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The change towards Industry 4.0 in small & medium-sized enterprises

Digital and smart industrial transformation for Global Electronics B.V.

The change towards Industry 4.0 in small & medium-sized enterprises

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Management summary

For small companies, incorporating Industry 4.0 (I4.0) in the production facility can be more difficult compared to larger companies. The implementation of new technologies for small companies can be a challenge because of a lack of resources, the increasing technological advancements and the relatively high investment cost. Especially when a company is growing, it is hard to focus on automation projects. Global Electronics B.V. (GE) is a Small and Medium-sized Enterprise (SME) that assembles printed circuit board for the high-tech industry that is growing quickly and therefore it is desired to automate part of the production process to move into the direction of I4.0. However, especially at the manual department, it is important to first look at the opportunities of Industry 3.0 (I3.0).

To keep up with the growth, GE wants to know which shop floor processes can be improved and which techniques would be helpful. In this research we look at the desires of automating the shop floor of GE and have formulated the following research question.

'How is Global Electronics B.V. able to make a digital and smart industrial transformation to keep up with the fast changing manufacturing due to Industry 4.0?'

An extensive current situation is described to map out the shop floor and all the challenges and possible automation opportunities for GE towards I3.0. Based on this current situation, a simulation model is designed to search for the bottlenecks and thus for the processes GE needs to optimise. A simulation model is used to visualise the behaviour at the production floor. Because of a lack of data, the processing times are measured manually and a rough approximation is used as input for the simulation. The simulation has been validated by comparing the actual production volumes of GE and the volumes produced by the simulation. The validation is done for two periods, namely the production in September 2021 and in April 2022. The most important difference between these two periods is the amount of employees available. Using these two periods, it is concluded that the simulation model gave reliable and realistic outputs.

Another method used to find the bottleneck of GE are general observations. Currently, components and finished-products are stored in the hallways because of a lack of storage space. Multiple possibilities for the optimisation of the warehouse are available of which pallet racks the and Vertical Lift Module (VLM) were the most suitable for the current warehouse of GE. Incorporating these systems into the warehouse will increase the capacity from the a storage capacity of 285.66 m^2 to approximately 382.66 m^2.

With the simulation, the bottlenecks are identified based on three Key Performance Indicators (KPIs) which are the processing time, utilisation rate and stocks in between departments. Based on these three KPIs, the simulation showed the main bottleneck to be the manual assembly, followed by the testing procedure. Finally, the preparation of components needs relatively many employees for the required quantities. In Table 1 the processing times and utilisation rates form the simulation in April 2022 are shown. Both KPIs show that the manual assembly has the highest processing time and have a utilisation rate of hundred percent.

To improve the output of the manual assembly station, more employees are needed. Automated assembly machines (though-hole machines) are too expensive and infeasible.

Table 1: Summary bottleneck identification based on processing times and utilisation rates - April 2022

Process	**Processing time (sec)**	**Utilisation rate (%)**
CutPCBs	19.24	25.26
PrepComponents	10.95	100
MAexpert	355.76	100
MAbeginner	711.53	100
MAexpert1	355.76	100
MAbeginner1	711.53	100
Soldering	310.00	43.14
CutInspect	106.12	98.53
Test	132.38	99.99

Therefore, it is important to focus on the processes that can assist the manual assembly. Currently, four employees are needed for the preparation of components at the manual department. If this process is automated, only one employee is needed instead of four. The preparation of components is done in axial and radial direction, meaning that different machines are needed. Not only are these preparation machines faster, they are also more precise and improve the quality of work. The second bottleneck was determined to be the testing of the Printed Circuit Board Assemblies (PCBA). Because of the simplicity and the highly repetitive task of the testing, a common technique used in production facilities is the collaborative robot, also called cobot. The processing time of a cobot is assumed to be one third less than the current processing time and has an expected stand alone time of approximately thirty minutes, meaning that the cobot can work during the breaks and approximately half an hour after closing. Automating the testing procedure will save one employee which is then available for the manual assembly. If both processes can be automated, four employees can be assigned to the manual assembly stations to increase the output en decrease the bottleneck. The possible improvement options for the automated preparation and the automated testing including their cost are mentioned in Table 2 where the manual labour cost are the cost that can be saved yearly.

Table 2: Possible automation techniques and the cost and savings of automation

Feasible improvement	**Investment cost**	**Manual labour cost**
Axial processing	€ 52,000.00	€ 8,611.74
Radial processing	€ 11,500.00	€ 4,269.98
Cobot	€ 90,615.00	€ 19,779.78

After determining feasible improvements for GE, the simulation model has been adjusted in which the cobot and the preparation machines are incorporated. Six investment options have been set up to review multiple possibilities. First, both techniques are implemented in the simulation separately, after which the techniques are combined to look at the effect on the production flow. Using the preparation machines and the cobot, employees were available for other tasks which is in this case the manual assembly.

Because with the above investment options, it could be seen that the bottleneck shifted towards the testing, a sixth option is added. In this option, both processes are automated but the employee that was testing the PCBAs is supporting at the cutting and touching-up process instead of the manual assembly. In this investment option seven employees are assigned to the manual assembly, one to the preparation of components and two to the cutting/touching-up of the PCBAs. All six investment options are evaluated based on the same KPIs as mentioned before, which are the processing times, the utilisation rates and the stocks between processes. In Table 3, the results from the improvement options are shown in which I0 is the current situation. In I1 the preparation of components is automated and in I2 the cobot is included with one test machine where I3 uses two testing machines. I4 and I5 have included both, automated preparation of components and automated testing with one and two testing machines respectively. Finally, in I6 one employee is assigned to the cutting and touching-up instead of the manual assembly.

Table 3: Bottleneck improvements investment options 1 - 6
*note that in the first options the testing includes the action of the operator

Process	**I0**	**I1**	**I2**	**I3**	**I4**	**I5**	**I6**
CutPCBs	25.26	25.34	24.61	24.61	24.61	24.61	24.61
PrepComponents	100	100	100	100	100	100	100
MAexpert	100	99.99	95.39	95.39	92.35	92.35	95.36
MAbeginner	100	100	95.92	95.92	93.65	93.65	95.91
MAexpert1	100	100	95.68	95.68	93.99	93.99	95.68
MAbeginner1	100	100	95.67	95.67	94.02	94.02	95.66
Soldering	43.14	71.07	52.43	52.43	78.08	78.08	73.91
CutInspect	98.53	100	88.76	88.76	91.77	91.77	80.49
Cobot	-	-	19.75	19.89	20.38	20.50	31.04
Test1	99.99*	99.90*	0.87	7.20	0.90	7.35	1.37
Test2	-	-	-	6.97	-	7.14	-
Bottleneck	MA	Testing	MA	MA	Testing	Testing	SMD
Produced	28,932	28,932	37,108	37,592	38,340	38,772	58,336

Resulting from the simulation, it can be seen that in all options, the utilisation rates are above the target rate of ninety percent. However, the sixth investment option shows the most balanced rates and the highest amount produced. In the sixth investment option it can be seen that the bottleneck has shifted to the Surface-Mount Devices (SMD) department instead of the manual department and the finished products did increase from 28,932 to 58,336 which is a growth of 101.6 percent. It is therefore recommended to introduce the preparation machine and the cobot assigning seven employees at the manual assembly and two at the cutting and touching-up of the PCBAs.

For future research it is recommended to incorporate more products to expand the simulation model. The simulation model can with some adjustments and expansion used to set up a planning tool for the production of GE. Finally, when making a decision about whether to invest in the warehousing systems, a more in depth research needs to be done to design the layout of the warehouse and allocate the products in the warehouse.

Acknowledgements

With this thesis, I finish my time as a student. I am proud of this achievement and I would never have missed my time here in Enschede. I learned much during my studies and have developed myself personally and professionally.

Without all the support at GE I could never finished this report as it is now. I especially want to thank my supervisorts at Global Electronics. Meino and Gerald, thanks for all the opportunities and for the support I got during this research.

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I am looking forward to implement my research at Global Electronics which gave me this great opportunity. I am convinced that they can teach me much more and I am looking forward to the upcoming year!

Sanne van Norel
August 2022

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1 Introduction

The introduction is divided into multiple sections. First, in Section 1.1 a brief description of Global Electronics B.V. is given. Second, I4.0 is introduced in Section 1.2 in which the importance of I4.0 in production facilities will be explained too. Next, the problem analysis is described in Section 1.3 and the motivation for this research with its research questions are mentioned in Section 1.4. Lastly, the research approach is set up in Section 1.5 which shows the structure of this report.

1.1 Global Electronics B.V.

GE is a fast-growing SME located in Haaksbergen, the Netherlands. In 1993, the company was founded and is specialised in Electronic Manufacturing Service (EMS), meaning that GE does not design the products itself, but only assembles the products for the end-customers that mostly operate within the high-tech market. GE produces PCBA for which the end-customer delivers the bill of material and the layout of these materials on the Printed Circuit Board (PCB) which is the basis of the PCBA. A make-to-order strategy is used by GE, meaning that they only buy the components needed for production when the customer has placed an order.

Besides PCBAs, GE also creates semi-finished and finished products that contain PCBAs. An example of such a product is the 'Homey'. This product is completely assembled and packed at GE. Because of these different products, GE is active in multiple market segments, including telecommunications, computer industry, high voltage engineering, laboratory industry, measurement and control engineering, chemical and petrochemical, defence and security and Internet of Things and medical industry.

Assembly of the PCBAs consists of two main processes, called surface mount and through-hole. For the assembly of components on the printed circuit boards, SMD are used, but also manual assembly fir the through-hole components is done. SMD machines are much more precise an a lot quicker than manual assembly. Unfortunately, there are still some components that need to be assembled by hand because of the complexity and the size of the components combined with the cost of the machines that can place these components. A more extensive description of the processes of GE will be discussed in Chapter 2.

1.2 Introduction to Industry 4.0

After the short introduction, there will be given an introduction to the industrial revolution which will give more insight in the development of I4.0. The industrial revolution already began in the 18th century. It all began with Industry 1.0 and during this revolution there was a big change in the volumes that could be produced. Production was mechanised with the use of water and steam power and it became possible to produce eight times more in the same amount of time. After Industry 1.0, the second revolution (Industry 1.0) began in the 19th century and during this period electricity and assembly lines were discovered. These changes increased both volume and variety and these results of Industry 2.0 are still widely used. Automation using information technology and computers made partial automated production possible and is part of Industry 3.0. Also, analogue changed to digital which made a big impact on the electronics industry. Currently, we are in I4.0 and already moving to Industry 5.0. However, for small companies such as GE, it is still a challenge to adapt I4.0 in their production facilities.

Prause and Weigand (2016) defined I4.0 as *"The combination of cyber physical systems with automated systems"*. I4.0 brought technological innovations such as IoT, electric vehicles, big data, cloud computing, 3D printing, Artificial Intelligence, and cyber physical systems to light (Yin et al., 2018). The different stages of the industrial revolution are summarised in Figure 1.1.

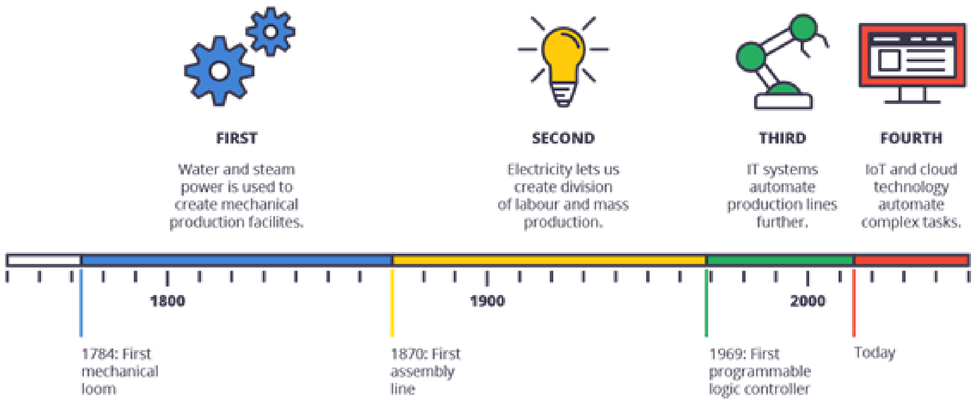


Figure 1.1: Stages of the industrial revolution

A competitive advantage of I4.0 is the possibility to realise individual requirements for different customers (Yin et al., 2018). For GE this is especially useful because of the customer specific PCBAs. Beside the competitive advantage, it is also cost-effective and time-efficient which can be translated in economic and operational benefits (Sony and Naik, 2019). The time to market can decrease and lead times will be reduced. Also last minute changes can be handled better resulting in less inventory. Another advantage of I4.0 is the quality of the products. Smart products will results in less faults, less scrap and a more reliable production (Meyer et al., 2011).

Beside the economic and operational benefits, I4.0 also results in socio-environmental benefits. The emissions of greenhouse gases will decrease because of the traceability of the carbon footprints (Kiel et al., 2020). I4.0 improves the resource efficiency and reduces waste and increases energy efficiency. Last but not least, the industrialisation will increase the quality of work. Robots will take over actions that are difficult to execute or actions that are simple and repetitive (Kagermann, 2015).

I4.0 also has its challenges. The implementation of I4.0 is a very complex and challenging process. First of all it needs acceptance by the employees which can be difficult because of the myth that jobs will disappear. Therefore, human factors are extremely important. However, the industrialisation has a big impact on the entire situation and will change the infrastructure, technologies, culture, processes and goals of the organisation. The implementation is a challenge due to among others finances, restructuring, and coordination (Sony and Naik, 2019).

1.3 Problem analysis

Besides the growth of GE and the challenges of I4.0, the growth in demand of semiconductors (shown in Figure 1.2) and the trigger of Covid-19, companies as GE struggle with their supply chain. There is a huge lack of components in the electronics industry already predicted in 1965. In 1965 Gordon Moore observed that the chip technology is becoming advanced in such a way that every year twice as many transistors fit onto a chip. On the other side it was expected that the size of the chips will become smaller. In 1975, he adjusted the observation to doubling to every two years and it appeared that he was right, The chip industry kept Moore's prediction alive (Eeckhout, 2017).

Figure 1.2: Growth of semiconductor market 2001-2022 (Gooding, 2022)

In the present day, Moore's law is flattening, but the complexity of the PCBAs is still growing. Beside the complexity, the PCBA market is growing too and with it is GE. The technologies for production become more complex, but also the complexity of the PCBA increases. I4.0 is becoming more and more important in the present day to be able to keep up with the growing market. To be able to compete within the PCBA market, it is important that their industrial management processes will be improved. Unfortunately, it is a big challenge for an SME company such as GE to introduce I4.0. This because of a lack of expertise and leadership, but also the big organisational changes the company has to make combined with the cost of these changes. Furthermore, it is difficult to start with the industrialisation and to know where to begin the process.

Currently, GE does not have the insights in the changes they have to make to be able to become a pioneer in their market. It is important to bring the shop floor processes to light as this information results in more insight in the processes and work flows of GE. This research will therefore mainly focus on the production processes. Figure 1.3 shows the problem cluster of GE and provides the core problems that need to be addressed.

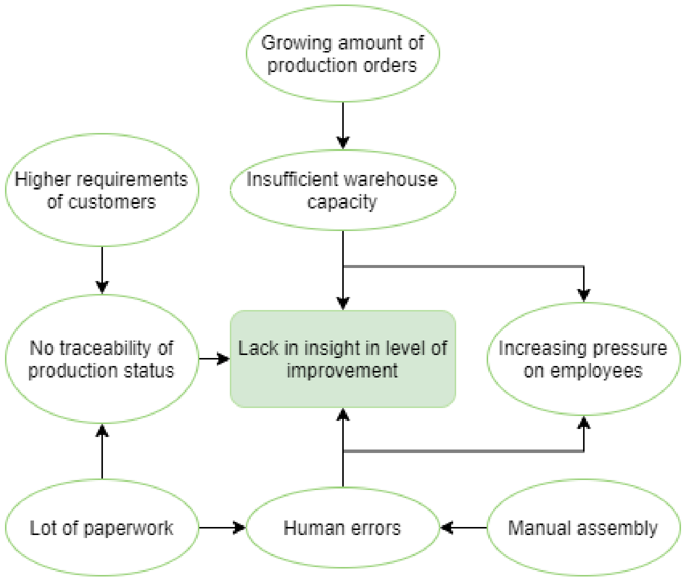


Figure 1.3: Problem cluster

1.4 Motivation and research question

After setting up the problem cluster, it is now possible to determine the motivation and the research questions of this thesis. The core problem of this research does focus on the shop floor processes. Currently, there is no insight in the exact shop floor processes and they are behind with the industrialisation of the production process. Therefore, the main research question resulting from the problem description is as follows:

'How is Global Electronics B.V. able to make a digital and smart industrial transformation to keep up with the fast changing manufacturing due to Industry 4.0?'

The main research question consists of multiple sections that are solved individually. By dividing the main research question into multiple sub-questions, the main question is answered at the end of this research. The sub-questions which are all answered in a different chapter are as follows:

Q1. *What is the current situation and what are the challenges on the shop floor of Global Electronics B.V. and how does that characterise the company?*

Q2. *What are the current technologies applicable to improve the shop floor of GE looking at Industry 4.0 and how can you determine the feasibility of these technologies?*

Q3. *What feasible improvements can be made by Global Electronics B.V.?*

Q4. *What are the possibilities to transform Global Electronics B.V. in a factory of the future and which are the most profitable?*

Q5. *What is the impact of the optimisation possibilities for the production flow at Global Electronics B.V.?*

Each question has been addressed in a separate chapter. Q1 is discussed by an extensive description of the current situation of the company in chapter 2. Q2 is handled in the literature review in chapter 3 after which Q3 is answered in chapter 4 where the opportunities for transformation towards I4.0 are discussed. Chapter 5 is dedicated to Q4 and discusses the optimisation possibilities after which the optimisation possibilities will be implemented in the simulation in Chapter 6 to see the impact of the changes.

1.5 Research design

After reading this thesis, the research question should be answered. To answer the research questions, sub-questions are drafted which each are handled in a different chapter. By the use of these sub-questions, the main question is answered and a conclusion is drawn.

In Chapter 2, an extensive situation of the shop floor of GE is described resulting in the as-is situation. Internal processes are mentioned and the characteristics and challenges of GE are mapped. To map out the important focus points of GE, a value stream map is made and a SWOT-analysis is done to find out the weaknesses and opportunities for improvement.

In Chapter 3, a literature review is done in which with a focus on improvement possibilities in the field of I4.0. During the literature review, it is especially focussed on SMEs. This resulted in points of attention that need to kept in mind when implementing new technologies.

After the analysis of GE its current situation and the literature review, the bottlenecks are determined using a simulation of the production process. The production process is visualised in 'Plant Simulation' to be able to show GE where improvements can be made. After determining the bottlenecks, the opportunities for automation are discussed.

After determining the processes that are interesting to improve, we will look at different options with which we improve the production process. Different investment options are examined to be able to choose the best option to implement.

Finally, in Chapter 6 the optimisation options from Chapter 5 are implemented in the simulation of Chapter 4. Technologies discussed in Chapter 5 are used as input for the simulation which show the influence of new technologies on the production flow. Based on these results, the most valuable plan of improvement is determined for GE.

2 Extensive analysis of the current situation

In this chapter, a detailed current situation of GE is mapped. This extensive current situation is described to 1) understand the processes going on at the shop floor and 2) to search for the problems at stake. At the end of this chapter, the following research question is answered.

'What is the current situation and what are the challenges of Global Electronics B.V. on the shop floor and how does that characterise the company?'

To be able to answer this research question, first the business process is explained in Section 2.1. Second, in Section 2.2 the shop floor process is discussed. Next, we zoom in at the production process in Section 2.3 after which the characteristics and challenges of GE are determined to retrieve an overview of possible opportunities for GE. In Section 2.5, a value stream map is made to introduce the challenging processes based on processing times after which a SWOT analysis is done in Section 2.6 which is built to map the internal and external challenges and opportunities.

2.1 Business process

From the arrival of an order till the shipment of the order, a standard process is followed. GE uses a make-to-order production system, which means that the process starts running after the customer places the order. In Figure 2.1 a comprehensive view of the business process is given. The different colours in the figure show which party is responsible for which step. The business process is divided into different departments, namely the customers, the sales and procurement department which is the office, the supplier and the shop floor including the warehouse, the production and the test & repair department. Currently, GE does not plan production based on promised delivery dates to the customer but on the arrival of the last component. However, the order confirmation should be done based on promised lead times which should be the trigger for the production process. Unfortunately, the electronics market has a huge shortage of components which makes it hard to plan production. The estimated delivery date changes from day to day and therefore the production plan is modified almost daily. This research however, will focus on the automation of the production process and therefore we do not look at the production planning.

If an order is placed, the sales department is accountable for the confirmation of the order to the customer. The order confirmation is done in dialogue with the work preparation department and the purchasing department. The work preparation department inserts the Bill Of Material (BOM) in Exact, the Enterprise Resource Planning (ERP) system of GE. The BOM generates demand of the different components. When the BOM is inserted in Exact, the order can be confirmed to the customer and the components can be purchased.

When all components for an order are delivered in the warehouse, the order can be produced. The order will be released in the warehouse and the components will be picked by operators in the warehouse. When the order is released, the production planner will plan the production based on the delivery date and production capacity. During production, different steps are followed which will be further explained in the

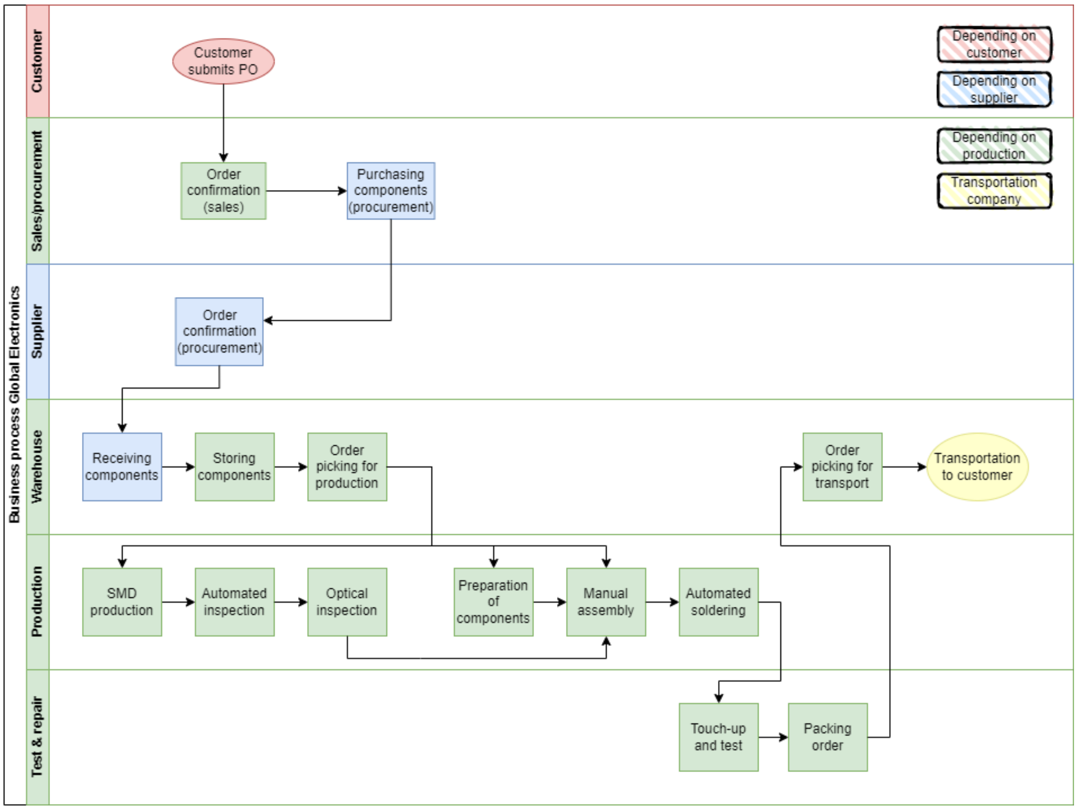


Figure 2.1: Business process model

next paragraph about the shop floor process. After production, each PCBA will be inspected optically and if needed repaired. The last production step is the test and repair. However, the test and repair is only executed if the customer specifically asks for it. Finally, the PCBAs can be packed and are ready for shipment.

2.2 Shop floor process

The shop floor is the area in which the production takes place. The shop floor is known as the area in a manufacturing facility where the assembly or production is carried out. The shop floor is responsible for the semi-finished products and the end-products. In Figure 2.2, a global overview of the processes is shown. The blue colour shows that the retrieval of components is depending on the supplier and the green colour means that GE itself is responsible.

The shop floor process from the beginning till the end is described as the moment the components arrive in the warehouse until the shipment of the products. The shop floor process is semi-fixed and proceeds as follows:

Pick-up/delivery -> Warehouse -> SMD -> AOI -> Manual assembly -> Soldering -> Warehouse -> Pick-up/delivery

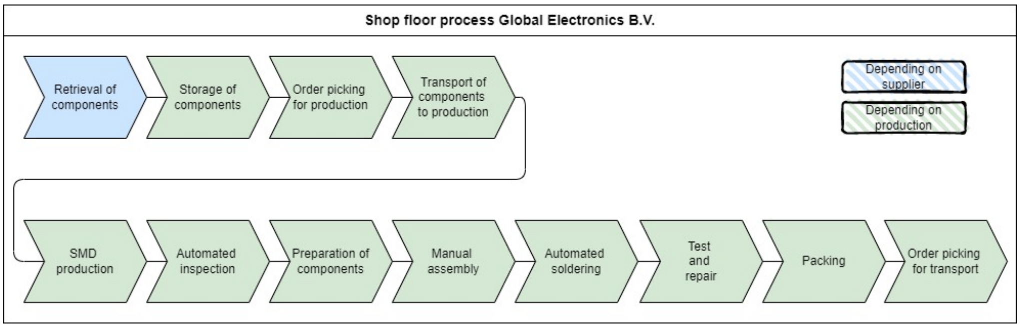


Figure 2.2: Flow of the shop floor process

Components always follow the same route through the facility. However, sometimes steps can be skipped because they are not needed for a specific PCBA. For example, it can occur that a PCBA only consists of SMD components and therefore skips the manual assembly. Figure 2.3 shows the shop floor of GE.

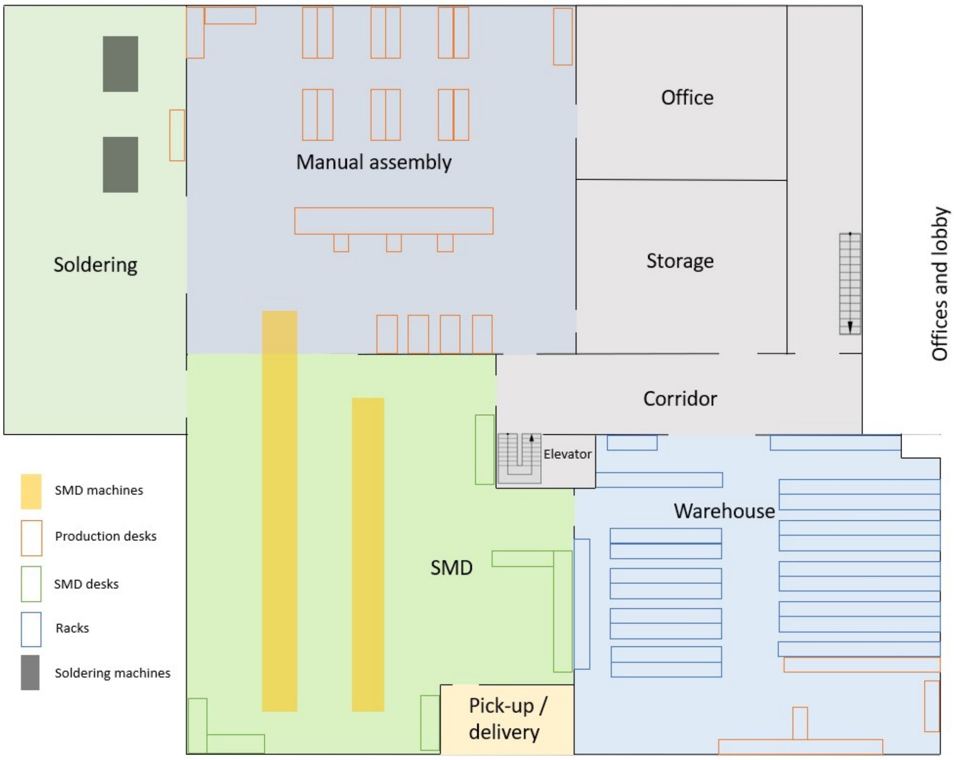


Figure 2.3: Shop floor of Global Electronics

If the components are delivered, they will be stored in the warehouse. If all components of an order arrived, the order can be released, picked and send to one of the departments.

The SMD-line uses components on reels. The manual assembly department retrieves the components in tubes, on tape or in bulk. At the manual assembly department, there are two types of components. Most components can be placed on the PCBA without any adjustments. However, some components need preparation before they can be placed on the PCBA. An example of preparation is the shortening or bending of the pins.

The production process always starts at the SMD department. When production at the SMD department is finished, the process continues with the manual assembly. Some finished products must be tested depending on the requirement of the customer. Finally, the products will be packed and stored in the warehouse until delivery.

Besides the components used for production, there are also secondary products needed during production and after production. The secondary products contain products as totes, protective materials and pasta for soldering. These secondary products are not incorporated in the figure, but occur at the same time as purchasing the components. Secondary products are bought in high volumes and are used during the production of all PCBAs.

2.3 Production processes

The production process of GE consists of SMD assembly, manual assembly, and different types of soldering. The production of PCBAs is done by automated machines, manually or with a combination of both. The process will be further elaborated below to give more insight in how the different machines and employees work.

GE uses two automated SMD-lines. An SMD-line mounts the components directly onto the surface of the PCB and is able to assemble components that are too complex or too small to assemble manually. The PCB goes through different stages within the line. First, the pasta that fixes the components on the PCB is applied. Next, the small components are located on the PCB after which the bigger components will be placed with three pick and place machines. When these components are placed, an Optical Inspection (OI) is done to check if the components are placed correctly. This is especially important during the first few PCBs because of the settings of the machines. Occurring mistakes will be repaired and production will continue. The PCBs go into the oven to harden the pasta. After the oven, the PCBs go through an Automated Optical Inspection (AOI). Abnormalities will result in a notification which they will check and correct if needed. The SMD machines produce approximately 5.000 PCBs each week.

Another important department is the manual assembly where the through hole components are assembled on the PCBs. The components are fixed by different methods depending on the components already assembled by the SMD-line. The components are fixed with the selective soldering machine, the wave soldering machine or occasionally by hand. Selective soldering mounts predetermined components on the PCBs and wave soldering uses a tin bath to fix the components at once. Selective soldering is used when there are already components fixed onto the PCB that can detach from the PCB if the wave soldering is used. Wave soldering uses a tin bath and is able to mount all components at once. It is also possible to solder components by hand. This is mostly done when one or two components need to be repaired.

2.4 Characteristics and challenges of Global Electronics

This paragraph will discuss the characteristics and challenges resulting from reviewing the business processes, the shop floor processes and the production process. One of the characteristics of GE is that they use a make-to-order shop floor strategy. GE does not use safety stocks but components are purchased after the customer places the order. Unfortunately, the lead times are currently extremely long and therefore it is a challenge to deliver on time. Besides, the demand for PCBAs keeps growing resulting in shortages of raw materials on top of the shortages occurring because of the long lead times.

GE is growing strongly with more customers, but also with higher volumes. This results in an increasing amount of components that are needed for production. As mentioned above, suppliers cannot always deliver on time resulting that there are components that need to be stored for a relatively long time, while other components are immediately send to production after delivery. Currently, this results in a lack of storage space. Looking ahead, this shortage will become bigger each year especially when order volumes keep increasing.

One of the characteristic of GE is the high precision currently delivered to their customers. However, a lot of manual assembly is required during production. Besides the amount of time the manual assembly requires, it is also sensitive to human errors. GE works in shifts of eight hours five days a week in which sometimes the same job needs to be repeated.

The final challenge is traceability. Currently, GE does not gather data during the production process. Therefore, there is little insight in the amount of PCBAs already produced. Besides, sometimes is important to track the components used during production. The importance of traceability will only increase. With the current system it is very time consuming and complicated to incorporate traceability on a high level. Therefore traceability is only used when it is a hard requirement of the customer.

2.5 Value stream map

In this paragraph, a value stream map is created. A value stream map gives an overview of how a product flows through the process. The value stream map contains all processes, including those that do not add value to the product. The value stream map will be used to get an idea about where in the process the bottleneck is located. The bottleneck will give insight in which challenge is the most attractive one to tackle. The focus of the value stream is from the moment that the production order arrives up to the point production is finished and the product is stored in the warehouse again. In Figure 2.4, the value stream map of GE is shown with the minimum time required, the maximum time required with which the average time required can be calculated.

When looking at the value stream map, it is shown that the processing time within the warehouse is the highest because of the long lead times. However, this problem is due to an external factor and is therefore beyond the scope of this study. GE start with the production of the PCBAs when all components arrived at the warehouse. A rather interesting challenge for this research resulting from the long lead times, is the available storage space. The storage space available is already becoming too small because of the growth of GE and this problem will become only bigger within a short time frame. Another noteworthy step in Figure 2.4 is the manual assembly. When looking at the production process, it is shown that the processing time of the manual assembly is the highest. The manual assembly consists of three phases, namely preparation, manual assembly and post processing.

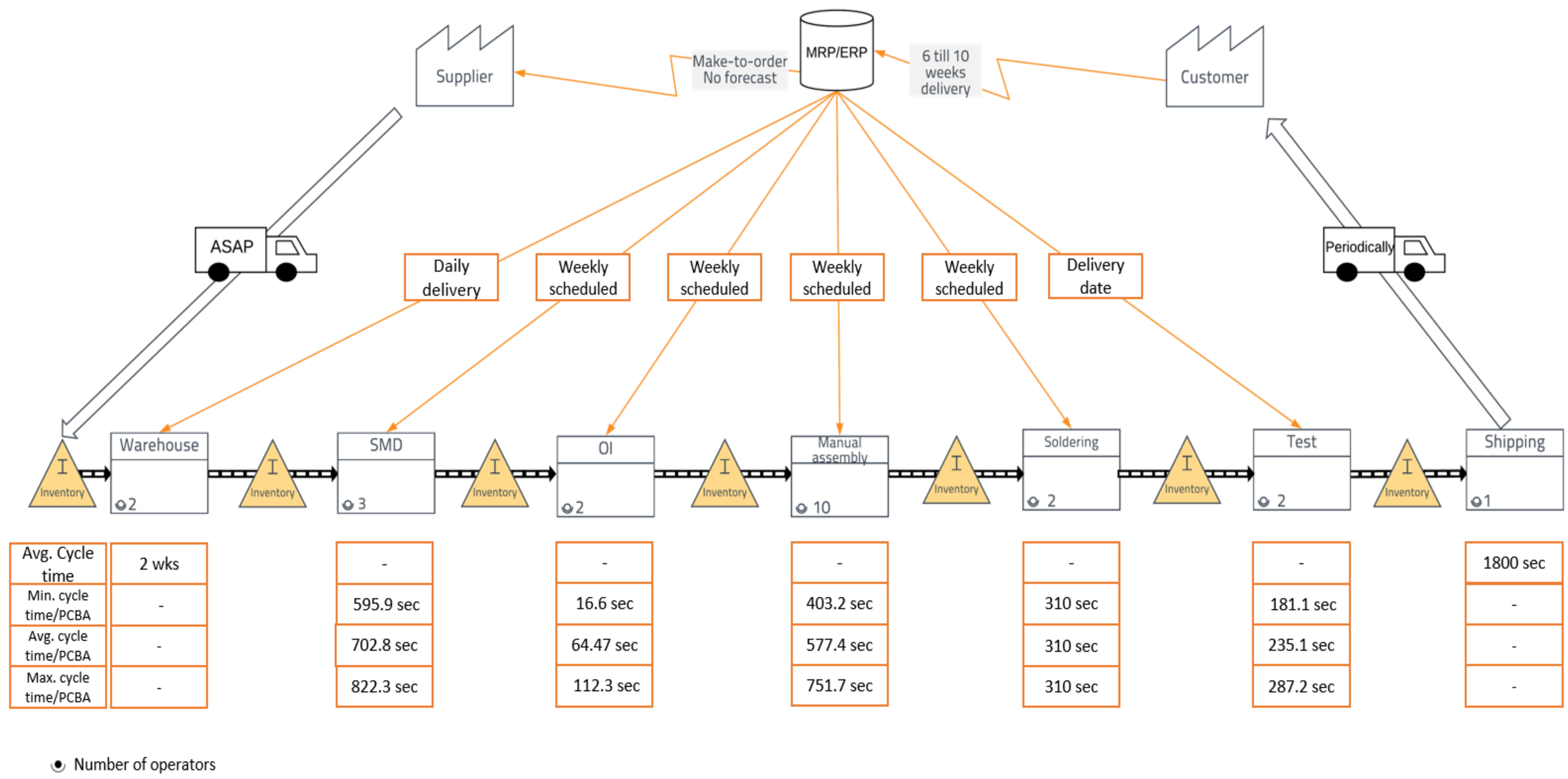


Figure 2.4: Value stream map Global Electronics

2.6 SWOT analysis

Another method to determine the focus points of the company is the SWOT analysis. The SWOT analysis is an approach that considers the internal Strengths and Weaknesses and the external Opportunities and Threats of a company. Strengths and opportunities are the enhancers of the desired performers while weaknesses and threats block the desired performance (Leigh, 2009). First, an internal analysis is done to determine the strengths and weaknesses of GE, using Abell's framework which will be further elaborated in the next subsection. Next, the external opportunities and threats are identified using the PESTLE analysis which will be further elaborated in Subsection 2.6.2. Based on Abell's framework and the PESTLE analysis, the strengths, weaknesses, opportunities and threats of GE can be determined which can be seen Table 2.1.

Table 2.1: SWOT analysis based on the Abell's framework and PESTLE analysis

Strengths	**Weaknesses**
- Customer satisfaction	- Use of technologies
- Quality of the products	- Short-term focus
Opportunities	**Threats**
- Automation of warehouse	- Conjunctive environment
- Automation of production	- Shortages of components

It can be concluded from the SWOT-analysis, the opportunities for GE are in the field of automation. GE wants to incorporate I4.0 within the production facility. However, currently GE did not yet implement I3.0 when looking at the shop floor. Most processes are still done manually, so it is important to first change into the direction of I3.0 instead of changing directly to I4.0.

On the other hand, there are weaknesses and threats such as limited budgets and the high cost of new technologies which are typical subjects for an SME company. Automation and digitalisation could seem very far away for SMEs. SMEs are sensitive for conjunctive environments and big expenses can be tricky. Finally, GE has a short-term focus and problems that can occur in the future will be discussed but will not be a focus point until necessary.

2.6.1 Abell's framework

The internal strengths and weaknesses of the SWOT-analysis can be determined using Abell's framework. This model is used to analyse the scope of a business. The analysis of the current business activities can help defining a strategy for the future that will help the company stay attuned to the changes that may occur in the fast changing market. Abell's framework defines three dimensions to determine the current scope which are the customer groups, the customer needs and the technologies applicable for the business. The most important topic is closest to the intersection of the axis and is the most important to focus on (Abell, 2006). In Figure 2.5 the Abell matrix is shown. The green cube shows the topics GE already incorporated while the topics outside the cube are targets for the future.

Looking at the Abell matrix, it stands out that there is not really a market segment

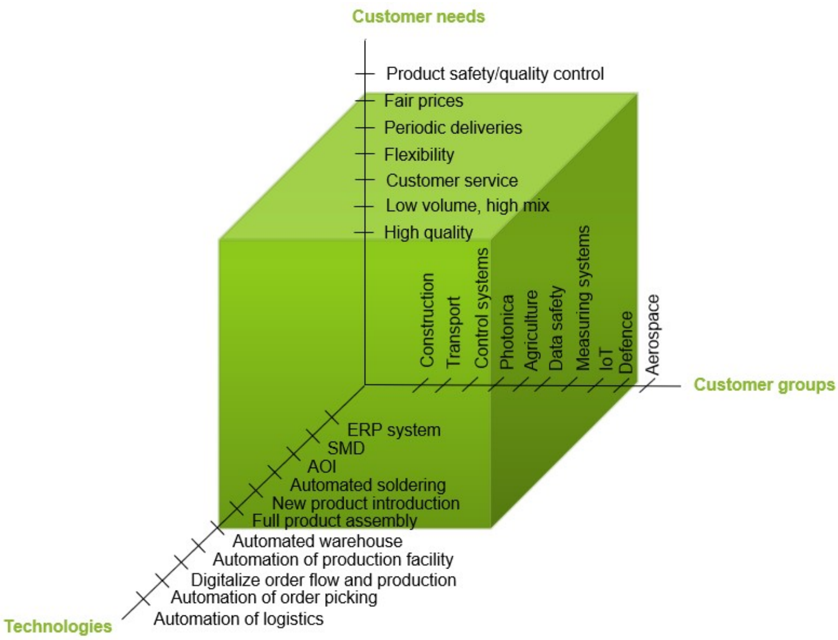


Figure 2.5: Abell matrix of the internal environment

that GE does not fulfil or that they want to enter. GE produces PCBAs for companies in the high-tech industry and therefore they do not focus on a specific customer group. When looking at the customer needs, it is shown that GE scores well on this dimension. The customers are satisfied with the quality, service, price and flexibility GE offers. One big improvement GE can focus on is the product safety/quality control that cannot be fully guaranteed currently. It can be seen that the biggest improvements for GE are the technologies. Looking at Figure 2.5, most topics outside the cubic are on the technologies axis.

It can be concluded that GEs weakness is the use of technologies and their strengths the customer satisfaction. As already mentioned before, it is difficult for SMEs as GE to decide where to start with the implementation of new technologies. It is expected that the technologies close to the green square are the most valuable technologies to implement and the ones furthest away may be interesting for the future.

2.6.2 PEST analysis

In this section, the PEST analysis is explained. The PEST analysis is used to get insights in the external environment of GE (Perera, 2017). The analysis can be used if a company wants to launch for example a new project or service. The letters PEST stand for Political, Economic, Socio-cultural and Technological. When executing a PEST analysis, it is important to brainstorm for ideas with different areas of the business. Opinions from outside the organisation are important as well. This could be from customers, suppliers or consultants that know the business well. All notes need to be combined and evaluated. In the final stage, the ideas need to be refined and repeated until you have a manageable number of points in each of the categories (Oxford, 2016). In Figure 2.6, the results of the PEST analysis can be found. Below, the different subjects of the PEST analysis are shortly elaborated.

Political factors
The political environment is based on political changes and actions or support of the government.

The sector in which GE operates does not have to deal with special rules but they have to take into account the general laws and regulations in the Netherlands. An example is the safety within the production facility or mandatory taxes. Another example is the minimum wage of employees. Besides these two examples, there are many more laws and regulations that companies must comply with.

Economical factors
Economical factors are important for the success of a business. Economical factors can be age- or income related but is also dependent on the employment and unemployment rates. Most important for a business are the customers because they are accountable for the profit of an organisation.

Economical factors that play an important role for EMS companies at the moment is the COVID pandemic. The economy is recovering of the pandemic worldwide. Many businesses closed their doors and therefore it is hard for the suppliers to deliver on time. Shortages occur everywhere and the expectation is that it is not yet recovered in the next couple of years. Another economic factor is the economic growth in the electronics market. The chip business is growing which results in even more shortages. Finally, the business is conjecture sensitive, meaning that the companies success is strongly dependent on fluctuations in the business cycle.

Socio-cultural environment
Ethical values, perceptions, and attitudes towards the business and the industry within the operating market should be considered under the socio-cultural environment.

Currently, businesses are noticing that there is a transformation in the availability of skilled people. Where previously more practically educated people were available, there are now more theoretically educated people available. This makes it hard to find suitable staff especially in a highly practical environment.

Technological environment
For a technology-based industry, the technological environment is highly relevant. In every business the technology is exponentially growing as mentioned earlier in section 1.3. The exponential growth of technologies makes it a highly dynamic market. The use of the internet is integrated everywhere and the use of technologies is growing in its complexity. Technical upgrades and infrastructure, technical competency and the productivity of technology are important factors that should be taken into account.

The amount of technologies and the importance of technology within companies is growing and a new wave of technologies is emerging. The use of robotics or automated production currently is a big trend.

Because of the automation and digitalisation, companies become dependent on the security of information. Most information is digitalised or production lines are automated and therefore security is needed for the safety of the company and the customers.

From the PEST analysis, we can conclude that the greatest opportunities are the ad-

Figure 2.6: PEST analysis of the external environment

option of new technologies and the automation of processes. The threats however are the uncertainty of the market. Careful consideration will have to be given to the implementation of new technologies.

2.7 Conclusion

In this chapter, we discussed the different processes at GE. GE uses a make-to-order production system and is currently not able to use a production planning beforehand. Production starts when all materials are delivered. Once production starts, a fixed production flow is used:

Pick-up/delivery -> Warehouse -> SMD -> AOI -> Preparation of components/Manual assembly -> Soldering -> Warehouse -> Pick-up/delivery

For the SMD-line, the preparation of components and the manual assembly, different components are needed which are sorted in the warehouse and when needed, picked and then send to the different departments for production.

The challenges of the production process of GE already starts with the incoming deliveries and the storage of these deliveries. Because of the growing market and the long lead times because of shortages, components are purchased far in advance to be able to start production in time. This results in bigger stocks and require more space than currently available.

Another challenge is the manual assembly of the PCBAs. With the increasing volumes, manual assembly gets more sensitive to human errors. It can also be seen in the value stream map in Figure 2.4 that the manual assembly is the process that has the longest processing time of the production process.

Using Abell's Framework and the PEST analysis, the SWOT-analysis is set up. It is determined that the biggest opportunities and threats are at the automation of the production facility combined with the cost involved. SMEs do not quickly invest in advanced technologies and therefore can give GE a lead if they choose to adopt technologies in their production process. In addition, automated production processes will help to keep up with the increasing volumes and the upcoming importance of traceability.

3 Literature review

This chapter discusses literature that is related to this research topic. After reading this chapter, the following research question will be answered:

'What are the current technologies applicable to improve the shop floor of GE looking at Industry 4.0 and how can you determine the feasibility of these technologies?'

We will first explain the challenges of a smart factory in Section 3.1 in which we will focus on industrial robotics and automated storage systems. In Section 3.1.2, multiple warehousing systems are explained. Section 3.2 discusses three different methods to determine the value of an investment. To discover the processes that need to be optimised, the bottlenecks will be analysed using bottleneck identification methods which are mentioned in Section 3.3. Finally, we will shortly discuss the sensitivity analysis in Section 3.4 followed by the conclusion that summarises the discussed topics.

3.1 A smart factory

Radziwon et al. (2014) defines a smart factory as *"a manufacturing solution that provides such flexible and adaptive production processes that will solve problems arising from a production facility with dynamic and rapidly changing boundary conditions in a world of increasing complexity."*

This could be related to automation, but also to collaboration. Automation can be seen as the combination of software with mechanics and hardware. With automation, manufacturing can be optimised and waste of resources can be minimised. Physically and mental demanding tasks can be taken over by for example robots. It can also be seen in a perspective of collaboration between industrial and non-industrial partners, where the smartness comes from the formation of a dynamic organisation (Radziwon et al., 2014).

An important misconception is that robots would simply replace tasks previously performed by people. However, the surrounding environment needs to be adjusted to accommodate the robot and new protocols may be necessary and staff needs to be trained. Robots are increasingly available, affordable, intelligent and appealing and cloud computing and internet connectivity are indispensable nowadays. Because of misconceptions, operators are tended not to use technologies. Good designs are needed not to slow down the processes by robots (Erasmus, 2019).

There are future scenarios proposed where humans and robots work in harmony to perform irregular and complex tasks. Where it was used to be unthinkable, SMEs also consider user-friendly automation within their company. An example is that the first time, a robot needs to be programmed and installed by an expert, but thereafter personnel itself can programme new activities (Erasmus, 2019).

3.1.1 Industrial robotics

According to ISO8373:1994 (1994) an industrial robot can be defined as *"an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or* *more axes, which may be either fixed in place or mobile for use in industrial automation applications."*

A mechanical arm is the most common industrial robot. An illustration can be found in Figure 3.1. Such an arm has characteristics that are anthropomorphic. Other human-like characteristics are decision making, communication with other machines and the response to inputs. These competences allow robots to execute certain industrial tasks (Groover, 2007).

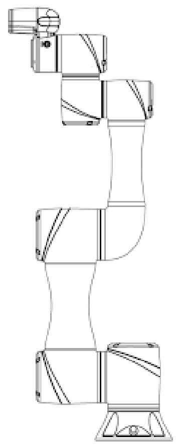


Figure 3.1: A visual example of an industrial robot arm

Typical qualities that make industrial robots interesting to incorporate in the production processes are the following:

- Robots can take over heavy and uncomfortable tasks.
- Robots can perform tasks with high consistency and repeatability.
- Robots can be reprogrammed when another task needs to be executed.

A mechanical arm can grab different objects by the use of different grippers. A few examples of different grippers are the following:

- Mechanical gripper: two fingers that can open and close to the work part.
- Vacuum gripper: suction cups can grab flat surfaces.
- Magnetised devices: can hold ferrous parts.
- Adhesive devices: to hold flexible materials such as fabric.
- Simple mechanical devices: hooks and scoops.

The most common gripper is the mechanical gripper that can easily grap parts and move them from one point to another.

Robots can be used for many application within the industry. Mostly they are used within manufacturing and can usually be classified as 1) assembly and inspection, 2) material handling and 3) processing operations. Material handling applications are tasks that move part from a specific starting point until a pre-determined end point. Processing operations performs tasks such as spray painting or laser cutting (Groover, 2007).

If you have determined for which process you want to use the robot, which gripper you want to and/or can use. It is of course also important to calculate if the robot can be economically justified. In Section 3.2 we will focus on how to determine if an investment can be economically justified. Finally, it is important to program the robot such that it is immediately ready to use. According to Groover (2007), a robot program can be defined as *"a path in space to be followed by the manipulator, combined with peripheral actions that support the work cycle."*

3.1.2 Warehousing

Material storage systems are used to store materials for a certain period of time and permit access to the materials when required for for example production. Storage can be done manually or automated. Manual storage of materials is often inefficient in terms of floor space, control of materials, and human resources. The efficiency of storage can be improved by automated methods currently available (Groover, 2007).

In a production factory, different types of materials are stored. Table 3.1 shows an overview of the different types of materials typically stored in a production factory.

Table 3.1: Different types of materials stored in a production factory

Type	Description
1. Raw materials	Raw stock to be processed
2. Purchased parts	Parts from vendors to be processed or assembled
3. Work-in-progress	Partially completed parts between processing operations and parts awaiting assembly
4. Finished products	Completed product ready for shipment
5. Rework and scrap	Parts that do not meet specifications, either to be reworked or scrapped
6. Refuse	Chips, swarf, oils, other waste products left over after processing; these materials must be disposed of, sometimes using special precautions
7. Tooling and supplies	Cutting tools, jigs, fixtures, molds, dies, welding wire, and other tools used in production; supplies such as helmets and gloves
8. Spare parts	Parts needed for maintenance and repair of factory equipment
9. Office supplies	Paper, paper forms, writing instruments, and other items used in support of plant office
10. Plant records	Records on product, production, equipment, personnel, etc.

Storage systems
If you want to implement an automated storage system, it is important to keep in mind multiple decision variables. When looking at storage systems, it is important to design the system as efficient as possible in fulfilling its function. Therefore, the storage system performance and storage location strategies will be further elaborated.

The storage system performance is an important factor if a new storage system is designed. The performance of a system must be sufficient to justify the investment and the operating expense. The performance of a system can be determined by various measures such as the 1) storage capacity, 2) storage density, 3) accessibility, 4) throughput, 5) reliability, and 6) utilisation (Groover, 2007).

Beside the performance, it is also important to think about the storage location of a Stock Keeping Unit (SKU). Most common the two strategies 1) randomised storage and 2) dedicated storage. These strategies influence the performance discussed above. When we look at randomised storage, SKUs are stored on an empty spot randomly allocated. Mostly, this is the closest open spot available. Dedicated storage means that each SKU has a fixed location and therefore the incoming goods are stored on a fixed position. Hereby, SKUs can be stored based on part number or based on activity level. Randomised storage generally required less storage space than dedicated storage allocation (Groover, 2007).

Storage methods and equipment
A company can have a lot of different materials that need to be stored. Therefore, a variety of storage methods and equipment is available. The choice for the storage methods and equipment depends on the different materials that need storage. Different types of storage systems and its advantages and disadvantages are shown in Table 3.2.

Table 3.2: Characteristics of the types of storage equipment and methods

Storage equipment	**Advantages/disadvantages**	**Typical applications**
Bulk storage	- Highest density is possible - Low accessibility - Low cost per square foot	Storage of low turnover, large stock, or large unit loads
Rack systems	- Low cost - Good storage density - Good accessibility	Palletized loads in warehouses
Shelves and bins	Some stock items not clearly visible	Storage of individual items on shelves and commodity items in bins
Drawer storage	- Contents of drawer easily visible - Good accessibility - Relatively high cost	- Small tools - Small stock items - Repair parts
Automated storage systems	- High throughput rates - Facilitates use of computerized inventory control system - Highest cost equipment - Facilitates integration with automated material handling systems	- Work-in-process storage - Final product warehousing and distribution center - Order picking - Kitting of parts for electronic assembly

Multiple storage systems exist suitable to improve the warehouse such that it can be used more efficient. For this research we will explain more about the operation of rack systems, shelves and bins and the automated storage systems. With rack systems, unit loads can be stacked vertically without the need for the load themselves to provide support. One of the most common rack systems are the pallet racks. An example of a pallet rack can be seen in Figure 3.2.

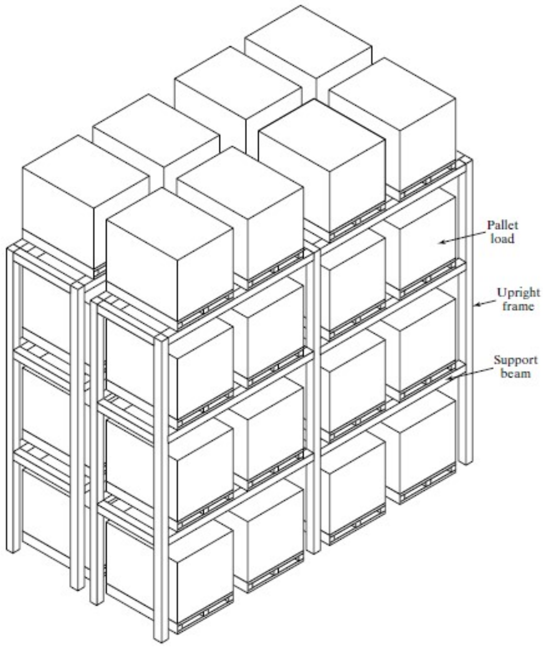


Figure 3.2: Pallet rack system for vertical storage (Groover, 2007)

The most common storage system is the shelving and bins. A horizontal platform within a rack is called a shelve. On the shelves products can be stored in different (smaller) packages. A typical size of the shelves is around 90x60 cm.

Pallet racks and shelves are static storage systems and the operator walks to the pick location to retrieve or store components. Storage equipment where the operator has to do the storage and picking himself is called operator-to-stock). If you have automated storage systems, the operator stands at one point while the components are brought to the operator automatically. There exist a variety of automated storage systems. The most interesting systems are the Vertical Carousel (VC) and the VLM (Tompkins et al., 2010).

A VC is a mechanical device that rotates the items. In a VC, only one row is visible. When a VC is higher, it takes also more time to retrieve the required items (Tompkins et al., 2010). An example of the VC is shown in Figure 3.3a. The VLM is a storage system that uses plateaus on which items are stored. Plateaus are stored on two sides of the system and in the middle, the plateau can move up and down. For an example see Figure 3.3b.

3.2 Investment evaluation

If a company is planning to integrate new technologies within their facility, an important decision factor is the payback period. The payback period can be determined by the use of the payback method. The payback method is used to indicate a projects liquidity meaning the time that an investment can be recovered (Sullivan et al., 2015).

(a) Vertical carousel (Hänel, 2022b)

(b) Vertical lift module (Hänel, 2022a)

Figure 3.3: Automated vertical storage systems

There are two categories of the payback method called the simple payback period and the discounted payback period. The simple payback period calculates the time needed that the cash inflow equals the cash outflow and can be used to measure the risk of a project. The discounted payback period does take into account the time value of money and produces the break-even life of a project (Sullivan et al., 2015). Formula 3.1 shows the equation of the discounted payback period method.

$$\sum_{k=1}^{\theta}(R_k - E_k) * \frac{1}{(1+i)^k} - I \geq 0 \tag{3.1}$$

Where,
R_k revenue earned in period k;
E_k expenses in period k;
I initial investment of the project;
i effective interest rate, or MARR;
k number of the period;
θ smallest value of periods that satisfies.

With equation for the discounted payback period, one can determine whether an investment can be recovered within a certain time period incorporating the future cash flows (theta). It can bee seen if the investment is paid back before the estimated lifetime of a purchase.

The payback period method is not including the cash flows that occur after the break-even point. Disregarding the cash flows can result in misleading outcomes. It is therefore recommended to use this method as supplementary information in conjunction with other methods such as the the Present Worth (PW) method (Sullivan et al., 2015). The PW method is based on the equivalent value of the incoming and outgoing cash flows relative to a starting point in time, also known as the present. That is, all incoming and outgoing cash flows are discounted to the present time at an interest rate that is generally the Minimum Attractive Rate of Return (MARR). The MARR is a return rate that a project needs to accomplish to be able to see the investment as feasible (Sullivan et al., 2015). Formula 3.2 shows the equation to calculate the PW.

$$PW(i\%) = \sum_{k=0}^{N} F_k * (1+i)^{-k} \quad (3.2)$$

Where, i effective interest rate, or MARR, per compounding period;
k index for each compounding period;
F_k future cash flow at the end of period k;
N number of compounding periods in the planning horizon.

If the calculated PW is larger or equal to zero $(PW(i = MARR) \geq 0)$, then the investment is acceptable. The higher the interest rate and the more in the future, the lower the PW. This is due to the time value of money which is predicted to be lower further into the future (Sullivan et al., 2015).

3.3 Bottleneck identification

To improve production flow, the most important step is the identification of the bottleneck. Many bottleneck identification methods for production are given in the literature (Urban and Rogowska, 2020).

First, the process times method is a fast method to detect the bottleneck. The process time method measures the process times of the material flow and therefore detects the capacity limit. The process with the longest processing time or the lowest capacity will then be the bottleneck. However, this method only detect a static bottleneck and does not include lost items, meaning that it does not necessarily have to be the bottleneck (Roser et al., 2014).

Another bottleneck identification method is the utilisation method. Utilisation is the productive time of a process or person. The process with the highest utilisation is noted as the bottleneck (Roser et al., 2014).

Bottlenecks can also be determined by looking at stocks in between the production processes. The process with the longest queue or waiting time is considered to be the bottleneck of the production process. This bottleneck method is known as the longest queue method.

Observations of the processes is another way that can determine the bottlenecks of a production process. This method is called the bottleneck walk. There are no measurements required for these observations. Buffers between processes can determine which process is the bottleneck. A shifting bottleneck can be determined if observations are done frequently(Roser et al., 2014).

Finally, the bottlenecks can be determined by the use of a simulation based method. A real life situation can be imitated by a simulation to gain knowledge about the processes. It is a useful method to visualise the product flow which can increase the acceptance within a company. It is however required to have accurate data to create useful outputs with the simulation. Simulations can be used to answer questions about possible optimisation issues (Nyhuis, 2008).

3.4 Sensitivity analysis

If a real-life simulation is modelled, it is hard to be completely certain of the correctness of the data. Therefore, it is often useful to determine the impact of a change in the data has on the optimal solution. A value can also be an estimation because sometimes data is unknown. For these reasons it is common to use a sensitivity analysis. A sensitivity analysis can make it unnecessary to solve the problem again to obtain a new optimal solution and analyses the influence of changes to the solution of the model (Rader, 2010) (Robinson, 2014) (Boucherie et al., 2022). There are three main areas in which a sensitivity analysis is useful to include:

- If you want to determine the effect of uncertainties in the data;
- Understanding how changes in the market or in the supply process affect the solution of your model;
- Determining the robustness of the solution.

Sensitivity analysis can be done by varying the model inputs and running the simulation model again. By keeping track of the change in the response, the sensitivity of the model can be determined. If the model has many inputs, this can be a very time-consuming process. Therefore, sensitivity analysis should be restricted to a few key inputs which are the most uncertain or have the most impact.

3.5 Conclusion

Nowadays, a lot of technologies exist that can automate a process and increase the efficiency of your production facility. For this research we found multiple warehousing systems and cobots that improve the material handling and flow of materials. It is a challenge to decide where to start automation because of the high amount of available techniques and the experience of small companies with technologies. Acceptance by the operators is one of the biggest challenges and a poor design will result in slowing down the operators or not using the new automation techniques.

There are multiple methods available to determine the worthiness of automation projects such as different types of payback periods and simulations of the internal process. Simulations show the current flow of the process with which the bottlenecks can be determined. Evaluation of investments and the use of a simulation to programme possible solutions, give a clear overview of the value of an optimisation project. Using priorities, multiple processes can be optimised within a company.

4 Simulation model of the current situation

In this chapter, we determine which processes are most valuable to optimise using a simulation. Using simulation model, the following sub-question can be answered:

What feasible improvements can be made by Global Electronics B.V. and which is most valuable?

First, we will shortly discuss the importance of this simulation model in Section 4.1 after which we will explain the simulation flow in Section 4.2 where the different processes will be explained. Next, we will show the processing times used for the simulation in Section 4.3. In Section 4.4 we will shortly discuss the experimental settings, after which we will validate and verify the simulation model in Section 4.5. Finally, we will analyse the bottlenecks in Section 4.6 which we will then focus on in the final chapters.

4.1 Introduction to the simulation model

Currently, GE wants to improve their production flow but does not yet know where to start. The order volumes are increasing and with the current process, there comes a point that they are not able to cope with the demand. To keep up with this growth, it is important to improve the production flow and with it the amount of PCBAs produced. GE mentioned that they want to keep up with the fast changing market by introducing automation in the production process. Therefore, it is important to identify the bottleneck processes and to find options for improvement. Automation is most valuable for processes with high volumes and low variability which is therefore the focus point for the simulation. Currently, GE has one customer, called customer 75, that requests high volumes and therefore it is decided to focus on this customer for the remaining of this research. GE produces three different main products for customer 75 called the 910, 920 and the reader. Figure 4.1 shows the order volumes over the last two years including 2022.

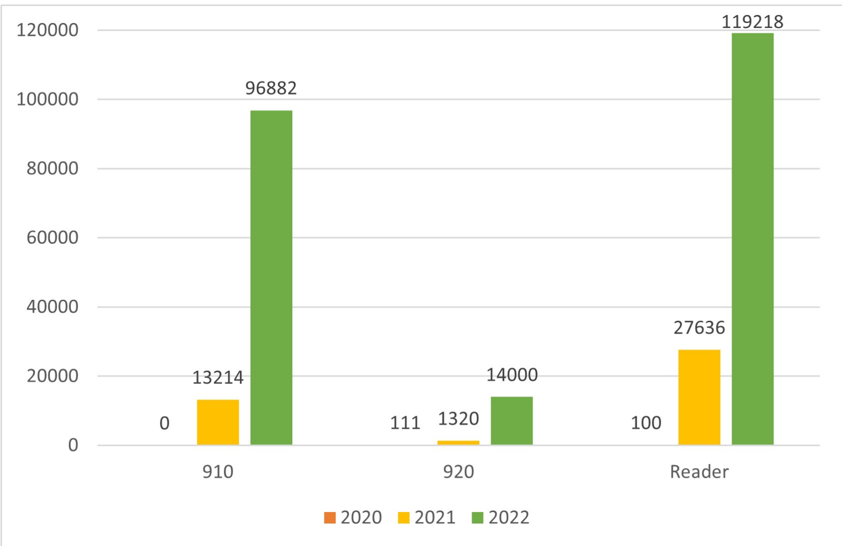


Figure 4.1: Order volumes customer 75

As can be seen in the figure, the order volumes have grown rapidly since 2020 and because of the growth of this customer, it is expected that the order volumes will increase the upcoming year and get stable in the years that follow.

As shown in Section 3.3, multiple bottleneck identification methods exist of which one is simulation. To map the points of attention which will be discussed in the remaining of this report, a simulation will be executed. With this simulation we want to identify the bottlenecks and with that the potential areas of improvement. A simulation of the current situation will be made with the software called *Plant Simulation*. Automation of processes is mostly valuable for production orders with high volumes and low variability. Bottlenecks will have a greater impact with such volumes and backlogs are harder to catch up with.

It is expected that especially with the order volumes in the figure above, multiple tasks such as the testing and the preparation of components become too time-consuming. To be able to validate these expectations, the production flow is simulated. It is decided to start with the simulation of product 910. Product 910 goes through each department at the production floor and is after the reader the most common PCBA. The reader only needs SMD production and does only go to the manual assembly department for testing.

The production process as mentioned in Section 2.3 also holds for the products produced for customer 75. The test and repair of the PCBAs is a customer specific procedure and for the testing procedure of customer 75, a specific testing machine is used. This testing machine is provided by the customer itself. In the next section, we will dive further into the production flow of the 910 and how to simulate this flow.

4.2 Simulation flow

Before simulating the current situation, it is needed to establish the flow to implement. Figure 4.2 gives an overview of the route at the shop floor that is simulated. In the following subsections, the simulation will be discussed per department which are determined by the coloured squares one until four in the figure.

4.2.1 Simulation flow in the warehouse

The simulation begins at the warehouse in the yellow square noted in Figure 4.2. The simulation starts running when the components are present in the simulation model. Because the processes in the warehouse are not modelled, the first building block of the simulation is the *OrderPicking*. The *OrderPicking* creates the components needed for the assembly of the PCBs which go through the simulation. The simulation has three different components that are placed onto the PCB. These components are used at three particular processes, namely the SMD-line, the preparation of components before manual assembly, and the manual assembly itself. In the *PartBuffer* these components are sorted and send to one of the corresponding buffers called *StorageSMDcomp, StorageMAcomp* and *StoragePrepComp*. It is assumed that the components needed for production are always available because GE start production when the order is complete.

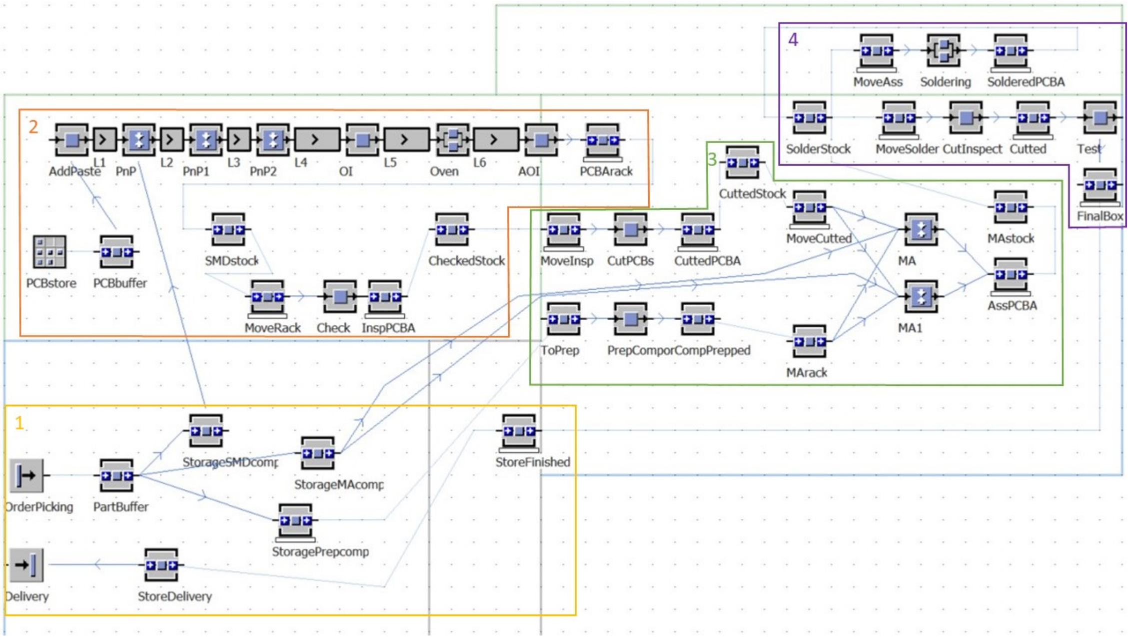


Figure 4.2: Production flow simulated

The buffers in the warehouse are locations at which the items are temporarily stored before they continue to the next process. For this simulation it is important to define the capacity of the different buffers. The buffers within the warehouse all have an infinite capacity because in reality there are no deliveries that are rejected.

When production is finished, the PCBAs are send to the warehouse again. Due to lack of space, the finished products are stored in the hallway in the buffer *StoreFinished*. This buffer serves as a pallet where the products are collected for shipment. At each pallet, a maximum of 504 PCBAs can be stored. The pallets are delivered at the customer via de buffer *StoreDelivery* and the building block *Delivery*.

4.2.2 Simulation flow at the SMD department

The next department of the simulation is the SMD department which is marked with the orange square in Figure 4.2. The SMD department consists of two different parts, namely the SMD-line and the check after the SMD-line. At the SMD-line, components are fixed onto a PCB. All components need to be assembled onto the PCB and therefore a container is used which is supplied by the *PCBstore*. The arriving PCBs will be stored in the *PCBbuffer*. In this case as well, the buffers have an infinite capacity because deliveries are always accepted. It is assumed that the PCBs are always available like the components in the warehouse.

The SMD-line consists, just as in reality, of processes that can handle one PCB at a time (SingleProc), are assembly stations (Assembly), or that can handle multiple PCBAs at a time (ParallelProc). The SMD-line starts with the station *AddPaste* at which the soldering paste is applied to the PCB. Next, there are three pick and place machines (*PnP, PnP1* and *PnP2*) which assemble the components onto the PCB. After placing the components, the components need to be fixed which is done in the *Oven*. In between the pick and place machines and the oven, an optical inspection is done at the *OI* for the first one until three PCBs to check if the paste is equally divided and if the components are placed correctly. Finally, all PCBs are checked at the *AOI*. All processes in the SMD-line are connected with conveyor belts called *L1, L2, L3, L4, L5* and *L6*. Except for the *Oven* and the conveyor belt, all stations can process one PCB at a time. The *Oven* can process a maximum of fifteen PCBs at a time.

When the PCB is finished at the SMD-line, it is put in a buffer called *PCBArack* which can be moved through production. The capacity of these racks, depend on the product. A maximum of three hundred PCBs of type 910 fit into the *PCBArack* after SMD production. When the capacity of the *PCBArack* is reached, the car is moved to the next station which is the station *Check* after the SMD-line. It can be that this station is still processing the previous batch and therefore the buffer *SMDstock* is added. The PCBs are waiting in this buffer until the next buffer *MoveRack* is emptied. When the buffer is empty, then a complete new batch will be retrieved.

The station *Check* checks every PCB for notifications given by the AOI. Any corrections are made after which the PCB is stored in a PCB rack called *InspPCBA* again. In this case too, the capacity of the buffer is three hundred. A batch is collected and finally send to the *CheckedStation* in which it is stored until the next department is ready. It is assumed that there is always one employee checking the PCBs at the station *Check*.

4.2.3 Simulation flow at the manual department

When the PCBs are finished at the SMD department, the PCBs continue to the manual department which is shown in the green square in Figure 4.2. The components that were sent to *StoragePrepcomp* in the warehouse, first need preparation before they can be assembled on the PCB which is done at the station *PrepComponents*. If the number of components available equals the order size, then the components are moved to the buffer *ToPrep* such that the preparation of components can start. After preparation the components are gathered in the buffer *CompPrepped* before sending them to the buffer *MArack*.

Another process at the manual department is the cutting of PCBs at the station *CutPCBs*. Batches are send from the SMD department to the buffer *MoveInsp*, where the PCBs are cut in half. Again, a batch is gathered in a PCB rack before sending it to the next buffer *CuttedStock*.

The final process at the manual department is the manual assembly. Through-hole components are placed on the PCBs. Through-hole components are generally bigger than the SMD components and therefore, the buffer *AssPCBA* after the manual assembly stations (*MA* and *MA1*) has a capacity of two hundred PCBs. The PCBs are gathered in the buffer *AssPCBA* before sending it to the soldering department.

One of the assumptions made for the simulation of the manual department is that there is always one employee preparing the components at the station *PrepComponents* which also holds for the cutting of the PCBs at the *CutPCBs* station. Finally, two employees are assigned to the manual assembly. One at the station *MA* and one at the station *MA1*.

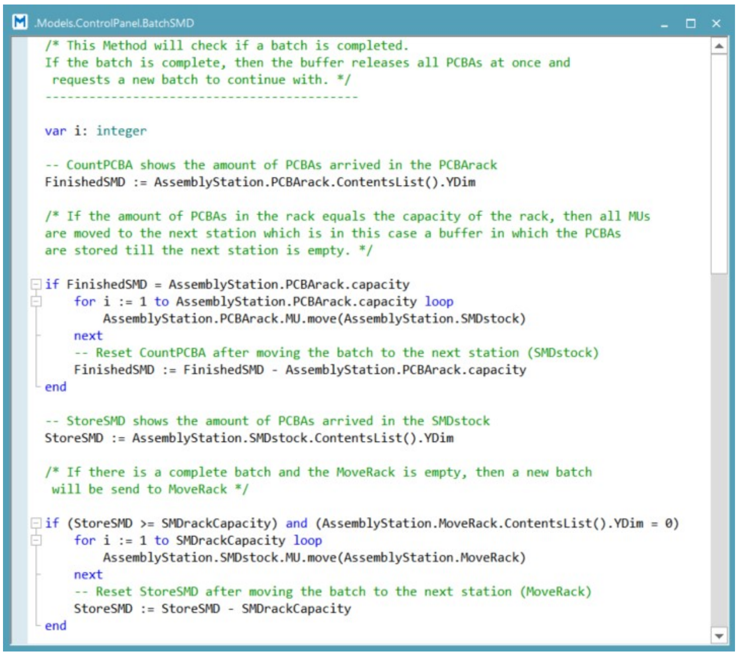
4.2.4 Simulation flow at the soldering and testing department

After the manual department, the PCBs continue to the soldering department. At the soldering department the components are fixed onto the PCBs by a wave soldering machine at the station *Soldering*. The soldering machine can handle multiple PCBs at a time and has a capacity of four. After soldering, the PCBs are gathered in the buffer *SolderedPCBA* before sending the PCBAs to the testing department. For this buffer it also holds that two hundred PCBs fit into the PCB racks.

After soldering the product is finished and now called a PCBA. The PCBAs are send to the testing department which contains of two processes, namely the cutting and touching-up of the PCBAs and the testing of the PCBA. First, the PCBAs are cut into single PCBAs and check for deviations at the station *CutInspect*. Next, they are placed onto a table, called *Cutted*, in between the cutting and testing. This buffer visualises a table at which the PCBAs are put next to each other before testing and has a capacity of hundred. After cutting and touching-up, the PCBAs will be tested by a testing machine at the station *Test* after which they will be put in a box that will be placed onto the pallet *StoreFinished* which we saw at the warehouse. The boxes in which the PCBAs are stored have a capacity of eighteen.

4.2.5 Methods in the simulation

Methods are needed to let the simulation model run. The most important methods for this simulation are the methods that collect batches. An example of such a method is given for the transportation from the *PCBArack* via the *SMDstock* to the *MoveRack*. The code for this method can be found in Figure 4.3.




```
/* This Method will check if a batch is completed.
If the batch is complete, then the buffer releases all PCBAs at once and
 requests a new batch to continue with. */
------------------------------------------

var i: integer

-- CountPCBA shows the amount of PCBAs arrived in the PCBArack
FinishedSMD := AssemblyStation.PCBArack.ContentsList().YDim

/* If the amount of PCBAs in the rack equals the capacity of the rack, then all MUs
are moved to the next station which is in this case a buffer in which the PCBAs
are stored till the next station is empty. */

if FinishedSMD = AssemblyStation.PCBArack.capacity
    for i := 1 to AssemblyStation.PCBArack.capacity loop
        AssemblyStation.PCBArack.MU.move(AssemblyStation.SMDstock)
    next
    -- Reset CountPCBA after moving the batch to the next station (SMDstock)
    FinishedSMD := FinishedSMD - AssemblyStation.PCBArack.capacity
end

-- StoreSMD shows the amount of PCBAs arrived in the SMDstock
StoreSMD := AssemblyStation.SMDstock.ContentsList().YDim

/* If there is a complete batch and the MoveRack is empty, then a new batch
 will be send to MoveRack */

if (StoreSMD >= SMDrackCapacity) and (AssemblyStation.MoveRack.ContentsList().YDim = 0)
    for i := 1 to SMDrackCapacity loop
        AssemblyStation.SMDstock.MU.move(AssemblyStation.MoveRack)
    next
    -- Reset StoreSMD after moving the batch to the next station (MoveRack)
    StoreSMD := StoreSMD - SMDrackCapacity
end
```

Figure 4.3: Batch PCBAs in the PCBA rack

The model first determines the contents of the buffer *PCBArack*. Next, if the capacity of the *PCBArack* is reached, all PCBs are moved to the buffer *SMDstock*. The second part of the code, checks if the *MoveRack* is empty and if there is a batch waiting in *SMDstock*. If this is the case, then an entire batch is moved to the *MoveRack*.

A method for the collection of data is used as well. Stations start collecting data from the moment the first PCBA arrives at the testing procedure. An example of the code is shown in Figure 4.4.

```
.Models.ControlPanel.ResetStat
-- Reset statistics

CountStat := AssemblyStation.Test.ContentsList().YDim

if CountStat = 1
		-- Start gathering statistics if each process contains an item
	AssemblyStation.CutPCBs.ResStatOn := true
	AssemblyStation.PrepComponents.ResStatOn := true
	AssemblyStation.MA.ResStatOn := true
	AssemblyStation.MA1.ResStatOn := true
	AssemblyStation.Soldering.ResStatOn := true
	AssemblyStation.CutInspect.ResStatOn := true
	AssemblyStation.Test.ResStatOn := true
end
```

Figure 4.4: Start collecting data at the stations

4.3 Processing times

Most processes at GE do not keep track of data. Except for the SMD-line, the processing times were measured manually. When measuring the processing times, additional activities were not taken into account. However, it is assumed that approximately twenty percent of the time, operators are executing different task such as setting up processes or restroom breaks. Therefore, in the simulation the effective working time is set to eighty percent. For each process, the times are measured five times to get a rough indication of the processing times. Based on these five measurements the averages, lower bounds, upper bounds and the standard deviations are determined. For the SMD department, the processing times are noted in Table 4.1. All times are defined in seconds and measured in September 2021.

Table 4.1: Individual processing times of the SMD-line (seconds)

	Paste	**P&P1**	**P&P2**	**P&P3**	**OI**	**Oven**	**AOI**	**Check**
1	32.20	15.70	43.40	59.60	50.60	460.00	55.40	42.66
2	29.50	16.60	38.00	60.00	25.09	460.00	50.80	89.43
3	35.90	15.70	37.90	68.60	19.37	460.00	87.30	57.05
4	29.30	22.80	42.80	60.00	18.15	460.00	60.60	59.22
5	30.00	20.10	44.50	57.40	20.33	460.00	50.60	74.00
Average	31.38	18.18	41.32	61.12	26.71	460.00	59.14	64.47
LB	23.93	9.71	32.90	49.53	0	460.00	19.91	16.62
UB	38.83	26.65	49.74	72.71	64.97	460.00	101.97	112.32
St.dev.	2.48	2.82	2.81	3.86	12.76	0	13.68	15.95

Parallel to the SMD-line, components needed for the manual assembly can be prepared. For product 910 there are four different components that need to be prepared. During preparation components are shortened or bent. Further explanation and a visualisation of the preparation steps of the different components can be found in Section 6.1. The average processing time per component is noted in Table 4.2.

Table 4.2: Average processing time for the preparation of components

	Cap	**Tr**	**Res1**	**Res2**
Pieces prepped	500	1800	20000	8000
Total prep. time (hour)	1	1.19	180	4
Total prep. time (seconds)	3600	4284	648000	14400
Prep. time per piece (seconds)	7.20	2.38	32.40	1.80

Finally, the PCBs go to the manual department. The processing times at the manual department are mentioned in Table 4.3. The processing times are based on four PCB(A)s. The times of the different processes are measured in September 2021 and in April 2022. The times were measured in April again because of significant changes in the amount of employees and an optimisation of the soldering machine resulting in less touch-up time.

Table 4.3: Processing times manual assembly in seconds, September 2021

	Cutting	**Manual assembly beginner/expert**	**Soldering**	**Cut&touch-up Sept/Apr**	**Testing**
1	18.14	588.36/294.18	310	97.03/88.14	125.95
2	15.89	673.96/336.98	310	104.69/100.65	145.59
3	18.27	781.24/390.62	310	99.33/102.17	131.49
4	29.45	710.08/355.04	310	98.90/86.39	126.93
5	14.43	804.00/402.00	310	130.65/109.56	131.92
Average	19.24	711.88/355.76	310	106.12/97.38	132.38
LB	3.32	479.12/239.58	310	68.54/70.95	111.31
UB	35.15	943.89/471.94	310	143.70/123.81	153.45
St. dev.	5.31	77.45/38.73	0	12.53/8.81	7.02

4.4 Experimental settings

In this section, we will shortly discuss the experimental settings of the simulation model. To achieve a steady state, the run length of the simulation will be sixty days. The run length can be increased, but because only one product is produced with this simulation model, the buffers between the stations will only increase because there is no space to eliminate these stocks.

A work shift at GE and in the simulation starts at 8:00 and finishes at 17:00. A new order will start at the beginning of the day and therefore a warm-up period is not needed for this simulation. Every two hours there is a break of fifteen minutes at 10:00 and 14:45 and thirty minutes at 12:15.

Finally, two different experimental settings are used. In April, more employees were assigned to the manual assembly and the preparation of components. The average processing time of the cutting and touching-up of the PCBAs did slightly improve after some changes at the soldering department. Finally, with the changes in April 2022, GE wants to produce thousand PCBAs more compared to September 2021. In Table 4.4, the experimental settings for both periods are shown.

Table 4.4: Input used for the simulation model

	September 2021	April 2022
# employees manual assembly	2 experts	2 experts 2 beginners
# employees preparation of components	2	4
Avg. processing time cutting/touch-up (sec)	106.12	97.38
Monthly output	2000	3000

4.5 Validation and verification of the simulation model

After explaining the flow and determining the input and the experimental settings, the simulation model can be validated and verified. When validating the simulation, we will look at the volumes produced in reality and compare these with the volumes produced by the simulation to be able to say if the simulation represents reality. The validation will be done with the inputs of September 2021 and April 2022 as we have seen in Table 4.4.

Sixty days of simulation is equivalent to 8.51 weeks of simulation. With the number of weeks available, the amount of PCBAs that need to be produced after the sixty days running time can be calculated. Thus, after sixty days, the simulation should have produced approximately $8.51 * 2,000 = 17,143$ PCBAs in September and $8.51 * 3,000 = 25,714$ PCBAs in April. After running the simulation for sixty days, the amount of PCBAs produced in reality and by the simulation are shown in Table 4.5.

Table 4.5: The number of PCBAs produced after 60 days

Month	# PCBAs produced in reality	# PCBAs produced by the simulation
September 2021	17,143	17,284
April 2022	25,714	28,932

The simulation produces slightly more than in reality but the differences between the output of the simulation and the actual volume produced is negligible.

To verify the model, the simulation model is compared to the actual process. The model is built part by part and per department. We started with a simplified model which was expanded step by step. Each part of the model is tested and debugged. Finally, we have done a visual verification to see if the flow through the simulation model showed a normal and realistic behaviour during the simulation.

With the validation and verification of this simulation model, the bottlenecks of the production process can be determined. The bottlenecks will be discussed in the next section by the use of different bottleneck identification methods.

4.6 Analysing the bottleneck

For GE to identify which process is most valuable to optimise, the bottleneck of the process must be determined. In Section 3.3 several methods were discussed to identify the bottleneck. When determining the bottlenecks we will use the simulation and look at the KPIs processing times, utilisation rates and stocks in between processes. We will look at these KPIs in the following subsections.

4.6.1 Bottleneck identification based on processing times

One of the bottleneck identification methods used is based on the processing times of the different stations in the simulation. If we look at the value stream map in Section 2.4, it can be seen that the manual assembly is the most time consuming process which the following processes must wait for. In Section 4.3, in which the processes are shown in more detail, it can be seen that the manual assembly has the longest processing time as well. After the manual assembly, the oven and the soldering department have the longest processing times. However, multiple PCBAs can be processed at once. Therefore, the entire testing department consisting of the cutting and touching-up of the PCBAs has the second longest processing time.

Another process that stood out is the preparation of components. The processing times of single items do look quite normal, but the components are prepared in batches that equal the size of an order which is two thousand in September 2021 and three thousand in April 2022. It was noted that when only one employee is preparing the components, the manual assembly had to wait for the first batch. After the preparation of the first batch of two thousand pieces which is equal to one order, the supply is sufficient such that the manual assembly does not have to wait for new components.

If the preparation of components is done by four employees instead of one which we saw in April, the manual assembly does not have to wait for the components but the components have to wait before they can be assembled on the PCB. After running both simulations, we could see when the first components arrived at the manual assembly stations and at the buffer for the components that are prepared (*MArack*). In Table 4.6 the arrival times of the components and PCBAs are shown.

Table 4.6: Arrival of products at the manual assembly stations

D:HH:MM:SS	**September**	**April**
Arrival components	4:13:51:30.2483	1:16:10:56.0516
Arrival PCBs	2:14:20:27.7177	2:14:20:01.9039
Bottleneck	Components	PCBs

Looking at the bottlenecks based on the processing times, it can be concluded that the manual assembly is the main bottleneck process followed by the testing and cutting / touching-up of the PCBAs. Furthermore, the preparation of components is a bottleneck when there are only two employees assigned to this task. When there are four employees assigned to the preparation of components, it appears that the bottleneck shifts. However, four people for a task as the preparation of components is many and a waste of skill.

4.6.2 Bottleneck identification based on utilisation rates

Another bottleneck identification method focuses on the utilisation rates of the different stations. With the simulation, it is possible to look at the utilisation rates of the stations and determine the bottleneck of the production flow as the station with the highest utilisation rate. During this research we will only look at the utilisation of the manual department. Table 4.7 shows the utilisation rates for each process at the manual assembly department in September 2021 and Table 4.8 shows the utilisation rates for each station in April 2022.

Table 4.7: Utilisation rates of the production processes in September 2021

Station	**Utilisation Sept. %**
CutPCBs	25.17
PrepComponents	100
MA / MA1	100/100
Soldering	36.94
CutInspect	97.60
Test	99.99

As shown in Table 4.7, the utilisation rate of the preparation of components, the manual assembly and the testing procedure are all above 95 percent which is relatively high. A hundred percent utilisation rate sounds perfect, but there is no possibility to expand the production or cope with emergencies. The high amount of intermediate products is, especially before the manual assembly, extremely high meaning that an availability of hundred percent is all but perfect. For GE, a utilisation rate of approximately ninety percent is an aim that should be achieved. A much lower or higher utilisation is not desired.

Table 4.8: Utilisation rates of the production processes in April 2022

Station	**Utilisation Sept. %**
CutPCBs	25.26
PrepComponents	100
MAexpert / MAexpert1	100/100
MAbeginner / MAbeginner1	100/100
Soldering	43.14
CutInspect	98.53
Test	99.99

Looking at the utilisation of the processes in April 2022, it is shown in Table 4.8 that the utilisation does not change significantly compared to September 2021. Only the utilisation of the soldering machine did increase because the manual assembly stations were able to achieve a higher output with four employees compared to two employees.

Based on the utilisation rates, it can be concluded that the preparation of components, the manual assembly and the testing are the bottlenecks processes for both periods.

4.6.3 Bottleneck identification based on stocks

After running the simulation for sixty days, we can also look at the buffers in between the stations. The location of the PCB(A)s can determine the bottleneck of the production process. After running the simulation for sixty days, the results were retrieved as shown in Figure 4.5 and Figure 4.6.

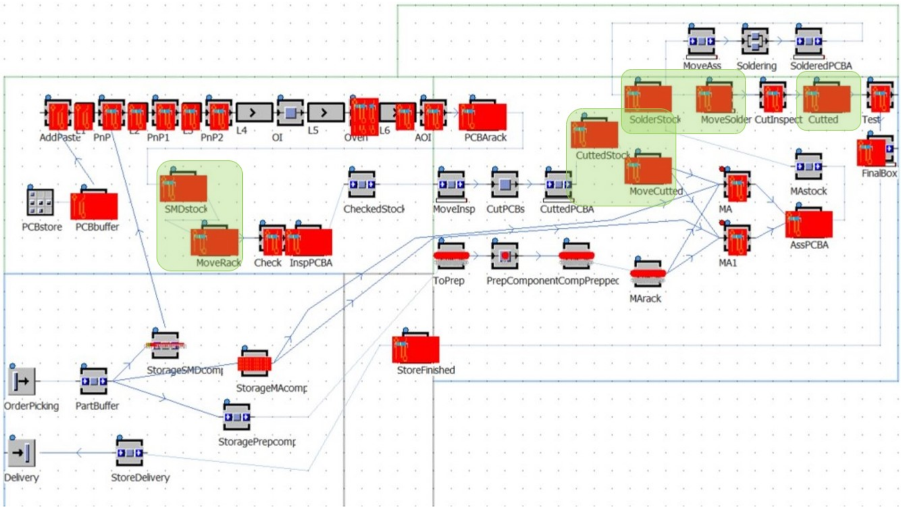


Figure 4.5: Simulation September 2021 after sixty days

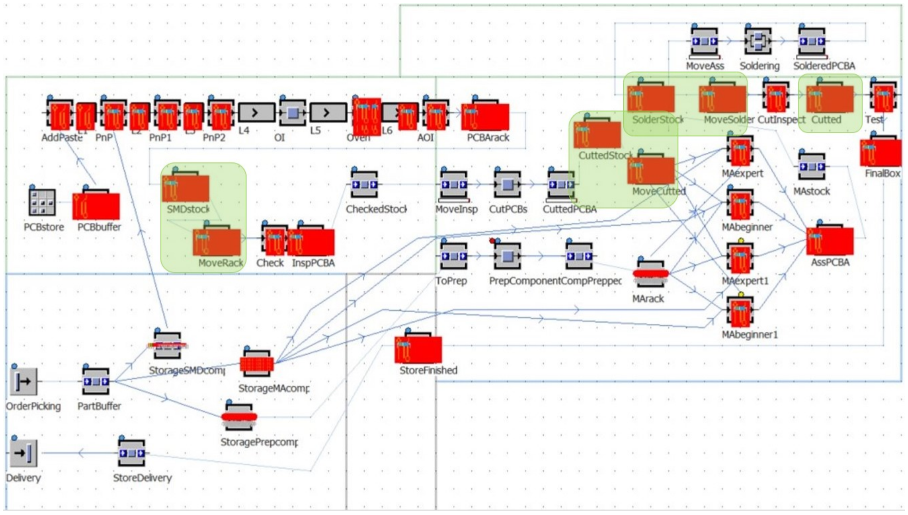


Figure 4.6: Simulation April 2022 after sixty days

As you can see in the figures, in both cases it can be seen that stock did built up before the *Check* after the SMD-line, before the manual assembly and before the testing department. The stocks are indicated by the green squares in the figures. To be able to say something about the size of the bottlenecks, we looked at the number of PCB(A)s at each department. Figure 4.7 shows these number of PCB(A)s in between the departments in which Figure 4.7a shows the results from September 2021 and Figure 4.7b represents the simulation from April 2022.

As can be seen in Figure 4.7, the manual assembly is the main bottleneck of the process in both cases. This result is not unexpected because of the processing times mentioned

(a) Stock results September

(b) Stock results April

Figure 4.7: Visualisation of the bottlenecks at each production department

earlier in this section. However, it can be seen that the amount of stock before manual assembly slightly decreases in April 2022 where more people were assembling the PCBs while the stock before testing increases significantly. The stock at the other processes remains roughly the same.

4.7 Conclusion

Looking at the growth of GE, it is important to improve the production flow. However, it was noticed that it is unclear with which process GE wants to start. To discover these processes, a simulation of the shop floor is made that will focus on product 910 of customer 75 because of the high volumes these product is made in. Each department is set-up individually after which the departments were connected to imitate the flow as it currently is. With the simulation we look at the bottlenecks using the KPIs processing time, utilisation rate, stock in between processes and a simulation of the current production process.

The input for the simulation are the processing times of the stations which can also be used to get an idea about the bottleneck processes. Figure 2.4 and Table 4.1-4.3 show that the manual assembly is the process with the longest processing time followed by the testing department, meaning that these are the bottlenecks when focussing on the processing times of the manual department. Table 4.9 shows the processing times of the bottleneck processes.

Table 4.9: Recap: Processing times of the bottlenecks

	September 2021	**April 2022**
Avg. processing time manual assembly	711.88	355.76
Avg. processing time testing	238.5	229.76

Another KPI used to identify the bottlenecks is the utilisation rate of the stations. It was seen that there are multiple stations that have a utilisation rate above ninety percent which are the preparation of components, the manual assembly and the entire testing procedure consisting of the cutting / touching-up and the testing of the PCBAs. Therefore, these processes can be noted as the bottlenecks of which the utilisation rates are summarised in Table 4.10.

Table 4.10: Recap: Utilisation rates of the bottlenecks

	September 2021	**April 2022**
Preparation of components	100	100
Manual assembly stations	100/100	100/100
Testing procedure	99.99	99.99

Finally, we looked at the KPI stock in between stations. It was noted that there are three processes that resulted in stock building up in front of the station. These stocks were built up after the SMD-line, before the manual assembly and before the entire testing department consisting of the cutting / touching-up and the testing of the PCBAs. The amount of PCBAs waiting before these stations are shortly repeated in Table 4.11 in which it can be seen that the manual assembly has in both cases the biggest contribution.

Table 4.11: Recap: Occurring stocks in the production process

	September 2021	**April 2022**
Stock after SMD line	15,260	14,888
Stock before assembly	43,200	30,228
Stock before testing	2,308	3,460

After using the simulation to identify the bottlenecks, it can be concluded that the manual assembly is the most valuable process to optimise followed by the testing procedure. Finally, relatively many employees are currently used for the preparation of components still resulting in a high utilisation rate. Therefore, the final process valuable for optimisation is determined to be the preparation of components.

As shown in the validation of the simulation, the flow as well as the output increased by assigning four instead of two employees to the manual assembly. During the next two chapters, we will look at different options to increase the amount of employees available for the manual assembly. This can be done by automating the preparation of components and automation of the testing procedure.

5 Opportunities for transformation

In Chapter 4, the bottlenecks of the process were determined. Using these results, it is now possible to look in more detail at the opportunities to improve the production flow of GE. After discussing these improvement options, the investments can be evaluated using the simulation which will be done in Chapter 6. In this chapter, the following research question is answered.

What are the possibilities to transform Global Electronics B.V. in a factory of the future and which is most profitable?

This chapter is divided in two sections. First, internal observations are done to get a view of the current points of improvement for GE. Second, the results of the simulation model in 4 are used to determine the points of improvement. Therefore, this chapter is divided into two sections, warehousing from the observations and production based on the simulation. In Figure 5.1, an overview of this chapter is given.

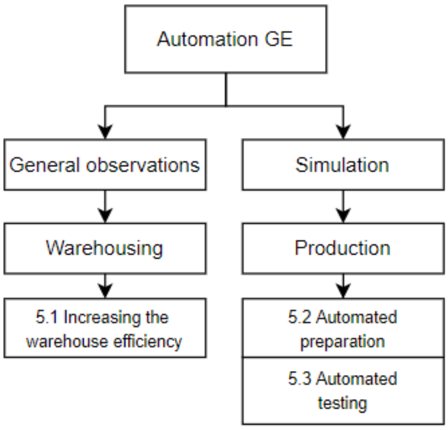


Figure 5.1: Format Chapter 5

General observations showed that the warehousing of GE is an important point of improvement. GE is growing resulting in a lack of storage space and an inefficient use of the warehouse. Warehousing will be shortly discussed in Section 5.1 after which an advice will be given to provide an overview of the possibilities.

The simulation model discussed in Chapter 4 showed that the manual assembly was the most important bottleneck of the production process of GE. However, to be able to automate the manual assembly, too many factors need to be changed. In agreement with GE it is decided to not look at these techniques because these are too expensive and with the current order volumes not yet profitable.

Besides the manual assembly, it turned out that there were two other processes that were interesting to look at. The preparation of components, which will be discussed in Section 6.1 and the processes at the testing department, which will be discussed in Section 6.2. Relatively many employees are needed for these processes while these are simple and highly repetitive processes.

5.1 Increasing the warehouse efficiency

The warehouse efficiency is not a topic discussed in the chapter above and was not taken into account in the simulation. It is however a visible problem of GE because pallets with components and finished products are currently stored in the corridors because of a lack of space. The growth of GE causes more and different storage space to be required. Components which were first delivered in cartons are now delivered on pallets because of the increasing volumes. These pallets have a dimension of 120x80 cm and thus require much more storage space compared to cartons or bags. Another factor contributing to the shortage in storage space is the shortage of components. Due to these shortages, anticipation stocks are build up meaning that sometimes components that are needed in the second half of the year are already delivered at the beginning of the year to be sure that the components are available when production is able to start.

To improve the warehouse efficiency, it is first needed to determine the amount of space currently available. Figure 5.2 shows the current layout of the warehouse. Products are delivered at the I/O point in the upper right corner. After booking in the components, the items are stored in the racks or, if there is not enough space, pallets are stored in the hallway or at the production floor. The incoming and outgoing goods (components and finished products) are stored interchangeably.

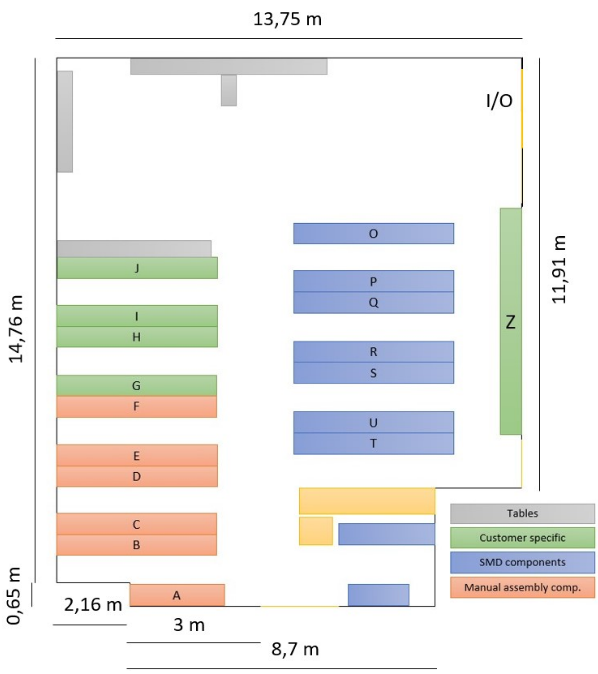


Figure 5.2: Warehouse of GE

When storing the components, it is important to keep in mind the two different kind of components and therefore different ways of storage. Components that are needed for the SMD-line are delivered on reels and components for manual assembly which are delivered in bulk, tubes or on tape. An example of a reel is shown in Figure 5.3a at which the components are winded. Figure 5.3b shows components that are delivered on tape. Finally, components delivered in bulk are individual components packed in bags or boxes which are mostly delivered in high volumes. Both components are stored differently. Reels are stored in single pieces in the racks, while the manual assembly components are stored in cartons or boxes.

Next, the available storage space, possible storage systems, and some possible layouts will be discussed.

5.1.1 Available space

When looking at the warehouse of GE, they currently have two types of storage systems, namely static storage shelves and drying cabinets. The drying cabinets are used for specific components that need to be kept under a certain humidity. The static racks are used for components that are delivered on reels and in boxes (bulk, tubes and tape).

The current layout consists of eighteen rows with in each row about five static storage racks. Each row has between five until seven layers of shelves of which every shelve has a dimension of 60*90 m^2. In total, there are 529 shelves available which is equivalent to 285.66 m^2 storage space. This storage space can be divided into different categories as we saw in Figure 5.2. Row A until F is used for components for manual assembly. G until J plus Z are customer specific rows and therefore are a mix between components for manual assembly and reels. Finally, in row O until T the reels for the SMD department are stored. More details about the storage space and the allocation to the different components is shown in Table 5.1.

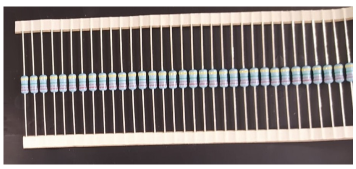
Table 5.1: Current storage capacity

	Height (mm)	**m^2**
Materials for manual assembly	150	165.24
SMD reels 18 cm	180	60.84
SMD reels 33 cm	330	15.84
Other SMD storage	150	54.54
	Total	285.66

The storage racks used at GE are static racks. The warehouse personnel has to be able to get to the top shelve and therefore the racks are currently only two meters high. The warehouse however, is around four meters high meaning that only half of the height is used.

Finally, there are two starting points that are important to keep in mind. First of all, the ERP-system GE is working with is Exact. Therefore, the warehousing systems must be compatible with this ERP-system if an automated storage system is used. Next to

(a) Components delivered on reels



(b) Components delivered on tape

Figure 5.3: Different ways of component deliveries

that, the order pickers currently pick around hundred pieces per hour. It is important that a warehousing systems will not slow down this process too much.

5.1.2 Extra storage space used

The available storage space discussed in the previous paragraph is, due to the growth, no longer enough. Pallets are stored in the hallway, at the production floor and next to the racks in the warehouse. Besides the incoming components, it is also hard to find extra storage space for the finished products because it is not always possible to immediately send them to the customer. Extra information about the storage of components outside the storage racks is shown in Table 5.2.

Table 5.2: Extra floor space used

Location	# of pallets	Height (m)	Extra m^2 needed
Production	3	0.5	4.8
Hallway	5	1.20	3.84
Warehouse	4	1	2.88
Extra storage	-	2	10.8
Total	**12**	-	22.32

As shown in the table, there is currently 22.32 m^2 extra floor space used throughout the shop floor. Hereby, there is only focussed on the storage of products on ground floor. On the first floor components are stored in bulk but these items will not be stored in automated warehousing systems. Products delivered in bulk are always delivered on pallets. For the storage of products delivered on pallets or end products, there is currently little space. Therefore, in a new warehouse design, it is important to incorporate storage space for pallets. For the storage of pallets, pallet racks are used. Another advantage when incorporating pallet racks is the fact that products do not have to be repacked. Currently, items delivered on pallets are unpacked after which they are stored in single boxes in the static racks.

Because of the present fluctuations in the market, the storage volumes can be different each month and sometimes even each week. Therefore, it is important to incorporate extra storage space of approximately 25 percent when optimising the warehouse and looking at the storage space required.

5.1.3 Conditions and other remarks

During the optimisation process, it is important to take into account conditions that a solution must comply with. Conditions taken into account during the process are the following:

- An automated storage system must be compatible with the ERP-system Exact.
- The number of picks per hour are currently about hundred pieces per hour. A new system cannot slow down this process too much.
- Because of the increasing components that are delivered on pallets, it is important to incorporate pallet racks.

- The height of the warehouse is currently not used and would be an efficient way to increase the density per m^2.
- There are three sub-warehouses within the warehouse (customer specific components, reels and manual assembly) that need extra attention when designing a solution.

Besides the conditions mentioned above, there are also other remarks that need to be taken into consideration. With the increasing stock volumes, more waste in the form of packaging is produced as well. This waste needs to be processed and can take up a lot of space. Another important thing to keep in mind are the components that need special storage. GE stores components that need to be kept under a certain humidity and therefore special drying cabinets are used. It is therefore important to keep at least the same amount of drying cabinets available in the warehouse.

Finally, looking at the current layout of the warehouse only static storage racks are used which two meters high while the warehouse is four meters high. Therefore, it is important to look at the use of pallet racks and automated storage systems for components delivered in bulk and components delivered in small volumes. Because of these different components, volumes and sub-warehouses a combination of static racks and automated systems seems the most conceivable. In the following paragraph, we will go into more depth about the pallet racks and the automated warehousing systems.

5.1.4 Storage systems

In this section, new storage systems suitable for GE will be discussed, which are delimited to pallet racks and the automated storage systems VLM and VC. One of the storage systems that GE wants to include are pallet racks. Finished goods or components delivered on pallets and in high volumes, must have the possibility of being stored in the warehouse. Currently, components delivered on pallets are repacked before storage or stored outside the warehouse. When looking at the extra pallet space required, there need to be storage space for at least twelve pallets as shown in Table 5.2. Because of the height of the warehouse, a three layer pallet rack (including ground floor) can be incorporated in the warehouse. This would mean that there is space needed for at least four pallets on ground level.

Another common storage system used to save storage space are automated storage systems. An automated storage system is valuable when smaller volumes need to be stored. In Section 3.1, two different systems called the VC and the VLM were discussed. Both systems can be suitable for the warehouse when designing it correctly. A VC needs less floor space compared to a VLM. However, when the height increases, the VC becomes slightly slower than the VLM. Finally, the components arriving at the opening are immediately visible with the VLM while you first have to open a tray to get to the components in a VC. Within the electronics industry the VLM is a commonly used system. The storage of reels can be regulated very efficiently in this system. A visual example of a storage system for reels is shown in Figure 5.4.

First, there will be looked at the storage of components in a VLM as shown in Figure 3.3b. A VLM contains multiple plateaus that have the dimensions 2,460x825 mm or 2.03 m^2. As shown in Table 5.1, at least 285.66 m^2 storage capacity is needed for a the

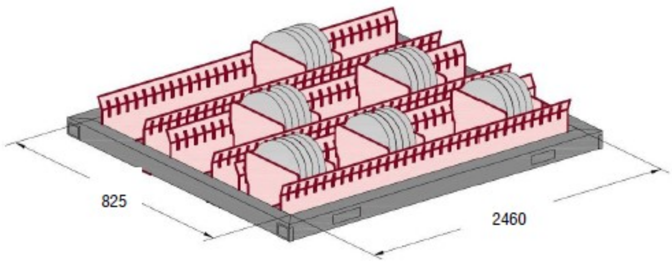


Figure 5.4: Storage of reels in a vertical lift module (Hänel, 2022a)

location of components at GE. To account for the fluctuations in the storage volumes of GE, it is internally decided to add an additional 25 percent to the current storage capacity which was already discussed earlier in this chapter. If the extra 25 percent of storage space is added, the required storage space sums up to 357.08 m^2.

Looking at the layout of the VLM, a total 357.08/2.03 = 176 plateaus are needed. If we look at a VLM of four meters high, the lift consists of approximately thirty plateaus. The location and hight of the plateaus in the lift can then be adjusted to the size of the components. To create 176 plateaus, GE would need six VLMs to be able to store all components. The floor space needed for a vertical lean lift is 7.9 m^2 meaning that for six VLM you need $6 * 7.9m^2 = 47.4m^2$ floor space. With these six systems, the amount of floor space needed is already significantly reduced. However, because of the layout of the warehouse and the space needed for six VLM units, little space remains for other storage systems such as pallet racks and the current static shelves that you can use as for example a supermarket/fast-pick area. Besides, in the industry the warehousing systems are usually between the seven and eight meters high resulting in a much higher density per m^2.

There are several situations in which a building was not high enough for the warehousing system. In these cases, a company can decide to built the system through the roof of the building. If this situation would be possible for GE, then the height of the system can be increased to eight meters, meaning that only three systems are needed. Per VLM, the capacity will then increase to 123.8 m^2 resulting in 371.14 m^2 for three VLM systems. The total floor space needed will then be reduced to 23.6 m^2.

Another suitable storage system is the VC which we saw in Figure 3.3a. A VC contains circulation shelves and a system of four meters high consists of twelve carrier sets with 24 levels. As mentioned before, GE wants to increase their capacity to 357.08 m^2. One VC has a capacity of 44m^2. Looking at this capacity, GE would need nine systems to achieve the desired capacity. Each system has a floor space of 5.5m^2. Thus, the total floor space needed for nine VC's is $9 * 5.5m^2 = 49.5m^2$. In this case as well, the floor space needed is significantly reduced. However, the implementation of nine systems has a big impact and is a major project. For this case too, it is interesting to also incorporate a system that is eight meters high instead of four. A system that is eight meters high has a capacity of 103m^2 meaning that there are four systems needed to achieve the desired capacity. The floor space of such a system is slightly higher compared to the four meter system, namely 5.7m^2. Still, the floor space needed will be reduced to 22.8m^2.

In Table 5.3 a short summary of the capacity, floor space and investment cost of all four systems is given. In all cases, four pallet racks of € 4,000.00 in total is included.

Table 5.3: Capacity, floor space and cost of the automated warehousing system

Machine	**Capacity per system m^2**	**# machines needed**	**Total floor space required m^2**	**Investment cost**
VLM 4m	60.09	6	47.4	€ 210,500.00
VLM 8m	123.8	3	23.6	€ 204,000.00
VC 4m	44	9	49.5	€ 220,000.00
VC 8m	103	4	22.8	€ 212,000.00

When designing a new warehouse, it is important to also keep in mind the secondary factors. Below, a few factors are given that are important keep in mind:

- If pallet racks are installed, then a pallet lifter is required to store and retrieve components from the racks.
- The use of pallet lifters do require extra attention in terms of safety. For example walking routes need to be created around the pallet racks.
- If the storage systems will be built through the roof, it is likely that a permit of the municipality is needed.

5.1.5 Investment options for the warehouse

In this paragraph, the payback periods of the different investments are discussed. Based on the conclusion of the investment cost, some possible layouts will be discussed. In these layouts, the storage systems that are involved are the following: automated storage systems, pallets racks, static shelves, and drying cabinets. GE prefers to have a payback period of three to five years.

To calculate the payback period, cost savings need to be known when new storage systems are placed in the warehouse. GE does not have lost sales because of a shortage in storage space. However, GE does hire an external location of € 3,540.00 per month which is € 42,480.00 per year that can be saved when increasing the storage space the warehouse. With the annual rental cost and the cost mentioned in Table 5.3, the simple payback period can be calculated. The formula used for the payback period as mentioned in Section 3.2 is as follows.

$$PaybackPeriod = \frac{CostOfInvestment}{AverageAnnualCashFlow}$$

Using this formula, the payback period for the VLM and the vertical carousel both including four pallet racks will be calculated. The payback period is calculated for the four and eight meters high storage system. In Table 5.4 the payback periods and the corresponding calculation are noted.

When including the cash flow, a more extensive calculation can be done. By adding the cash flow, the discounted payback period and the Present Worth (PW) can be calculated. The discounted payback period and the PW, are calculated by the use of

Table 5.4: The simple payback periods for the VLMs

Warehouse type	Payback period	years
VLM 4m	€ 210,500.00 / € 42,480.00 =	5.0
VLM 8m	€ 204,000.00 / € 42,480.00 =	4.8
VC 4m	€ 220,000.00 / € 42,480.00 =	5.2
VC 8m	€ 212,000.00 / € 42,480.00 =	5.0

Formula 3.1 and 3.2 respectively. For these calculations, the effective interest rate is set to five percent and the life cycle of an automated warehousing systems is estimated to be thirty years. Extra cost such as maintenance cost are negligible. In Table 5.5 the discounted payback periods with the corresponding PW are noted.

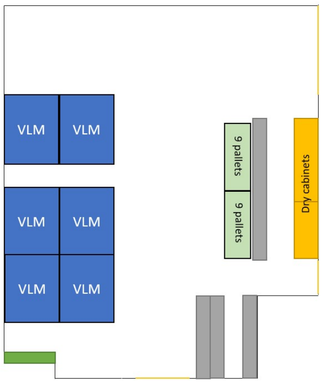
Table 5.5: Discounted payback periods and PW for automated warehousing systems

Machine (incl. pallet rack)	PW	Payback period
VLM 4m	€ 5,115.40	6
VLM 8m	€ 11,615.40	6
VC 4m	€ 1,116.60	7
VC 8m	€ 9,166.60	7

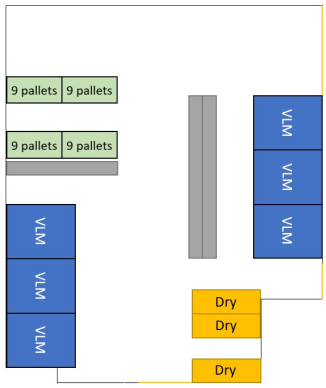
As noticeable, the payback period will increase if the cash flow is taken into account. The PW is much higher for the eight meter systems since the investment is significantly lower for the eight meters systems compared with the four meter systems. As mentioned in the beginning of this paragraph, the aim is to retrieve a payback period of a maximum of five years. The discounted payback periods of both systems are however slightly longer than five years, but the life time of an automated warehousing system is long and has the possibility to be moved to another location if needed. Besides, the capacity of a warehouse increases enormously which makes it possible to stay in the same location for a longer time than without. It is therefore recommended to still look at the implementation for automated warehousing systems.

To make a decision about which storage system to incorporate, it is important to look at the cost, the payback period and the floor space needed. As shown in Table 5.3, a VLM is less expensive and has slightly more space available looking at the systems of eight meters high. Therefore, less systems are needed compared to the VC and the payback periods are shorter. The floor space needed is almost similar. However, more systems are needed when we choose for a VC and therefore more openings are needed which also require space, but will reduce the waiting time for the operators. Finally, to retrieve components from a VC, an extra operation is needed to retrieve the components. In a VC, components are stored in bins that you first have to pull out like a drawer before you can reach the components. A VLM on the other hand, gives have a quick and clear overview of the components at the plateau.

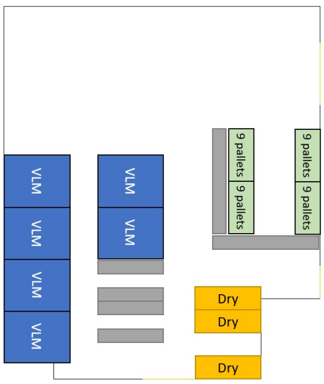
Because of the above reasons, it is more likely to implement a VLM system because it is less expensive and with the same hight faster than a VC. Based on this decision, a few designs including four meter VLMs, pallet racks, drying cabinets and static racks are given in Figure 5.5 to give an idea of possible layouts. During the design phase it is especially important to look at the safety when determining the location of the storage systems. Another important thing to keep in mind is the space a pallet lifter needs to turn meaning that there must be enough space between the paths of the pallet racks.



(a) Design 1



(b) Design 2



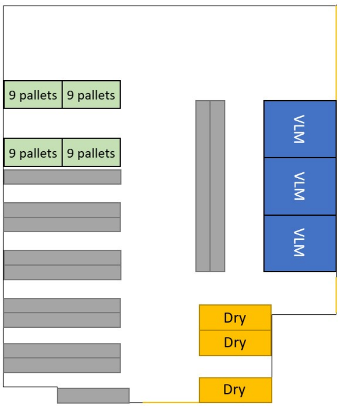
(c) Design 3

Figure 5.5: Warehousing designs with a height of four meters

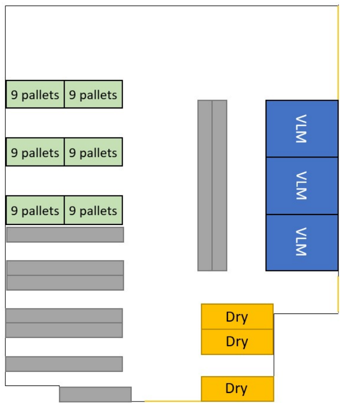
Looking at the designs, it is noticeable that the pallet racks are placed close to the I/O point in the upper right corner. The space around the pallet racks is kept as broad as possible. In Figure 5.5b and Figure 5.5c, static racks are placed to eliminate the access for pedestrians to the pallet racks. Besides these three examples, there are of course many more possibilities for GE to look at. However, to get the best possible layout, a more in depth research need to be executed, but this is out of scope for this research.

Another possibility is to implement the eight meters high VLM. As mentioned before, the amount of systems will decrease to three systems. However, the location of the VLMs will be fixed because of the construction of the building. Figure 5.6 shows two possible examples of a new warehouse design with three VLM. With these designs it is important to look at safety and the walking routes as well.

Looking at both options (Figure 5.6a and Figure 5.6b), it is noticeable that there is a lot more space available beyond the VLMs. The designs are more future proof and the static racks can easily be replaced by extra dry cabinets, pallet racks or other systems. Therefore, it is concluded that the warehouse is more efficiently used if GE chooses to incorporate a VLM that is eight meter high.



(a) Design 1



(b) Design 2

Figure 5.6: Warehousing designs with a height of eight meters

5.2 Automating the preparation of components

GE mentioned that the preparation of components was one of the bottlenecks of the production process. As discussed in Section 4.6 it was concluded that the bottleneck is dependent on the amount of employees assigned to the preparation. It was seen that the preparation of components will be a bottleneck if only one employee is assigned to the preparation. However, if four employees are assigned, then the employees at the manual assembly have to wait for the PCBs to arrive. The shift in the location of the bottleneck is valuable occurrence. It is shown that when more people are assigned to the preparation of components, the bottleneck eliminates at this station. However, these employees are needed for the manual assembly to be able to reduce the bottleneck at the manual assembly stations which is for GE the main bottleneck. Besides, professionals are more important for this process. Besides the fact that the preparation does not need professionals, it is also ergonomically and mentally a difficult task. Product 910 consists of four different components (resistor 1, resistor 2, capacitor and transistor) that need to be prepared before assembly. Machining of the components is done axially or radially. Radial loads are forces acting perpendicular to the axis while an axial load is a force in the longitudinal direction of the axis. In the next sections the axial and radial processes are described after which possible optimisation options will be discussed.

5.2.1 Axial processing

The components that need to be processed in the axial direction are resistor 1 and resistor 2 which are shown in Figure 5.7. Before assembly, both resistors must be bent and cut to the correct size. After cutting and bending the resistors, resistor 1 needs a heat shrink which is put around the resistor and heated manually. Figure 5.7 shows the components before and after preparation to give a visual example of the process.

(a) Resistor 1, including heat shrink (b) Resistor 2, excluding heat shrink

Figure 5.7: Axial preparation of the resistors

The components are cut and bent into the right size with the use of a semi-automated machine which is operated manually. A lever is turned to move the components through the machine. An example of the machine is shown in Figure 5.8.

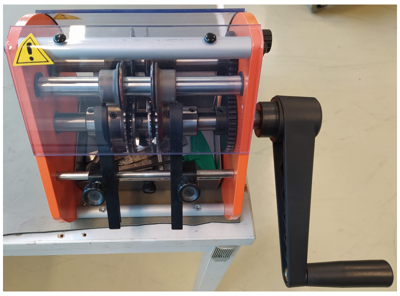


Figure 5.8: Preparation machine for axial components

To improve and/or automate the preprocessing of axial components, it is important to get more insight in the procurement cost of the components and the labour cost of the preparation. To calculate the labour cost, the processing times as mentioned in Chapter 4 are needed. Beside the processing times, Table 5.6 shows the amount of Full Time Equivalent (FTE) needed for the preparation and the translation of the FTE into the labour cost. When calculating the amount of FTE and the labour costs we assume that 1) there are 1800 effective working hours in a year and 2) an employee cost GE approximately €40,000 per year. The number of FTE needed per year is calculated by dividing the hours needed for the preparation by the effective working hours in a year. The labour cost per year can then be calculated by multiplying the amount of FTE yearly needed by the yearly cost of an employee.

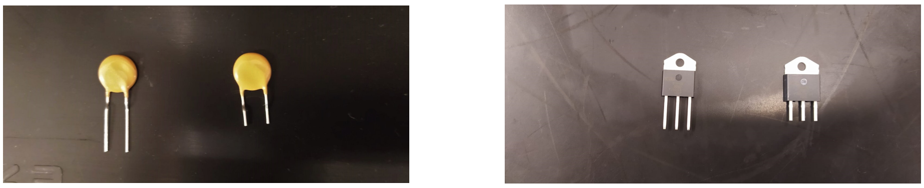
Table 5.6: Preparation cost axial components product 910

	Resistor 1	**Resistor 2**	**Total**
# on PCBA	1	1	-
# components 2022	96,882	96,882	193,764
Purchasing cost/pcs	€ 0.29	€ 0.04	€ 0.33
Purchasing cost 2022	€ 28,483.31	€ 3,681.52	€ 32,164.82
Prep time (hr)	1	180	181
Pcs prepped	500	20000	20500
Prep time needed (hr)	194	872	1066
# FTE/year	0.11	0.48	0.59
Labour cost/year	€ 4,305.87	€ 19,376.40	€ 23,682.27

As shown in Figure 4.1, the order volume of customer 75 in 2022 will be 96,882 of product 910. The purchasing cost for the two resistors together is € 32,164.82 if GE prepares the components for 96,882 PCBAs. In addition to the purchasing cost, we can calculate the labour cost. As shown in Table 5.6, the yearly labour cost is € 23,682.27 which is approximately 73 percent of the purchasing price meaning that a total of € 55,847.09 is paid before the component can actually be assembled onto the PCB. This is extremely high knowing that almost half of the total price is deformation of the original components. The biggest factor of the high rice is the heat shrink that needs to be added to resistor 1. Unfortunately, it is not feasible to automate this process and therefore there will be looked at the labour cost of only cutting and bending both resistors which would then be € 4,305.87 * 2 = € 8,611.74. Next, the radial processing of components is discussed. Finally, different automation possibilities and its payback period will be mentioned.

5.2.2 Radial processing

There are two components, the capacitor and transistor, that are processed in radial direction. Both components have pins that need to be cut into the correct length. A visual example of the components before and after preparation is shown in Figure 5.9.



(a) Capacitor　　　(b) Transistor

Figure 5.9: Radial preparation of the capacitors and transistors

For both the capacitor and transistor, the pins are shortened before assembly. The components are prepared semi-automated by the use of the machine shown in Figure 5.8. The components are placed in the mall with the pins in the slot and with a pedal the components are cut with air pressure.

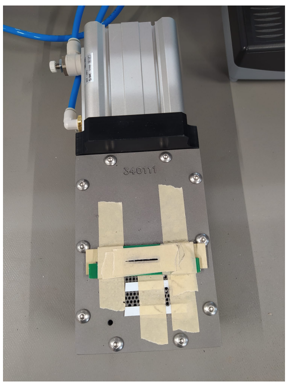


Figure 5.10: Preparation machine for radial components

For the radial components, the processing times determined in Section 4 are used as well. Table 5.7 shows the purchasing cost of the components and the amount of FTE needed for the preparation of the components. Finally, the amount of FTE can be translated into the labour cost of the preparation. Both, the amount of FTE needed and the cost per year, are calculated the same way as for the axial components.

Table 5.7: Preparation cost radial components product 910

	Capacitor	Transistor	Total
# on PCBA	1	3	-
# components 2022	96,882	290,646	387,528
Purchasing cost/pcs	€ 0.04	€ 1.07	€ 1.11
Purchasing cost 2022	€ 3,671.83	€ 312,066.61	€ 315,738.44
Prep time (hr)	4	1.19	5.19
Pcs prepped	8000	1800	9800
Prep time needed (hr)	48	192	241
# FTE/year	0.03	0.11	0.13
Cost/year	€ 1,076.47	€ 4,269.98	€ 5,346.45

As shown in the table above, the purchasing cost of the radial components is € 315,738.44 for the 96,882 PCBAs GE expects to produce in 2022. The labour cost are, compared to the axial components, much lower. The labour cost are € 5,346.45 which is approximately 1.7 percent of the purchasing price meaning that the extra cost are in this case less effective than for the axial components. The purchasing cost however are much higher.

Given the labour cost of the preparation in axial- and radial direction, the optimisation possibilities for automation can be discussed. In the next paragraph multiple machines are discussed and determine the payback periods for these machines are calculated.

5.2.3 Investment options for preparation of components

Currently, the preparation of components is done manually. To increase the production flow, it is important to increase the amount of components that can be prepared in the same amount of time. This can be done in multiple ways such as outsourcing, semi-automated preparation machines and fully automated preparation machines.

Outsourcing does not increase the speed of the process, but gives the personnel more time for the other production steps. Automated and semi-automated machines do increase the speed and the accuracy of the preparation. Besides, the preparation of components is highly repetitive. These high repetition makes these tasks valuable to automate and possible machines cannot only be used for this particular customer, but for all products that need components that must be prepared before assembly. For example, a resistor is one of the most common component and always needs to be bent and cut.

Besides the two different operations, one of the challenges for fully automating the preparation is the different packages of the components. Resistors are nearly always delivered on tape, while components that need radial preparation are delivered in multiple ways such as in bulk, tubes or on tape. All these packages are feed to the machine in a different way and therefore multiple machines exist. Next, multiple fully automated machines will be discussed. Outsourcing has been left out of scope for this research. This also holds for semi-automated machines because they already use semi-automated machines for the preparation of components as shown in Figure 5.8 and Figure 5.10.

For the optimisation of the preparation of components, three fully-automated machines are found. The machine called CF-8 is a machine that can process axial components automatically. Components can be supplied on tape or in bulk and the mechanics are comparable with Figure 5.8, only the lever is replaced by a motor. An example of the CF-8 is shown in Figure 5.11.

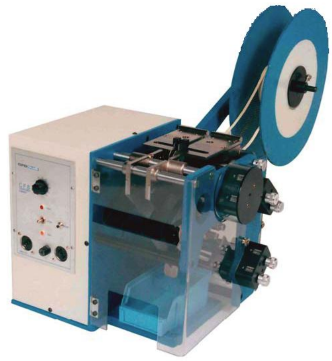


Figure 5.11: CF-8 Taped or bulk axial component lead formers (GPD-Global, 2022)

Another machine, the CF-10, processes the components in radial direction and can be supplied by components in bulk or in tubes. The components are feed one by one and the pins are cut into the right size. Figure 5.12 shows an example of the preparation machine for radial components.

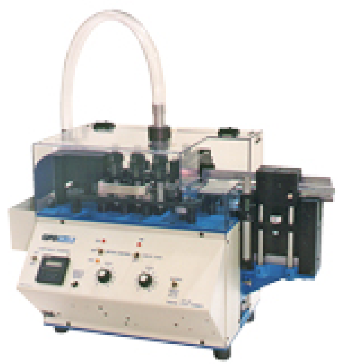


Figure 5.12: CF-10 Bulk or Loose radial component lead formers (GPD-Global, 2022)

Finally, the Ebsomat 120 is a fully-automated machine for radial direction in which components in tubes can be supplied to the machine. The machine will retrieve the components out of the tube and the pins will then be cut into the right length. See Figure 5.13 for an example of the Ebsomat 120.

Figure 5.13: Ebsomat 120 Automatic Radial Trimmer (Ebso, 2022)

In Table 5.8 the parts per hour and the investment costs for all three machines are noted. The processing type and the package that the machine can handle is repeated shortly.

Table 5.8: Fully automated preparation machines for multiple pre-treatments

Machine	**Type**	**Package**	**Production rates**	**Investment cost**
CF-8	Axial	Tape or bulk	Tape: 25,000 pph Bulk: 4,000 pph	€ 52,000.00
CF-10	Radial	Bulk or tubes	Bulk: 6,000 pph Tubes: 5,000 pph	€ 62,300.00
Ebsomat 120	Radial	Tubes	Tubes: 3,600 pph	€ 11,500.00

Looking at the production rates in Table 5.8, it can be seen that the CF-8 can produce up to 25,000 parts per hour compared to 2,000 parts per hour when preparing the components manually. The machine can prepare 12.5 times more parts per hour than preparing manually. The CF-10 can process both radial components and can prepare 3.3 times more components than manually if delivered in tubes. For the capacitor which is delivered in bulk, the machine can process 12 times more than preparing manually. The Ebsomat 120, which can be used for the transistors delivered in tubes, can process 2.4 times more components.

Besides the increase in output, it is also important to calculate the payback periods with the procurement cost mentioned in Table 5.8 and the labour cost of € 23,682.27 and € 5,346.45 for the axial and radial components respectively that can be saved when automating. For the payback period we divide the savings by the investment. The payback period is calculated separately for the axial and radial components. Table 5.9 shows the simple payback periods for the three machines.

Table 5.9: The simple payback periods for automated machines

Machine	**Type**	**Payback period**	**years**
CF-8	Axial	€ 52,000 / € 8,611.74 =	6.04
CF-10	Radial	€ 62,300 / € 5,346.45 =	11.65
Ebsomat 120	Radial	€ 11,500 / € 4,269.98 =	2.69

Next, the cash flow is included and the discounted payback period and the PW method can be calculated to compare with the simple payback periods. While calculating the discounted payback period and the PW, an effective interest rate of five percent is used and it is assumed that the life cycle of the preparation machine has a minimum of ten years. Besides the initial investment, the extra cost such as maintenance cost, are negligible. Table 5.10 shows the first year in which the PW is higher than zero.

Table 5.10: The discounted payback periods and PW for automated machines

Machine	PW	Payback period
CF-8	€ 3,659.51	8
CF-10	€ 197.79	18
Ebsomat 120	€ 128.21	3

Taking into account the cash flow of the future, we see that the payback periods are slightly longer. For the preparation machines, it is desired to achieve a payback period of three years, meaning that only the Ebsomat 120 would be a good fit. However, the payback periods are only calculated for the preparation of components for product 910 while almost each PCBA that requires manual assembly, requires preparation of components. The preparation machine of the axial components is for approximately one-third of the time used for product 910. If the CF-8 is used for other PCBAs too, the payback period will decrease to approximately three years.

If we take into account a life span of ten years, it can be seen that the CF-10 cannot be recovered within this time frame if the machine is only used for product 910. In this case too, more than only product 910 requires preparation suitable for this machine. One-fourth of the time, it is used for product 910, meaning that the payback period will decrease to approximately four years resulting in a reasonable payback period.

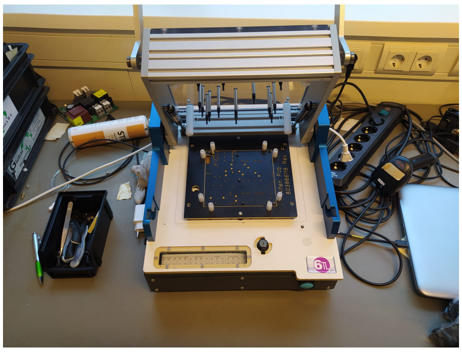
Finally, the Ebsomat 120 has a payback period of three years, meaning that the investment lies within the desired payback period. Also for the Ebsomat 120, the machine can be used for more products reducing the payback period.

5.3 Automation of the testing procedure

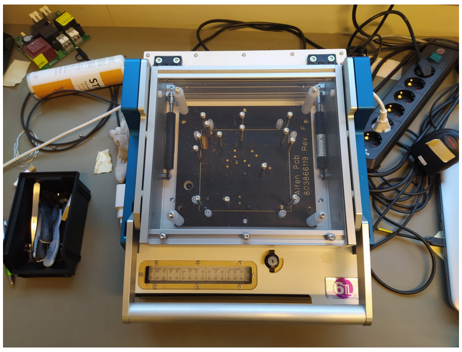
As shown in Section 4.6, the testing of the PCBAs is one of the bottlenecks of GE. Customer 75 requires all PCBAs tested before packing and delivery of the products. The PCBAs are tested with a testing machine that is connected to a computer with a specific testing software. The testing machine is shown in Figure 5.14 and is provided by customer 75. In the following paragraphs we first discuss the testing procedure after which we will continue with the labour cost of the procedure followed by the possibility of automation.

5.3.1 Testing procedure

This section will first explain the testing procedure and the steps the PCBA goes through during this procedure. All PCBAs are tested before shipping to check if all components are assembled correctly and to check if there are errors in the components on the PCBA.



(a) Testing mall open



(b) Testing mall closed

Figure 5.14: Testing mall for product 910

The testing procedure is executed by two operators. Before the PCBAs can be tested, one of the operators first cuts the PCBAs into single pieces and checks them for deviations resulting from assembly or the soldering of the components. It is for example commonly seen that the pins are too long or that components are forgotten during assembly. These deviations are corrected by hand after which the PCBA is ready to be tested.

After the touch up of the PCBA, the PCBAs are collected for testing. The second operator picks the PCBAs and screws a fuse into each PCBA. Next, the PCBA can be tested one by one. If the operator puts the PCBA into the testing mall, the QR-code of the PCBA is scanned with a scanner after which the operator closes the valve and starts the testing programme at the computer. If the testing machine is finished, a signal will be given that communicates if the PCBA is approved or returns an error. If the PCBA is approved, it can be packed and the operator puts it in a box. If an error contains it will be repaired and tested again. When the box is full, it will be placed on a pallet and send to the customer. In the next section we will continue with the testing cost of this procedure.

5.3.2 Test cost

The labour cost of the testing procedure can be determined such as the preparation of components using the processing times in Table 5.11. These times can be translated into the amount of FTE needed by dividing the preparation time by the yearly working hours. Finally, the labour cost that can be saved when automating the testing can be calculated by multiplying the FTE needed by the yearly cost of an employee.

As shown in the table above, the total labour cost of the testing procedure is € 15,856.10 for cutting and touching-up the PCBAs plus € 19,779.78 for the testing itself which is in total € 35,635.88. Looking at these numbers, it is shown that with the number of PCBAs GE expects to produce there is always one person needed.

5.3.3 Using cobots for testing

As described earlier, the testing of the PCBAs is done manually and is done with two employees. If GE wants to increase the production flow, the testing is a simple and highly

Table 5.11: Test cost product 910

	Cutting / touch-up	Testing
# of PCBAs 2022	96882	96882
# pieces processed	6	6
Average processing time pieces (sec)	159.18	198.57
Average processing time 2022 (sec)	2568688	3204324
Average processing time 2022 (hr)	713.52	890.09
# FTE / year	0.40	0.49
Labour cost / year	€ 15,856.10	€ 19,779.78

repetitive task that can be automated easily. Automation of the testing procedure will decrease the amount of people needed, will decrease the processing times and improve the quality of work.

Currently, GE does not have experience with robots. Therefore, it is important to keep in mind that the technology must be easy to use and easy to implement. Because of the simplicity of the process, it is not needed to introduce a complex and expensive technology. An interesting technique commonly used in production is the Collaborative Robot (cobot). These robots can imitate the task of a person and therefore reduce the amount of employees at the testing procedure to one employee.

The automation of the testing procedure can be done at different levels. In Figure 5.15 these different phases are shown where phase 0 is the current situation. Each phase does follow-up the phase before, meaning that phase b cannot be achieved when phase a is not yet designed.

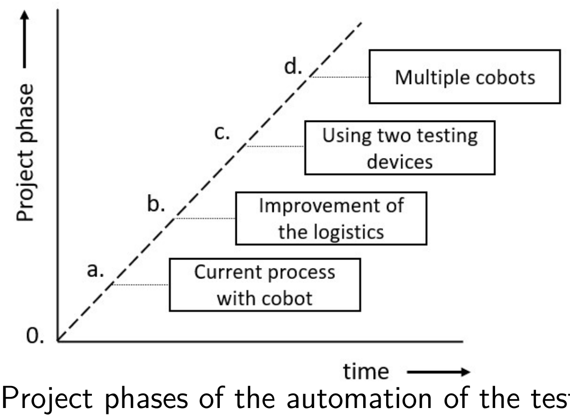
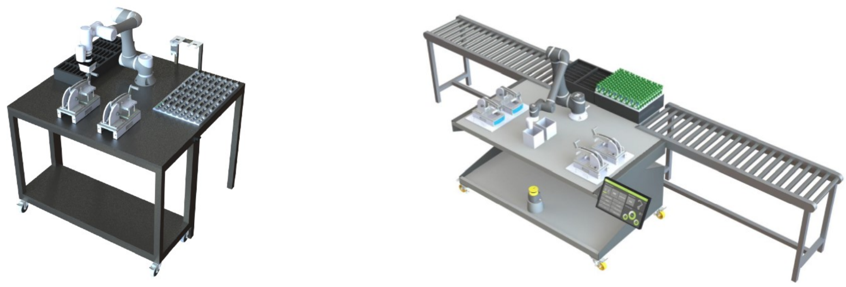


Figure 5.15: Project phases of the automation of the testing procedure

The minimum that the cobot must be able to do are the exact same actions that is currently executed by the operator. These actions are noted as phase a. The future phase of the automation process is a set-up with which the different PCBAs of customer 75 can be tested simultaneously with both testing machines that are available. With this end-goal it is also important to look at the logistics around the testing procedure such as the supply and disposal of the PCBAs.

It is important to keep in mind that if GE wants to implement a cobot, the process must be user-friendly. The adoption of new technologies is a process itself and employees should not start thinking that it is easier to do the task themselves. To make the process not too complex, but to relieve the operators that do the cutting and touch-up of the PCBAs before testing, it is desired to make a concept that is similar to phase c. Together with a cobot supplier, two different concepts are designed. The first concept (phase a) imitates the current process while in the second concept (phase c) the supply and discharge of the PCBAs has been expanded. In Figure 5.16 both concepts are visualised with an illustration.



(a) Concept A (b) Concept C

Figure 5.16: Concepts of two cobot set-ups

Concept A is a much simpler design in which the employee needs to change the bins every 18 PCBAs while with concept C the bins need to be replaced after 54 PCBAs. The seconds concept can work stand alone for approximately thirty minutes meaning that the cobot can work during the breaks and after closing time of the factory.

To say more about the investment, the simple payback period is calculated for both concepts. To be able to calculate the payback period, the investment cost are needed. The investment cost for concept A are € 76,841.00 and the investment cost for concept B are € 90,615.00. After calculating the simple payback period, the cash flow will be incorporated. It is important to keep in mind that only product 910 is incorporated in the calculations. However, the designs also take into account the possibility to test the readers. Therefore, the payback periods will decrease if the readers will be included later on. In Table 5.12 the simple payback period for both concepts is shown. The payback period is calculated by dividing the investment of a cobot by the labour cost that will be saved using a cobot.

Table 5.12: The simple payback period for cobots

Concept	**Payback period**	**years**
A	€ 76,841.00 / € 19,779.78 =	3.9
C	€ 90,615.00 / € 19,779.78 =	4.6

As noticeable, the simple payback periods lie within a range of approximately four years. Looking at the PW and the discounted payback period, an effective interest rate of five percent is included and the cobot has an expected life cycle of 28 years. The extra cost such as maintenance cost and electricity are negligible. Table 5.13 shows the results of the discounted payback period and the PW method for Concept A and C.

Also for the cobot the payback periods are slightly longer if the cash flow is taken into account. The payback periods are now five or six years for concept A and C

Table 5.13: The discounted payback periods and PW for cobots

Concept	PW	Payback period
A	€ 8,795.10	5
C	€ 9,780.83	6

respectively. Furthermore, to see if the concept does optimise the production flow, the cobot will be incorporated in the simulation model. Further explanation and the effect of implementing a cobot at the testing procedure will be given in Section 6.2.

5.4 Conclusion

To keep up with the growth GE faces already, it is concluded that there are three processes that require capacity increase to improve the production flow. One of the processes that is in need of a capacity is the warehouse. The VLM and pallet racks are the most suitable ways of creating more capacity with less floor space needed. Three VLMs will increase the storage capacity from 285.66 m^2 to 371.14 m^2. Including pallet racks in the warehouse increases the capacity to 382.66 m^2.

Another process suitable for automation is the preparation of components. Currently, GE uses semi-automated machines which can be changed to fully automated machines. For the axial components 12.5 times more components per hour can be processed and when using the CF-8 for product 910 only, the payback period lies between six to eight years which is higher than the target of two until five years. For the radial components, two different machines were found of which the Ebsomat 120 can be used for components delivered in tubes and the CF-10 for components in tubes and bulk. Per hour the Ebsomat 120 produces 2.4 times more than when doing it manually and the payback period is approximately three years. The CF-10 can produce 3.3 times more for components in tubes and twelve times more for components delivered in bulk. However, the payback period lies between twelve to eighteen years which is far outside the target of maximal five years. Looking at these payback periods, only the Ebsomat 120 is recommended. However, when using the machines for other products as well, the CF-8 for axial components also has a payback period of approximately three years, which is equal to the desired payback period given by GE.

The final process is the testing procedure. The testing procedure reduce the amount of employees needed and increase the available testing hours. These employees can be used to decrease the bottlenecks at the other processes. Two different concepts in two different phases are made. The first concept which imitates the current process including a cobot requires more support of an employee in terms of the supply and removal of the bins. The second concept shown can operate stand-alone for about half an hour because of the conveyor belts before and after the testing machines. The payback period for both concepts are four to five years for concept one and four and a half to six years for concept two, if only the 910 is tested. If the cobot will be used for the other products of customer 75 as well, then the payback periods will decrease to the desired payback period of two until five years. It is recommended to implement concept c because of the expected acceptance by the employees.

6 Implementing the opportunities

With the bottlenecks mentioned in Chapter 4 and the opportunities for optimisation discussed in Chapter 5, we can now use the simulation to validate the optimisation of these technologies. After this chapter, the following research question is answered.

What is the impact of the optimisation possibilities for the production flow at Global Electronics B.V.?

In Section 4.6, the bottlenecks were determined to be the preparation of components, the manual assembly and the testing of the PCBAs. The warehouse was determined to be a problem as well, but this was not incorporated in the simulation. Chapter 5 discussed possible optimisation techniques that can be useful to eliminate the bottlenecks. To evaluate the impact of these techniques, the simulation will be used. For the manual assembly the automated preparation machines will be implemented and for testing a cobot will be used. In Section 6.1, the preparation of components is implemented after which the testing procedure is examined in Section 6.2. Lastly, the impact of the new technologies on the manual assembly will be looked at in Section 6.3. During these simulations, five different investment options were implemented. After implementing these five options and evaluating the results, it is decided to add an extra investment option to the list which will be further elaborated in the final section.

6.1 Automation of the preparation of components

As noted in Section 6.1, three automated machines that are able to improve the preparation of components were mentioned. However, only two machines were recommended for the investment based on the payback periods and the PW of the machines after a life cycle of ten years. The preparation machines that will be simulated are therefore the CF-8 for the preparation of axial components and the Ebsomat 120 for the components prepared in radial direction. For each machine, the parts per hour were mentioned which are used as input for the simulation. Table 6.1 shows the parts per hour the machine can process and the translation into the preparation time needed for a single component.

Table 6.1: Processing times automated preparation machines

Machine	Processing	Parts per hour	Time per part (sec)
CF-8	Axial	25,000	0.0024
Ebsomat 120	Radial tubes	3,600	0.0167

Still one person is needed for the preparation of components to supply the machines with components. Because of this, it means that three employees can now be assigned to the manual assembly instead of the preparation of components. In Section 6.3 the optimisation by the use of the simulation will be executed. The new processing times of the machines will then be used as input for the preparation process called *PrepComponents* and the extra employees will be assigned to the manual assembly.

6.2 Automation of the testing procedure

As shown in Section 6.2, an interesting option for automation is the use of a cobot. A cobot can reduce the amount of employees needed to one employee instead of two. The cutting, touch-up, supply and removal of the PCBAs still needs to be done manually, but the second employee can support the manual assembly to decrease the bottleneck at the manual assembly.

Assumptions need to be made when determining the processing times of the cobot. It is expected that the processing time of the cobot is approximately two third of the current processing time mentioned in Section 6.2. Therefore, there will be looked at two investment options which are the cobot working on two third of the speed using one or two testing machines. For the cobot, the processing times are split up in the time the test machine needs and the expected time that a cobot needs. In Table 6.2, the processing time of the test machine and the expected processing time of the cobot are shown.

Table 6.2: Processing times of the cobot and a single testing machine

	Cobot	**Test machine**
Average processing time	49.50	4.77
Standard deviation	5.76	0.18
Lower bound	32.21	4.22
Upper bound	66.79	5.32

The processing times mentioned above, will be used as input for the simulation. In the next section there will be looked at both investment options. Finally, a decision will be made about the amount of testing machines use.

6.3 Implementing technologies in the simulation

With the processing times noted in the sections above, new simulations can be executed to see the effect of automation on the production flow. Different investment options will be looked at which are further explain in the remaining of this section. It is decided to implement the new technologies for the simulation in April 2022 because it is assumed that GE will keep growing and therefore does not go back to the situation as it was in September 2021.

The first investment option includes the automated testing machines. Both, the CF-8 for axial components and the Ebsomat 120 for radial components are implemented. These machines do require in total only one employee for the supply and removal of components meaning that three extra employees are assigned to the manual assembly. These employees consist of two beginners and one experts, resulting in a total of four beginners and three experts that are now assigned to the manual assembly that was determined to be the main bottleneck.

For the second and third investment options, there will be looked at the cobot for which the processing times in Table 6.2 are used. The second investment option looks at the cobot using one testing machine while the third investment option will use two testing machines instead of one. In both cases, one expert employee that was assigned to the testing is now assigned to the manual assembly.

The fourth and fifth investment options will include both automated technologies. The fourth investment option will look at automated preparation and automated testing with one testing machine and the fifth investment option expands the testing with an extra testing machine.

All investment options above will be implemented in the simulation model as used in Chapter 4. The testing machine is replaced by a cobot as shown in Figure 6.1. For the preparation of components the processing times were changed.

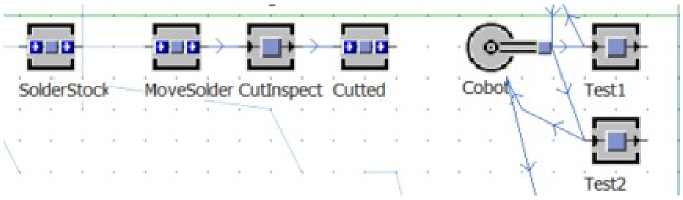


Figure 6.1: Implementation of a cobot in the production of GE

As can be seen in the figure, there are two test machines (*Test1, Test2*) available. However, GE can choose the amount of test machines they want to use.

After running the simulations for the different investment options as mentioned above, the production flow will be examined by the use of the different bottleneck analysis as in Section 4.6. In the following subsections, the different investment options will be further explored. In these cases as well, the simulation will be executed for sixty days to end up in a steady-state.

6.3.1 Automated preparation

To analyse the production flow after incorporating automated preparation machines, we look at the location of the products in the production process and the utilisation of the processes itself at the entire manual department. As mentioned above, three employees of which two beginners and one expert are extra assigned to the manual assembly. Therefore, it is expected that the amount of stock before the manual assembly stations will decrease. After running the simulation for sixty days, the buffers and utilisation rates of the manual assembly stations will be checked. The location of the PCB(A)s in the system and the utilisation of the stations will determine the improvements of the production flow after optimisation. In Figure 6.2 the amount of PCB(A)s in each of the buffers is shown.

As shown in Figure 6.2, the extra employees assigned to the manual assembly have a large effect on the stock before the manual assembly. Before the optimisation, the bottleneck was noted to be the manual assembly while the bottleneck now shifts to the testing procedure of the PCBAs. Automating the preparation results in a total amount of 28,932 PCBAs produced which is equal to the current situation. Because of the bottleneck at the testing and the maximum speed of this process, it is logical that the amount of produced PCBAs did not change.

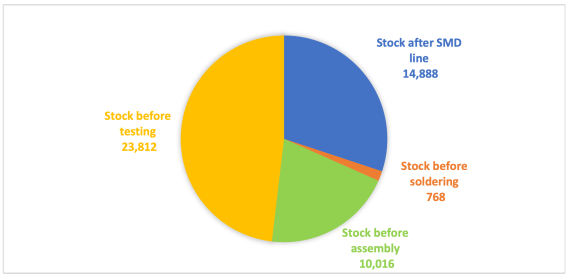


Figure 6.2: Stocks after the simulation with automated preparation

Besides the location of the products in the process, it is also important to look at the utilisation of the stations. As mentioned before, GE has a target of a utilisation of ninety percent. For each process at the manual assembly department, the utilisation rates are mentioned in Table 6.3.

Table 6.3: Utilisation per station with automated preparation

Process	**Utilisation %**
CutPCBs	25.34
PrepComponents	100
MAexpert	99.99
MAbeginner	100
MAexpert1	100
MAbeginner1	100
Soldering	71.07
CutInspect	100
Cobot	-
Test	99.90

Still, the preparation of components, the manual assembly and the testing have a utilisation above 95 percent which is still too high. The preparation of components has a utilisation of hundred percent because one employee is currently preparing the components full-time. However, a buffer of approximately 20,000 components has been built up meaning that it is not needed to prepare components full-time with the automated machines. Therefore, when automating the preparation of components, the bottleneck is eliminated and the testing is the most important bottleneck to focus on. Therefore, in the next section, we will look at the effect of a cobot on the production flow.

6.3.2 Automated testing with one testing machine

The second investment option incorporates a cobot for the testing procedure of the PCBAs. One employee is replaced by a cobot that will support the other employees at the manual assembly. It is also expected that the processing time of the testing will decrease resulting in more output. First, only one testing machine is used. After running the simulation for sixty days, we looked at the stocks in between the departments and the utilisation of the different stations. The stocks between the processes are shown in a pie chart in Figure 6.3.

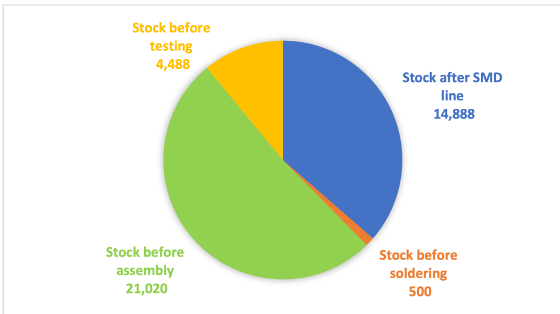


Figure 6.3: Stocks after the simulation when using a cobot - 1 test machine

It can be seen that the stock before assembly is much higher when automating the testing. Compared to the automated preparation, only one extra employee is assigned to the manual assembly instead of four. It can be concluded that with the automation of the testing, the production flow is not yet optimal. The amount of PCBAs produced after sixty days increased to 37,108 because the flow at the testing is more smooth after automation. Besides, the cobot works during the breaks and after closing for half an hour and is therefore able to eliminate the buffers such that production can start without PCBAs before testing the day after. The stock before assembly did decrease compared with the current current situation, but is still the main bottleneck process. Next, the utilisation of the stations will be discussed. The utilisation of the stations can be found in Table 6.4.

Table 6.4: Utilisation per station using a cobot - 1 test machine

Process	**Utilisation %**
CutPCBs	24.61
PrepComponents	100
MAexpert	95.39
MAbeginner	95.92
MAexpert1	95.68
MAbeginner1	95.67
Soldering	52.43
CutInspect	88.76
Cobot	19.75
Test	0.87

Compared to the first investment option, the utilisation rates of the manual assembly did slightly decrease. However, most processes still have a utilisation above ninety percent which is too high. The cobot and the test machine on the other hand have a significant low utilisation rate meaning that the cobot over achieves. Unfortunately, there still is a buffer of approximately 4,500 PCBAs that needs to be tested. The throughput did increase, but the cutting and touching-up of the PCBAs cannot keep up with the speed of the cobot. Because of this, an extra investment option will be added in which the person replaced by the cobot, will now be assigned to the cutting and touching-up of the PCBAs.

The next investment option will look at two testing machines. It is however not yet interesting to look at two testing machines if we look at the utilisation rates when using one testing machine. The findings of this investment option is shortly discussed in the following section.

6.3.3 Automated testing with two testing machines

To expand the second investment option, an extra testing machine can be incorporated meaning that twice as many PCBAs can be tested. In the previous section it was shown that the utilisation rates appeared to be extremely low. However, it is still interesting to compare these results in later investment options. The extra employee will again be used at the manual assembly. After running the simulation for sixty days, the stocks in between stations are noted and can be found in Figure 6.4.

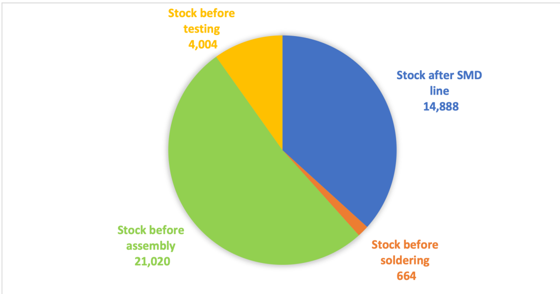


Figure 6.4: Stocks after the simulation when using a cobot - 2 test machines

As expected, the results did not change much looking at the buffers. The bottleneck still is the manual assembly when using two cobots. The stock before testing did slightly decrease because two PCBAs could be tested at the same time. The total amount of PCBAs produced in investment option three is 37,592 pieces which is slightly more than the previous investment option. This can be explained by the improved flow of the testing procedure. For more explanation, it is important to look at the utilisation rates too. The utilisation rates of the different stations can be found in Table 6.5.

Table 6.5: Utilisation per station using a cobot - 2 test machines

Process	**Utilisation %**
CutPCBs	24.61
PrepComponents	100
MAexpert	95.39
MAbeginner	95.92
MAexpert1	95.68
MAbeginner1	95.67
Soldering	52.43
CutInspect	88.76
Cobot	19.89
Test1	7.20
Test2	6.97

It can bee seen that the utilisation rates are comparable. Only the testing procedure shows some small differences. The utilisation of the testing machines did slightly increase because the PCBA had to wait for the cobot to return before packing. The following investment options will look at the automated testing including the automated preparation machines.

6.3.4 Automated preparation and testing with one testing machine

Investment option four looks at the automated preparation in combination with the use of a cobot. The production flow will be examined using one testing machine. In total, four experts and four beginners are assigned to the manual assembly and one employee to each of the stations preparation of components and the procedure. After running the simulation for sixty days, the location of PCB(A)s in the buffers is shown in Figure 6.5, the distribution of the products is shown.

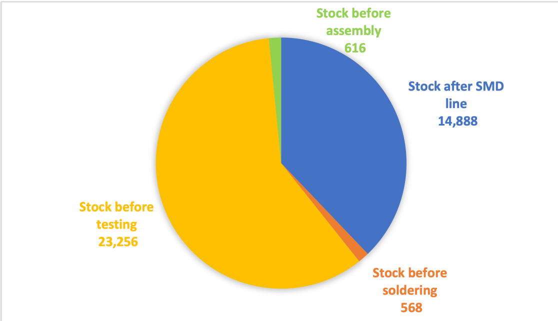


Figure 6.5: Stocks automated preparation and testing - 1 test machine

It can be seen that if eight people are assigned to the manual assembly, the bottleneck is completely eliminated and shifted to the testing procedure. The stock after the SMD-line is now compared to the other processes the second bottleneck of the production flow. However, the focus of this research lies at the manual assembly department and will therefore not be taken into account in this research. After running this simulation, 38,340 PCBAs were produced. While the bottleneck shifted to the testing procedure, the throughput using a cobot still increased significantly because without optimisation, the testing was the bottleneck of the testing procedure. Compared to the first investment option, the stock before the manual assembly stations is much lower because there is one extra employee assigned. To give more insight in the bottleneck procedure, the utilisation rates are given in Table 6.6.

As can be seen in the table, the utilisation rates of the manual assembly are moving to the desired utilisation rate. The preparation of components is still hundred percent, but the buffer built up is high enough to prepare components only part time and support the other processes. It can also be seen that the utilisation of the cobot and the test machine is extremely low and the utilisation of the CutInspect above the desired rate. Therefore, it can be concluded that the bottleneck shifts towards the cutting and touching-up of the PCBAs. The following option will look at two testing machines.

Table 6.6: Utilisation per station automated preparation and testing - 1 test machine

Process	**Utilisation %**
CutPCBs	24.61
PrepComponents	100
MAexpert	92.35
MAbeginner	93.65
MAexpert1	93.99
MAbeginner1	94.02
Soldering	78.08
CutInspect	91.77
Cobot	20.38
Test	0.90

6.3.5 Automated preparation and testing with two testing machines

During this investment option, both testing machines will be incorporated and the preparation of components is done automatically. It is expected that the results will be the same as for the fourth investment option so the results will be discussed shortly. In Figure 6.6, the location of the products in the buffers is shown.

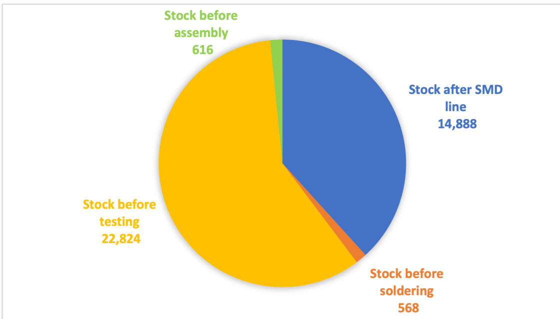


Figure 6.6: Stocks automated preparation and testing - 2 test machines

In this case as well the bottleneck appears to be at the testing procedure. Using eight people at the manual assembly does eliminate the main bottleneck as we concluded before. The total amount of PCBAs produced in by this simulation is 38,772. This is slightly more because two PCBAs can be tested at the same time as was also visible in investment options two and three. Because two testing machines were used, the amount of stock before the testing procedure did decrease slightly, but not enough to eliminate the bottleneck because of the processing time of the cutting and touching-up of the PCBAs. Lastly, the utilisation rates will be discussed which can be found in Table 6.7.

In this case, it can be seen that the utilisation rates of the testing machines increased compared to investment option four. This is logical because the testing machine has to wait for a short amount of time until the cobot is available. The other utilisation rates do not differ because the settings around these processes did not change compared to the previous investment option.

Because the flow of the production processes is still not equal and the bottleneck shifted to the cutting and touching-up of the PCBAs, it is decided to add another investment

Table 6.7: Utilisation per station automated preparation and testing - 2 test machines

Process	Utilisation %
CutPCBs	24.61
PrepComponents	100
MAexpert	92.35
MAbeginner	93.65
MAexpert1	93.99
MAbeginner1	94.02
Soldering	78.08
CutInspect	91.77
Cobot	20.5
Test1	7.35
Test2	7.14

option in which one beginner from the preparation of components will be assigned as an extra employee for the cutting and touching-up the PCBAs instead of the manual assembly. It is expected that the stocks will then be more divided over the different processes. In the next section, investment option six and the settings of this option are further explained.

6.3.6 Automated preparation and testing alternative

As already mentioned above, two employees will now be assigned to the cutting and touching-up station. The output of the manual assembly increased such that the cutting and touching-up station could not keep up with the speed. Besides, the utilisation rates of the cobot and the testing machines are too low and therefore the use of the cobot is currently not efficient. It is decided to expand investment option four where one testing device is used. During this new investment option, seven employees are assigned to the manual assembly, while two employees are assigned to the cutting and touching-up. After running the simulation for sixty days, the location of the PCBAs can be found in Figure 6.7.

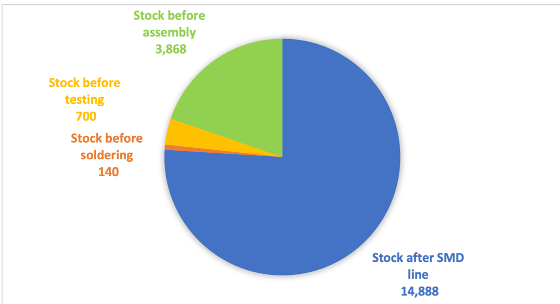


Figure 6.7: Stocks after assigning an extra employee to cutting/touch-up

As can be seen in the figure, the entire flow at the manual department is more fluent implementing this option. The bottleneck is shifted to the check station at the SMD department. The output at the manual assembly stations did decrease slightly because there is one employee less at the manual assembly stations, but the output of the simulation has increased significantly. Currently, GE produces 28,932 PCBAs in sixty days which can be improved to 58,336 with the settings from investment option six. Finally, the utilisation rates are shown in Table 6.8.

Table 6.8: Utilisation per station extra employee to cutting/touch-up

Process	Utilisation %
CutPCBs	24.61
PrepComponents	100
MAexpert	95.36
MAbeginner	95.91
MAexpert1	95.68
MAbeginner1	95.66
Soldering	73.91
CutInspect	80.49
Cobot	31.04
Test	1.37

The biggest improvement shown in the table above is the CutInspect station. The utilisation rate is decreased to 80.49 percent and the utilisation of the cobot increased to 31.04 percent. The utilisation rates of the manual assembly did slightly increase and thus it is still valuable to add extra employees at the manual assembly. However, it can be seen that the process CutPCBs has a utilisation of 24.61 percent meaning that the employee assigned to the cutting of the PCBAs can also support with the manual assembly while waiting. Furthermore, the preparation of components is done continuously and therefore a buffer is built up. The employee preparing the components can also switch between preparation and manual assembly.

6.4 Conclusion

This chapter implemented the optimisation possibilities discussed in Chapter 5 in the simulation model of Chapter 4. Automating the preparation and testing procedures reduces the processing times used as input for the simulation. For the testing of the PCBAs, a new set-up is implemented.

Multiple investment options are compared based on the KPIs processing time, utilisation and output. Both processes are incorporated in the simulation model individually and together in order to properly analyse the effect of the optimisation. The running time of the simulation is set at sixty days just as in Chapter 4.

Investment option one focuses at automating the preparation of components. Three extra employees are assigned to the manual assembly to reduce the bottleneck. If the preparation of components is automated and the manual assembly is reinforced with three employees, the bottleneck process does shift to the testing procedure and the amount produced is the same.

In the second and third investment options, only the testing procedure is automated using a cobot. Investment option two discusses the use of one testing machine while option three discusses two testing machines. One of the employees can be assigned to the manual assembly when automating the testing procedure. The bottleneck process stays the same however, production increased with almost 10,000 PCBAs.

Investment option four and five look at a combination of both techniques using one or two testing machines respectively. Four extra employees can be assigned to the manual assembly. Therefore, the bottleneck process is again shifted to the testing and again, more PCBAs are produced.

Finally, a sixth investment option is added. In this case, seven employees are assigned to the manual assembly and two employees are assigned to the cutting and touching-up of the PCBAs. In this case, the production flow at the manual department increased and many more PCBAs could be produced compared to the other options.

A summary of the results of all six investment options is shown in Table 6.9. The table shows the utilisation rates, the number of products finished and the bottleneck process resulting from the simulations. In this table, the six options are compared to the current situation I0 in which I1 looks at automating the preparation of components, I2 and I3 at the automation of the testing and I4 until I6 at the automated preparation and testing together with multiple settings.

Table 6.9: Summary of the utilisation rates in percentage of investment options 1 - 6 *note that in the first two options the testing includes the action of the operator

Process	**I0**	**I1**	**I2**	**I3**	**I4**	**I5**	**I6**
CutPCBs	25.26	25.34	24.61	24.61	24.61	24.61	24.61
PrepComponents	100	100	100	100	100	100	100
MAexpert	100	99.99	95.39	95.39	92.35	92.35	95.36
MAbeginner	100	100	95.92	95.92	93.65	93.65	95.91
MAexpert1	100	100	95.68	95.68	93.99	93.99	95.68
MAbeginner1	100	100	95.67	95.67	94.02	94.02	95.66
Soldering	43.14	71.07	52.43	52.43	78.08	78.08	73.91
CutInspect	98.53	100	88.76	88.76	91.77	91.77	80.49
Cobot	-	-	19.75	19.89	20.38	20.50	31.04
Test1	99.99*	99.90*	0.87	7.20	0.90	7.35	1.37
Test2	-	-	-	6.97	-	7.14	-
Bottleneck	MA	Testing	MA	MA	Testing	Testing	SMD
Produced	28,932	28,932	37,108	37,592	38,340	38,772	58,336

Resulting from the simulation, it is concluded that it is most efficient to automate the preparation of components and the testing using one testing device. It is most efficient to assign seven employees to the manual assembly and two employees to the cutting and touching-up of the PCBAs. The employees that are assigned to the preparation of components and the cutting of the PCBs before assembly, can help with the manual assembly on a part-time basis.

7 Conclusion

In this chapter, the following will be discussed: the conclusion, the discussion with the limitations of this research, the contribution to theory and practice and finally, recommendations for further research. The next section starts with the conclusion of this research. At the end of this chapter, the following research question will be answered.

'How is Global Electronics B.V. able to make a digital and smart industrial transformation to keep up with the fast changing manufacturing due to Industry 4.0?'

7.1 Research conclusion

To be able to answer the research question, multiple sub-questions were set up. First, an extensive analysis of the current situation of GE was executed. The growth of the company results in challenges such as component shortages, but it also became clear that processes are not yet optimised to keep up with this growth. Especially the production process of GE shows challenges such as inefficient tasks or long processing times because most processes are done manually. It is a challenge to introduce new technologies, especially within SMEs. The complexity of technologies keep growing, but also the investment decisions do have a lot more impact on smaller companies.

With these challenges in mind, research was done to look at available and applicable technologies to improve the production process of the shop floor of GE. One of the most common technologies in production facilities are industrial cobots that work in collaboration with employees. Cobots can take over heavy and uncomfortable tasks, but can also execute very simple and highly repetitive tasks. Another technology applicable for GE are automated warehousing systems. Automated warehousing systems can store components very efficiently and increase the available capacity.

To determine which technologies could be feasible for GE, a simulation was developed to identify the bottlenecks in the production process. A simulation was made of the entire production process from the order picking until shipment. Resulting from the simulation, it was concluded that the main bottleneck process is the manual assembly, followed by the testing of the PCBAs. The utilisation rates, bottleneck process and the number of PCBAs produced are summarised in Table 7.1.

Automation of the manual assembly was determined to be infeasible and therefore can only be improved by assigning more employees to the manual assembly. Currently there are four employees preparing components and two employees testing the PCBAs. For the difficulty of the tasks, the volumes produced and the amount of employees needed are both useful processes for automation.

When the bottlenecks were determined, different options for automation were found. For the preparation of components multiple fully-automated machines can be used to decrease the amount of employees needed, but improve the output and the quality of work. Three employees can be saved using these machines who can be assigned to the manual assembly. The testing of the PCBAs can be executed by a cobot replacing one employee that can be assigned to the manual assembly as well. The cobot works in

Table 7.1: Utilisation of the stations with the current production process

Process	Utilisation %
CutPCBs	25.26
PrepComponents	100
MAexpert	100
MAbeginner	100
MAexpert1	100
MAbeginner1	100
Soldering	43.14
CutInspect	98.53
Test	99.99
Bottleneck process	MA
Finished products	28,932

collaboration with the employee at the cutting and touching-up of the PCBAs.

After investigating possible technologies, adjustments can be made to the simulation model. The processing times of the preparation of components are changed and a cobot was included in the production flow. Several investment options are set-up with the assumption that the cobot will be faster than an employee. The scenario in which the preparation of components is done automatically and a cobot is implemented. Table 7.2 shows a summary of the outcomes of the different investment options in which I0 is the current situation. In I1 the preparation of components is done automatically, I2 and I3 incorporates a cobot using one and two testing machines respectively. I4 and I5 include automation in both processes using one and two testing machines respectively and in I6 both processes are automated and one testing device is used, but instead of assigning eight employees to the manual assembly, one was assigned to the cutting and touching-up of the PCBAs.

Table 7.2: The outputs and bottleneck processes of the investment options for GE

Process	**I0**	**I1**	**I2**	**I3**	**I4**	**I5**	**I6**
Bottleneck process	MA	Testing	MA	MA	Testing	Testing	SMD
Finished products	28,932	28,932	37,108	37,592	38,340	38,772	58,336

Finally, it can be concluded that to improve the production flow and grow towards I4.0, it is most valuable to immediately automate the preparation of components after which the cobot is important to introduce.

7.2 Discussion

The simulation is a useful tool to determine the weak spots in the production flow of GE. It can be expanded by adding the other products from customer 75 to the simulation. If all products are incorporated, a more precise recommendation can be given. It would then also be possible to use the simulation as the first input of a production planning system at GE.

Before GE is going to invest in the warehouse, it is important to conduct a research about the layout of the warehouse and the location of the components within the warehouse.

7.3 Contribution to theory and practice

During the literature study it was noticeable that the industrial revolution is a big challenge for SMEs, where larger companies have much more resources and are therefore often further along in the industrial revolution. A lot of theory is available, but it is not easy to translate is to your own SME. This research could be valuable for other SMEs and especially other EMS companies due to the comparable processes.

This research contributes to an improvement of the production process of GE. It is shown with the simulation that the production flow can be improved significantly by introducing automated preparation machines and the cobot. Also, more scenarios can be evaluated by using this model with some small adjustments. It is therefore suggested to also incorporate other products of GE to further improve the production process.

7.4 Future research

As already mentioned, it is useful to include the other products in the simulation. If the other products are implemented, it is possible to further improve the production process, but also start production planning. The simulation model can be used to create an understanding of the processing times of different order sizes.

Besides the planning of production, it is also important to get a better understanding of the purchasing process. Strategic planning can be useful to get more insights in the lead time of components and to reduce the amount of components delivered too late.

When GE decides to improve the warehouse efficiency, further research need to be done in the field of manufacturing facility design. Good considerations must be made regarding the placement of storage systems. The location of components can also be determined by further research.

Finally, it was seen that the bottleneck shifted to the SMD department. Therefore, it is very important to incorporate the SMD department when further improving the production flow.

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