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Alternative design of robot cell concepts for flexible production

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UNIVERSITY WEST

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Summary

Flexible manufacturing is something that most companies is aiming to accomplish due to the increased demand for variety and a competitive global market.

This thesis report includes an introduction to the automation concept and the development towards flexible automation. A general flexible assembly cell is presented and its content and requirements are discussed. The work has been done with focus on an assembly process with dedicated fixtures at VCE (Volvo Construction Equipment).

Based on the literature review and the general example, a list of actions to take while planning and implementing a process is developed. The actions roughly include: mapping of the process, defining goals, investigation of automation level, holistic view while planning, definition of the need for flexibility, investment plan, designing and comparing concepts, investigation of possible issues and implementation in small scale.

The current manual process at VCE is presented and analysed. Three concepts are designed with product flexibility as an alternative to processes in which traditional dedicated fixtures are used. The designed concepts are a fully automated concept, a hybrid concept with separated workspace and a human-robot collaboration.

Finally, the concepts are analysed and compared based on following parameters: productivity, product cost, investment, flexibility, space requirement and setup time. One final comparing summary of the concepts is done. The analysis shows that a fully automated concept is to prefer in this case. However, a human-robot collaboration could be appropriate to use if the process is expected to improve with the human workforce. Examples of when it could be reasonable to use human-robot collaboration despite this are: if the task provides better quality when conducted by human or if the task is complex to automate.

Preface

The thesis is the final work before graduation and it is challenging but interesting. The project demands a lot of planning and independent work to get it done. The courses leading to this thesis has been useful to me and this work is where students show what we are capable of.

This thesis work has demanded a lot of creative ideas and thoughts. One of the best ways to develop ideas are through discussions. I want to thank my supervisor Anders Appelgren for the participation and guidance in my project. Other teachers from University West to contribute with ideas to the project are Anders Nilsson, Svante Augustsson and Bo Svensson.

I also want to thank Erik Åstrand from Volvo Construction Equipment (VCE) and Gunnar Bolmsjö from University West for involving me in this project. Special thanks to Ferry Clément and Le Pol Martin Vincent, working on a similar project at VCE, for practical questions about the process and rewarding discussions.

Affirmation

This master degree report, *Alternative design of robot cell concepts for flexible production*, was written as part of the master degree work needed to obtain a Master of Science with specialization in Robotics degree at University West. All material in this report, that is not my own, is clearly identified and used in an appropriate and correct way. The main part of the work included in this degree project has not previously been published or used for obtaining another degree.

Linda Gislén

2016-06-07

Signature by the author

Date

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1 Introduction

1.1 Background

There is a global trend to offer more customised products and it is a challenge to adapt traditional automation systems to manage high flexibility. The effect of the transition is a demand for lower production volume but with a low cost per unit. During mass production when flexibility was not required, the fixtures were customised for each part. The cost for dedicated fixtures becomes a problem when the volume decrease which is why flexible alternatives are needed.

1.2 Problem description

The project is done in cooperation with VCE (Volvo Construction Equipment) to explore the possibility of designing a flexible robot cell. The robot cell should manage to handle about 70 different plates and assemble about 14 different subassemblies. The handled plates weight up to 30 kg with a total subassembly weight of up to 115 kg and they are medium sized, around $0.5m^2$. Most of the subassemblies are outsourced but there is a quite common desire for Swedish companies to take back production.

There are many benefits of keeping the production in-house. One major benefit is that it is easier to control and change details in the production when it is located in the same building. Profitability, quality and space requirements is expected to be positively affected by taking back the production. That is, if one system can handle the process of all subassemblies in a one-piece production flow. One problem with producing more subassemblies with the current configuration is that more assembly stations are needed, maybe one for each subassembly. Additionally, all the assembly stations need at least one fixture each. It would require a lot of space and dedicated fixtures, which both increase the fixed cost noticeable.

The main purpose of the robot cell is to support high product flexibility instead of creating new jigs for every product. The system could be designed to be fully automated or to use human-robot collaboration and the appropriate automation level depends on the situation. The process can be divided into tasks and each task has a suitable automation level for the situation. Which one is preferred is dependent on a number of parameters and can be complicated to decide.

1.3 Aims

- Research suitable automation levels to support a flexible production system
- Design alternative concepts to the traditional system with dedicated fixtures and build simulations in RobotStudio
- Compare concepts with appropriate key figures related to flexibility and automation level

1.4 Method

The thesis report begins with a literature review of all the relevant components in automation. To be able to provide alternatives to traditional assembly systems the main focus is kept on assembly processes. Research articles about alternative methods will be searched for and reviewed. Based on the literature and some knowledge of the process, a general assembly process is divided into tasks. A discussion will be done about each task to decide how it can be configured and advantages with the alternatives are presented. A method to plan and define a process will be developed, based on the literature review and the discussions that followed, to make structured decisions of how to design a system based on the requirements of the process. To provide a flexible solution it is possible to design concepts in different variants. A few promising concepts will be designed which will be analysed. The concepts will be defined based on conclusions from the literature and input from discussions. The discussions will be done with experienced staff at the university and with involved people at VCE. The defined concepts will be simulated in RobotStudio to provide a visual illustration of the concepts. The concepts will be analysed mostly in a qualitative way with respect to following parameters: Productivity, product cost, investment, product flexibility, space requirement and setup time. Additionally, a comparison of the concepts as a whole will be discussed.

2 Literature studies about automation

The production systems have evolved over the years. It started with personal trade and craftsmanship of goods like a cobbler making shoes for example. A number of technological advancements and an increased demand for goods triggered the industrial revolution. Large-scale production was introduced in factory systems, which lowered the cost per unit significantly, and the new price drove the craftsman out of business.

Automation is defined as the replacement of human involvement with controlled machines. It is mentioned in the book by Gunnar Bolmsjö [1] that the introduction of industrial robots has been an important enabler for automation in the industry and especially so in the automotive industry. At first, the robots replaced human workers in repetitive, heavy and dangerous tasks. The Handling of material in between manufacturing operations was typical for the first systems, like pick and placement in an automatic machine. The processes were repetitive but the robot has the capability to adapt to different processes in contrast to other more dedicated machines. Systems with the ability to reconfigure became important as product's life span started to decrease. The problem could be managed with a system of robots instead of dedicated machines. In the seventies, robots became more involved in manufacturing processes like spray painting, deburring and arc welding. The requirements of the robot capability increased and demanded better control systems.

In all manufacturing processes, handled parts need to be positioned and supported in a specific way by some kind of fixture solution [2]. This to ensure that the manufacturing operation is done in the same way every time. During the mass production era, the fixtures were designed for each part and because of the large volume produced with each fixture the cost was not an issue at the time.

2.1 Levels

A production can be configured according to three levels: manual work, fixed automation and flexible automation [1]. Manual work is appropriate for complex tasks with low volume and it means that the human workforce makes the tasks. Fixed automation refers to systems with dedicated machines, which has a very low flexibility. A flexible automation system usually contains robots, which can be controlled to do many things and can be adapted to new processes. The unit cost for handling one product is usually the lowest if it is done manually and in the other end, the lowest unit cost for many products will be achieved by fixed automation. Within these extremes, it might be appropriate to use flexible automation depending on the situation. There are a number of parameters that should be considered when deciding the level, for example the batch size, working environment and complexity etcetera.

2.2 Equipment

The robot is equipped with some kind of end-effector appropriate to the given task. Grippers are common in tasks like material handling and assembly. The functionality of the gripper can be controlled mechanically, by vacuum or magnetism. The appropriate gripper depends on the application and the environment. Flexible grippers like an imitation of the human hand are available but not commonly used in the industry. If there is a need to use different tools in a robot system, there are tool changers available to change tool quickly. If the robot is used for manufacturing, a processing tool like a welding gun will be used as a tool [1].

When a manufacturing operation is conducted, the right information about the tool centre point and the position of the part is needed to control the process. Equipment used for ensuring the right positioning of parts is referred to as fixtures. Many industries still use dedicated fixtures to ensure the right position when joining parts together with welding for example. The fixtures are designed for specific parts and when the produced volume is low, the unit cost increase due to specially designed fixtures for each part. There has been done research about reconfigurable fixtures to avoid expensive redesign for different parts. In the article written by S. Arzanpour et al. [3], a fixture to handle different types of parts is designed. The flexible fixture is mounted on an industrial robot and is designed to arrange suctions cup to enable pick up of different parts. The feasibility of the flexible fixture is tested through an experiment with four different parts. The conclusion is that it is appropriate to use in the industry.

A process needs to be controlled in a way that interference do not pose a threat to the production or surrounding people. All tasks in an automatic system need to be triggered by something. In manual systems, there is a person using human senses to identify objects for example. In automatic systems signals from sensors is used to control functions. There are some limitations to human sensing capabilities. Human senses are not reliable if the person is focusing on something else or if the speed is higher than the reaction time. In some applications, sensors are more accurate than human senses, like in the welding process as an example. However, human capabilities can be complicated to replace with sensor systems. Human senses together with a brain to interpret and adapt is a pretty robust and flexible system. A problem while using sensors in industries is interference in the operating environment, which can significantly interfere with the result. Types of sensors commonly used are inductive, capacitive, optical, acoustic, magnet, safety, tactile and force and machine vision [1].

2.3 Safety

Due to the increasing usage of programmable equipment, it is even more important to carefully consider the safety in the system. According to Gunnar Bolmsjö [1], the increased complexity and flexibility in systems can make it behave in an unexpected way. The focus should be on keeping the operator safe during operation and maintenance. However, a system adapted to a safe environment should be designed with functionality to avoid longer production stops. It is stated that there is a positive effect on equipment safety when designing safety for operators.

Gunnar Bolmsjö [1] divide the safety in a robot system in external- and internal safety. All precautions concerning keeping the working space free from operators are included in external safety. Equipment commonly used for this is fences, carpet or light beams and the most suitable one depend on what kind of operation is conducted. Sensors used in safety equipment must be reliable and cannot be sensitive to interference. If the restricted area is entered, the process must adapt directly to ensure the safety. Sometimes it is needed to work inside the restricted area, like during maintenance work or programming task, in which the system needs an internal safety. The process can be controlled with limited speed during a manual state with a dead man’s control to run it.

2.4 Human-Robot Interaction

Production systems with robots enable operations with good repeatability and high efficiency. However, robots can limit a production system which needs to be adaptive and flexible due to varying tasks. Combining the best qualities of human and robot in a hybrid system will provide a more flexible system and complex assembly processes can be improved with human-robot interaction (HRI) [4].

A system with HRI can be hard to manage because the regulation of safety in hybrid production systems is strict, with good reason because of the great damage an industrial robot can cause a human. It is possible to make it safe but the trade-off is speed and force.

There is a lot of ongoing research about systems to ensure the safety of humans in industrial environments. J. Krüger et al. [4] present systems that are controlled by using external sensors to locate obstacles and these are usually used to make industrial robots safe for collaboration.

SafetyEye made by Pilz is presented in the paper [4] which is a camera system used for 3D surveillance of the shared workspace. The SafetyEye can replace physical fences to separate humans from robots. The system includes a sensing device with three cameras, a safety and control system and a computer. Complex algorithms process the image from the sensing device and the result is a 3D image. The image is used to check if a detection zone has been violated. The workspace can be divided into different zones depending on the type of danger. As an example, it can be configured with one zone to let a human get close but with reduced robot speed and one zone for immediate danger that will trigger an emergency stop. An emergency stop always demands a manual restart of the system. The zone for reduced speed, however, should be configured to resume the standard speed when the zone is clear. This function to resume to the original state is important to avoid production stops. Furthermore, if the safety system is complicated to use there is a risk that it will not be used the right way. In the paper written by S. Augustsson [5], there is some criticism pointed to the SafetyEye. Using vision solutions is problematic due to the sensitivity to different light conditions. It is also stated that it cannot separate humans from objects which can cause unnecessary production stops.

2.5 Mass customization

There has been a transformation from mass production to mass customization, which requires changes in the production system to sustain high production flexibility. Mass customization is a strategy concept that aims to fulfil customer demands of high variety products. In the paper, mass customization: literature review and research directions [6], literature about the mass customization concept is reviewed. The paper concludes that companies' ability to adapt to the market's demand has become of high importance. Another aspect to consider with flexible manufacturing is the possibility to bring back production in a profitable way. The automotive industry faces a number of challenges while adapting the production to mass customization. G. Michalos et al. [7] provide an overview and discussion of existing technology in the area. There is an increasing demand for car models with many variants produced faster and with fewer resources. A process based on mass production does not support product variability or a quick change of car models. It is mentioned that the customization mostly takes place during the final assembly stage, which not coincidently is the stage where most of the human workforce is utilised.

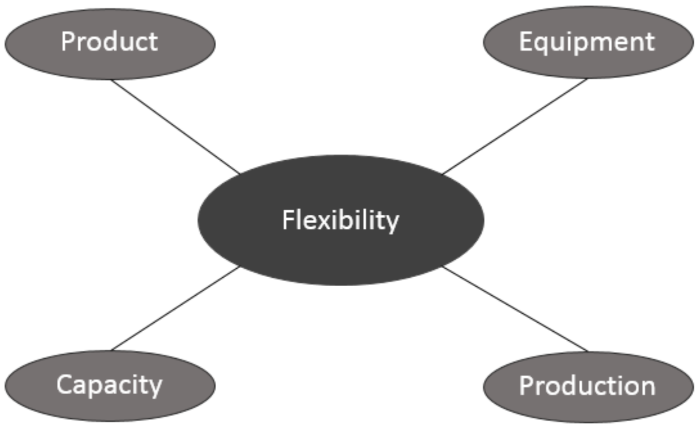

Figure 1. Flexibility defined with sublevels. Inspiration from the book written by Gunnar Bolmsjö **[1]**.

2.5.1 Definition of flexibility

It is important to find the appropriate level of flexibility in a production system. Flexibility is a broad concept and can mean different things. In the book written by Gunnar Bolmsjö [1], flexibility is divided into four sublevels, which can be of different importance in each production system as Figure 1 shows above. Product flexibility refers to the ability to handle similar products in the same system. Equipment flexibility is meaning the ability to modify or change equipment in the system without interfering the system as a whole. Flexibility in capacity is how well the system response to changes in volume and at the same time retain the same cost. Production flexibility refers to the capability of reconfiguring the production to meet new requirements. It is important to pick the right level of flexibility appropriate for the given system. The flexibility comes at a higher cost but if it is needed it will have a positive effect on the overall cost. However, if flexibility is not a requirement it is a waste of money to make the system flexible.

2.6 Assembly

Automatic assembly was first implemented in processes for assembly of small electrical components, which are mentioned in the book written by Gunnar Bolmsjö [1]. The assembly required advancements in repeatability, speed and acceleration. There was also a demand for more flexible surrounding equipment to feed, separate and fix components. The traditional automation systems were adapted for mass production and resulted in low unit cost. However, it was not designed to be flexible and research for more flexible solutions handling high-mix and low-volume production has been investigated since at least the 1990s. In the paper written by Y. Kusuda [8] the effort to obtain more flexibility at the company IDEC Corporation is described. A transition from a line-based system to an automated work cell was implemented for high-mix and low-volume production. In contrast to robot requirements in a line-based system where robots are single-skilled, the robots in the work cells need to be multi-skilled. The system must also be able to adapt to changes in grip point and joining point of the product [9].

2.6.1 Robotic fixtureless assembly

A replacement of dedicated fixtures can be a system with Robotic fixtureless assembly (RFA) which uses multiple robots with grippers to position and hold the workpiece while another operation is conducted. Existing RFA systems is mainly used for small and rigid parts [10]. There are some obstacles when handling larger and less stiff parts with a robot. Assemblies usually require a high level of accuracy to ensure good quality when joining parts together with welding for example. Case studies with research about how dedicated fixtures for assembly can be replaced with robot systems is reviewed and presented below.

In the article, Vision-guided fixtureless assembly of automotive components [11], RFA is described and its purpose is to replace inflexible fixtures with sensor-guided robots with programmable grippers. The article presents an RFA cell in which experiments are conducted of the assembly of four automotive body parts. In the experiment, a system containing two robots with programmable grippers with connecting video cameras were used. The parts are located on a worktable with a 2D vision algorithm and after the parts are picked up alignment is done with the help from a 3D vision system to compensate for errors. The results of the research work done were that the work cell had some limitations. It is only possible to assemble rigid parts and the designed grippers had some limitations as well in which type of parts to handle. The accuracy and assembly speed was lower than required in most industries. However, the motion speed was limited due to safety in the test environment. In the article [11] G. M. Bone and D. Capson suggest some improvements in the 3D vision system to increase the accuracy.

Energy efficiency of products is a concern of most industries today and one approach to optimise it is to decrease the mass of the products produced. In the article, spatial alignment of joining partners without fixtures based on component-inherent markings [9], it is stated that frames made of aluminium extrusion profiles are used in some industries. It is suggested that fixtureless assembly by industrial robots can increase both profitability and repeatability. The problem is that the alignment accuracy when joining parts must be high to replace the traditional fixtures. Low accuracy is one drawback with flexible production systems, especially caused by the usage of several robots. If every robot has problems with accuracy, the total error might be too large for correct alignment. J. Fleischer et al. argues that the combined errors in the flexible system will result in deviations larger than 1 mm, which is not sufficient. An additional system to increase the accuracy is proposed in the article. In contrast to other existing methods, the method handles rotationally symmetrical parts as well. A component-inherent scale is used to locate the components position and rotation. Thereafter a multi-robot system containing two robots pick up the parts to join. A gradual alignment process is used to align the components where one is fixed and the other moves in small adaptive steps. Experiments were conducted with the proposed measuring system and algorithm to define the accuracy of the system. The result of the experiments was that the approach is suitable.

The paper, Adaptive robotic assembly of compliant aero-structure components [12], present a system for assembly of aero-structure components. The components are positioned with part-to-part holes. The system contains an industrial robot, a metrology system with a laser seam finder, a configurable gripper and an algorithm to calculate the 'best fit' points. A number of different experiments are presented in the paper. The robot performance is tested and solutions of different type of errors are proposed. The laser seam finder is used on different surfaces to map the connection between surface and disturbance. The overall system performance is tested to verify that the combined errors are low enough. Experiments of the actual assembly are done both with two and three holes. The result of assembly with two holes was a tolerance within 0.5 mm and the tolerance of assembly with three holes was within 1.588 mm, which according to the authors of the article, N. Jayaweera och P. Webb, is good enough for typical aerospace production assembly.

2.6.2 Assembly by human-robot collaboration

In the following article, Cooperation of human and machines in assembly lines [4], research about assembly cooperation between human and robot or machine is reviewed. The concept of hybrid assembly is discussed in the article, which means that the assembly process is divided into sequential tasks. Two groups of hybrid assembly are discussed. One group where the workplace is shared and the human performs a handling task while the robot performs an assembly or the opposite but not at the same time. In this configuration, the only interaction between human and robot is collision avoidance. Activities in the second group are based on a shared workplace and the possibility to work at the same time. A high level of interaction is needed when human and robot are working together at the same time. An example of this configuration is that a robot picks up a part while a human prepares an aligning part. The robot slows down in the shared working space, for safety reasons, and park close to the operator where the robot is moved by the human to put the parts together. The subassembly is transported to a bin by the robot where after it picks up a new part to assemble.

2.7 Dedicated fixtures or flexible fixture solution

Like mentioned before dedicated fixtures are suitable for high volume production with low variation. It will provide good repetition, which will provide a process with high reliability. However, the cost of dedicated fixtures is high and therefore not suitable when the volume is low and variants is high. The alternative, flexible fixtures, is designed to handle variants but it is required to get the same result as with dedicated fixtures. This is a challenge and demands additional systems to handle the flexibility. The fixture itself can be flexible in a way that the fixture can be configured to adapt to changes in production. It is also possible to use a robot system as a fixture solution, by mounting it on a robot. Robots are great tools when it comes to flexibility; they are designed to manage different tasks. There are however problems in flexible systems which the robots cannot handle by them self. Vision systems are needed to control the system and it is expensive to implement with risks of failure due to interference. A semi-automatic process can be effective to handle complex tasks but there are limitations with safety directions when including human workforce in robot systems. The developments in all these areas progress quickly with a lot of research efforts to solve problems connected to them.

3 Tasks in a flexible assembly cell

The chapter contains a discussion about general tasks in an assembly cell with important things to consider. Each task can be configured to work automatically or manually, the discussion in this chapter takes up pros and cons with each.

3.1 Loading and fixture

A robot cell for the given process needs an input of parts to assemble and the parts need to be positioned in some kind of fixture solution. A human can position the parts in a correct way on the robot if the robot is equipped with a fixture solution to ensure the correct position of the part. The robot could also automatically pick up the parts from a pallet or a conveyor. To ensure a repeated pick up position the system needs additional equipment like a vision based sensor system.

Manual loading could be inappropriate if the parts are large or heavy but it is possible to use additional equipment to avoid injuries due to heavy lifting. Even if human senses are effective with its capability to see the whole picture and adapt to unforeseen events. A sensor system with a camera to locate and calculate the right pick up position has been extensively researched and implemented in different situations. Most sensor systems are sensitive to interference which makes it important to consider all situations before choosing a sensor system or alternatively stick to manual loading. If a sensor system is implemented, which can be expensive and complex, it is expected to get it right at least most of the times.

3.2 Assembly

A manual assembly is not considered for assembly because the focus is on medium-mix and medium-volume products, which usually is not suitable for manual work. It is assumed that robots will conduct the assembly. Parts positioned on the robots should be aligned with other parts in a predefined way. Alignment, during assembly of parts, usually demands high accuracy.

Theoretically, if the pick-up points and joining points were the same every time it would be pretty easy to design the process for an assembly. In reality, it is hard to ensure this repeatability and it might be necessary to use an additional system to ensure proper alignment. In chapter 2.6.1, some case studies are presented and in one of them, a 3D sensor system is used to adapt the points during assembly to compensate for errors. The accuracy for this type of system was not good enough in their experiment and it implies that the sensors need to be improved before implementation, if high accuracy is needed. Further on, another article used a method which seemed to reach a reasonable accuracy. In the method, a component-inherent scale was used and the parts were aligned in a gradual process as in the former experiment. In the third case study, an additional experiment to test the system performance and find the different type of errors was conducted. This was done to show that the overall system performance depends on the surroundings like used material for example. Proposals to solve all the identified errors was presented and the combined errors were measured. It is one way to increase the accuracy in a system.

3.3 Joining

When the parts have been aligned in the right way, they can be temporarily joined by tack welding for example before the final joining procedure is conducted.

When the parts are aligned, a human could conduct a welding operation if appropriate safety solutions are applied. The human and robot could share workplace but without direct interaction, which would mean that the robots will be fixed in space during welding operations. Depending on how the welding operation needs to be done in the specific case, it might be necessary for the robots to move during the joining procedure. To turn around the workpiece for example and this will demand further safety measurements due to increased interaction. The robot would have to operate at a low speed while the operator is close to the robot. A vision system to detect the location of the operator is needed to ensure the safety.

A robot could join the parts together after an assembly and the productivity will be high compared to manual joining. Especially so if the procedure is done fast like during tack welding. The robot used for welding can be integrated with the assembly robots, which will provide a relatively low cycle time. If a sensor system is used in the assembly task, it could be modified to be used for the welding procedure as well. How the joining operation should be designed, depend mostly on:

- the quality of the application
- the cycle time
- productivity
- safety limitations

If the quality of the weld, for example, is better with robot or human it will affect the choice greatly. If the productivity and the cycle time is high in automation compared to a manual process it will lean towards automated joining. The safety limitations of working in a shared workplace with or without direct interaction could make the process too complex with HRI. There are also positive sides to HRI, like more flexibility and a visual quality check before and after an operation.

4 Method to plan process

When there is a need for a new process or a redesign of an old process, it is important to do the right preparatory work. It is crucial to put enough effort in this task to succeed with a process. There are many things to consider and explore before a process should be implemented. It is quite common that the planning step fails due to an eagerness among the involved people. The result can be a failed project, which is expensive. Some guidelines that can be helpful during the design of a process is found below.

Actions:

1. Map the process, everything that needs to be done in the process should be included. It is common to use a flow chart to break down the process in functions and decisions.
2. Define the goal of the new or improved process. Avoid heavy lifting, hazardous environment, increase productivity or improve the quality of product etcetera.
3. Use the mapped process to investigate which of the tasks that could be beneficial to automate.
4. If a task seems appropriate to automate, a thorough analysis should be conducted to see if there is something that will affect the change, like input and output.
5. These changes should always be planned according to a holistic view to avoid sub-optimisation. The flow, from material to finished product, should be kept as steady as possible. It means that storage between operations is only used if necessary, the lead-time will be kept low and the cost of storage handling will be low. When a process is defined, the logistics should have a high priority because it will affect the whole process as well as the cost.
6. Figure out if the process/task needs to have a flexible approach or not. If it does, define what type of flexibility that is required and what level to use. It is usually quite easy to figure out which parameters that need flexibility in a system. Like written earlier in section 2.5.1, the flexibility can be divided into sub-levels: product, equipment, capacity and production. The level of flexibility can be a bit harder to predict but as an example, the following questions could be considered: How many different products should the system be able to handle or how often would the production system need to be reconfigured?
7. Investment in new equipment might be needed and in most cases, there are a lot to choose from. The most important thing to consider is to never pay for more functionality than needed. At the same time, if it will be needed it might be worth investing in. As an example, if the long-term goal is to automate a line this should be considered when deciding which robot to use even if the first change might be of a smaller character. The decision is one of the harder ones to take but the chances of taking the right decision will increase with a solid plan to base it on.
8. The planning phase should lead to at least one documented concept. If there is more than one concept, an investment- and a product cost estimation could help deciding which concept to implement. Simulation of concepts is also one way to decide the feasibility of an idea.

9. At any time in this list, it is possible to figure out some problems with the idea. It will save a lot of money to figure these things out before implementation and it is a reason to be critical about the outcome through the whole process. A decision to drop the whole project or to do some of the steps again will always be less costly than finding problems later.
10. To ensure that the implementation succeeds, it is preferred to begin with a smaller change. A small-scale change will diminish the risk of failure and makes it easier to find and correct problems. The change should be studied to see if it fulfils the goal and work in a satisfying way. Further changes might be needed and useful lessons could be learned.

5 Concepts

The chapter introduces the process in which subassemblies are produced now. Three alternative concepts are designed to be able to produce all or most of the assemblies. One fully automated concept and a hybrid concept with separated workspace. Additionally, one concept that is a combination and development of the first concepts. The concepts are explained and analysed individually in the chapter.

5.1 Current process for subassembly

Two of these typical subassemblies are assembled in a manual process in-house while the assembly of the rest is outsourced. The assembly is done in one station, see Figure 2, which shows the placement and measurements of the equipment. The figure also shows the space required around the station to maintain access to it.

The plates needed for the assembly are cut in-house and stored in racks close to the station. The station contains two dedicated fixtures, one for each subassembly. The plates are gathered by the human worker from the racks surrounding the station and positioned in the dedicated fixture to ensure correct alignment. The operator uses welding equipment located in the station to conduct tack welding to join the plates together. The subassembly is too heavy to carry by hand so there is manual lifting equipment to move it to a three-axis positioner located in the station. The part is mounted on the three-axis positioner that is used for access during manual final welding of the subassembly. Thereafter, the finished subassembly is moved to a pallet assigned to finished parts with the help of lifting equipment.

The space requirement for the actual station, without the extra space to access the station, is measured to be about 16m^2 and it can handle two different parts. A rough estimation of

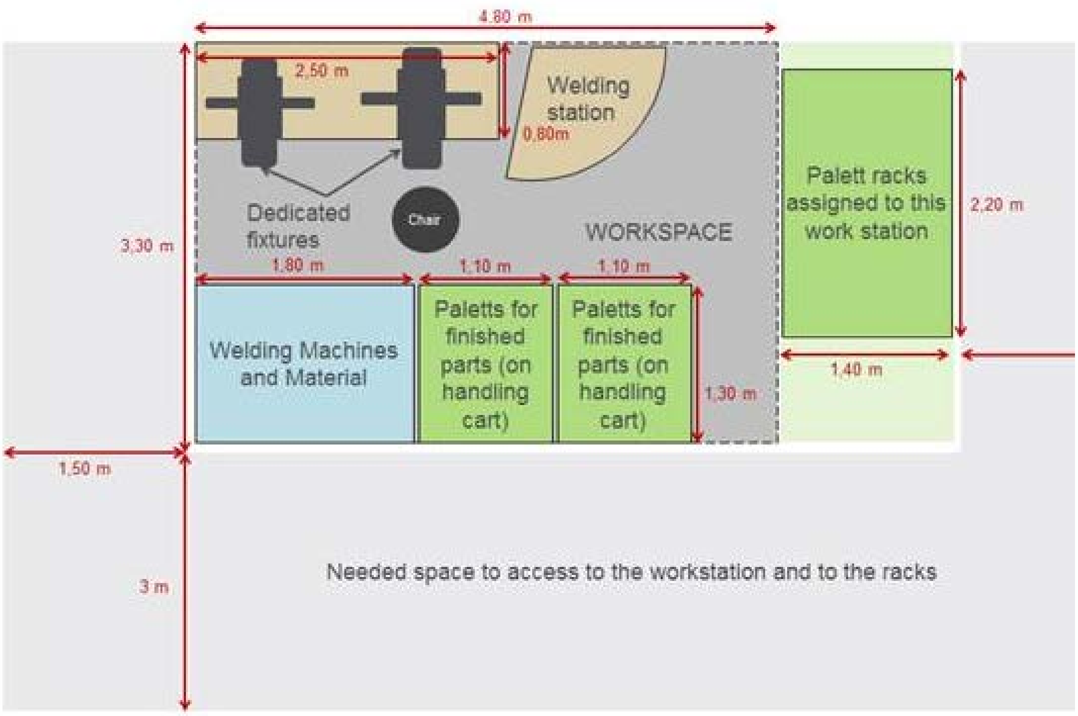

Figure 2. The layout of the current workstation, made by Ferry Clément and Le Pol Martin Vincent from VCE.

the required space needed to assemble 14 different subassemblies in 7 similar stations is about 112 m^2.

5.2 Fully automated concept

The current process is, like mentioned before, fully manual and there is no product flexibility in the system due to the usage of dedicated fixtures. One natural alternative is a fully automated robot cell system with built in product flexibility. It demands that the plates and subassemblies have similarities. The more the products differ the more complicated system is demanded and thereby costlier to automate.

In the following scenario, see example in Figure 3, the system is configured with three robots. The number of robots in a robot system does not affect the cost a lot. The price of robots has decreased a lot over the last couple of years and should not alone affect the number of robots used. If a short tact time is needed, it might be achieved by investing in more robots for example. The chosen robots in the system could be replaced with robots of different brand and size. In the software, RobotStudio, it is only possible to use ABB robots, which is the main reason for the choice in this case. The size of the robots in the simulation is picked based on its specific task but can be exchanged by other robots.

5.2.1 Input

The robot cell is designed with an AGV (Automated Guided Vehicle) to deliver input to the robot cell. The idea is to gather all the plates needed for one subassembly directly from the cutting machine and transport it on the AGV directly to the robot cell. Horizontal placing spread out on top of the AGV is chosen in this case to make the picking easier but it is possible to use other solutions to gather the plates in one kit. In this way, the handling costs will be minimised and the lead-time will be kept low.

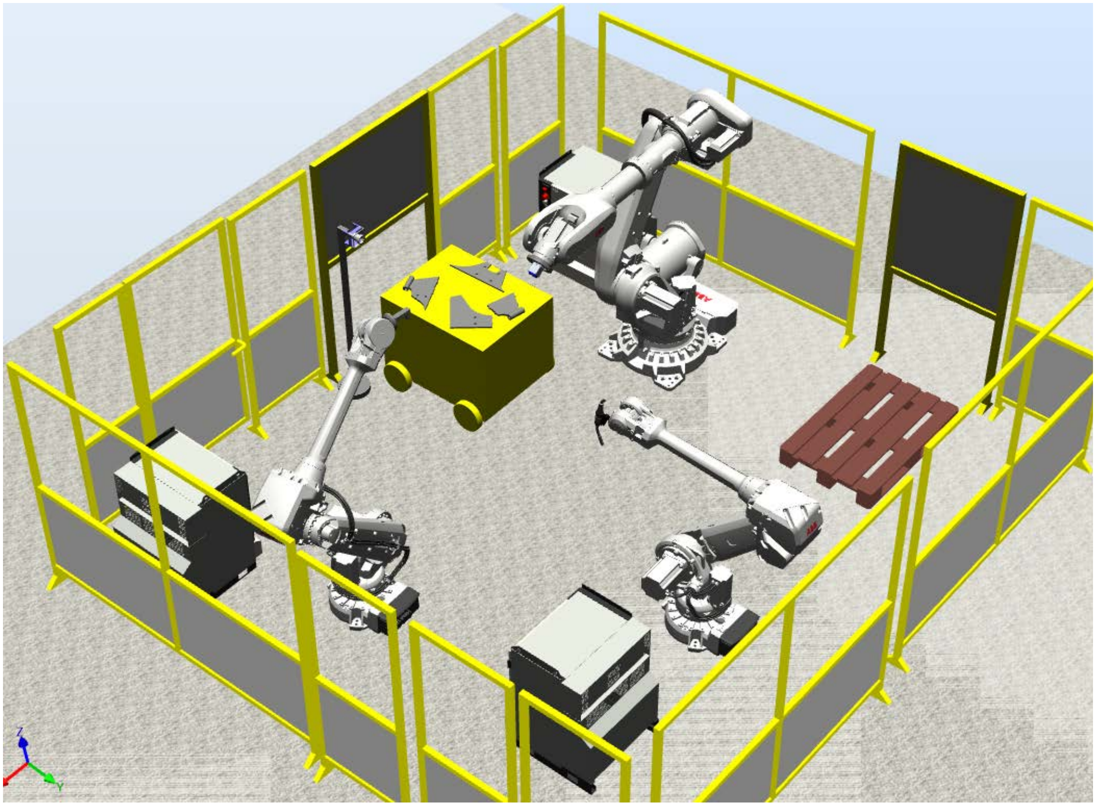

Figure 3. Example of automatic concept

It is common to try to utilise the machines as much as possible, which can be contra productive when the whole process is considered. Instead of cutting the plates that are needed directly, a storing system is used which makes it possible to cut a specified quantity of plates when the storage is almost empty. If this kind of system is used the plates will be picked from the cutting machine and put into a pallet rack. When the plate is needed, it will be picked up again. In the current manual process, it can be accepted because the plates are put in the fixture by hand anyway. However, in an automated system, it is not to prefer because a human worker will have to pick all the plates from storage and put them on the AGV. The cost of the AGV will be low in contrast to the handling and storage cost described above. To change the cutting schedule according to this one-piece flow, a thorough analysis needs to be done to keep a stable process without interference.

5.2.2 Positioning

The input of the plates into the system must be controlled to ensure that the robot knows which plate to pick up and to pick it up at the same point every time. In section 2.6.1 several case studies present research and suggestions to ensure a proper alignment. Correct alignment must be achieved either by ensuring the right position before pick-up or alternatively a vision system to detect the error after pick-up. In this system, the idea is that the AGV will transport the plates in an organised way but it is assumed that they are not perfectly positioned. Say that a robot stationed at the output of the cutter, picks up the plates and drop them off on the AGV in the same spot every time. Then the plates can be picked up in the robot cell and positioned in front of a 2D camera that takes an image of the plate. The image can be analysed by an algorithm to decide the difference between the actual pick up point and the planned pick up point. This works if the plates are positioned in the same area every time. If not, the algorithm can be designed to identify which plate it is as well or placing the camera on the AGV to identify the position before pick up. This type of positioning method can be adapted to handle plates of many subassemblies through robot programming and vision algorithms. The product flexibility is thereby high. When the image is analysed, either the robot puts down the piece and picks it up again according to the error found in the image. Alternatively, the robot program is created with variables to make it possible to compensate for errors. The latter can lead to problems if the error is large and the pick-up point is located close to an edge for example.

5.2.3 Fixture

The concept includes one larger robot, with a great payload to carry heavy parts, with an end-effector in the form of a magnet tool. The robot picks up the reference plate, put it in front of the camera and adapts to get a good hold of the plate. The robot will hold the plate during the assembly and act as a fixture. It will position the reference plate to make both the assembly and the welding possible. If the total weight of the subassembly is large, it might be necessary to keep the reference plate horizontal to avoid repositioning of the part due to gravity. This will limit the reachability and this need to be considered when choosing which robot to use. The robot fixture support product flexibility as long as it is possible to use the magnet tool to pick up all reference plates with it. It is also a possibility to use a tool changer if different tools are required. Furthermore, the setup between different subassemblies is not time-consuming; the robot program is the only thing that differs.

There is one alternative similar to this fixture, which is a fixed magnet tool. The reference plate would be picked up by an assembly robot and placed on the fixture. This would, however, affect the reachability in a negative way and it is not necessarily a cheaper solution.

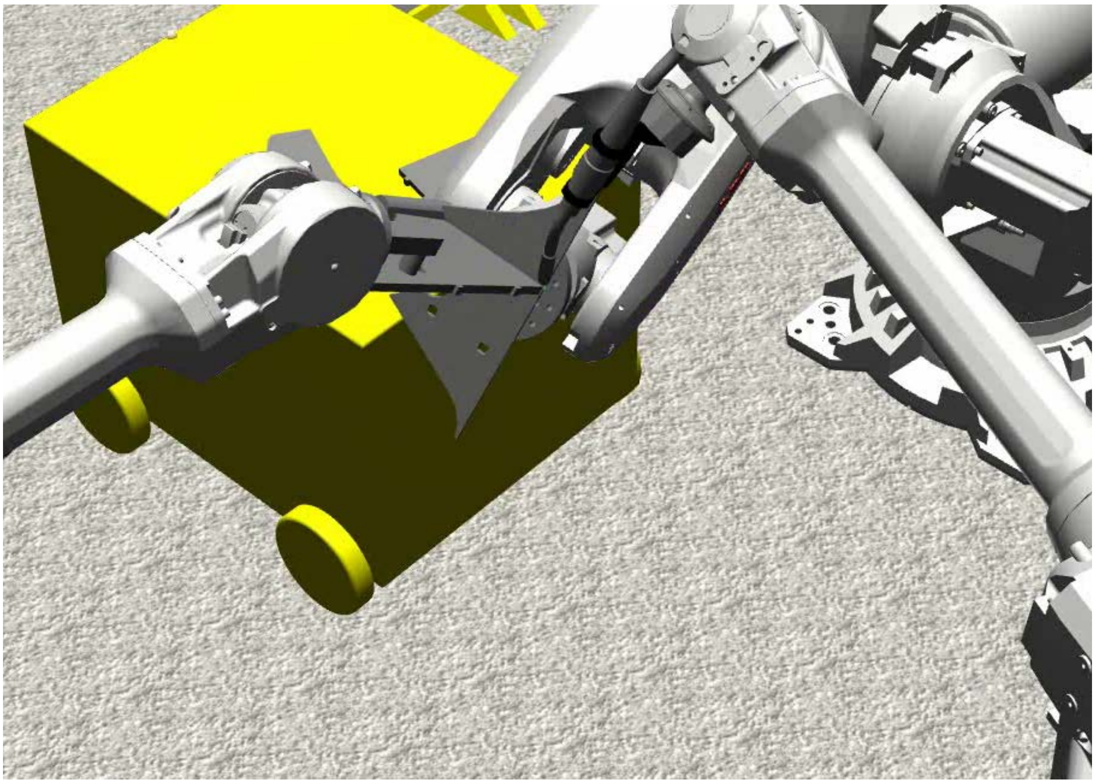

Figure 4. Automatic assembly and tack welding

The programming will be more complicated and it has no second hand value in contrast to a robot.

5.2.4 Assembly and joining

Two robots with lower payload but high reachability are chosen for alignment of pieces and for joining the pieces together. One of the robots pick up the pieces with a magnet tool, use the camera to decide the right pick-up point and align the plate to the reference plate.
The other robot is equipped with a welding tool, which is used for welding the pieces together. Each plate is then tack welded when aligned to the assembly, see Figure 4. When all the pieces are aligned and tack welded together, the fixture robot will continuously position the subassembly while the welding robot does final welding. When final welding is conducted, the part is put down on a pallet.

5.3 Hybrid concept with separated workspace

It is true that dedicated fixtures are connected to a large fixed cost but there are some advantages to it as well. A system with dedicated fixtures is not particularly sensitive to interference because most fixtures are designed to make it impossible to assemble it in the wrong way. The handling of plates for different subassemblies can be a complex task to automate and in some cases, it can be more beneficial to take advantage of the flexibility that human workforce provides with. The human workforce has the ability to make complex decisions based on several parameters and has a holistic view of the situation. An alternative to the current manual process is a semi-automatic process, see example in Figure 5. The productivity in a system containing human workforce will always be lower than in a fully automatic system. The example is designed with two robots, one AGV, one turning table and movable fixtures for every subassembly. Any robot can as before replace the robots with the right features needed for the task, like enough reachability and payload.

5.3.1 Input

This concept is also designed with an AGV to deliver the needed pieces for one subassembly. In Figure 5, the AGV is loaded with picking racks containing kits of plates for one assembly together with a movable fixture. The idea is that the kits are gathered directly after the cutting process and preferably transported directly to the robot cell. The rack is designed to make it easier for a human worker to pick from it and load it into the fixture, which in this case is mounted on a turning table. Depending on the chosen AGV and the size of the picking racks, multiple picking racks can be delivered at the same time to the station. There is no need for additional equipment to position the plates in this concept because the human can identify the location of the plates and the fixture will ensure the right positioning.

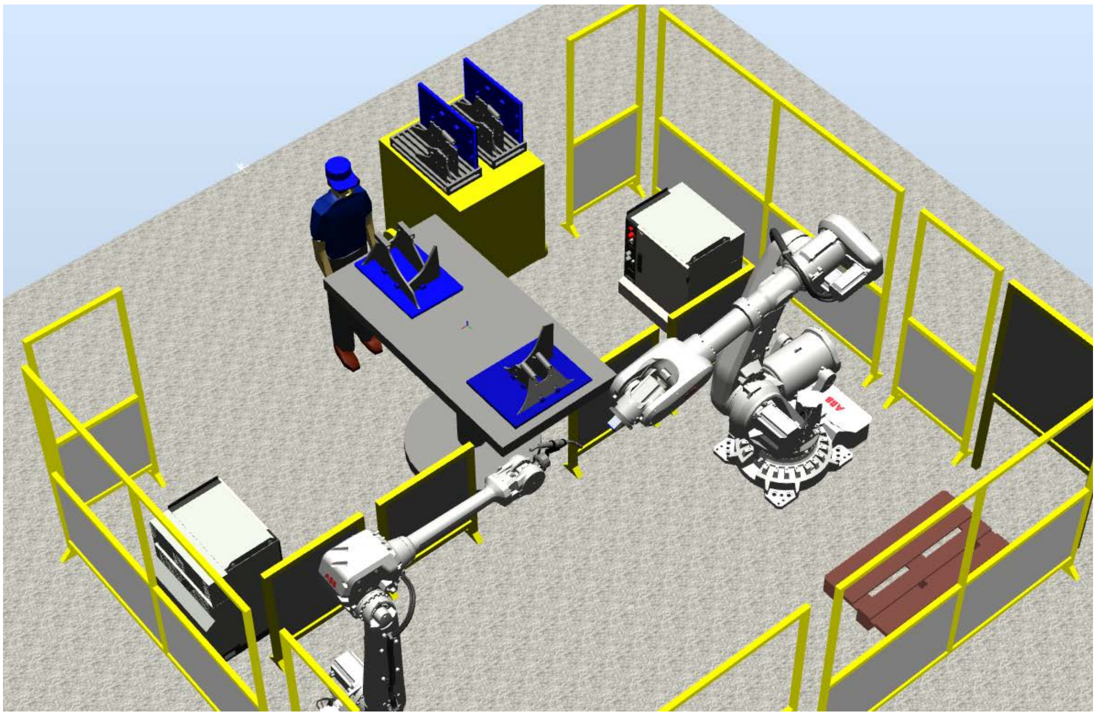

Figure 5. Example of a hybrid assembly concept

5.3.2 Fixture

In Figure 5, dedicated fixtures are still used, but it could be possible to replace them by some kind of modular fixture that can handle different assemblies. The idea is to introduce the idea of movable fixtures as an alternative to flexible fixtures. If the fixtures can be moved like suggested, or something similar, it will minimise the amount of space needed to produce all the subassemblies. However, there will be a setup time to consider when changing the fixture on the turning table.

5.3.3 Handling, assembly and tack welding

The handling task showed in Figure 5 is not optimal. A human worker mounts the movable fixture on the turning table, picks up one plate at a time and load them into the fixture. The plates are a bit too heavy to comfortably carry by hand and it should be avoided to reduce work injuries. It is one of those tasks, which would be beneficial to automate. When the fixture is loaded, manual tack welding is done and a turning table is used to divide the working space from the robots. When one part is ready for final welding an indication from the operator will start a rotation of the table and the assembly of a new part will begin.

5.3.4 Final welding

The assembly is picked up, from the fixture connected to the turning table, by a large robot, which acts as a fixture while a second smaller robot will conduct final welding. The robot fixture will rotate to enable the right reachability for the welding robot. When final welding is finished, the part will be put down on a pallet. There probably need to be further safety equipment installed to protect the eyes of the worker.

5.4 Concept with human-robot collaboration

This final concept was designed as an improvement of the hybrid concept, see section 5.3, which has some obvious disadvantages. The new concept includes solutions from the fully automated (see 5.2) and the hybrid concept. The idea is that the human and robot will share workspace but not conduct the tasks at the same time, human-robot collaboration is introduced in section 2.6.2. The concept was developed when the simulation phase was ended and is therefore explained in this chapter without a simulation to visualise it.

The concept could be designed in the following way. Automation is used to perform the following tasks: the input of plates, correct positioning and fixture solution. The design of these tasks are identical to the fully automated concept with AGV, 2D camera and magnet tool attached to the robots, read the details in section 5.2.1, 5.2.2 and 5.2.3. The assembly task is also done in the same way as in the fully automated concept, two robots with magnet tools attached to them, see 5.2.4. The difference is that a human worker conducts tack welding while the robots hold the plates in the right way.

The aligned and tack welded subassembly could be final welded by a robot directly or transported to a connected cell where final welding is done separately. Increased productivity could be achieved by a middle storage between tack welding and final welding. This because the first part of the process, until final welding, is more time-consuming than the automated final welding process and it demands human workforce. An automated final welding process can be done after office hours.

6 Results and discussion

This section includes a definition of three different robot cell systems and the current process, which will be compared. First, the effect on separate parameters of each concept is analysed and finally a summarised analysis is done. The compared concepts are defined below:

1. The current manual process, see layout Figure 2 and details in section 5.1.
   Equipment: Dedicated fixture, worker, three-axis positioner, welding machines and material, plates and output pallet.
2. Fully automated concept, see example Figure 3 and details in section 5.2.
   Equipment: One large handling robot, one assembly robot, one welding robot, 2D vision system, AGV and output pallet.
3. The hybrid manual concept, see example Figure 5. The human and robot does not share workspace and does thereby not interact directly. The human takes care of changing the fixture, assembly and tack welding while two robots thereafter take care of the final welding.
   Equipment: One large robot, one welding robot, one human worker, movable dedicated fixtures, turning table, AGV, manual picking racks and output pallet.
4. Human-robot collaboration concept. One robot holds the reference plate while another robot aligns plates to it. A human worker tack welds all the plates continuously and thereafter a third robot conduct final welding.
   Equipment: One large handling robot and one assembly robot with a safety system to allow human-robot interaction, one human worker, one welding robot, AGV and output pallet.

6.1 Productivity

The current manual assembly process, described in section 5.1, is only utilised during the work hours of the personnel. Additionally, the time to produce one subassembly is relatively high compared to automated solutions. The station is designed to have one person working there which limit the possible productivity. An expansion of the process to make it possible to assemble fourteen subassemblies in one station, with movable fixtures like mentioned before, could become a bottleneck for the whole process.

A fully automatic robot cell, on the other hand, can work the whole day and night without breaks. The time to produce one subassembly should be significantly lower than making the tasks manually. It is always expected to achieve high productivity in an automatic system compared to a manual system.

In a hybrid cell with separated workspace, compared to the current manual assembly the productivity could be increased. The time of manual final welding is excluded in the task and the time saved makes it possible to assemble more subassemblies in the cell. If the subassembly is assembled and tack welded in a system of human-robot interaction and stored before final welding, the productivity would increase compared to the current process. In both cases, the final welding could be handled in a separate automatic welding cell and could possibly be integrated with another welding process.

6.2 Space requirement

In section 5.1 the current process is described and it includes an estimation of the required space to produce all the subassemblies in the same way; seven stations with two subassemblies in each require roughly 112m^2. The current process could be reconfigured to manage more subassemblies in the same station with movable fixtures, which is described in section 5.3.2, and it would not require significantly more space. It will, however, affect the throughput time because the station is designed to have one worker there. The throughput will of course increase if the subassemblies produced in the station increase from two to fourteen and still one worker. Thereby, an increased throughput time.

The space requirement in a fully automated cell with a flexible fixture solution will always be relatively low. A hybrid process like suggested in section 0 or a human-robot collaboration like 5.4 would not require a lot of space either. Something that should be included in the space requirement in all concepts is the storage used to store metal plates waiting to be processed. The importance of the proposal to avoid cutting plates for storage needs to be stressed and one reason is the space requirement.

6.3 Product flexibility

Flexibility is a wide term and in this case, the aim is mainly to have high product flexibility. To produce different but similar products with the same system and equipment is the goal. The current process has no product flexibility, there are two dedicated fixtures in the station and they can only be used for the specific assembly that it is designed for. It is the only thing the station is used for. The other concepts have been designed especially with this parameter in mind. The effect is that all the ideas mentioned can more or less handle fourteen different subassemblies. The things that differ between the different products is the robot programming. One exception is the hybrid concept with separated workspace that is designed with movable fixtures, which makes it harder to introduce new products. The setup in this concept includes a change of robot program and change of fixture.

6.4 Setup time

The setup time is the time it takes to switch from one product to another. The setup time in the fully automatic concept, as well as the hybrid human-robot collaboration, is low, at least if it is assumed that a tool change is not required. The input and program change need to be controlled in some way to change between products. It is not a physical change, which means that it does not take a noticeable amount of time.

In the hybrid manual concept, except for a change of program as before, there need to be a physical change of movable dedicated fixtures attached to the turning table. This is expected to take a few minutes to do manually.

6.5 Investment and product cost

The investment of designing a robot cell with all including systems, like safety and sensor system can become high. During the planning phase, which is explained in section 4, possible issues are handled and a cost estimation of the investment is done. The cost of the investment itself should be compared with the expected savings of the planned change and the expected product cost. If all the preparatory work is done, the risk of making a bad investment is quite small.

The investment of a fully automatic robot cell, which is explained in section 5.2, is usually quite high. However, it does not include designing dedicated fixtures for every part, which is one large fixed cost. The product cost is also expected to be lower with a fully automated system. The cost of a robot cell does not depend too much on the robots themselves.

6.6 Summarised comparison

Table 1 below, shows an overview of the effect on the parameters, which are all described individually earlier in this chapter. The concepts are graded based on their effect on the parameters, compared with the other concepts. The positive effects in the table have the colour green and negative effect have red. The squares without colour should be viewed as something in the middle.

The table makes it obvious that the hybrid manual concept has its limitations. The required space is low at the expense of the possible productivity, which is low. New products or design changes of old products require new fixtures, which have a bad effect on the product flexibility. The setup time is high compared to the other concepts due to the mounting of fixtures to change the product to assemble. The investment could be kept low but the product cost will be negatively affected by the workload conducted by the human workforce. However, compared to the current manual process where a human worker does final welding manually, it is probably an improvement. It could also be viewed as a step toward automation, as suggested in chapter 4, where one task is automated at a time.

A concept with human-robot collaboration has, according to the table, a good influence on several parameters with no specific bad effects. The productivity will not be bad but not as good as a fully automated system. The concept is expected to affect the space requirement and setup time in a good way. A new product will demand special programming but no specially designed physical equipment, which results in good product flexibility. The investment is probably close to the fully automated system but the product cost will be higher because the human workforce is needed for the production. The fact that a human is needed will also result in lower productivity than the fully automated system. However, human involvement result in a visual overview and it is possible to integrate a manual quality check.

The fully automated concept has mostly good effects with the investment cost as an exception. The comparison, visualised in the table, reveals that the distinctive positive effects of the human-robot concept are shared with the fully automated concept. The fully automated concept has more distinctive positive effects and the investment, as mentioned before, is probably very close.

The conclusion is that the fully automated concept and the human-robot collaboration concept are comparable. Something to consider is if it is worth the expected losses to keep a human in the process. In this case, the tack welding is not something that is better done by the human workforce. Further, the automated assembly process itself is complex and it is probably not a big issue to automate the tack welding as well.

Table 1. Matrix to visualise the effect, on set parameters, of each concept. Green=positive effect, red=negative effect

Concept / Parameter	Fully automated	Hybrid manual	Human-robot collaboration
Productivity	high	low	
Space requirements	small	small	small
Product flexibility	high	low	high
Setup time	low	high	low
Investment	high	low	
Product cost	low	high	

7 Conclusions and future work

As an introduction to the subject, the change from traditional automation to flexible automation is presented which is caused by the changed demand from mass production to mass customization. This affects the needed requirements of production systems today. The process needs to be easy to configure and should have the ability to handle variants. The unit cost is a major driver when picking which system to use and flexible fixture solutions are one requirement to maintain low costs while producing low-volume high-variant products. The aims of the thesis work are defined in the following way:

- Research suitable automation levels to support a flexible production system
- Design alternative concepts to the traditional system with dedicated fixtures and build simulations in RobotStudio
- Compare concepts with appropriate key figures related to flexibility and automation level

A literature review together with an analysis of an assembly system, based on the process at VCE, led to the development of a list of structured actions to consider when planning a process change. The actions include mapping of the process, defining goals, investigation of automation level, holistic view while planning, definition of the need for flexibility, investment plan, designing and comparing concepts, investigation of possible issues and implementation in small scale.

The current process at VCE is presented and concepts are designed as alternatives to provide more product flexibility. The first concept is fully automated with one large robot to pick up and hold a reference plate with a magnet tool, one smaller robot to align plates and one robot with a welding tool. One AGV to deliver plates to the cell and a 2D vision system to ensure the right positioning. In the second concept, a human worker assembles the plates, delivered by AGV, in a movable fixture and conduct tack welding. Thereafter, one robot picks up the assembly and another robot conducts final welding. In the third concept, two robots handle the assembly and a human tack welds it. Final welding is done automatically separately in another cell. Two of the concepts are simulated in RobotStudio.

The concepts are analysed and compared, the effect on following parameters are discussed: productivity, product cost, investment, flexibility, space requirement and setup time. The conclusion is that a fully automated system will affect the parameters in a good way and the same for a human-robot collaboration like the third concept. In this case, it is recommended to continue the work with a fully automated concept due to better effects but also because there is no obvious advantage with manual tack welding.

The work done is done with qualitative data collected by experience, ideas and literature. Future work is needed to confirm the feasibility of the concepts. The ideas need to be confirmed with more tangible results through quantitative studies.

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