the statements option. Repeat the statement from step 23. The worker will now transport the products.
25. Press the process node on the specialized lifting tool. Press the statement button and choose the create statement, pick the fully assembled black sand core component.
26. Add a transport out of that same product.
27. Pick the process node on the second conveyor, right click, and pick the statement transport in. Add all the necessary transport in and add which products that's going to be transported into it.
28. Now all the necessary statements have been made for the flow to operate.
29. Repeat all these steps for the other side where the other assembly is created.
30. To make the simulation run smoothly delay statements must be added to some of the nodes. These are necessary for every sequence to operate correctly and not at the same time.
31. Illustrations on how it is supposed to look are found in Appendix B.

# B

## Appendix

### B.1 Flow and process statements for D4 assembly:

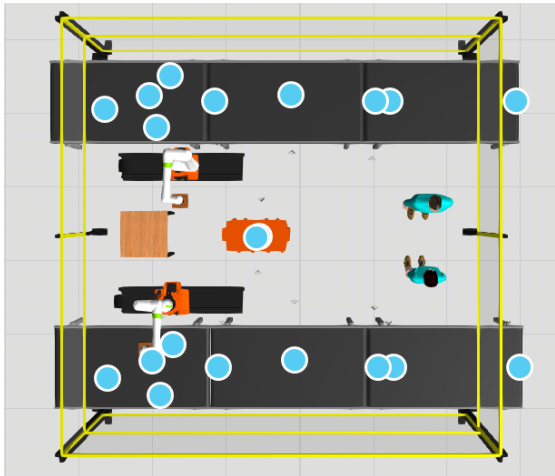


Figure 34: Process nodes placement

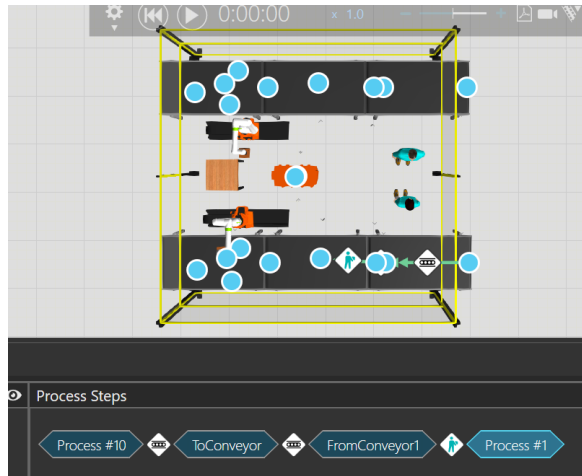


Figure 35: Flow first bottom conveyor

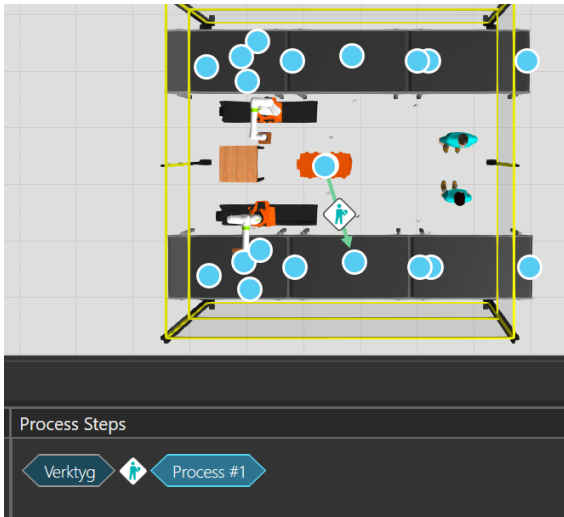


Figure 36: Flow special tool closest assembly

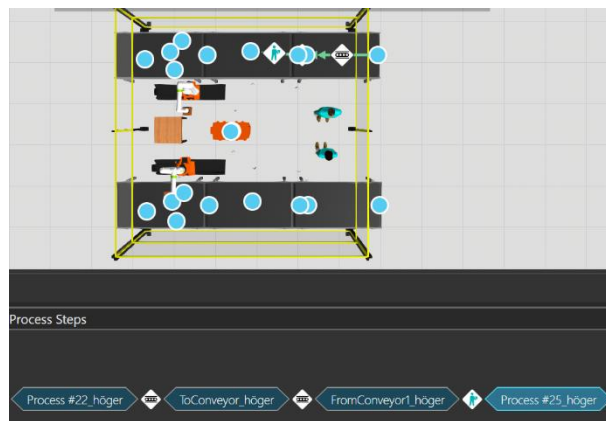


Figure 37: Flow first top conveyor

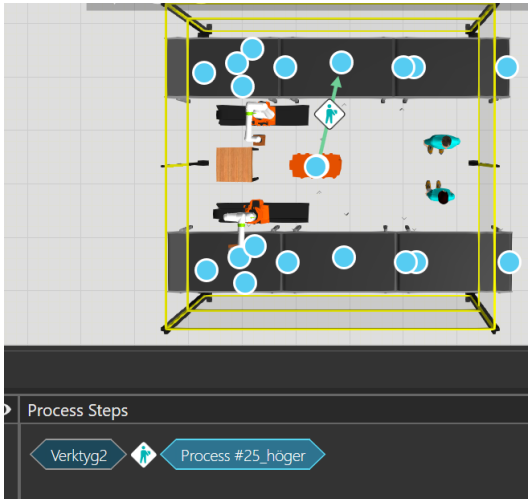


Figure 38: Flow special tool top assembly

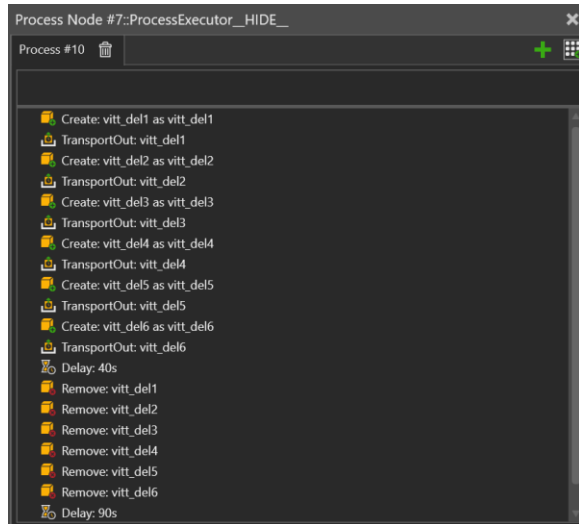


Figure 39: First process node bottom assembly statements

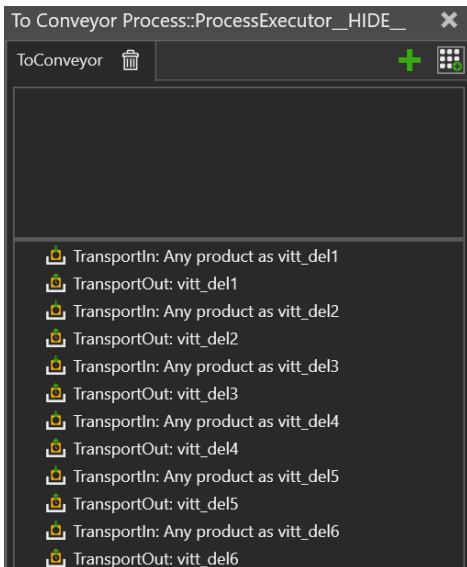


Figure 40: To conveyor bottom assembly statements

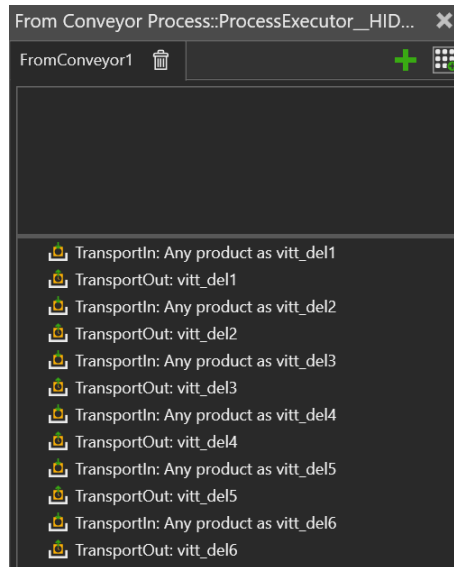


Figure 41: From conveyor bottom assembly statements

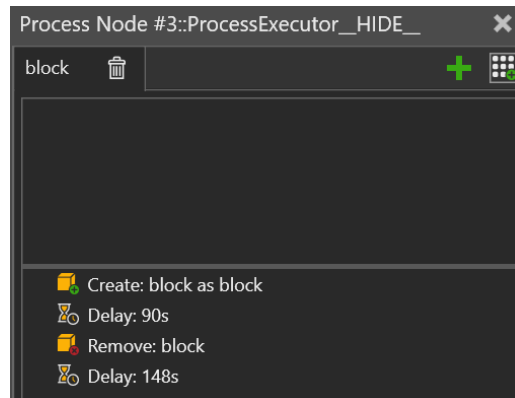
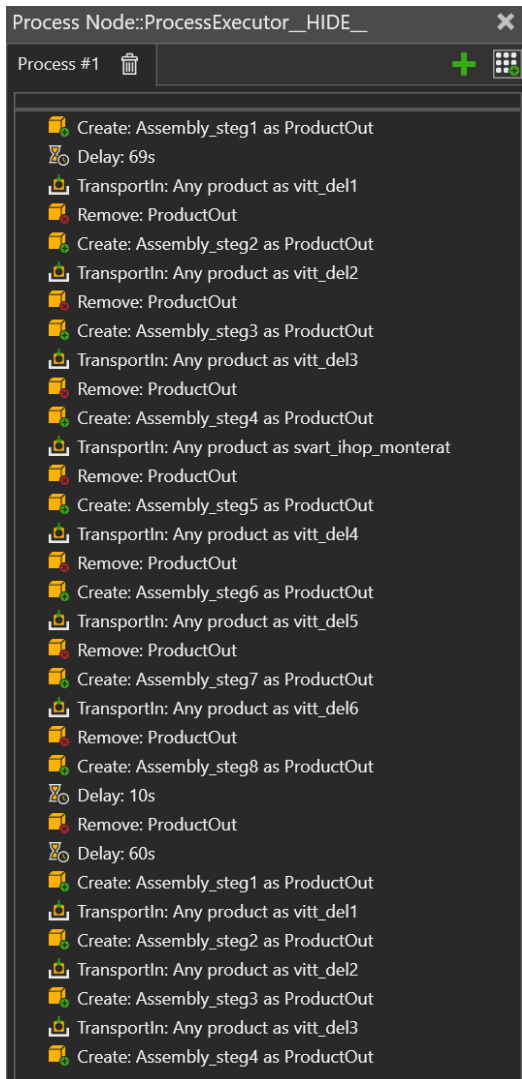


Figure 42: Second conveyor process node bottom assembly

Figure 43: Third conveyor process node bottom assembly

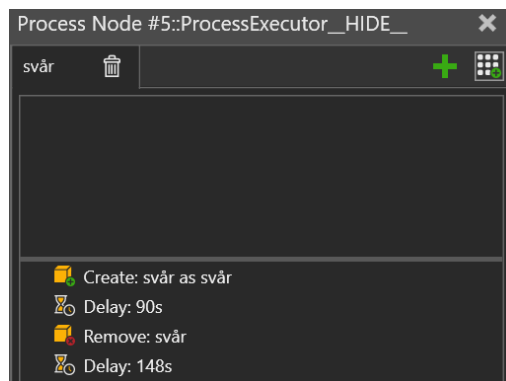
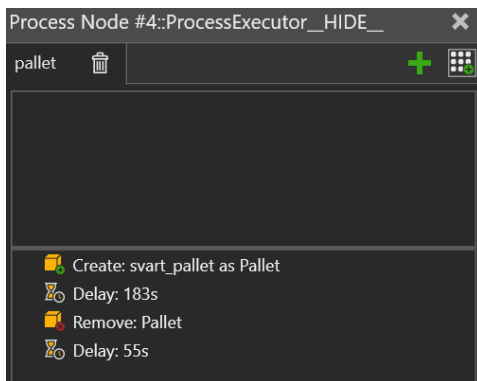


Figure 44: Third conveyor process node bottom assembly

Figure 45: Third conveyor process node bottom assembly

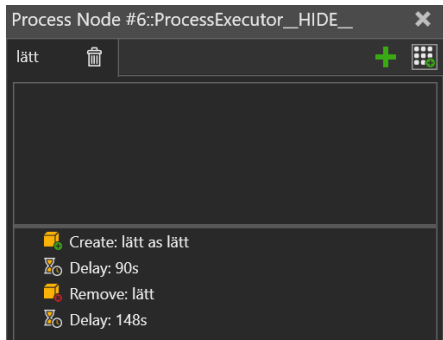


Figure 46: Third conveyor process node bottom assembly

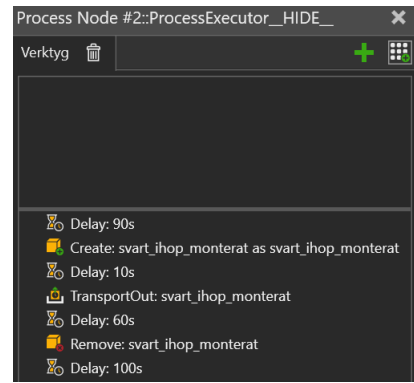


Figure 47: Special tool first process node

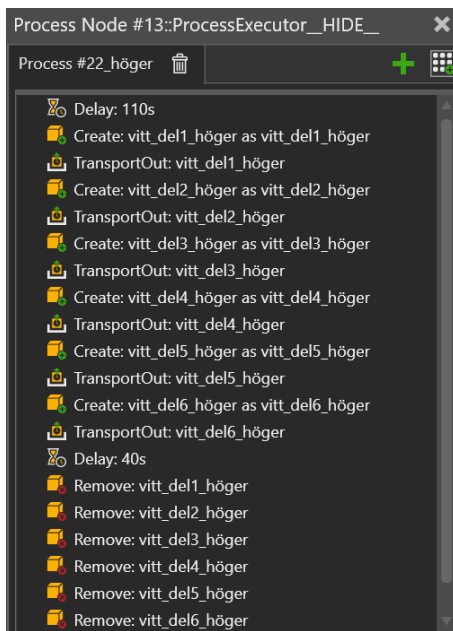


Figure 48: First top conveyor process node

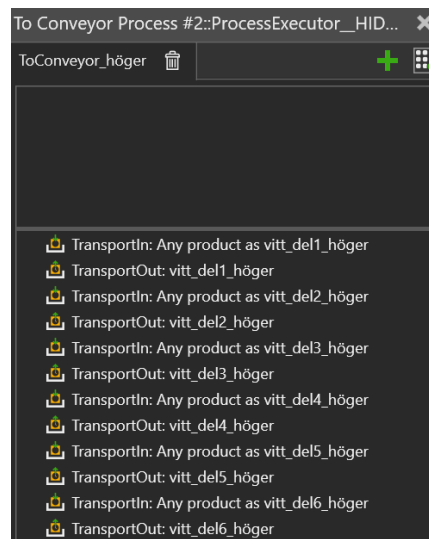


Figure 49: First conveyor to conveyor process statements

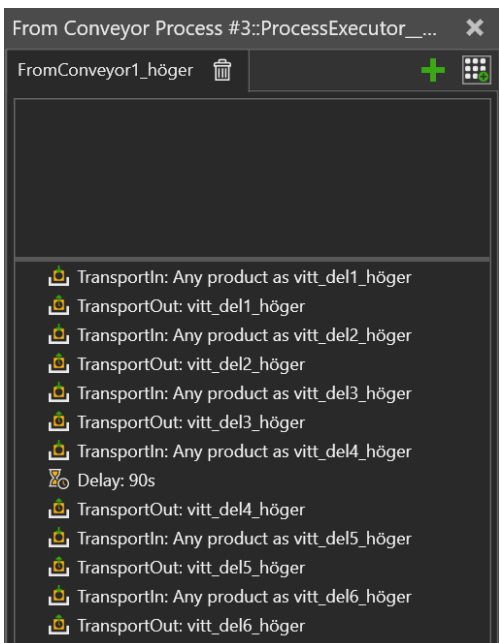


Figure 50: First top conveyor from conveyor statements

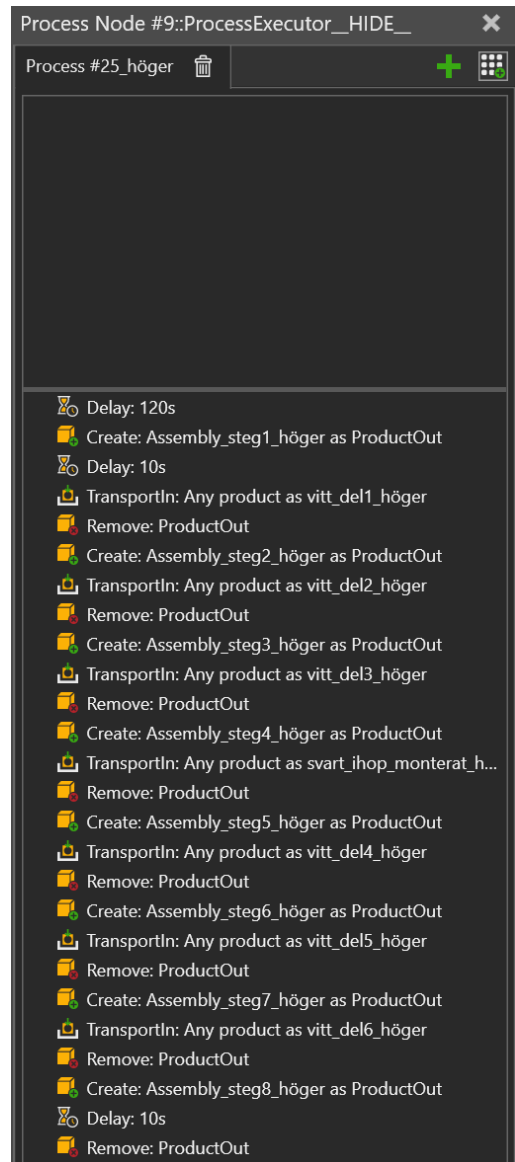


Figure 51: Second top conveyor statements

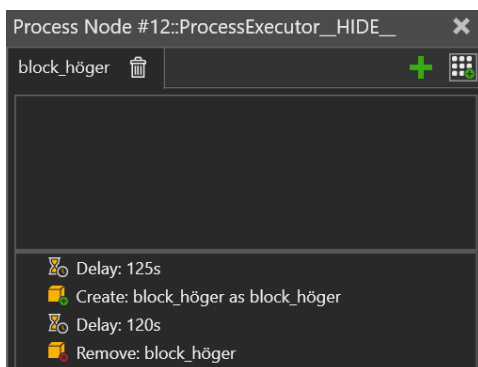


Figure 52: Third top conveyor block statements

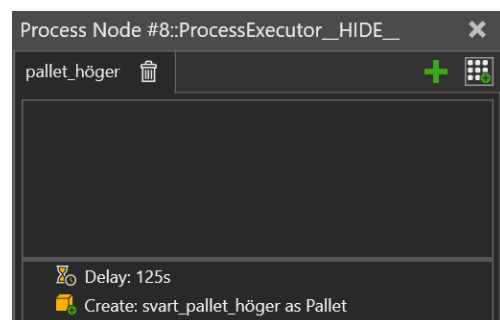


Figure 53: Third top conveyor pallet statements

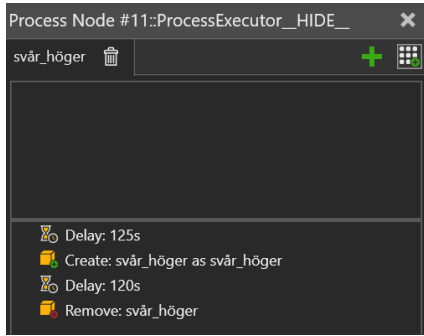


Figure 54: Third top conveyor process node statements

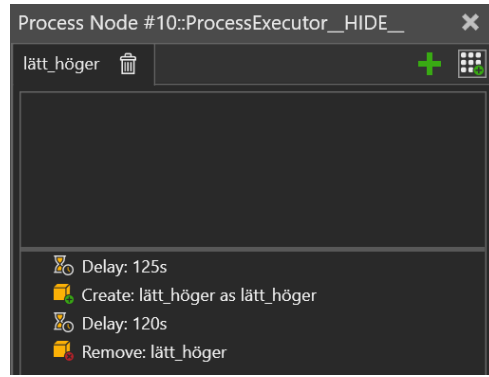


Figure 55: Third top conveyor process node statements

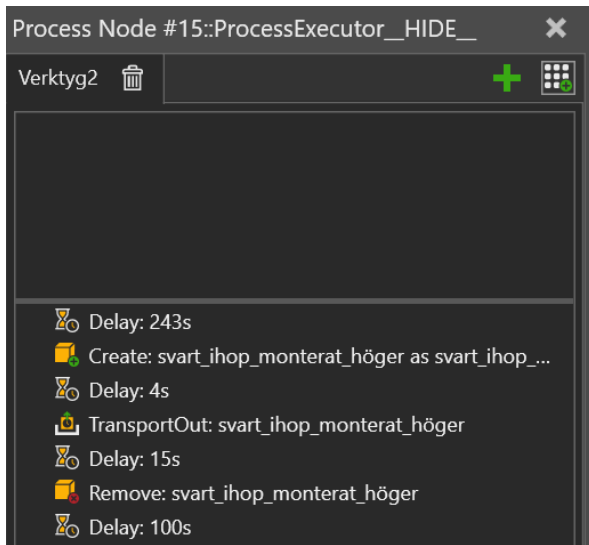


Figure 56: Special tool second process node

Flow and process statements for D6 assembly:

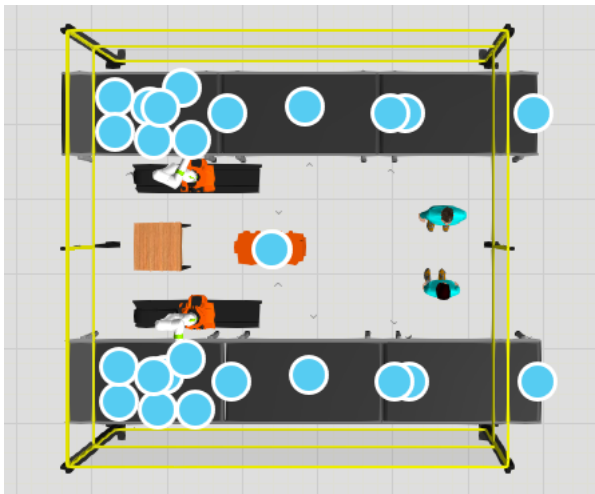


Figure 57: Process nodes placement

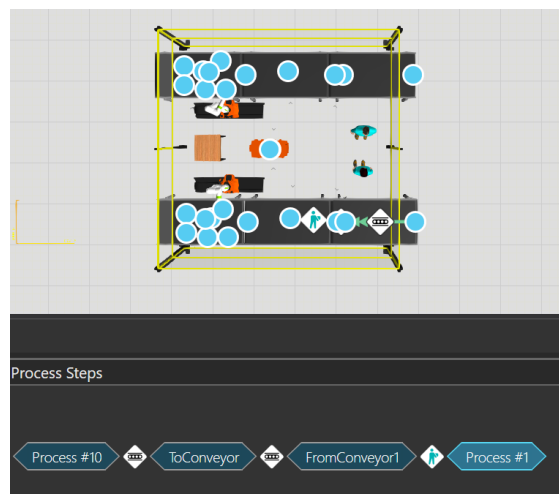


Figure 58: Flow first bottom conveyor

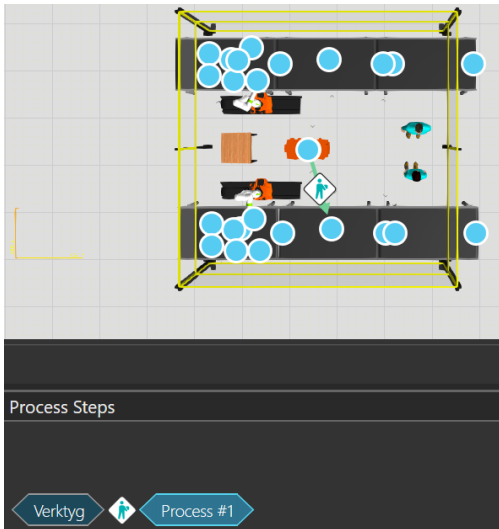


Figure 59: Flow special tool closest assembly

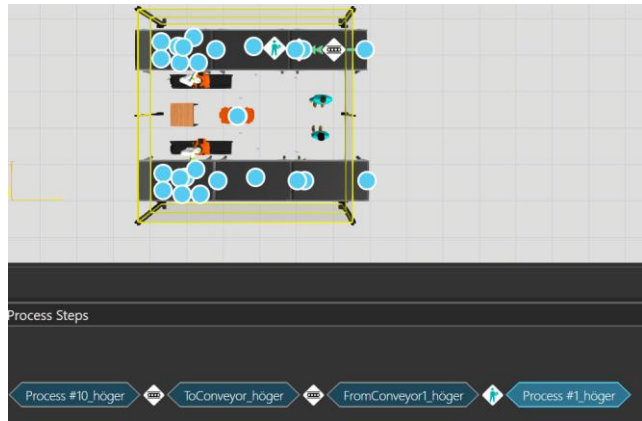


Figure 60: Flow first top conveyor

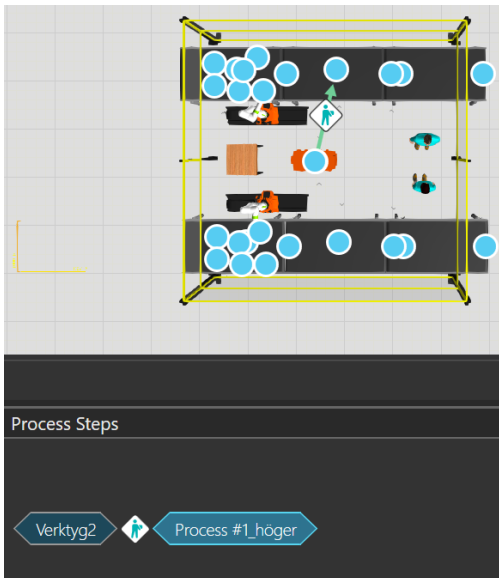


Figure 61: Flow special tool top assembly

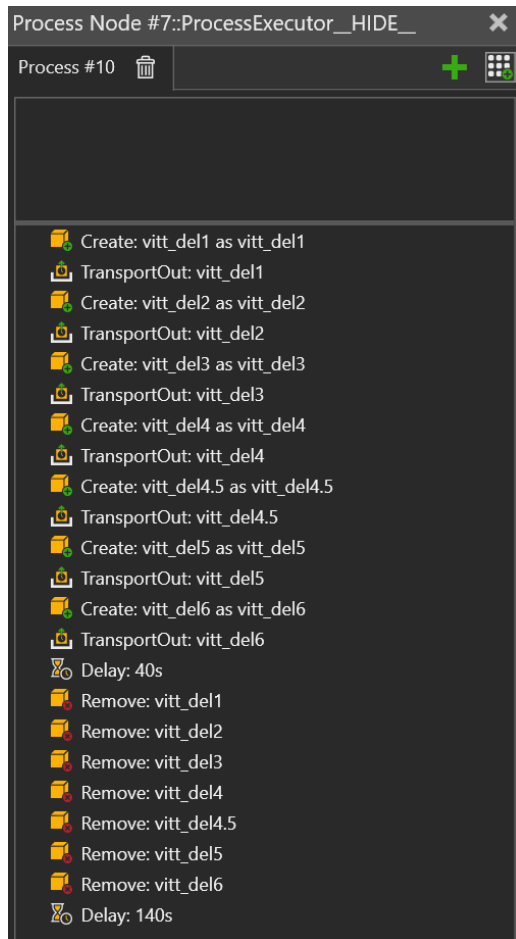


Figure 62: First process node bottom assembly statements

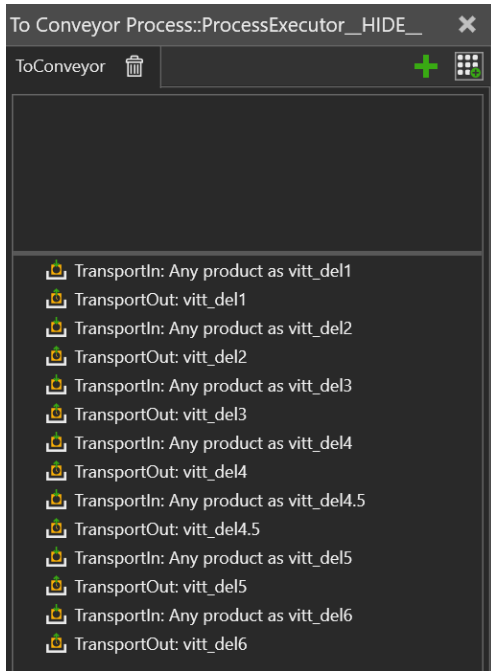


Figure 63: To conveyor bottom assembly statements

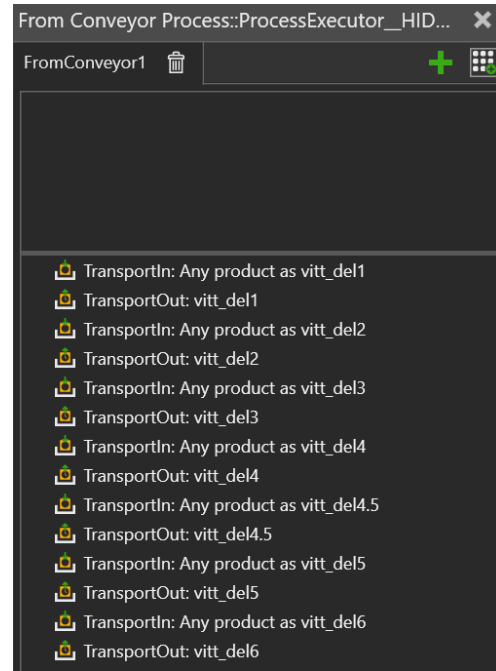


Figure 64: From conveyor bottom assembly statements

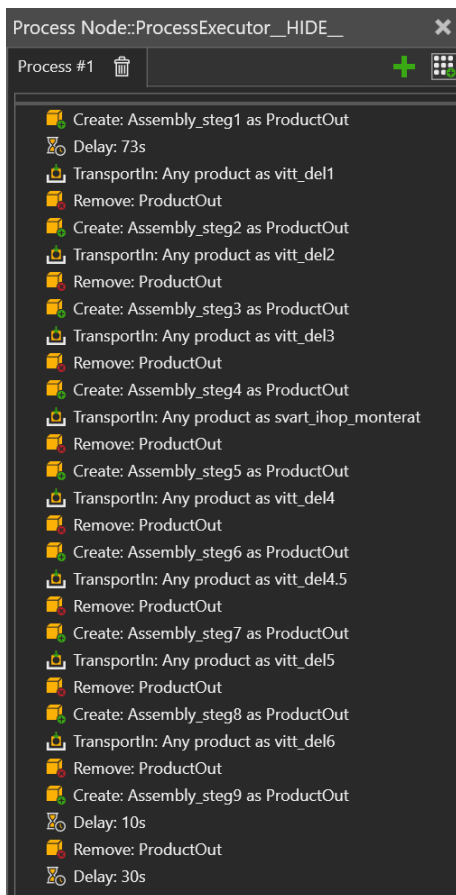


Figure 65: Second conveyor process node bottom assembly

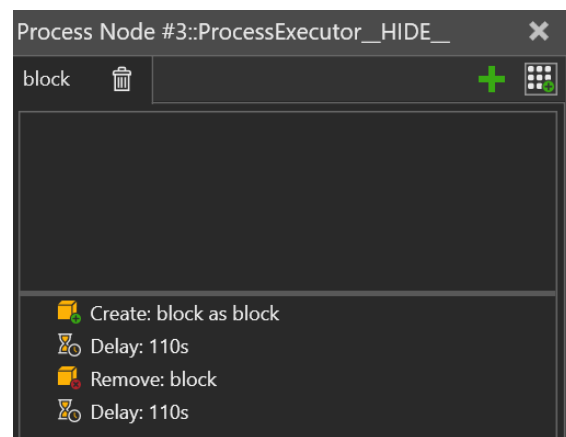


Figure 66: Third conveyor process node bottom assembly

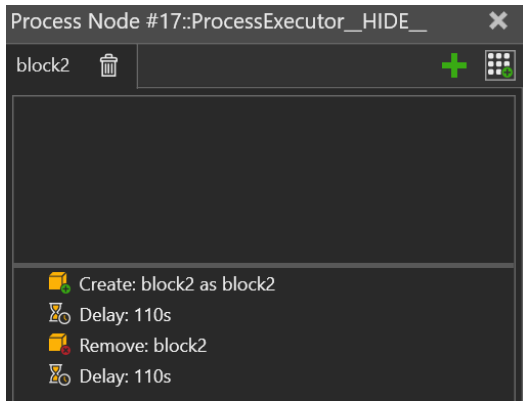


Figure 67: Third conveyor process node bottom assembly

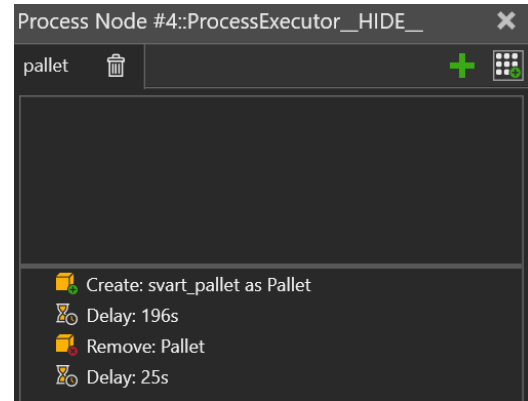


Figure 68: Third conveyor process node bottom assembly

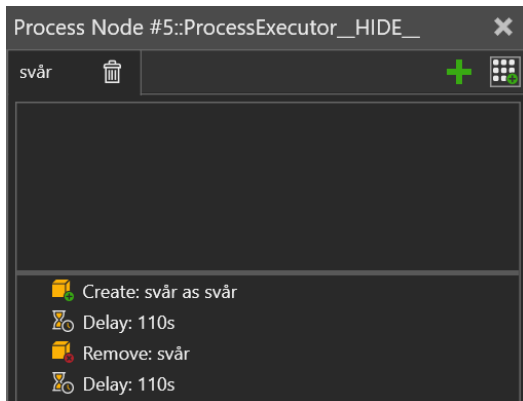


Figure 69: Third conveyor process node bottom assembly

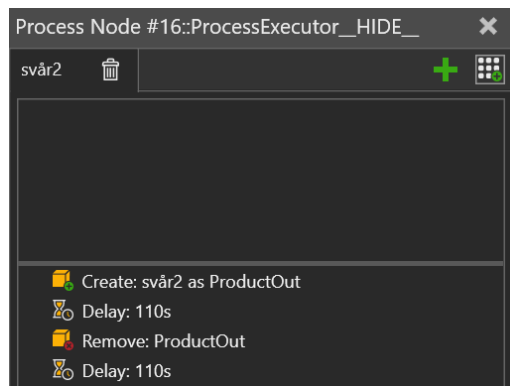


Figure 70: Third conveyor process node bottom assembly

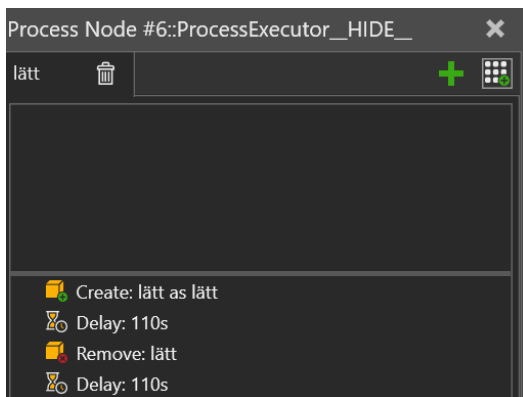


Figure 71: Third conveyor process node bottom assembly

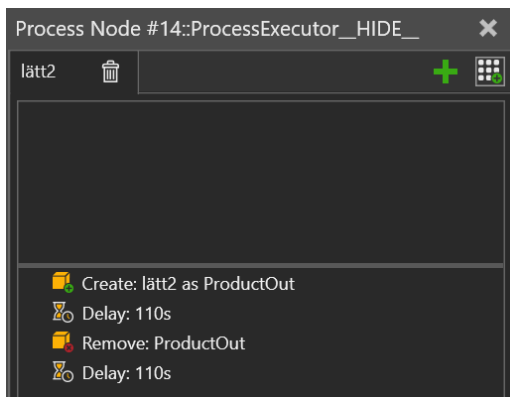


Figure 72: Third conveyor process node bottom assembly

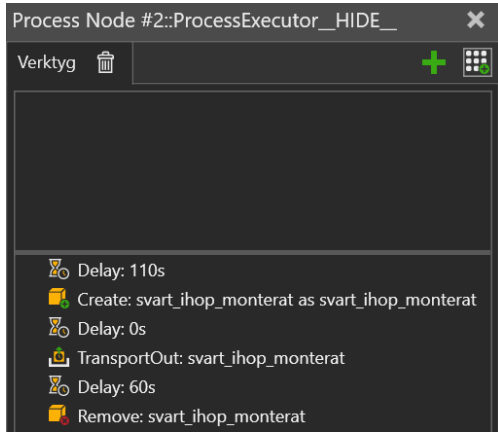


Figure 73: Special tool first process node

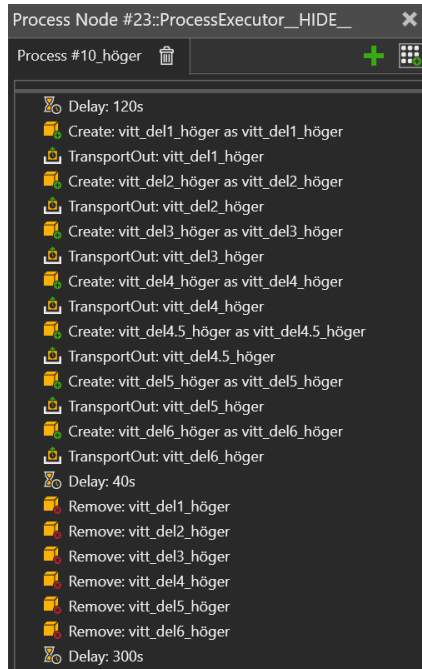


Figure 74: First top conveyor process node

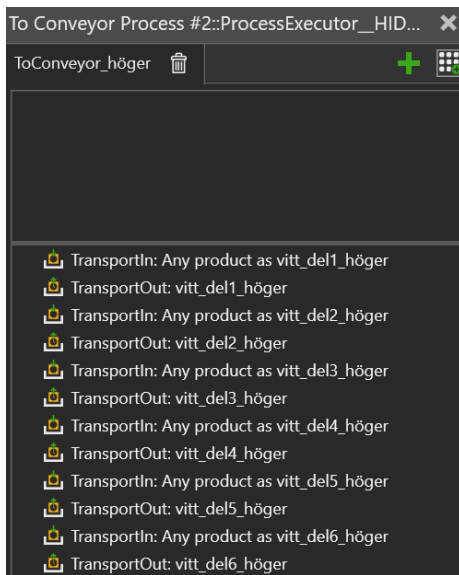


Figure 75: First conveyor to conveyor process statements

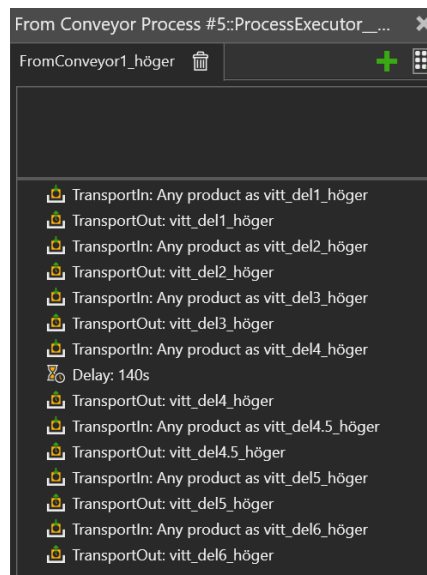


Figure 76: First top conveyor from conveyor statements

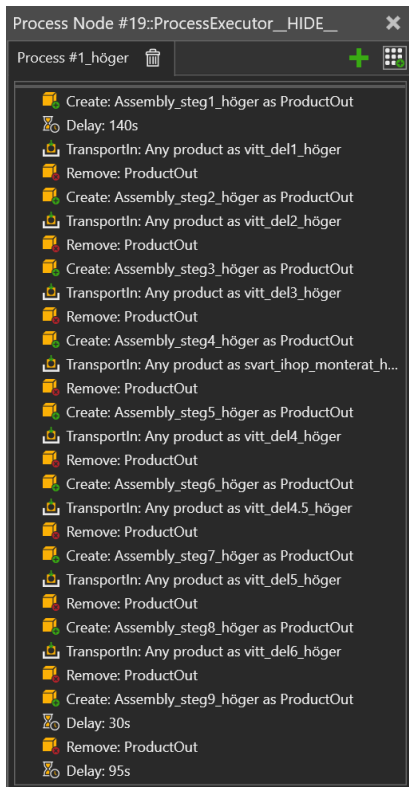


Figure 77: Second top conveyor statements

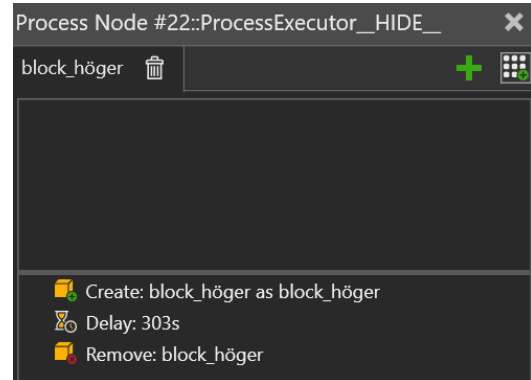


Figure 78: Third top conveyor process node statements

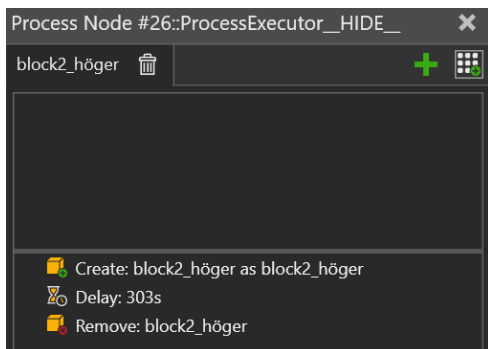


Figure 79: Third top conveyor process node statements

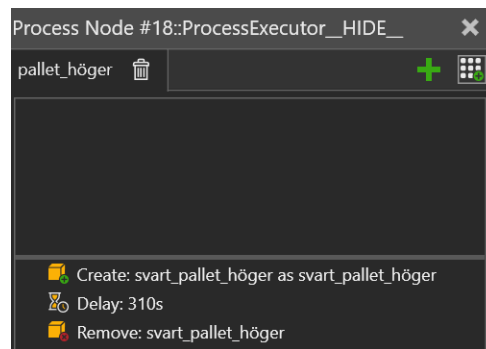


Figure 80: Third top conveyor process node statements

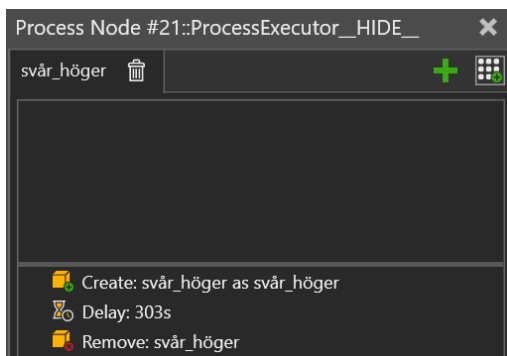


Figure 81: Third top conveyor process node statements

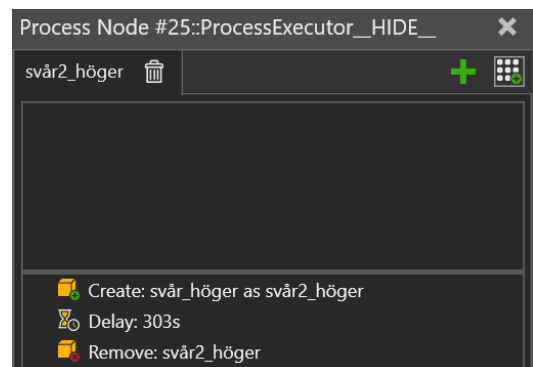


Figure 82: Third top conveyor process node statements

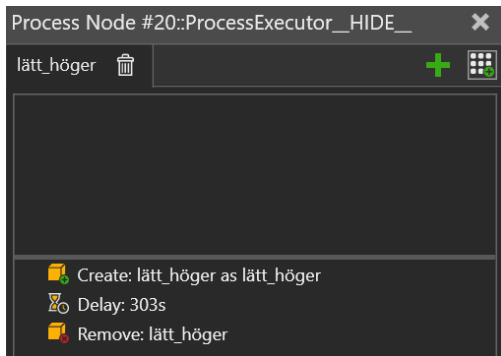


Figure 83: Third top conveyor process node statements

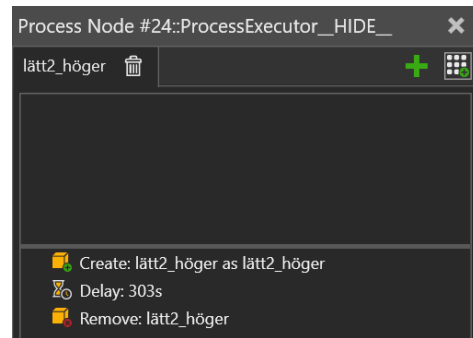


Figure 84: Third top conveyor process node statements

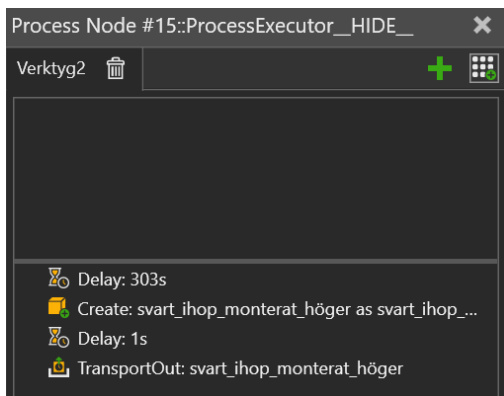


Figure 85: Special tool second process node

# C

## Appendix

### C.1 Gripper components and sand cores:

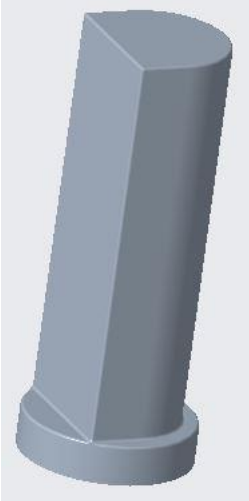


Figure 86: Finger

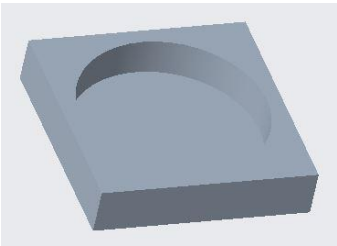


Figure 87: Plate

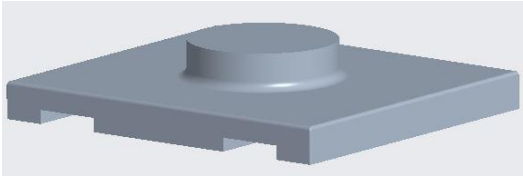


Figure 88: Main component

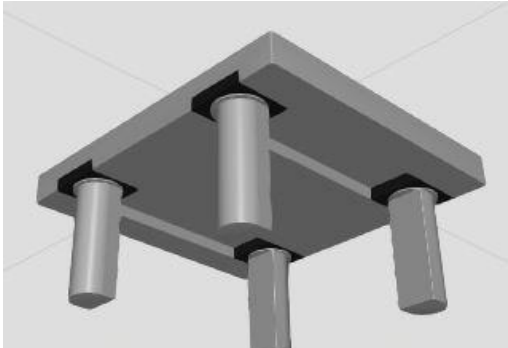


Figure 89: Complete Gripper

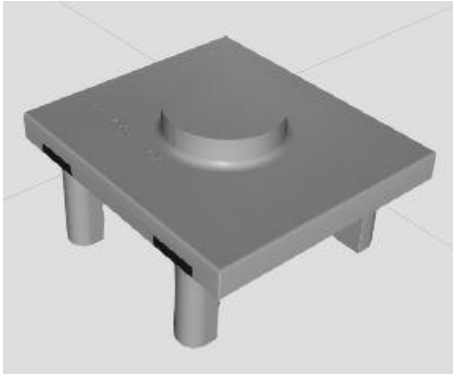


Figure 90: Complete Gripper

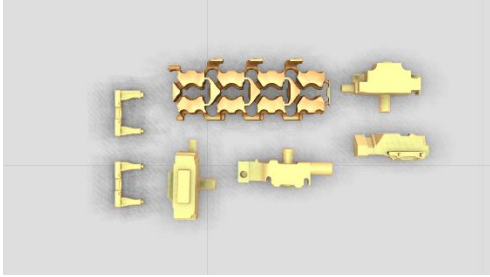


Figure 91: White sand cores for D4 engine

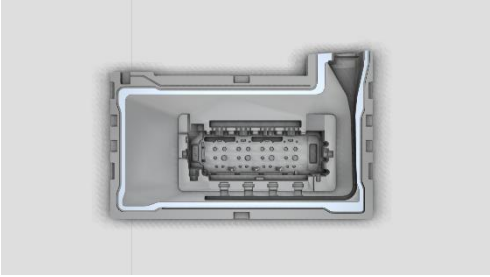


Figure 92: Main mold for D4 engine

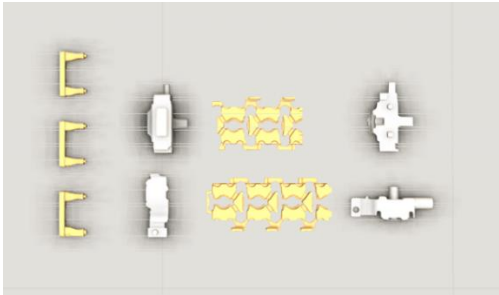


Figure 93: White sand cores for D6 engine

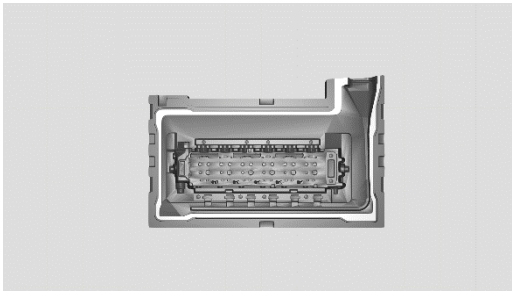


Figure 94: Main mold for D6 engine