A FEASIBILITY STUDY TO THE IMPLEMENTATION OF A NEW PRODUCTION FACILITY FOR HIGH VOLUME PCBAs

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5-10-2022

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Title:
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Publication date:
5-10-2022

MANAGEMENT SUMMARY

Global Electronics is a small and medium enterprise (SME) that is specialised in the assembly of printed circuit boards (PCBs). The company has grown a lot in the past few years, which is visible in higher demand and larger order volumes. Customer 75 is currently the biggest customer of GE and has the largest order volumes. For this customer, the focus is slightly shifting from high mix-low volume to low mix-high volume. Because of these changes, there is a lack of space, and capacity will become too low in the long run. Next to this, there is a lot of manual work required, components cannot be traced, and there is no integration of sub-processes. The core problem is that GE is behind in market innovations. Because the company wants to gain strategic insight in the feasibility of opening a new facility, they want to know how such a new facility would look like. Therefore the research question is: "What is the feasibility of opening a new facility for the production of high volume PCBAs?".

Alternative state-of-the-art equipment was researched, of which a few methods and technologies were found to be promising: an automatic wheel cutting machine, a cobot for testing, manual assembly (MA) and soldering in-line via a conveyor belt, and an automated guided vehicle (AGV) for internal transport. These potential concepts were further evaluated using a simulation. The evaluation is done using three cost factors:

- Investment of the machines
- Space requirements of the buffers
- Cost of personnel during the production time

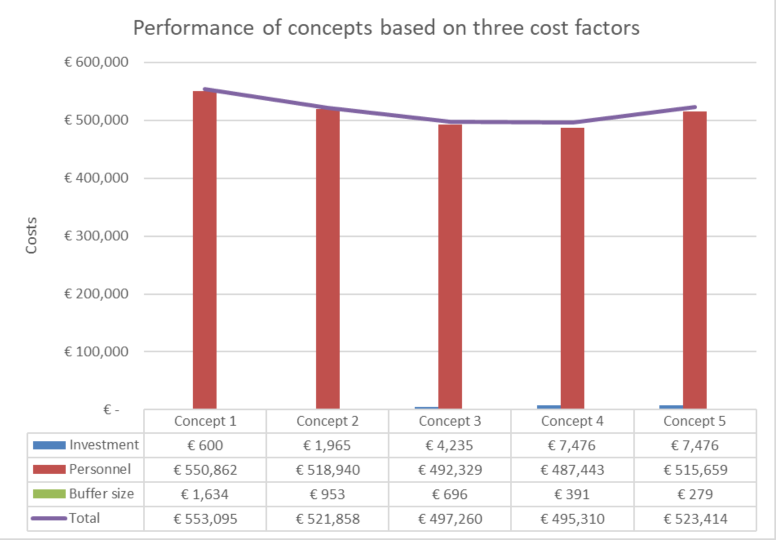
The simulation researches five concepts. Each concept adds a new method or technology compared to the previous concept.

1. The first concept uses the same processes as in the current facility, but an AGV is used for material handling between departments in the newly designed layout.
2. Then, instead of manual testing as in the first concept, a cobot is used for the testing.
3. Added to the second concept, is the automatic wheel cutting machine.
4. In concept 4, MA and soldering are placed in-line using a conveyor belt.
5. The fifth concept places all investigated technologies in-line.

The results of the simulation, as seen in Figure 0-1, show that adding the cobot for testing, AGV, and the automatic wheel cutting machine reduce total costs with 5.6% and 4.7%, respectively compared to the previous concept. For the concept with MA and soldering in-line, the costs decrease with 0.4%. However, some flexibility of production is lost because of the conveyor belt. Only one type of product can be produced at the same time because of the soldering machine. This machine requires different settings for different products. For the

concept with all technologies in-line the total costs increase with 5.7% compared to the previous concept.

What can be seen in the figure is that the cost of personnel is an important cost factor and that the costs of the buffers and investment are negligible for the total costs. However, only three cost factors are included, so the total cost give a biased view. However, it is true that cost of personnel accounts for almost 60% of the total costs at GE currently.



	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Investment	€ 600	€ 1,965	€ 4,235	€ 7,476	€ 7,476
Personnel	€ 550,862	€ 518,940	€ 492,329	€ 487,443	€ 515,659
Buffer size	€ 1,634	€ 953	€ 696	€ 391	€ 279
Total	€ 553,095	€ 521,858	€ 497,260	€ 495,310	€ 523,414

Figure 0-1 Cost performance of concepts based on: investment, personnel and buffer size

From the cost performance, and the payback period in Figure 0-2, it can be concluded that a testing cobot, AGV and automatic wheel cutting machine are justified investments. The costs decrease and the payback periods of both concept 2 and 3 are within the preferred payback time of five years. After a more thorough market research, these technologies can be implemented in the short term. The concept where MA and soldering are placed in-line is also a cost decreasing investment, but the payback period is longer than preferred. Placing all machines in-line is not an improvement in terms of these three cost factors, because extra personnel is required for a decrease in production time.

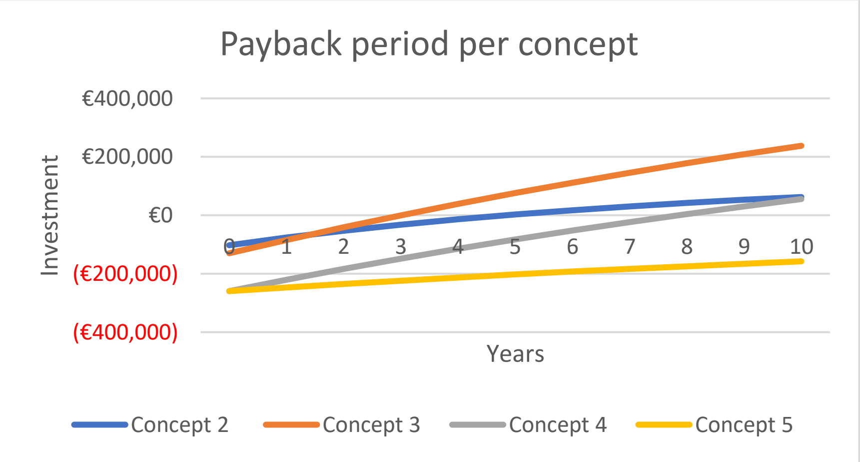


Figure 0-2 Payback period per concept

During the course of this research, the viewpoint of the company changed. They realised that there is a lot more room for improvement in the current facility. They are therefore also interested in the possibilities of these investments in the current facility. Since the effect of these new technologies have not been researched with a simulation, only an advice is given.

- It is advised to implement the automatic wheel cutting machine and testing cobot in the current facility after a thorough investigation. This could increase capacity.
- Placing MA and soldering in-line requires more space, and is thus only possible with a new layout in the current facility. A part of the flexibility will be lost, as mentioned before, and thus has to be considered further.
- The fifth concept is not advised with the current products of GE. The routings differ too much for an automated production line.

This research shows its relevance in the strategic conclusions that can be drawn by the company. They gained insight in the possibilities of a new facility, but also in what can still be done to expand capacity in the current facility. The testing cobot and automatic wheel cutting machine can increase the capacity, but research in the current facility is required for this. Further research is therefore recommended for the improvement of the current facility. The layout can be evaluated with the approach used in this thesis, and the suggested technologies require further market research.

A limitation of this study, is that it is based on a non-existing facility. Therefore, assumptions are made about processing times, space requirements and other input for the simulations. Comparison of the current facility and this new facility is beyond the scope of this research and therefore the advice that is given about the current facility, is limited.

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GLOSSARY

Abbreviation	*Definition*	*Introduced in*
AOI	Automated optical inspection	Section 2.2
AW	Annual worth	Section 3.2
BOM	Bill of materials	Section 1.1
Cobot	Collaborative robot	Section 4.5.1
EMS	Electronic manufacturing system	Section 1.1
FLP	Facility layout problem	Section 3.1.2.2
FW	Future worth	Section 3.2
GE	Global Electronics B.V.	Section 1.1
MA	Manual assembly	Section 1.1
In-line	A continuous sequence of machines, connected via, for example, a conveyor belt	Section 4.2
IRR	Internal rate of return	Section 3.2
MARR	Minimal attractive rate of return	Section 3.2
MOQ	Minimum order quantity	Section 2.1
PCB(A)	Printed circuit board (assembly)	Section 1.1
PW	Present worth	Section 3.2
QAP	Quadratic Assignment Problem	Section 3.1.2.2
SMD	Surface mounted device	Section 1.1
TH(T)	Through hole (technology)	Section 1.1
WIP	Work in progress	Section 4.8

1. SUMMARY OF INTRODUCTION

This introduction is a confidential summary of the report. In the introduction chapter of the master thesis multiple topics are discussed. First, an introduction is given to the company, Global Electronics B.V. Then, the motivation and problem identification are discussed. In the third section the scope of the research is given, after which the objectives of the research are discussed. This chapter is concluded with the methodology of the study and finally an outline of this thesis.

1.1. SUMMARY OF ABOUT GLOBAL ELECTRONICS B.V.

In this section, a small introduction is given to the company. It explains that Global Electronics is a company specialized in the assembly of printed circuit boards (PCB's) and in which industries it operates.

The following paragraph explains that GE, a make-to-order strategy is used, meaning that required materials are purchased after a customer confirms its order. The main operation of GE is the assembly of PCB's, of which through-hole components are placed manually, and surface mounted components are placed with a surface-mount device (SMD).

1.2. SUMMARY OF PROBLEM IDENTIFICATION AND MOTIVATION

In this section the problem is identified and motivated. What has been found is that the company has grown a lot in the past few years, which is visible in higher demand and larger order volumes. Customer 75 is currently the biggest customer of GE and has the largest order volumes. For this customer, the focus is slightly shifting from high mix-low volume to low mix-high volume. Because of these changes, there is a lack of space, and capacity will become too low in the long run. Next to this, there is a lot of manual work required, components cannot be traced, and there is no integration of sub-processes. The core problem is that GE is behind in market innovations.

1.3. SUMMARY OF RESEARCH SCOPE

The research scope is concerned with what has to be researched during this thesis. Because this thesis investigates the long term strategic possibilities of the company, expansion in the form of a new facility is researched. The scope includes (i) investigating and deciding on the processes, layout, machines and equipment, and labor requirements, and (ii) an assessment of the whole capital investment and (iii) change in unit costs of the product(s) that this facility will produce.

Machine equipment selection and the flow of products through the facility with new equipment is the main focus of this research. It is researched via market research and a simulation. Since many changed were made during this research and improvements became possible at the current facility as well, there is also an advice given on improvements that can be made in the current facility.

1.4. SUMMARY OF OBJECTIVE OF THE STUDY

The objective of this study is to fill the gap between the current situation, where there is no knowledge about the feasibility and the capital investment of opening a new production facility, to the situation where there is an investment roadmap for the facility. The research question which will be given an answer to during this research is given below.

What is the feasibility of investing in a new facility for the production of high volume PCBAs?

To support the main research question, sub questions are formulated. These are based on the systematic approach of facility planning as will be discussed in Chapter 3.1. The second question, about literature to support this research, is added compared to the systematic approach, to substantiate the steps in facility planning with theory.

Chapter 2: What is the current production process?
Chapter 3: What is said in literature about the design of a production facility?
- 3.1 What approach is used in literature to design a facility?
- 3.2 How are the costs and benefits of investments analysed in literature?
- 3.3 How are different scenarios analysed in literature?
- 3.4 What methods are used from literature during this research?

Chapter 4: What will the new production process look like?
- 4.1 What KPIs are to be satisfied with the new production facility?
- 4.2 What are the product(s) and/or service(s) that are to be provided in the new facility?
- 4.3 What is the role of the facility in the supply chain?
- 4.4 What are the primary and support activities and their requirements?
- 4.5 What state-of-the-art machines and equipment are required in the new facility?
- 4.6 How will the stock be managed in the new facility and what will the level of automation be?
- 4.7 What are the IT requirements in the new facility?
- 4.8 How will material be handled and stored in the new facility and what will the level of automation be?
- 4.9 What are the labour requirements and activities for all process steps?

Chapter 5: What are the alternative facility plans?

5.1 What are the space requirements for the activities and machines?
5.2 What are the alternative designs for the handling and storage of material?
5.3 What are the alternative layout plans for the facility?

Chapter 6: How do the activities interact with or support one another within the boundaries of the facility in a simulation?

6.1 What are the alternative concepts?
6.2 What are the performances of the concepts, based on a simulation?
6.3 What are the costs and investments for the facility plans?

Chapter 7: What is a roadmap for the implementation of the new facility?

The outline of the thesis will be based on the sub-questions as stated previously. These questions are answered in separate chapters to answer the main research question. The thesis is concluded with a conclusion.

The intended deliverables to GE are a roadmap and a simulation. The roadmap is intended to capture the major steps that are planned and is some advice on when to do the investments given a certain scenario. The simulation is used to show what a new facility could look like and what its performance would be under certain circumstances. It will be a deliverable to substantiate the selection of a preferred design.

2. SUMMARY OF THE CURRENT SITUATION

This chapter is a confidential summary of the report. In this chapter, an analysis is done on the current situation of GE. The current situation will help to understand what processes are going on at GE and where bottlenecks occur. For the description of the current process, the research of a previous student (van Norel, 2022) and observation, are used. The processes are then validated by the employees of GE. Next to this, current movements are tracked and visualised with a spaghetti diagram, to show the flow through the facility.

2.1. SUMMARY OF BUSINESS PROCESS

The process of an order starts when the sales department receives a request of a customer, which shows that a make-to-order process is used. After a request is received, a quotation is made. If the quotation is accepted, the order is processed and the components are ordered. If the offer is not accepted, the order is negotiated, after which the order is either confirmed or the process ends.

Once the ordered components are delivered, the warehouse department stores the components in the warehouse. When an order needs to start its production, the components that are needed for SMD are manually picked. The components that are required for MA are picked when the production is scheduled for MA. When the PCBAs fulfil the requirements, the orders are packed and sent to the customer.

2.2. SUMMARY OF PRODUCTION PROCESS

The largest part of the business process is concerned with the production of the products, so after the components are received. Therefore, this process is mapped in more detail in this section. A visualisation of the process is given in Figure 2-1. Further explanation of the flowchart is kept confidential.

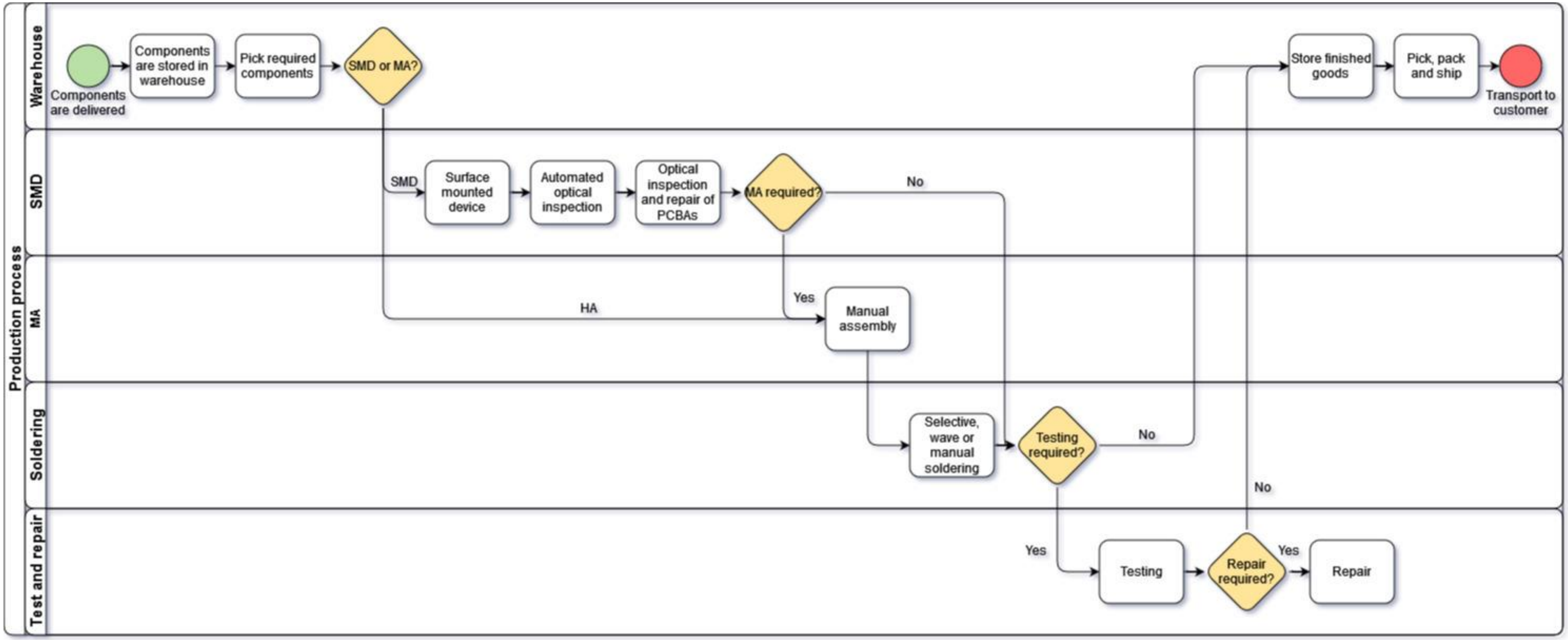


Figure 2-1 Flowchart of the production process

2.3. SUMMARY OF CURRENT SITUATION ANALYSIS

In this section the current situation at GE will be analysed. This will be done by looking at the current layout and the routes that are walked by the employees. Next to this, it will be investigated how much space is occupied by what. This will help to confirm the problems that are stated in Section 1.2. It also creates an as-is situation, which can be compared to a to-be situation.

A spaghetti diagram shows the routes that are walked by employees. A map of the ground, and first floor are made and the lines that are walked are drawn. This is done by observation. The map shows a chaos of lines and it can be concluded that there is no consistent flow of movement through the facility.

Next, the space occupation is determined. This is done by measuring the available space and the space that is occupied with workstations, inventory, work-in-progress and more. What can be concluded that on the first floor, less than 5% of space is available for further growth. The ground floor does have more space available, but part of this available space also has to remain available for other customers.

3. THEORETICAL PERSPECTIVE

In this chapter on the theoretical perspective, two main objectives will be handled on the topic of facility planning. The first objective is to search in theory for a framework which will be used to give structure to this research. This objective will be discussed in Section 3.1, where a systematic approach is given to design a facility. Next to this, alternative design concepts will be discussed to see what systems exists for facility design. To analyse the results once researched, cost and scenario analysis will be done. These topics are therefore also included in the literature study. The goal of this chapter is to answer the question on what is said in literature about the design of a production facility.

3.1. FACILITY PLANNING

The layout of a facility involves the analysis of planning and design of the interrelationships between physical facility arrangements, material movements and activities that are associated with information and personnel. Facility planning is therefore a very broad term and concerns an area which involves many activities. It is therefore convenient to divide a facility into two categories: facilities location and facilities design. The term facilities design is concerned with the facility systems design, layout design and handling system design (Tompkins, White, Bozer, & Tanchoco, 2010). A visual representation of this hierarchy can be seen in Figure 3-1.

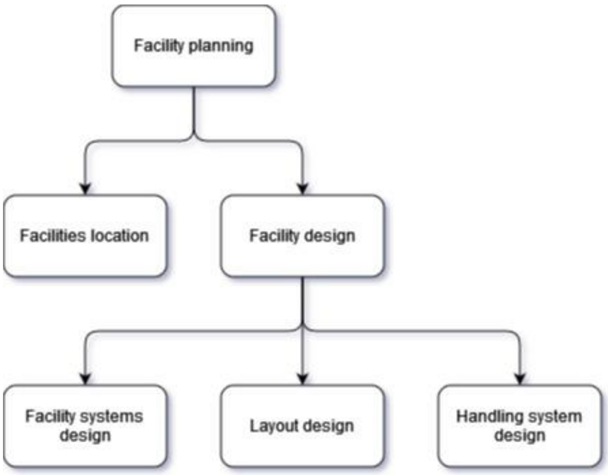


Figure 3-1 Hierarchy of facility planning

For facility planning (Tompkins, White, Bozer, & Tanchoco, 2010) uses a systematic way to approach this complex process. This is based on the traditional engineering design process.

1. Define the problem
    - The product(s) and/or service(s) that are to be provided in the new or changed facility must be defined. The volumes that are to be produced and the levels of activity must be determined quantitatively for whatever period possible. Next to this, the role of the facility in the supply chain is to be determined.

  - In this first step of defining the problem, the primary and support activities to accomplish the objective are to be defined. This includes operations, equipment, personnel, and material flows. Support activities are activities that are to be performed to let primary activities function with minimal interruptions and delays. An example of a support activity is maintenance.
2. Analyse the problem
   - In this step the interrelationships among all activities are determined. This should be done for both quantitative and qualitative relationships.
3. Generate alternatives
   - Space requirements for all equipment, material, and personnel must be determined for each activity. The facility design alternatives must include alternative layout designs, structural designs, and material handling system designs. When multiple locations are evaluated, this should also be included in the alternatives.
4. Evaluate the alternatives
   - Using the accepted criteria, the facility plans are ranked. Subjective factors must be determined and evaluated what the impact will be on the facility or its activities, and objective factors must be researched.
5. Select the preferred design
   - A plan must be determined which is the most acceptable in satisfying the objective of the company and/or project. This does not only include costs, but all information which is generated in the fourth step of this approach is used in the selection.
6. Implement the design
   - The implementation of the facilities plan requires a lot of planning, before the actual construction of a facility can start. Steps that are included in the implementation phase are supervision of the installation, preparing for start-up, starting up, running, and debugging.
   - After implementation, the plan must be maintained, meaning that when requirements change or are added, the plan must be modified. When activities are changed, changes in handling equipment or flow patterns might be needed, which in turn changes the facility plan.
   - When expansions or modifications take place in the organization, the objectives of the facility might have to be redefined. Changes must be considered and integrated in the layout plan.

As the plan moves from planning, to designing, building, installing, and commissioning, the costs of the project increase exponentially. Since the planning of the facility is a strategic process, and often concerned with large investments, the planning must be an integral part of the strategy of the company (Tompkins, White, Bozer, & Tanchoco, 2010). The decisions during this process must also consider the impact on the supply chain, as such strategic changes often impact the facility, material handling, information systems and purchasing.

3.1.1. Facility location

The question on where to locate a facility has become more complex with the upcoming global production strategies. The critical decision has a long-lasting impact on operational and logistical decision. It should consider not only the current state of the system, but also state over the course of the facility's lifetime (Owen & Daskin, 1998). In determining the location and size of the facility, it is essential that the product designs, process selection, production schedules and facilities plans are mutually supportive. These plans should therefore not be made independently and sequentially but should adapted and improved continuously.

When there already exists a facility with the required production operations, the facility might not be changed by introducing a new product, changing a product, changing the production process, or modifying the production schedule. These changes might, however, require changes in terms of layout, material handling or inventory storage.

3.1.2. Facility design

The design of the facility for manufacturing is very important for a company in terms of economic impact. The process of manufacturing is value adding and the efficiency of the activities is therefore determining for the short- and long-term profitability of the operations. The focus during the design phase should therefore lie on improving quality, decreasing inventories, and increasing productivity.

Nowadays, quickly responding to the customer is expected in many industries. Therefore, methods such as just-in-time (JIT) and lean have emerged as methods to increase efficiency. The term JIT is associated with getting the right amount available at the time that it is needed. (Groenevelt, 1993). This can be achieved by having an efficient flow of material in the factory, which can be achieved by eliminating waste. The definition of waste ranges from “everything that is not useful”, to “whatever does not contribute to profitability”. Most used is that activities which are useful, add value. So, it can be said that everything which does not add value to the product, is classified as waste (Hirano, 2010).

Concepts and techniques that are related to JIT production have impact on the facility design. For example, the inventories, point-of-use deliveries, quality at the source and communication, line balancing and multifunctional worker impact what the facility should look like.
One of the main objectives of JIT is the reduction of inventory, which can be achieved by for example smaller lot sizes. This impact the space requirements of the warehouse, but also buffer storage, meaning that machines can be placed closer to each other. For the material

handling it means that smaller loads are to be handled, meaning that there are other requirements for the material handling equipment.

When smaller lot sizes are used, the products should be delivered to the point-of-use to avoid stockouts. However, if multiple docks are required to handle the loading and unloading op the products, extra material handling is also required at these decentralised storages. The parts should be moved shorter distances and fewer times. The storage policy, e.g., Kanban should be adjusted to these decentralised storages by centralising the system or by using a returnable policy for the Kanban containers as well.

To ensure the quality of the product proper packaging and stacking, efficient transport, handling and storage of parts, and a production system without time pressure could be required. This is all to ensure that the product that leaves the warehouse is equal to how it entered the system.

To make JIT production successful, there are some requisites that must be pursued. These include: (1) stable production schedules; (2) small batch sizes and short setup times; (3) on-time delivery; (4) defect-free components and materials; (5) reliable production equipment; (6) pull system of production control; (7) a capable, committed and cooperative work force; (8) a dependable supplier base (Groover, Fundamentals of Modern Manufacturing, 2020).

1. JIT production is most successful if there is a smooth flow of work through the facility. Any disturbance in the operations upstream causes disturbances in the downstream operations. A production schedule that is relatively constant over time is a method to ensure a smooth workflow and minimizes disturbances and changes in production.
2. As mentioned before, the inventories are minimized when there are small batches and short setup times. Setup times can be shortened by for example preparing a setup when a previous job is still running, using quickly adjustable tools, such as clamps instead of bolts, minimizing adjustments in the setup and using group technology so that comparable products are produced on the same equipment.
3. 4. 5. When products or parts are not delivered on time, stock-outs occur at downstream stations. And if parts are defective, they cannot be used during the production. Breakdowns at the machines is also always at the expense of the JIT system.
6. A pull system is required in a JIT production, which means that the trigger to produce comes from a station downstream which requires those parts. So, the upstream workstation replenishes when the supply of parts becomes exhausted. A push system is the opposite of a pull system, where parts move to the next station downstream when the parts are finished. This can cause overloading at stations.
7. 8. Suppliers and the workforce must have the same standards as the company for zero defects, quality, and other JIT requisites. Vendor policies that are frequently used to implement JIT are minimization of suppliers, selecting suppliers with high quality

and delivery standards, establishing long-term partnerships, and selecting suppliers located near the plant.

One of the things that makes Lean efficient, is a continuous flow of products. This is achieved by, in the ideal scenario, using a batch size of 1. For companies that work with larger batch sizes, because of for example limited space, or changing orders, this is a difficult method to implement. In that case, Lean is a principle which reduces the flexibility of such a company. Small and Medium Enterprises (SMEs) need to make the most of the limited space and capacity available, while often adapting to growth and changes in the demand and/or industry. The idea is to be as agile as the company (Clifton, 2022). Variation that a manufacturing system might have to deal with is the raw material, the size and weight of the part, geometry of the part, complexity, and different assembles. To become a system which can adapt to different parts, which is called a flexible manufacturing system, the following functions are important:

1. Identification of different work units. The system must be able to identify which unit it is working on to perform the correct operations. This means that for an automated system, some sort of automatic work unit identification must be in place.
2. Quick changeover of operating instructions. When a part passes a station, it must be arranged that the instructions correspond to the required operation of that part. When a system is controlled manually, this means that the operator must recognize which part passes and which operations need to be performed and have the skills to execute these operations.
3. Quick changeover of physical setup. Flexibility in manufacturing is achieved by not producing the different parts in batches. Necessary changes that need to be made to produce a next part need to be made in a very short time. The ideal changeover time is approximately the time it takes to exchange the completed part for the new part that needs to be operated.

As variety of products increases, the complexity of part changeover becomes more difficult as well. The material handling system must be designed to handle these changeover and differences in shapes and sizes. The logistics within a facility also become more involved as quantities and starting work parts differ. Scheduling and coordinating the system also becomes more difficult (Groover, 2018).

3.1.2.1. Facility systems design

Processing businesses are comprised of highly complex processes to make, store and transport products. There is a major system of equipment, structures, and pathways. Each facility is made up of several systems, which is again a collection of equipment, structures, and parts. Therefore, the total system must be considered when looking into a new capital project. This project entails the capital equipment, ancillary components, support structures and connections to the rest of the plant.

To clearly define what is required for the system to operate optimally, the Basic Unit Specification (B.U.S.) Profile is built. This is a document which could be provided to equipment vendors when asking for bids. The first thing to analyse for the system that is required, is what will the unit service. Then, the performance requirements are important. So, specify exactly what the facility needs the equipment to do. This can be in terms of required process rate, maximum process rate, minimum up-time etc.. Then, the conditions in which the system will operate, such as temperature, humidity, pressure are listed. The last thing that in required for the B.U.S. is the available utilities that the system requires. So, what are the specifics of the material that the equipment will be processing, this is important for the sensitivity of the product to the parameters of the equipment (AMG Incorporated, 2017).

3.1.2.2. Layout design

According to the definition of (Shayan & Chittilappilly, 2004), the facility layout problem (FLP) is concerned with the optimization of a layout while considering interaction between facilities and material-handling systems while designing the layout. An optimum arrangement of machines, workstations or any manufacturing or support factory is looked for with the FLP. Its decisions are strategic, as the decision is often capital intensive, difficult to reverse, used for the operations over a long-time span and affect the whole organization.

The generation of layout designs is an important step in facility planning, as it determined how material will flow and what the physical relationships are between activities. The layout strategy should represent the overall strategic point of view of the company. There are four basic types of planning departments: fixed material location departments, production line departments, product family departments and process departments. Planning departments are workstations that are grouped together in the facility layout. As can be seen in Figure 3-2, there are general rules to determine a fitting layout based on the volume and variety of the products (Tompkins, White, Bozer, & Tanchoco, 2010, pp. 83-113).

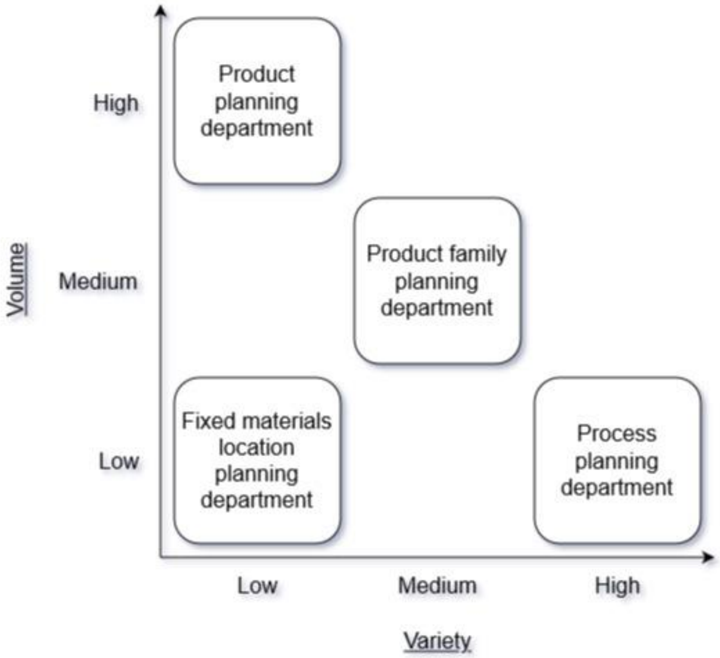


Figure 3-2 Volume-variety planning departments

Fixed material location departments are used for products with a low or sporadic demand and usually that is difficult to move. In this layout design the resources are moved to perform the operations on the products. Fixed material location departments have low volumes and low variety (Drira, Pierreval, & Hajri-Gabouj, 2006).

The layout for a process planning department exists of grouped products that required the same resources. This layout design is used when the volume of products is low and therefore does not justify a product of product family department (Tompkins, White, Bozer, & Tanchoco, 2010, p. 110). Also, this type of layout is suitable for when there is a high variety of products. Product planning departments are used when there is a low variety of products and high volumes. The layout is then determined by the sequence of the operations that are to be performed on the products (Drira, Pierreval, & Hajri-Gabouj, 2006).

Product family planning departments are used when products can be grouped based on commonalities, such as shapes, materials, required tools, etc.. For each family, a manufacturing cell is determined which has its own layout requirements. For this layout type, there is usually little interdepartmental flow and a high degree of intradepartmental flow (Tompkins, White, Bozer, & Tanchoco, 2010).

To structurally approach the layout design, Muther's systematic layout planning (SLP) is used (Muther, 1973). This approach can be used both qualitatively and quantitively and is relatively straightforward in its use. The procedure of SLP is shown in Figure 3-3.

The SLP starts with data gathering (step 1). This step can also be called PQRST as data is gathered concerning Product (P), Quantity (Q), Routing (R), Supporting (S) and Time (T).

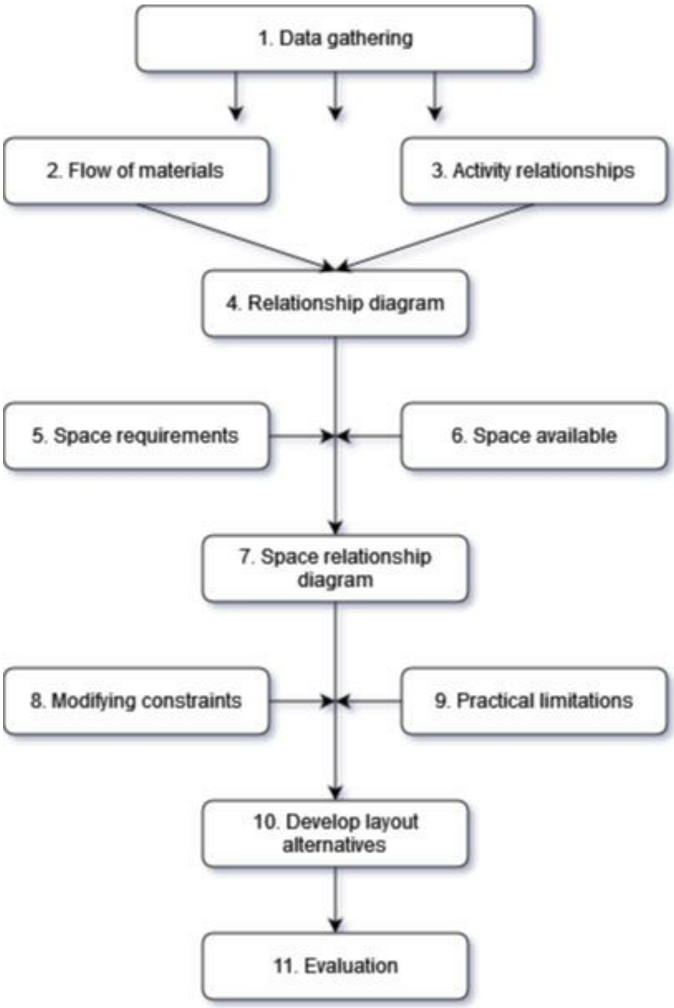
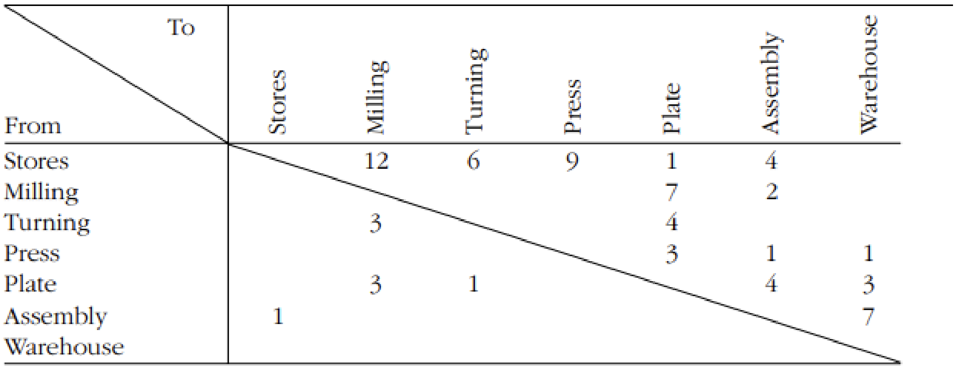


Figure 3-3 Muther's SLP

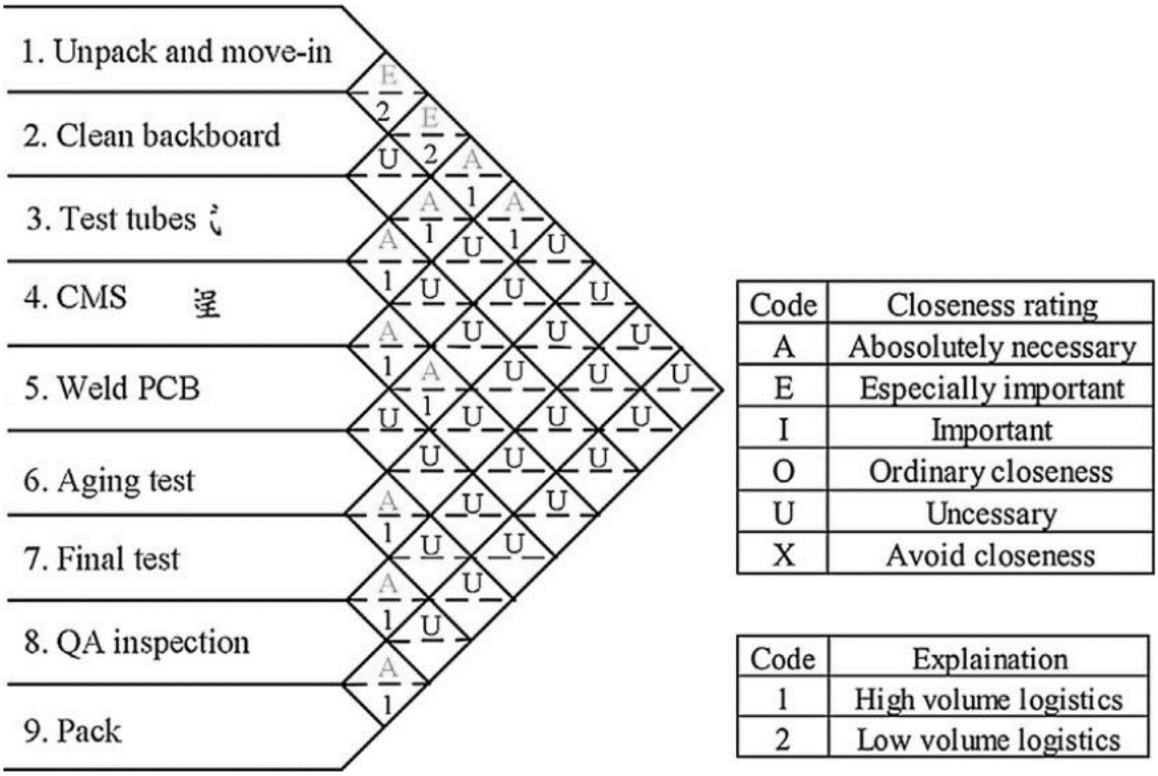
In the step flow of materials (step 2), all the flows of materials are gathered and put into a from-to-chart which show the intensity of flow among workstations or departments. A from-to-chart quantitatively shows the pieces per hour, moves per day, or kilograms per week for example. The diagonal is left blank, as movements within a department are not captured with this matrix. An example of a from-to-chart is given in Figure 3-4.



From \ To	Stores	Milling	Turning	Press	Plate	Assembly	Warehouse
Stores		12	6	9	1	4	
Milling					7	2	
Turning		3			4		
Press					3	1	1
Plate		3	1			4	3
Assembly	1						7
Warehouse							

Figure 3-4 From-to-chart (Tompkins, White, Bozer, & Tanchoco, 2010, p. 115)

Activity relationship (step 3) is a quantitative analysis towards the closeness relationship among different departments. It displays the closeness rating among all activities or departments. The rating varies from A – absolutely necessary to X – avoid closeness. A reason for the importance of a relationship can be given below the rating. An example of an activity relationship is shown in Figure 3-5.



Code	Closeness rating
A	Abosolutely necessary
E	Especially important
I	Important
O	Ordinary closeness
U	Uncessary
X	Avoid closeness

Code	Explaination
1	High volume logistics
2	Low volume logistics

Figure 3-5 Activity relationship diagram (Kamal, 2019)

Departments which have a strong relationship are placed close to each other in step 4. The relationship diagram shows a potential positioning decision among the functional areas based on the from-to-chart and the activity relationship diagram.

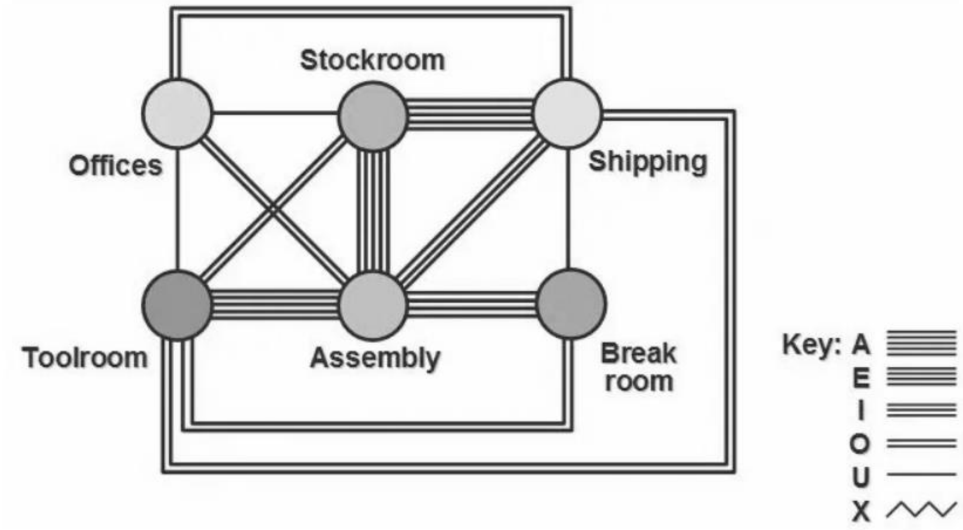


Figure 3-6 Relationship diagram (Loucka, 2006)

Step 5 and step 6 determine the amount of space that is required for each department, future expansions should be considered here. In the space relationship diagram of step 7 the sizes of the departments are added to the relationship diagram from step 4.

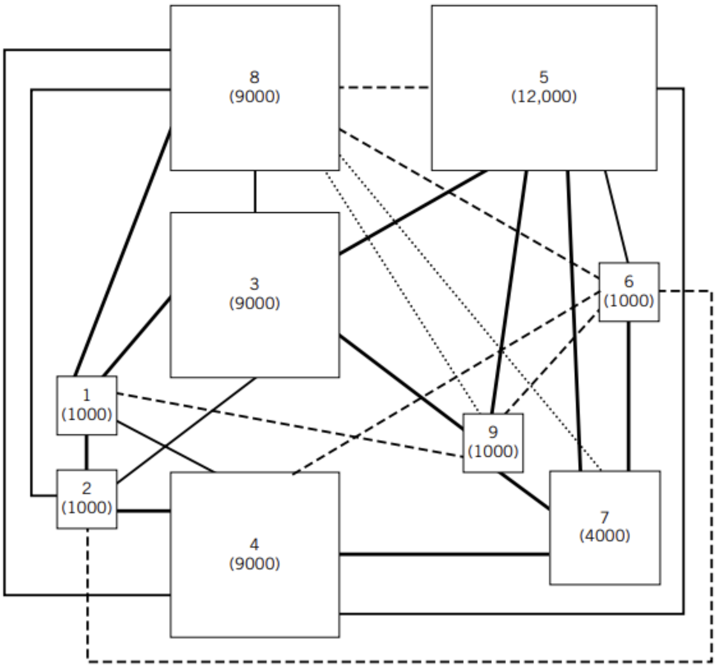


Figure 3-7 Space relationship diagram (Tompkins, White, Bozer, & Tanchoco, 2010, p. 301)

Additional constraints or limitations can be added in step 8 and 9 and the alternatives for the layout designs are developed in step 10.

For the best methods to determine layout designs, computerized algorithms are used. These methods are however not commercially available and will therefore not be evaluated and researched in this literature study.

It must be known that there are multiple classifications of layout methods. First, the input can either be quantitative or qualitative. Where the from-to-chart is an example of quantitative input and a relationship chart of qualitative input. Then, the method is based on the objective. If the goal is to minimize the total weighted distance (weighed by flow), the Quadratic Assignment Problem (QAP) is suitable, where other methods are more suitable for maximum adjacency. Then, the format of the layout must be chosen, where it can either be discrete or continuous. The two types are shown in Figure 3-8.

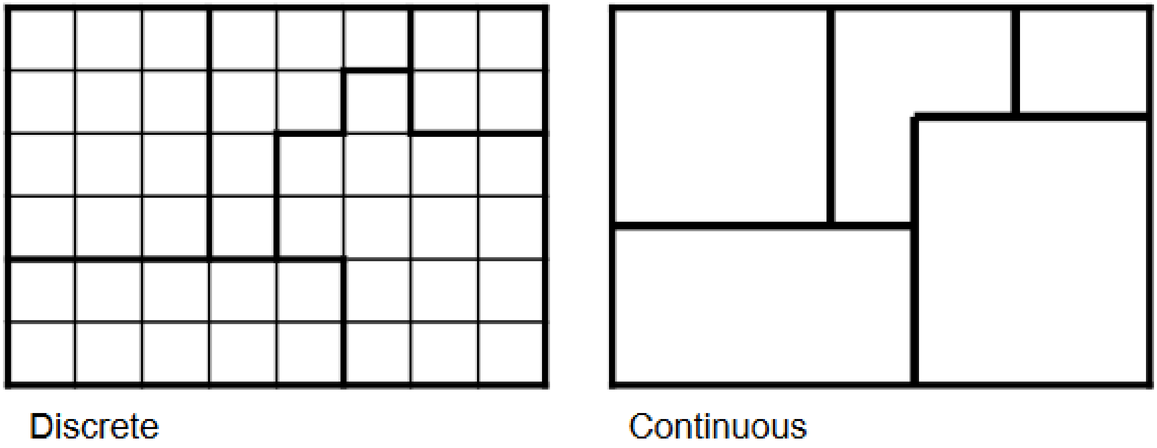


Figure 3-8 Discrete and continuous layout format

It must also be considered whether the department shapes are unsplittable or not, and that for a continuous format, only rectangular shapes are possible. Concerning the shape of the layout, it must be determined whether the site plan is a constraint or a construction or if it is an improvement to the current situation.

The QAP is used to determine the number and the location of new facilities. The objective of this method is to minimize the cost of assigning facility *j* to site *k* when new facility *h* is assigned to site *l*. The solution space is discrete in this formulation. The disadvantage of this method is that department are considered to be equally sized.

CRAFT is an improvement procedure, and is referred to as a steepest descent, pairwise exchange method. The procedure starts with an initial solution, after which all pairwise exchanges are considered. The exchange with the biggest cost reduction is chosen. This continues until no further improvements can be made. A local optimal solution is picked and is dependent on the initial solution. A choice to be made with CRAFT is how to calculate the costs in terms of distance. Distance can be calculated in two ways: rectilinear and Euclidean. The difference is shown in Figure 3-9.

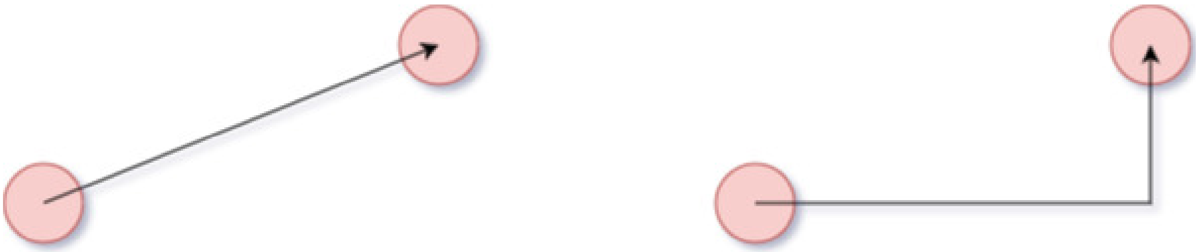


Figure 3-9 Euclidean (left) and rectilinear (right) distance

As the result of CRAFT may consist of irregular shapes, manual adjustments need to be made afterwards to let the department get the preferred shape.

The graph-based method is used for building a layout from scratch and results in a block layout. First, the two departments with the largest closeness rating are paired. The third department is chosen by adding the department with the largest sum of closeness rating with the first two departments. Departments are added until the graph is formed. Based on this graph, a block layout can be made.

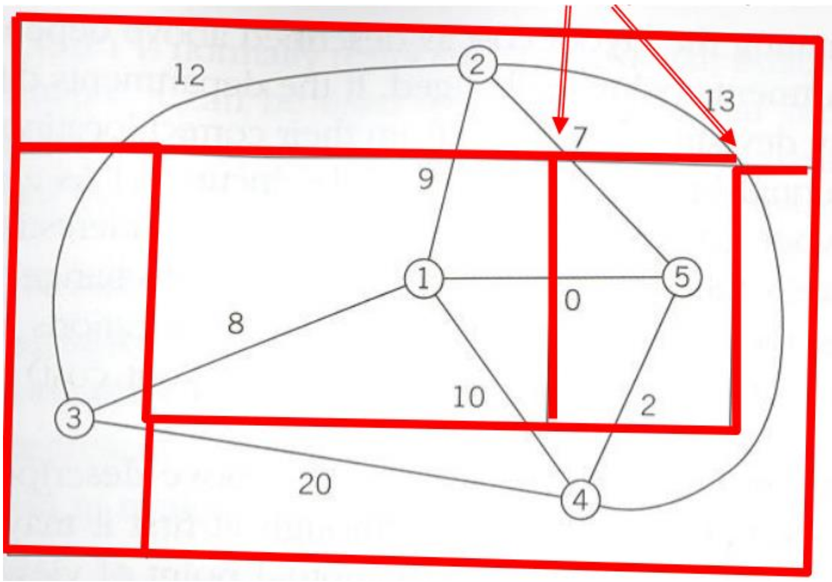
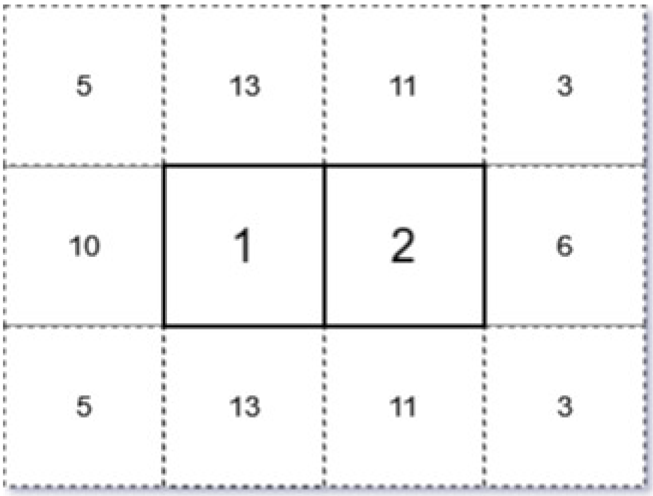


Figure 3-10 Block layout based on a graph

The disadvantage of this method is that the required size of the department does not always correspond to the size from the block design.

The last considered method is CORELAP, which stands for Computerized Relationship Layout Planning. It is an adjacency based, constructive method where the closeness rating is considered. Numbers should be assigned to the closeness ratings, and the department with the highest total closeness rating is chosen as the first building block. The department with the strongest relationship to this department is chosen. If there is a tie, the department with the highest total closeness rating is chosen. The third department is chosen based on the highest closeness rating with the first two department. Its position is chosen by looking at the highest total score, where the corners count as half the worth of the closeness rating. In the example below, department 3 has a closeness rating of 10 with department 1, and a total closeness rating of 6 with department 2.



5	13	11	3
10	1	2	6
5	13	11	3

Figure 3-11 CORELAP positioning of departments

The chosen position in Figure 3-11 will be either above or below department 1. Alternatives are generated in a short time, but strange shapes may be the result.

The final step is step 11, where a final design is chosen by the evaluation of the alternatives (Yang, Su, & Hsu, 2000).

3.1.2.3. Handling system requirements

The layout design and the handling system requirements cannot be designed separately because of their impact on each other. Improving the material handling process will make the flow of materials and manufacturing more efficient. Because of its high impact on the total cost, between 15% and 70%, total manufacturing costs can be decreased drastically by efficiently managing material flow, improving safety, and decreasing inventory (Tompkins, White, Bozer, & Tanchoco, 2010, p. 176).

Material handling is conserved with the movements, storage, control, and protection of goods. This is required during not only the transport, but also during the manufacturing, storing, consumption and disposal. Therefore, the handling of materials means that the right products are provided in the right amount of the right material, in the right condition, in the right sequence, in the right position, at the right place, for the right cost, by the right method (Tompkins, White, Bozer, & Tanchoco, 2010, pp. 176-178).

- The right amount is concerned with the amount that is needed, not the amount that is anticipated. Smaller lot sizes are preferred in getting the right amount.

- The right material means that the correct material is picked. This can be guaranteed by an automatic identifier. Simplifying numbering and keeping up the accuracy of the database can assist in keeping faulty picks to a minimum in case of manual picking.
- The right condition means that the goods are received by the customer without any damage.
- The right sequence is the order in which the activities are performed and the impact this order has on the efficiency on the operation.
- The right position is critical when automated systems are used for material handling, as sometimes a specific orientation of the product is required for a robot, for example, to handle the product.
- The right place is for both the transportation and storage of goods. For example, storing products at the point of use is sometimes for desirable that storing at an intermediate location.
- The right time tries to reduce the variation of the delivery time. The goal is a handling system which reduces the total throughput time, not reduce the time of material handling.
- The right cost is not necessarily the lowest cost. The objective should be to design the most effective material handling systems for reasonable costs.
- The right methods are concerned with selecting a technology which fits to the application.

Material handling is typically seen as a movement of waste, as no value is added for the customer. A lean manufacturing assessment is therefore a good approach to determine the potential locations where waste can be reduced. By positively changing the material handling system, the productivity, lost time injuries and costs generated can be improved (Green, Lee, & Kozman, 2009).

A major component of a flexible manufacturing system, which has been discussed in Section 3.1, is the material handling and storing. The following functions are performed by a flexible manufacturing system (Groover, 2018):

- Random independent movement of work parts between stations. The system must move the parts from its current, to its next location. This next location can be any location in the system and should be able to change when certain stations are busy or broken down.
- Handling a variety of work part configurations. The fixture must be designed to handle a variety of parts. Common components are ideal for a rapid changeover for given parts.

- Temporary storage. As the number in a system is usually higher than the number that can be processed at the same time, a station must be able to accommodate a queue. This increases the machine utilization.
- Convenient access for loading and unloading work parts. Location for the loading and unloading a station must be provided.
- Compatibility with computer control. To direct a part to a workstation, load/unload station, or storage area, the handling system must be under direct control of a computer system.

Industry 4.0 refers to the fourth industrial revolution, where there is a focus on achieving a higher level of operational efficiency and productivity, but also a greater level of automation. The activities that are linked to Industry 4.0 are digitization, manufacturing optimization and customization, automatic data sharing and communication, enhanced human-machine interaction, and value-added services (Lu, 2017). These new technologies also affect the supply chain activities and intralogistics and material handling, as these technologies lead to a higher efficiency, increased traceability, and better responsiveness to customers (Efthymiou & Ponis, 2019). The potential of these developments and their application in the in-house handling and logistics will be analysed briefly.

- Internet of Things is a system of connected computing devices, mechanical and digital machines, objects, animals of people. It can monitor and synchronize information between the physical processes and cyber systems (Strandhagen, et al., 2017). Cyber-physical systems will make it possible for people, machines, and materials to interact easily and continuously, making their history, current status, and future tasks available (Kagermann, 2014).
- Order fulfilment and transportation logistics can be improved with the use of Virtual Reality, Augmented Reality, simulation, and 3D-printing. It improves the enhanced flexibility, quality of the products, efficiency, and productivity (Tjahjono, 2017).
- Information Security is crucial and challenging in Logistics 4.0. It is crucial because of the increasing use of technology and challenging because of the increasing interaction and complexity of systems (Barreto, Amaral, & Pereira, 2017).
- Automated Guided Vehicles (AGVs) increase the flexibility of a warehouse compared to for example a conveyer system, which is a fixed system. This flexibility is of high importance with the quickly changing technologies and trends. Free autonomous robots can deal with such changes as well as changes in the environment and routing (Lutz, Verbeek, & Schlegel, 2016).
- RFID is a technology which can track items real-time in a warehouse or manufacturing facility. It also helps to enable complex production system and for a better life cycle assessment of the products (Hakeem, Solyali, Asmael, & Zeeshan, 2019).

The goal of these technologies is to create a flexible, interconnected, complex and distributed material handling and in-house logistics system (Efthymiou & Ponis, 2019).

For the transport of material, two categories can be distinguished: fixed and variable. Fixed routing can be used when all work unit require the same sequence of stations of have similar routings. Variable routing is mostly used in flexible manufacturing systems, where work units are moves through different workstation sequences. Five main types of material transport equipment can be described. The equipment types are briefly described in Table 3-1.

Table 3-1 Five types of material transport equipment (Groover, Fundamentals of Modern Manufacturing, 2020, p. 919)

Type	*Description*	*Typical Production Application*
Industrial trucks (flexible)	Powered trucks include forklift trucks. Hand trucks include wheeled platforms and dollies	Movement of pallet and container loads in factories and warehouses. Hand trucks used for small loads over short distances
Automated guided vehicles (flexible)	Independently operated, self-propelled vehicles guided along defined pathways. Powered by on-board batteries	Movement of parts and products in assembly lines and flexible manufacturing systems
Rail-guided vehicles (fixed)	Motorized vehicles guided by a fixed rail system. Powered by electrified rail	Monorails used for overhead delivery of large components and subassemblies
Conveyors (fixed)	Apparatus to move items along fixed path using chain, moving belt, rollers, or other mechanical drive	Movement of large quantities of items between specific locations. Movement of product on production lines
Hoists and cranes (fixed)	Apparatus used for vertical lifting (hoists) and horizontal movement (cranes)	Lifting and transporting heavy materials and loads

As described in Section 3.1.2.2, there are four types of layout designs. With each of these layout types, certain equipment and material handling methods are most preferred. These associated methods and equipment are briefly described in Table 3-2.

Table 3-2 Typical methods and equipment associated with layout types (Groover, Fundamentals of Modern Manufacturing, 2020, p. 920)

Layout Type	*Features*	*Typical Methods and Equipment*
Fixed position	Product is large and heavy, low production rates	Cranes, hoists, forklift trucks
Process	Medium and hard product variety, low and medium production rates	Forklift trucks, automated guided vehicles, manual loading at workstations
Cellular	Soft product variety, medium production rates	Conveyors, manual handling for loading and moving between stations
Product	No product variety or soft product variety, high production rates	Conveyors for product flow, forklift trucks or automated guided vehicles to deliver parts to stations

3.1.3.Increasing capacity

As the EMS industry is a fast growing and very competitive industry, companies are stimulated to do as much as possible with the available resources. Immediate capacity growth can be achieved by adding shifts of working overtime to use the existing equipment for more time or outsourcing production, so using the equipment that is available at someone else's production factory. To increase future capacity, existing capacity can be used more efficiently, or new equipment could be purchased (Sowmya & Chetan, 2016).

Most equipment is not used to its full capacity. A typical Overall Equipment Effectiveness (OEE) score is 60% in manufacturing, whereas an OEE score 85% is reached in best-of-class manufacturing according to Vorne Manufacturing Improvements (2022). OEE is a metric that can be broken down in Availability, Performance and Quality. This low OEE score means that instead of looking into additional shift or outsourcing, the capacity of the current facility and equipment can be analysed and potentially increased as well. Lean tools are commonly used to increase capacity, as lean is focussed on the reduction of waste and the creation of value for the customer (Lydianne, 2011).

The lean implementation has five main steps (Kilpatrick, 2003):

1. Specify the value from the customers' perspective. An activity adds value for a customer if the shape or form of the products is changes and the customer is willing to pay for it. The step is only adding value if the step is done right the first time.
2. Map all the steps that are taken to bring a product to a customer. Every activity can be classified in value adding, business value adding and non-value adding. The first, the customer is willing the pay for, the second is required form the business perspective,

and the last is waste. Waste requires resources but add no value to a product. There are eight types of waste:

- Overproduction: anything produced that is not demanded by the customer require valuable labour and resources that otherwise could be used for other customer demands.
- Waiting: waiting for material, information, equipment is all considered as waste, which is why lean requires JIT production.
- Transportation: when materials are delivered to its point-of-use, instead of moving from the vendor to a warehouse, to the assembly line, no time and resources are wasted during the transportation.
- Non-value-added-processing: common examples of non-value-added-processing are reworking of parts that should have been done correctly the first time and inspecting of parts which could be minimized by using statistical process control.
- Excess inventory: when inventory is held, cash flows are negatively impacted, and valuable floor space is wasted.
- Defects: with defects, materials are wasted, and labour is wasted on 1) the production of the part the first time, 2) the rework of the product, and 3) the processing of customer complaints.
- Excess motion: wasted motion is caused by a poor workflow, poor layout, and inconsistent work methods.
- Underutilized people: when the mental, creative, and physical skills and abilities of employees are not used to its full potential, this is seen as waste.

3. Create a continuous flow of products, services, and information throughout the entire process.
4. Only create products when a signal is given by the downstream customer, this is called “pull”.
5. Eliminate waste by producing near perfectly. Then, all activities create value for the customer.

Some tools that are used in manufacturing to eliminate these types of wastes are:

- Kanban cards are used to indicate when a station downstream required parts of materials from a station upstream.
- Work cells are used to improve the utilization of people and the communication among process steps.
- Total Productive Maintenance (TPM) is used for predictive and preventive maintenance to optimize the performance of equipment. TPM can reduce breakdowns and downtime and improve the utilization, throughput, and product

quality, of which breakdowns, downtime, throughput, and quality are seen as the biggest losses for OEE (Sowmya & Chetan, 2016).

- 5S is used to organize a workspace. The five steps are: sort, set in order, shine, standardize, and sustain. These easy steps immediately provided return on investment and is applicable in any workspace.
- Quick changeover, pull and batch size reduction have been mentioned before as tools to reduce waste.

These lean principles vary between operational, administrative, and strategic improvements. Even though the most common category to improve in is the operational side of the business, the other two categories are interesting as well. The optimizations there can be in terms of reducing order processing errors, reduction of paperwork, and reducing staffing demands.

3.1.4. Conclusion

Facility planning is concerned with the location of the facility and the design of the facility. The location of the facility has impact on the operational and logistical decision to made and is crucial for the entire lifetime of the facility. The facility design can be divided into three categories: facilities system design, layout design and handling system. These three categories are influenced by the design that is chosen for the facility. Just-in-time and Lean are facility design which increase the efficiency of a facility by getting the right amount at the right place at the right time. The techniques that are used in increase the efficiency impact the agility of the facility, however. As lean works best with a small batch size, the changeover time of machines may increase. Agile manufacturing introduces methods which can help to increase the flexibility of a facility.

To approach the complex process of planning a facility from location to its design, the systematic method of Tompkins et al. (Facilities Planning, 2010) is introduced. In this approach the problem is first defined and analysed, after which alternatives are generated and evaluated. Then, the preferred design is selected and implemented. To generate alternative designs, Muther's systematic layout planning is used. This method gather information, makes a (space) relationship diagram, and develops layout alternatives based on this.

Instead of solely focussing on expansion of equipment and space, it is also wise to consider improving the Overall Equipment Effectiveness in a facility. This OEE shows what the availability, performance and quality of the equipment is. For equipment with a low OEE score, a lot of waste can be reduced to increase the utilization by using lean methods. Lean focusses on steps that create value for the customer and remove the activities that the customer is not willing to pay for.

3.2. COST EVALUATION

When considering a capital project, the return that the project will or should produce should be calculated. The capital investment and all its associated expenditures should be sufficiently attractive in terms of risk and the potential of the alternative projects to be recovered by revenue over time. Because there are many differences in terms of capital investment, revenue cash flows, and expense cash flow, many alternatives are used in practice to compare the economic profitability of an investment project. These methods are: Present Worth (PW), Future Worth (FW), Annual Worth (AW), Internal Rate of Return (IRR) and the External Rate of Return (ERR). According to (Sullivan, Wicks, & Koelling, 2015) the PW, FW, and AW are methods to translate cash flows from an alternative into their equivalent worth at a certain point (or points) in time. The interest rate that is used is known as the Minimum Attractive Rate of Return (MARR); this is the minimum rate of return that is required for the project to balance out the costs of the investment. The IRR and ERR methods are used to calculate annual rates of profits and are then compared to the MARR. The payback period is also commonly used for the evaluation of a project, here the speed with which an investment is paid back with the cash inflows is determined. However, this method does not the principles of time value of money, meaning that money now is worth more than the same amount later. It is therefore often used as supplement information (Sullivan, Wicks, & Koelling, 2015, p. 187).

As we are interested in how much money we would have to spend today to finance the entire project, the PW is investigated further. The PW determines the value of cash flows relative to the present. When the PW of a project is positive, it means that the project is profitable.

The present worth discounts all the cash inflows and outflows to the present point in time, with an interest rate that is the MARR. The following function is used to determine the present worth:

$$PW(i\%) = F_0(1+i)^0 + F_1(1+i)^{-1} + F_2(1+i)^{-2} + \cdots + F_k(1+i)^{-k} + \cdots + F_N(1+i)^{-N}$$
$$= \sum_{k=0}^{N} F_k(1+i)^{-k}$$

Equation 1

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

In this equation it is assumed that the interest rate is constant throughout the planning horizon N. If the interest rate changes over time, the PW must be computed in multiple steps

(Sullivan, Wicks, & Koelling, 2015, pp. 189-190). As can be concluded from the PW function, the PW is lower the higher the interest rate and the farther into the future a cash flow occurs.

Next to the evaluation of a single project, alternatives engineering project should be evaluated with their different amounts of capital, annual revenues, and costs. The projects that are to be compared should be mutually exclusive, meaning that if one project is selected, the other alternative is excluded. The PWs of the alternatives are calculated and in case the decision is to select the alternative with the minimum cost, then the alternative with the lowest PW is selected. When the objective is to select the project with the maximum profit, then the alternative with the highest PW is selected as base alternative (Gnanasekaran & Sivakumar, 2014). If the PW of the additional capital of a project compared to the base alternative is positive, then the additional investment is justified.

This method can only be used when the useful lives are equal to the study period. When the useful lives of alternative an unequal, there are multiple alternatives.

- The repeatability assumption is used when the study period is a common multiple of the useful lives of the alternatives. The cash flows will in this case be repeated in all cycles.
- With the AW method the AW of the alternatives are compared. This can be done because the costs are then compared for the same cycle and for the same study period. It is assumed that the economic estimates for the initial useful life cycle can be/are repeated in the next replacement cycle
- Fictitious liquidation is used when the repeatability does not hold, and the planning horizon is not a common multiple and cannot or may not be adjusted to a common multiple. In this case, the market value of an alternative at the end of the planning horizon is used as cash inflow.
- Another method is to assume that for the remainder of the planning horizon, an alternative must be leased. The costs of the contract are to be discounted next to the costs of the alternative.

The discounted payback period is used to evaluate a single project based on the time it takes to recover from an investment. This is also a measure of the risk that is concerned with the investment. As this method does not take desirability into account, this calculation can produce misleading results. This method is therefore only used as supplemental information, in addition to the PW.

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

The discounted payback period θ' is calculated by finding the period θ' for which the discounted revenues minus expenses, minus the investment in period $k = 0$, is larger than 0 for the first time. This shows how long it will take for the investment to earn itself back.

To conclude, the present worth (PW) is calculated to determine whether an investment is justified or not. The investment done in the present and the cash in- and outflows in the future are looked at. Equation 1 is used to discount the expenses to the present time. If a PW is positive, the investment is justified.

When multiple investment alternatives are to be compared, the PWs are compared. The alternative with the highest PW is selected as the best alternative in terms of costs. However, this method is only applicable when the alternatives have equal lives. When this is not the case, there are four methods that can be used to compare them. These are: repeatability assumption, annual worth, fictitious liquidation.

The discounted payback period is used in addition to the PWs of investments. This shows how long it takes for an investment to earn itself back. This is calculated by discounting the revenues and expenses and subtracting the investment in period 0. The period for which this value is larger than 0 for the first time, is the discounted payback period.

3.3. SCENARIO ANALYSIS

Scenario analysis is used to make sense of complexity and critical uncertainties in organizations. It focusses on the ability to adapt to the future environment of a firm, which can change because of both internal and external pressure. Its analytical approach helps to structure the possibilities in the shape of a scenario, which is shaped over time and can emerge over time.

One the pioneers in scenario analysis, is Royal Dutch/Shell (hereafter named Shell). As the failures of planning based on forecasting kept increasing, Shell knew they had to increase the analysis of scenarios that could not be predicted with forecasting. The idea was based on the Kahn philosophy, which says that if everything is 100% unpredictable, planning makes no sense. Therefore, predictable elements can be forecasted whereas unpredictable elements are analysed using different scenarios (van der Heijden, 2005).

Each project around two or three scenarios are developed and evaluated, which results in a total of two or three performance outcomes. With these possible outcomes, the development of a project is evaluated, as the scenarios give insight in the potential and possible risks of the project.

As scenario analysis is considered to be subjective, there are not many clear approaches to use. However, the basics of the methods overlap and are mostly based on the approach of Shell. The process of scenario planning starts with concerns of a client. The first step is to define the issue or decision that needs to be made by the problem owner (Maack, 2001). Asking the important questions is crucial to understand the underlying structure of the situation. The nature of the concerns can be understood this way and the predetermines can be distinguished from the indeterminates (van der Heijden, 2005).

The driving forces of the problem, social, economic, environmental, political, and technological, are identified in step 2. They are prioritized according to their importance and level of predictability. Then, the scenarios are written. They explain the effects of the driving forces on the project or situation. They will be explained in more details in step 4, where the trends and the outcomes are described for the scenarios. In step 5, the consequences of the scenarios are studied on the operational level. The leading indicators are chosen in step 6, which helps the decision makers to monitor the changes in the external and internal developments. The scenarios are then made known within the organization and to the public, in a language that is easy to understand. In the final step, step 8, change is required in the affected areas. The change should be towards the strategic goals that are formed based on the scenarios.

These steps are to be taken iteratively by the scenario planner. As more information becomes known, or as situations change, some earlier steps might need some rework or need to be changed completely (van der Heijden, 2005).

In conclusion, to be able to adapt to changes that cannot be forecasted, scenario analysis is used. Even though there are not many approaches, as scenario analysis is assumed to be intuitively, there seems to be overlap in the steps to be taken. It is important that the problem and the forces of the problem are known to the scenario planner. Then, the scenarios are written in full-length, with the effects of the scenarios. Once the scenarios and their strategic implications are known, they are made known to the organization and public.

3.4. CONCLUSION

To conclude the literature search, an overview is given of which found methods will be used in the thesis and why.

The approach that has been found during the literature study will be used as a guidance for this thesis. During this approach, a layout will have to be made for which the SLP by Muther (1973)will be used. During this systematic approach for a layout, a heuristic has to be chosen for the design of the layout. CRAFT has been chosen for this. As will also be explained in Section

5.3, this approach suits best for the objective that has been chosen. Next to this, it is the heuristic which takes into consideration both the relationships between departments and the size requirements.

Throughout this research there are some concepts that will be taken into consideration which have been researched with literature. Flexible manufacturing and lean for example are two concepts which will impact the decision on whether a concept is feasible for GE or not. Also, waste reduction is lean term which be the goal to reduce throughout this thesis.

As for cost evaluation, the two methods as mentioned during the literature research will be used. So first, the present worth will be calculated, after which the payback period is used to determine if an investment falls within the preferred payback period.

For scenario analysis , the steps as research during the literature study will be followed broadly. So, the decision that needs to be made is defined and the driving forces are identified. This will not be done via workshop as frequently suggested, but driving forces are determined based on conversations at the company throughout this thesis. Step 5, where consequences are studied on the operational level, can only be done in the simulations as built in Section 6.2. Therefore, the scenario analysis ends after this step.

4. SUMMARY OF THE NEW PRODUCTION PROCESS

This chapter is a confidential summary of the report. In this chapter the new production process is constructed. This is done by looking at the KPIs that are to be satisfied within the facility, and which products and services are to be provided. Then, the role within the supply chain and the primary and support activities and their requirements are determined. Based on these requirements will be determined what machines and equipment, IT and labour requirements are. Finally, methods to manage and handle stock and materials are researched, as well as their level of automation. The goal of this chapter is to answer the sub question: *"What will the new production process look like?"*

4.1. SUMMARY OF KEY PERFORMANCE INDICATORS

The Key Performance Indicators (KPIs) measure the performance of the facility. The KPI that GE is most interested in is the demand of customers. The demand is determined for customer 75, for 2022 and following years in this section.

4.2. SUMMARY OF PRODUCTS AND SERVICES

GE wants to focus on high volume, low variety products in the new facility, as explained in Section 1.2. The products of customer 75 each have their own routing, which is explained in this section. For each production step, a brief explanation is given. Processes parallel to the production process are briefly discussed as well. This shows what processes are expected to be performed at the new facility.

4.3.SUMMARY OF SUPPLY OF RAW MATERIALS

In this section, the supply of the raw materials are discussed. As mentioned before, a make-to-order strategy is used. However, in the entire industry the delivery of components is a bottleneck. It can take weeks, months or sometimes even years before components are available again. GE is offering multiple options to work around this bottleneck.

4.4. SUMMARY OF PRIMARY AND SUPPORT ACTIVITIES

This section on primary and support activities explains the main operations at GE. This is the assembly of PCB's. Surface components are assembled via the SMD, and through hole components are assembled manually. Other activities that will be performed at GE's new facility are specified as support activities, such as material handling and storage, and inspection and testing. In most manufacturing plants, material spends more time in a buffer and being handled than being processed. Therefore, efficient handling is important.

These activities, primary and support, are considered during the design of a facility.

4.5. SUMMARY OF STATE-OF-THE-ART EQUIPMENT

In this section, alternative state-of-the-art equipment is be discussed and evaluated. It is researched what these alternatives exactly entail and what opportunities they may or may not offer to the facility.

Alternatives are suggested by employees of GE with experience in the field of the automated PCB assembly processes. These alternatives were then researched further, and other options for automation were found. Automatic wheel cutting was suggested by a company which provides laser cutting machines and automatic wheel cutting machines. Cobot insertion is an alternative that is praised on the internet by its flexibility, and is therefore also researched.

4.5.1. Depanelizing

During production, individual PCBs are sometimes manufactured together on a larger panel to make the moving through an assembly line easier. This is called panelizing. The individual boards are later removed or depanelized from the array to finalise the production. Automatic and manual methods for depanelizing are considered.

Laser depanelizing and automatic wheel depanelizing are the most promising methods, they are therefore researched further in terms of processing times per product. Automatic wheel depanelizing is considered during the rest of the research is two forms: as a standalone machine, and in-line with other machines.

4.5.2. Through hole assembly

For through hole assembly, two alternatives are considered. The supply of components, as well as the utilization of the machine with the expected demand are determined. Based on the results of this research is concluded that through hole assembly is done manually for the remainder of this thesis.

4.5.3. Testing

The optimization of the testing of PCBAs has already been investigated by Van Norel (2022), so evaluating the relevance of automating this process is already done. The testing of PCBAs is currently done manually, but this will become a bottleneck when space and personnel will become scarce. A technique that is commonly used to automate the process of testing, is the use of a cobot. A concept with the cobot is currently being implemented.

A next improvement is to increase the efficiency of the cobot, which is done by using two test machines parallel to each other. These improvements will be made after the current concept has been proven to function well. A last stap is the addition of a second cobot, which can test simultaneously. This also makes it possible to test multiple types of products at the same time.

4.5.4. Optical inspection

During interviews with employees of GE, an alternative, or additional machine, for the AOI was discussed. According to these employees, this alternative is an unnecessary investment. Their insights have been confirmed by looking at the function of this alternative market research. It has been concluded that this alternative will therefore not be considered during this thesis.

4.6. SUMMARY OF STOCK MANAGEMENT AND AUTOMATION OF WAREHOUSE

In this section is explained why there is a need for an improved stock management and warehouse. This is done by looking at the current warehouse and methods of stocking, and looking at several alternatives that could improve this situation. Because of previous research, there already was a selection of alternatives and no extensive research has been done. It is concluded that for fast movers, static racks are preferred.

4.7. SUMMARY OF MATERIAL HANDLING AND AUTOMATION

In the section on material handling, multiple handling movements are researched. It is researched if manual movement can be decreased by adding automated solutions, such as conveyor belts or automated guided vehicles (AGVs). For the AGV, multiple methods for navigating through the facility are considered. Based on what the new facility will look like, and on flexibility that is requested to be high, one of the methods is preferred.

Next, the storage of work-in-progress in between stations is discussed. Because the storage racks are fixed, only limited options are offered. A promising method to reduce material handling, is to place manual assembly workstations and the soldering machine in-line with the use of a conveyor belt. This method is used as a potential concept for the remainder of this thesis.

4.8. SUMMARY OF IT REQUIREMENTS

Collection of data is important in manufacturing as it makes the business measurable and able to be optimised. Data can be most successful if the infrastructure of data supports automated real-time shop floor data collection. This data is required to understand what is happening at the shop quantitively and optimize production at that exact moment. When there is no real-time data collection, only data of the past can be assessed. In this section is determined which data should be collected in a digital factory.

Because a Manufacturing Execution System (MES) is a very high investment, the modules of an MES are considered. For each module is explained what its most important function is, if it is relevant for GE and why.

4.9. SUMMARY OF LABOUR REQUIREMENTS AND ACTIVITIES

Looking at the possibilities for automation, the requirements for labour will change, as well as the tasks that are executed by the employees. An overview of the changed tasks that require labour are shown in this section. Even though tasks are dropped because of automation, new tasks emerge for these departments. The machines must be supplied with products and finished products must be removed. The change in time for these tasks is not exactly known, therefore assumptions are done in Section 6.2.

4.10. SUMMARY OF CONCLUSION

Based on the research conducted in this chapter, conclusions are drawn. These conclusions are drawn based on the information that was gathered in the current situation, from market research, and by the knowledge that was already available at GE.

Conclusions that are drawn are about:

- The expected demand of customer 75 in the next few years.
- Concepts that are considered further for the improvement of the production process:
    - A cobot for testing
    - An automatic wheel depanelizing machine
    - An AGV
    - Placing manual assembly workstations and soldering in-line
- The use of VLM and static racks in the warehouse
- The modules of an MES that could be relevant for GE on short, medium and long term.
- The impact of these decisions on the labour requirements

5. FACILITY DESIGNS

In this chapter the alternative designs of the facility will be generated. This will be done by following the steps of Muther's SLP as discussed in Section 3.1.2.2. So, first all the requirements of the new production system will be determined, in terms of space requirements and closeness between other departments. Also, the requirements for material handling and storage are briefly discussed. Based on this information, the layout designs are generated. Following these steps will help to answer the research question: *What are the alternative facility plans?*

5.1. SPACE REQUIREMENTS

For the new production process a lot will change in terms of space requirements. In Chapter 4 is already discussed which processes will be executed in the new facility and which state-of-the-art equipment is required for this. As the workstations will be changing from a manual station to a more automated process, some space requirements will be altered completely. Therefore, the space that is required for the departments will need to be determined to make a new layout. As concluded from Section 2.3, 30% of the available space is required for paths. Therefore, during the calculations, an extra 30% is added as requirements for the department.

5.1.1. Cutting

For the cutting of PCBAs, an automatic wheel cutting machine will be used. To determine the required space, the Yush Electronics products are used (YUSH Electronic Technology Co., 2022). The machine has a working area of 35 cm x 35 cm, which is sufficient for the products of Customer 75. The system has a width of 87.5 cm and depth of 112.5 cm.

In front of the wheel cutting machine, a PCB magazine loader will be placed. In this loader, as seen in Figure 5-2, three magazines with PCBAs can be placed (JWide, 2022). The loader has a width of 143.0 cm and depth of 160.0 cm. There will also be space available for buffering products, but the size will be determined by the simulation. A width of one PCB chart outside of the safety zone has been used for the dimensions. Together with the pathway allowance, a space of $6\ m * 3.4\ m * 1.3 \approx 26.5\ m^2$ is required.

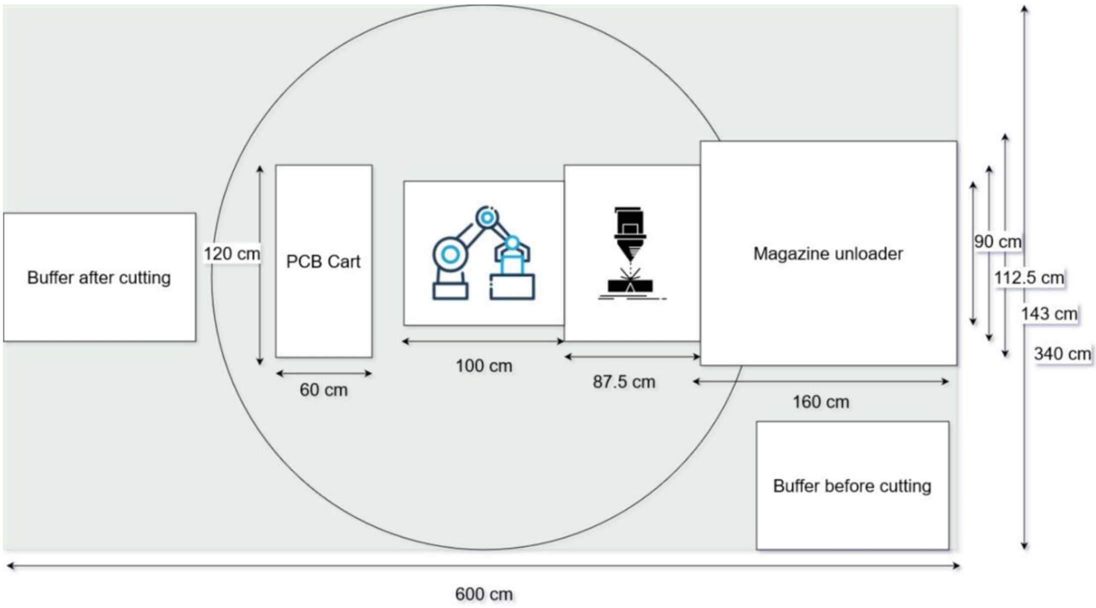


Figure 5-1 Setup cutting machine

The wheel cutting machine can also be placed in line with for example the soldering machine. In that case the magazine unloader at the beginning of the system is not required and will be replaced by a conveyer belt.

Figure 5-2 PCB(A) (un)loader (JWide, 2022)

Figure 5-3 Cart with components

5.1.2. Through hole assembly

As determined in Section 5.1, manual assembly of through hole components is still required in the setting of a new facility, their space requirements are determined as well. These requirements are based on the current occupation. Currently, there are ten manual assembly workstations, with a required space of 160 cm by 125 cm. This is the space required for a table

(160 cm by 70 cm), and space for the chair and movements of the employee. Next to this table, there is a cart upon which components are placed, as seen in Figure 5-3.

As we have seen in **Fout! Verwijzingsbron niet gevonden.**, there is a conveyer belt between the two lines of tables. The length of this conveyer belt depends on the number of employees that is required for the manual assembly. A table and space for the employee to sit and move is 150 cm. Then, per two employees one PCB cart with a width of 60 cm is required. In Figure 5-4 a setup is shown with 6 employees. If the number of employees increases to eight, a length of 150 cm should be added, since the employee requires a table and space to move, but the cart can be shared. If the number is increased to ten, another 150 cm should be added, but also 60 cm for the extra PCB cart.

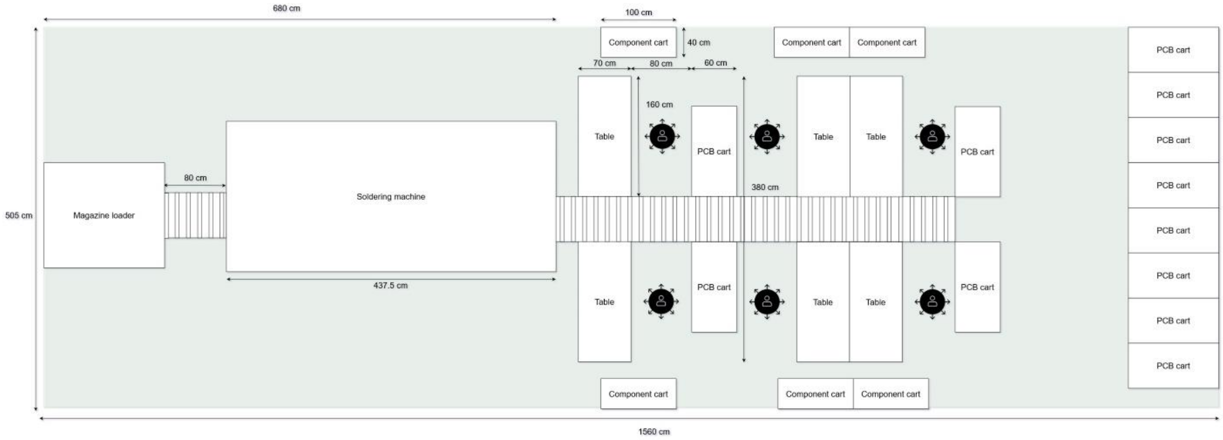


Figure 5-4 Setup through hole assembly

As seen in the setup, there is a loader at the end of the setup to buffer the PCBAs for the next step of the production process. With six working stations the space requirements, together with the pathway allowance, are: $15.60\,m * 5.05\,m * 1.3\ \approx 102.4\,m^2$ for through hole assembly and soldering. Since for the remainder of the facility design soldering and manual assembly are seen as separate departments, the space requirements for both departments are determined. For soldering $6.8\,m * 5.05\,m * 1.3 \approx 44.6\,m^2$ is required and $8.8\,m * 5.05\,m * 1.3 \approx 57.8\,m^2$ for manual assembly, both including pathway allowance.

5.1.3. Testing

As the process of testing will be automated completely, the space requirements will change. The setup of the testing will consist of two conveyer belts, supply, and disposal. As these belts both need to fit three large crates, the minimum length of these belts is 180 cm. So, the total length of this setup is at least 360 cm. The conveyer belts are 60 cm wide and the table upon which the cobots stands had a width of 90 cm. The cobot has a safety zone which depends on the speed of the movements of the arm. It is estimated by the supplying company to have a radius of 200 cm, meaning that this space is preferred to be empty and used for walking as little as possible. If there are movements within this radius, the cobot will slow down its movements. The setup is shown in Figure 5-5. Because the conveyer belt will be placed against a wall, the radius of the safety zone of the cobot is truncated beyond the belt.

For the supply of the PCBAs, a buffer of racks is required. The size of the buffer will be determined with the use of the simulation. At the disposal side of the testing setup a pallet is required upon which the completed and tested products in the crates can be placed. A pallet has a size of 80 cm times 120 cm.

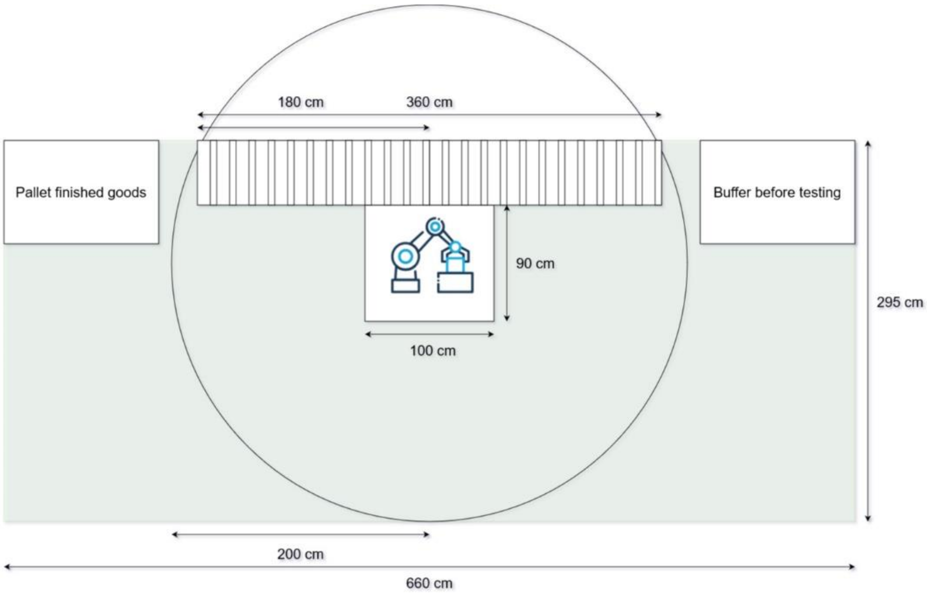


Figure 5-5 Setup testing cobot

The setup requires a total surface of 660 cm by 295 cm. So, together with the pathway allowance a total area of $6.6\ m * 2.95\ m * 1.3 \approx 25.3\ m^2$ is required for testing.

5.1.4. Optical inspection

The optical inspection is connected to the SMD machine. To determine the space requirements, we therefore must know how much space the SMD machine and optical inspection requires and how much space is taken by carts, inspection and preparation tables and materials. As can be seen in Figure 5-6, most space is required for the SMD line. This line starts with a magazine loader and is followed by the SMD machine. This consists of a machine where the paste is put onto the PCB, after which small, medium, and large components are picked and placed. An optical inspection can be done quickly for the first PCBAs after which it moves to the oven. Then, we move to the AOI after which the PCBAs are loaded with a magazine loader.

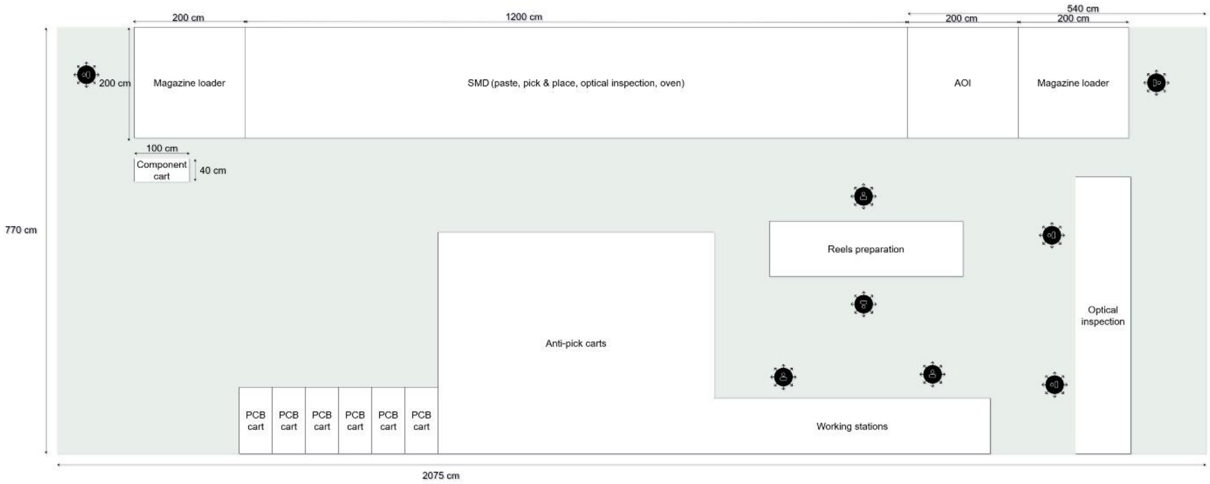


Figure 5-6 SMD line and (automated) optical inspection

Next to the SMD line, we also see tables for optical inspection. This optical inspection is done after the AOI. The tables are used for the preparation of reels and other preparation and planning. Space is also required for the carts upon which the PCBAs, the reels and the components are placed. This is also considered in the space requirements.

For the entire SMD and (A)OI department, together with the pathway allowance, an area of $7.7m * 20.75m * 1.3 \approx 207.7m^2$ is required. In the remainder of this chapter, SMD and (A)OI are considered as two separate departments with space requirements of 153.7 m^2 and 54.1 m^{2,} respectively.

5.1.5. Warehouse

As discussed in Section 4.6, the company is interested in the installation of VLM for better material handling and stock management in the warehouse. These VLM systems are mostly used for high mix production and can be used for the storage of reels and other components. The company has chosen to use VLMs in the new facility because of the slightly higher capacity and easier material handling.

Another preference that has been discussed during meetings about the warehouse, is a separate receiving and shipping area. So, the incoming (I) and outgoing (O) point are separated. Because pallet racks are preferred for incoming and outgoing goods, the pallet racks are placed near the I and O point.

There currently are 50 pallets with goods in the facility or the external warehouse. Because the inventory of raw materials is supposed to be decreased, 4 pallet racks which can store 12 pallets are required in the warehouse.

Then, there will be a forward pick area, in which the fast runners can be stored for a cheaper pick. These racks need to be refilled from the pallet racks and are therefore placed near the pallet racks. The same holds for the VLM.

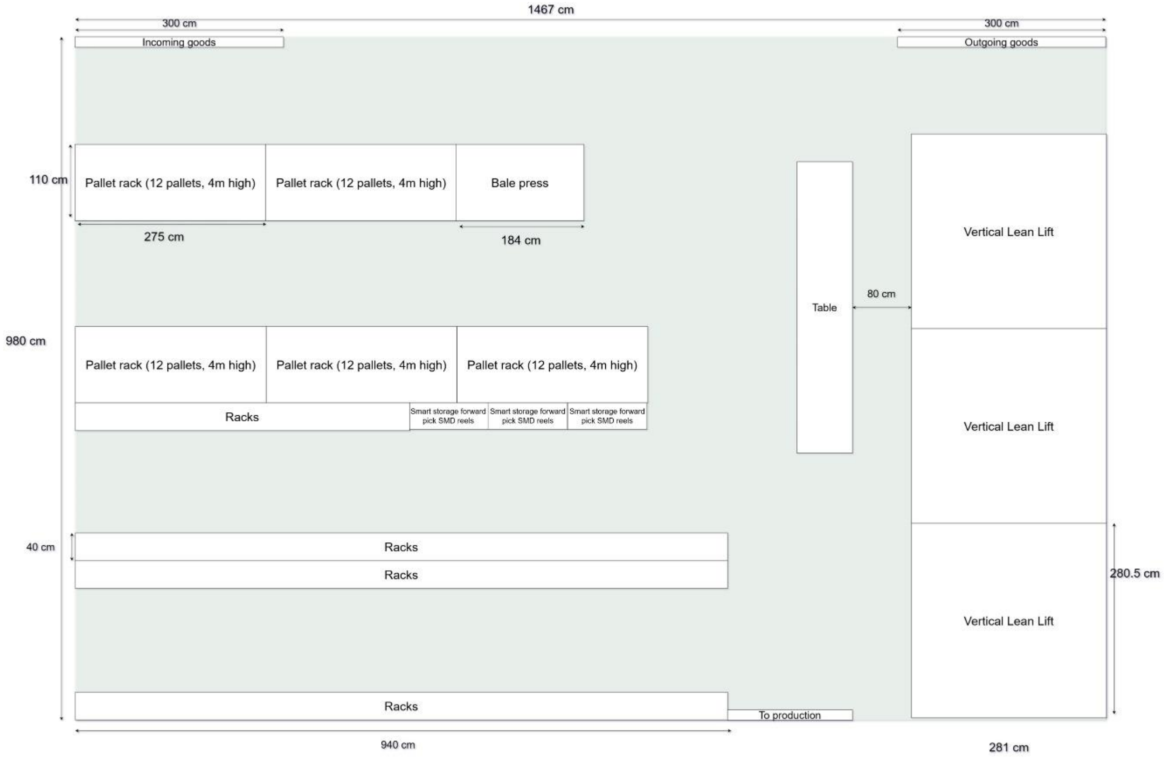


Figure 5-7 Setup warehouse

In front of the VLM there is a working space of 80 cm reserved. Because pallet trucks will drive from the I and O point through the pallet racks, a table is placed between the working space of the VLM and the pallet racks. This table can also be used for the preparation of picking.

Because the racks in the forward pick area are quite long, an aisle can be included to make picking faster.

5.2. MATERIAL HANDLING AND STORAGE

For the material handling, there are some alternatives. As discussed in Section 4.7, conveyer belts and AGVs are alternatives which can be used for material handling. Next to these two automated alternatives, the current method of manual movement is also an option.

Conveyer belts are mostly used when large quantities of items must be moved between specific locations and is a fixed type of transport (Section 3.1.2.3). Because the facility should be flexible, random independent movement of work parts between stations is required. These movements should be able to change at any given moment. Next to this, a variety of parts should be able to be handled. These functions are not easily applicable for conveyer belts. They are therefore of better use within the departments, as these processes do not require this flexibility. The flexibility is mostly required for the handling from department to department. Therefore the conveyer belt will be seen as an alternative for the MA department, but not for internal flow.

The AGV does offer the flexibility that is requested between departments. The advantage of AGVs compared to industrial trucks, such as forklift trucks and hand trucks, is that no personnel is needed for the movement. This means that the employees can work on those tasks that add value to the product. However, the flexibility of manual transport is higher than the flexibility of AGV's, because changes must be made in the guidance and/or programming of the AGV.

For the storage of products, there are two things that will be considered. First, the storage in the warehouse of reels and component of low volume products will be placed in the VLM. This is already decided by the company. For high volume products, racks are advised. Since the warehouse will not be simulated in detail, the required capacity and flow of the warehouse will not be research further. Second, we have the storage of products within the production process. To be flexible during manufacturing (Section 3.1.2.3), decentralized storage of material is best. However, there are also some advantages to centralized storage. For example, to increase the machine utilization. The requirements for this temporary storage will be determined with the simulation in Chapter 6.

5.3. ALTERNATIVE LAYOUT PLANS

To design alternative layout plans, Muther's SLP, as described in Section 3.1.2.2, is used. The first step is to gather data concerning the product, quantity, routing, supporting activities and time. This data has been gathered in Chapter 4 already.

The next step is to make a from-to-chart, in which can be seen how much products flow from one department to another. The from-to-chart of the products of Customer 75 can be seen in Table 5-1. The values are based on the demand per week, as shown previously in **Fout! Verwijzingsbron niet gevonden.**.

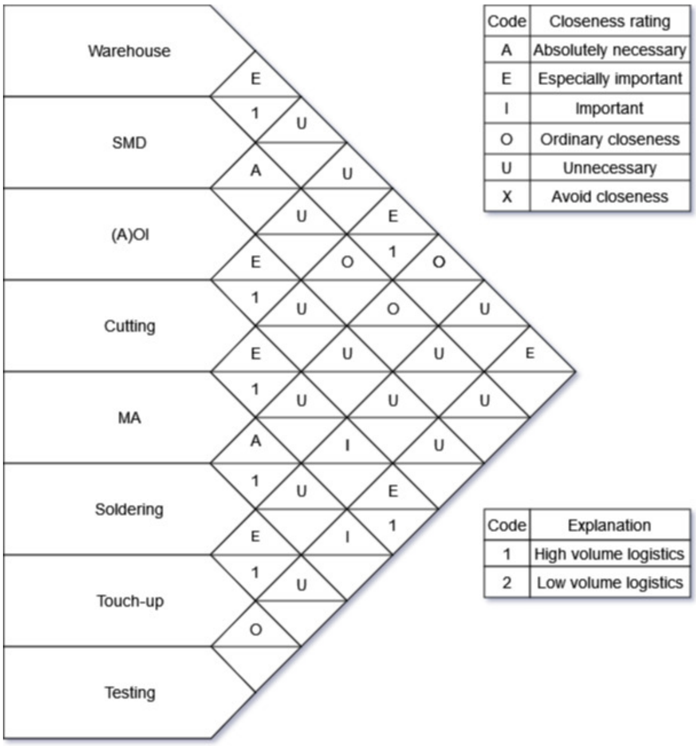
Table 5-1 From-to-chart customer 75

	Warehouse	*SMD*	*AOI*	*Cutting*	*MA*	*Soldering*	*Touch-up*	*Testing*
Warehouse		9300	0	0	0	0	0	0
SMD	0		9300	0	0	0	0	0
AOI	0	0		9300	0	0	0	0
Cutting	0	0	0		5300	0	0	7400
MA	0	0	0	0		5300	0	0
Soldering	0	0	0	0	0		5300	0
Touch-up	0	0	0	4400	0	0		900

Testing	9300	0	0	0	0	0	0

Important to realise is that the movements from and to the warehouse are only bare PCBs or finished products. Other movements from the warehouse, such as components and by-products are not included in this chart.

Step 3 of the SLP is to make an activity relationship diagram, which can be seen in Figure 5-8. The meaning of the codes is explained in the figure. As an example for the relationship diagram, we take (A)OI and cutting. Their closeness rating is especially important because of the high volume of products that move from one department to another. This can also be confirmed with the from-to-chart. The closeness of SMD and (A)OI is absolutely necessary as these two are placed in-line.



Code	Closeness rating
A	Absolutely necessary
E	Especially important
I	Important
O	Ordinary closeness
U	Unnecessary
X	Avoid closeness

Code	Explanation
1	High volume logistics
2	Low volume logistics

Figure 5-8 Activity relationship diagram customer 75

The fourth step according to Muther, is to take the from-to-chart and the activity relationship diagram and combine them in a relationship diagram. This diagram is shown in Figure 5-9 and shows the importance of closeness in the layout. The number of lines show the closeness rating and is also shown in the legend in the figure.

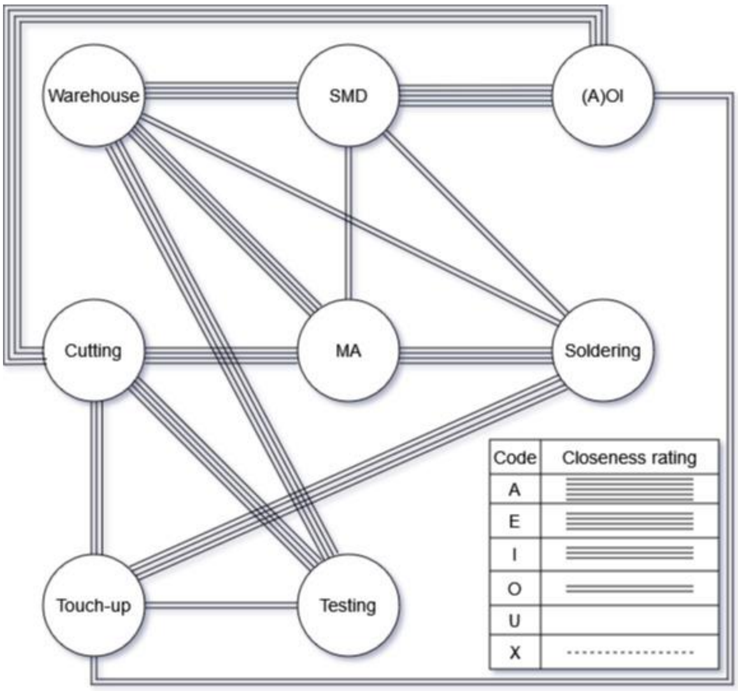


Figure 5-9 Relationship diagram

The next steps are to determine how much space is required to be able to execute the operations as indicated, which can be found in Section 5.1, and see if there are restrictions to the available space in terms of size and shape. This information is then used to make a space relationship diagram. The space relationship diagram can be found in Figure 5-10.

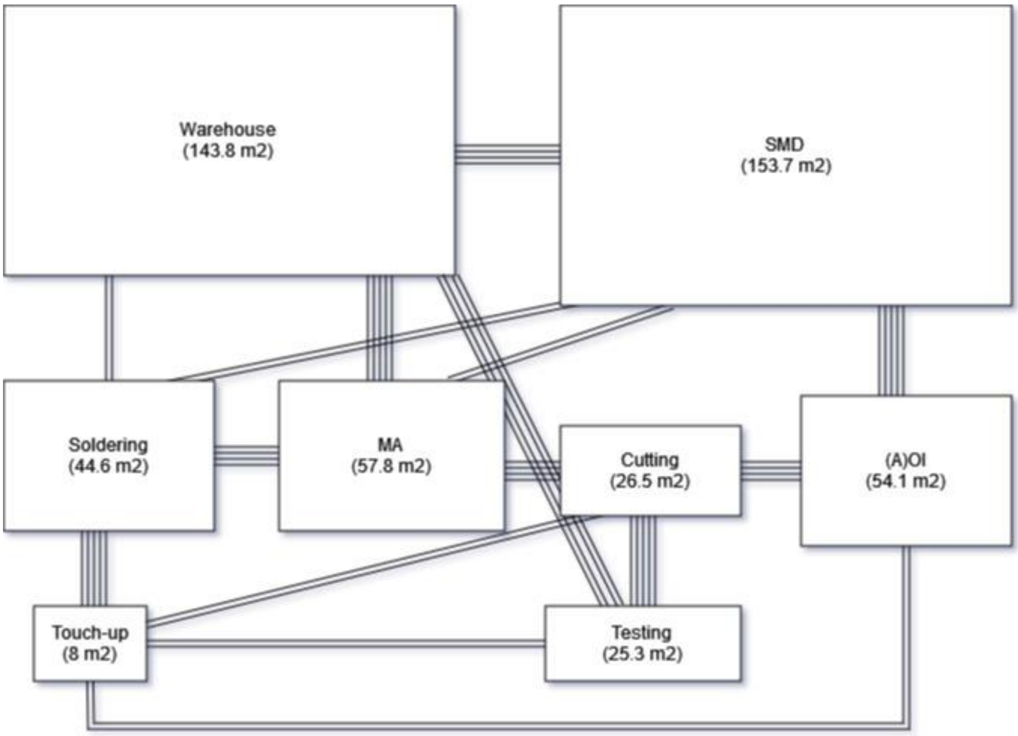


Figure 5-10 Space relationship diagram

Based on the collected information, a layout will be determined. But first, a method to make this layout must be determined, based on the literature study in Section 3.1.2.2. Since the objective of the QAP is different than what is required for this problem, this method will not be used. The QAP is focussed on minimizing the costs if a facility is assigned to a location, whereas the objective of this layout assignment is to get an efficient flow. CRAFT is an improvement method, meaning that an initial solution, usually the current situation, is improved. When there is no current situation, an initial solution is made by randomly assigning departments or making a layout intuitively. If an initial solution can be made, this method would apply to the problem. The graph-based method is not suitable for this problem. This method is concerned with the closeness rating of departments and does not consider the required area. Therefore, the block design will result in irregular shapes with for example many corners or a long length but small width. CORELAP is another method which is suitable for the objective of an effective flow. However, during the construction, the sizes of the departments are not considered. To conclude, CRAFT is most suitable for the improvement of a layout. The initial solution will be made based on intuition and in consultation with employees.

For the limitations of the space, a building at the back of GE is chosen. This building has been chosen because of its square size and because the company has shown interest in buying this building. Using this building makes it easier to give shape to the layout. This building has a size of 934 m^2, with a width of 27 m and a length of 34.6 m. Because this surface is larger than the sum of all the space requirements of the departments, each department has gained some space in the layout. In this layout, SMD and (A)OI are considered as one department, as well as MA and Soldering. The initial solution, which is made based on intuition, is shown in Figure 5-11.

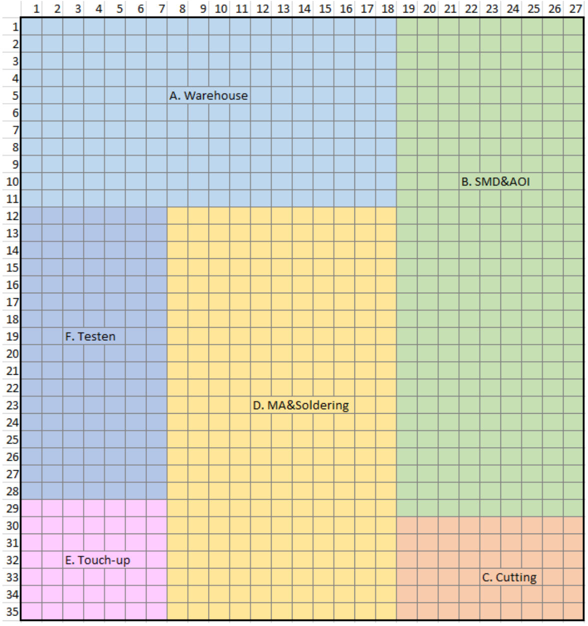


Figure 5-11 Initial layout

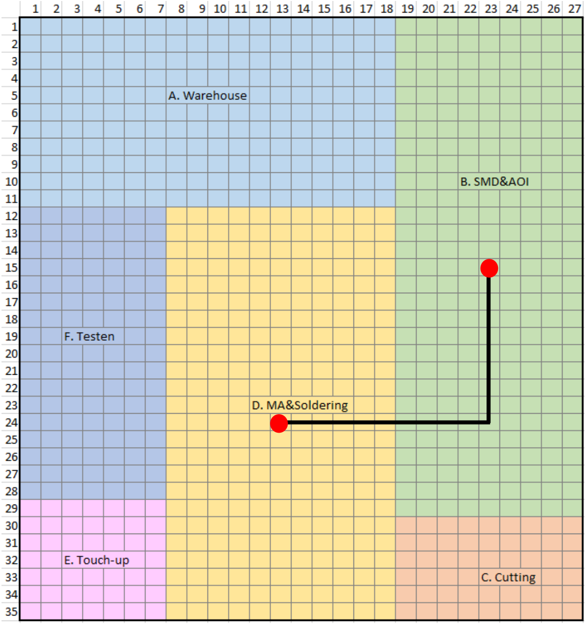


Figure 5-12 Rectilinear distance centre points

The objective of this layout is determined by multiplying the rectilinear distance from the centre of the department to another department with the value of their closeness rating. An example of the rectilinear distance is shown in Figure 5-12. The scores that are used for the closeness rating are: A = 1000, E = 500, I = 250, O = 100, U = 0 and are based on a lecture from W. de Kogel (Layout planning and design algorithms, 2021).

Table 5-2 Distance matrix

	A	B	C	D	E	F
A	-	22.5	40	21	31.5	19.5
B		-	17.5	19	36	24
C			-	18.5	19.5	31.5
D				-	17	13
E					-	12
F						-

Table 5-2 shows the rectilinear distances from each department to another department. Only the upper right half is filled, which means that the distance from A to B is the same as from B to A. These distances are then multiplied by the closeness rating as described above. The results can be seen in Table 5-3.

Table 5-3 Cost matrix

	A	B	C	D	E	F	Total
A	-	11250	0	10500	0	9750	31500
B		-	8750	1900	0	0	10650
C			-	9250	4875	15750	29875
D				-	0	3250	3250
E					-	1200	1200
F						-	0
Total							76475

This initial solution has an objective of 76475, and the distance between cutting and testing is the most expensive one. The next layout to be considered will exchange department F and D, because this will bring department C and D closer to each other. Because the departments are not of the same size, they cannot be exchanged without changing the shape of the departments. The new layout is shown in Figure 5-13.

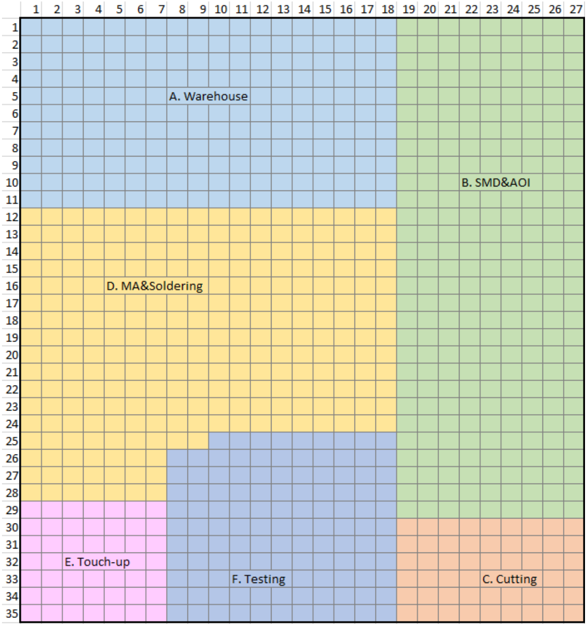


Figure 5-13 Layout after iteration 1

Table 5-4 Cost matrix after iteration 1

	A	B	C	D	E	F	Total
A	-	11250	0	7500	0	13750	32500
B		-	8750	1950	0	0	10700
C			-	14500	4875	6250	25625
D				-	0	4125	4125
E					-	1100	1100
F						-	0
Total							74050

As can be seen in Table 5-4, this exchange of two departments has been successful and results in lower costs. The exchange of department C and E has also been tested. With an objective of 74725 this does not result in a better alternative. As a second iteration, the exchange of E and C has been tested, to lower the costs between C and D. The costs after this exchange become higher, with an objective of 76000. Since no further exchanges can be made which can improve the flow of products, we have found a local optimum.

Because the optimum of this solution is very dependent on the initial solution, a second initial solution is made. In this initial solution the warehouse has a central location, as can be seen in Figure 5-14. The choice to place the warehouse here is based on a suggestion of an employee during a meeting.

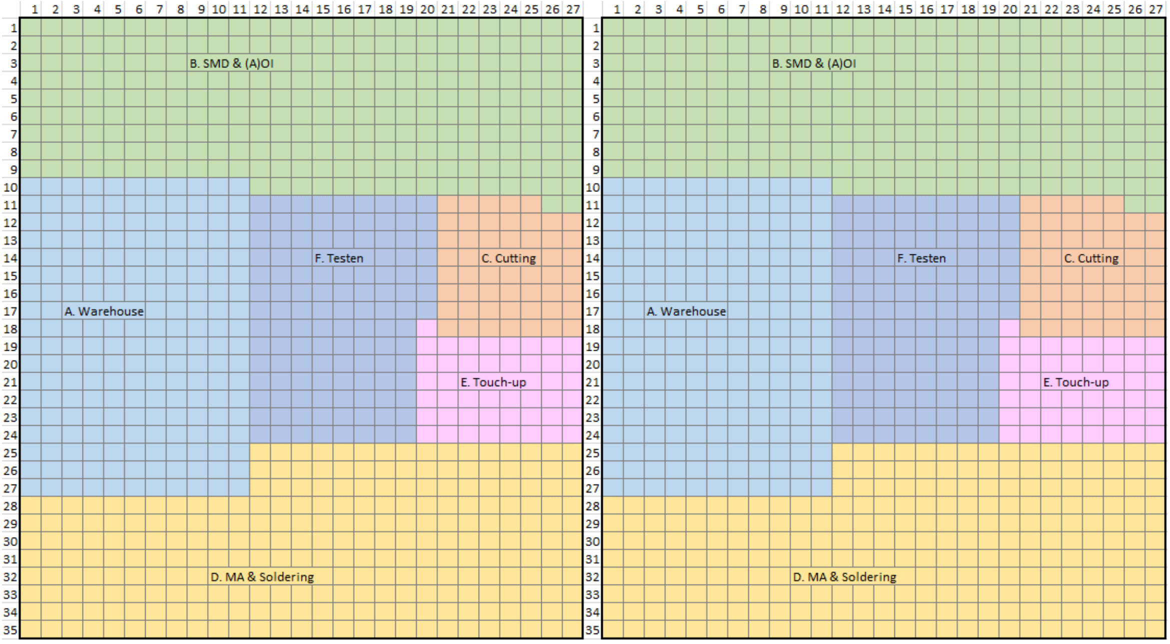


Figure 5-14 Initial solution 2

Table 5-5 Cost matrix of initial solution 2

	A	*B*	*C*	*D*	*E*	*F*	*Total*
A	-	10750	0	10000	0	5250	26000
B		-	9750	2550	0	0	12300
C			-	13000	1875	5750	20625
D				-	0	3625	3625
E					-	1850	1850
F						-	0
Total							64400

As can be seen in Table 5-5, there a huge improvement by moving the warehouse to a central location in the facility. An improvement step that can be made, is by moving C and D closer to each other. This can be done by exchanging department C and E.

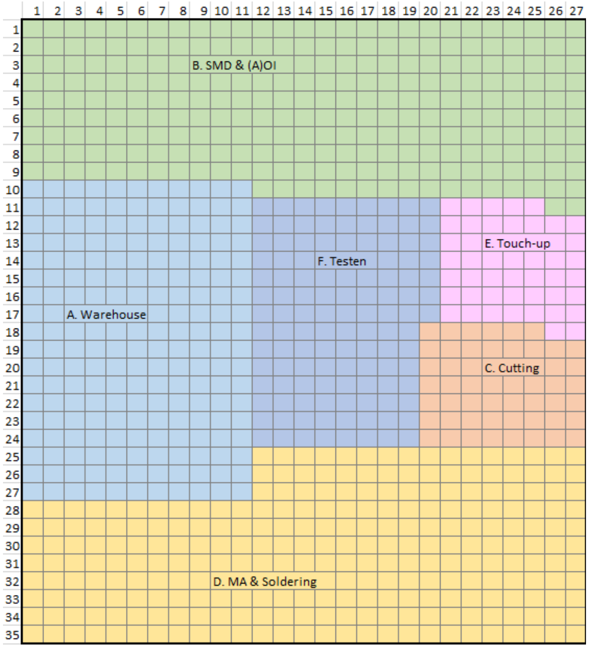


Figure 5-15 Solution 2 after iteration 1

Table 5-6 Cost matrix after iteration 1

	A	*B*	*C*	*D*	*E*	*F*	*Total*
A	-	10750	0	10000	0	5250	26000
B		-	12750	2550	0	0	15300
C			-	9500	1750	5750	17000
D				-	0	3625	3625
E					-	1150	1150
F						-	0
Total							63075

As seen in Table 5-6, the solution has improved by exchanging department C and E. The objective has decreased from 64400 to 63075. The highest costs here are between B and C. This can be decreased by exchanging C and F in the layout.

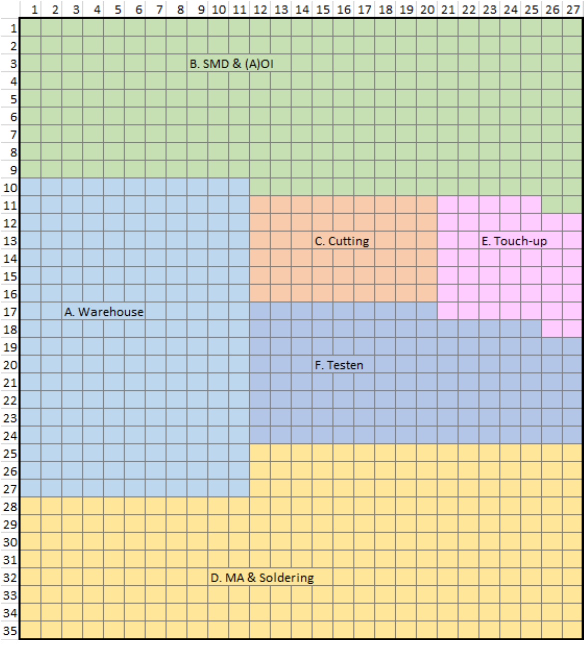


Figure 5-16 Solution 2 after iteration 2

Table 5-7 Cost matrix after iteration 2

	A	*B*	*C*	*D*	*E*	*F*	*Total*
A	-	10750	0	10000	0	7250	28000
B		-	5250	2550	0	0	7800
C			-	9500	2250	5250	17000
D				-	0	3625	3625
E					-	1150	1150
F						-	0
Total							57575

As concluded from Table 5-7, the costs have decreased again. The highest costs are now from the movements between A and B. These costs cannot be changed by exchanging two departments as they are already connected. The second highest costs are from A and D, but again, the departments are already connected. The third highest costs are from C and D, because they have increased with the previous movement. The exchange to be made to decrease these costs is C and F, but they we go back to a previous, and worse, solution. The layout as shown in Figure 5-16 is therefore the chosen layout.

Because the shapes of the departments are not convenient, they are manually altered into rectangles. The final layout can be seen in Figure 5-17.

Figure 5-17 Final layout

5.4. VALIDATION OF THE SOLUTION

To validate the solution that was found in Section 5.3 internal validation is investigated. The internal validity is checked, which will show if correct reasoning is used and that the results are correct. Then, the CRAFT method is checked on reliability. This shows that if the same method is used, the same results will emerge.

To confirm that the layout is correct, the input must be validated. The most important input is the relationship between the departments and the initial layout. The relationship diagram is validated by the employee that is responsible for material handling at the manual assembly department. From the viewpoint of MA, she agrees that the relationship between MA and the warehouse is important, but not absolutely necessary. Next, there should be communication possible between the MA and SMD & AOI department, but these is not a large flow of products, so she agrees with the ordinary closeness of this relationship. Soldering is the most important relationship according to her as well. Since touch-up, testing and cutting are done by the same people who work on MA, she says that all these relationships are important. When looking at the flow of products together, she agrees with the current prioritization of relationships. The relationships between departments are therefore valid.

The next question which is asked to the same employee, is about the final layout. Two layouts were presented to her: the layout after improvement with the first initial layout as shown in

Figure 5-13, and the final layout after improvement with the second initial layout as shown in Figure 5-16. If she had to choose between these two layouts, she agrees that the final layout is preferred.

CRAFT is a method of which the result is dependent on the starting solution. There is no guarantee that a global optimum is found with the starting solution, only the local optimum can be found. This means that if the same heuristic is used with another initial solution, another solution, better or worse, will be found. If we assume that the same initial solution is used, there could still be differences in the final solution. Figure 5-18 shows to options for one iteration. This iteration, which is swapping Touch-Up and Cutting, allows the performer of the heuristic to choose the allocation of the squares to the departments. However, when designing the final layout, departments with many corners and irregular shapes are manually altered. The red line in Figure 5-18 shows how these layouts are altered afterwards and shows that the results are not very different.

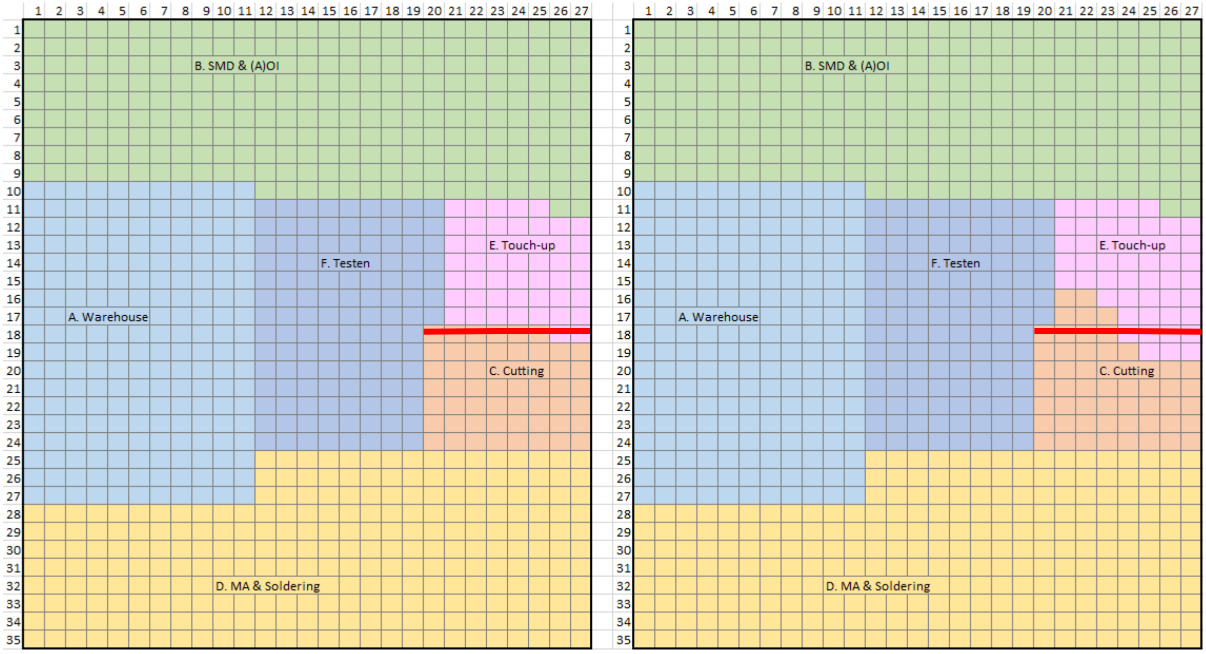


Figure 5-18 Two options for one CRAFT iteration

5.5. CONCLUSION

In this chapter the steps of Muther (Systematic Layout Planning, 1973) have been followed to come to a final layout. For each potential concept, the space requirements were determined as well as the mutual relationships and flow from department to department. Gathering this information, as layout has been made and optimizing using CRAFT iterations.

The final layout is chosen in Figure 5-17, and validated as a realistic and efficient layout by employees of GE. In order to check the improvement of this layout compared to the current layout, a similar spaghetti diagram as in Section 2.3 is made. This spaghetti diagram can be seen in Figure 5-19. What can be concluded from this figure is that there are only two lines crossing departments. This is from cutting to MA & soldering, and from MA & soldering to touch-up. This layout seems to be more efficient, as there is mostly a flow of products from department to department, instead of through other departments.

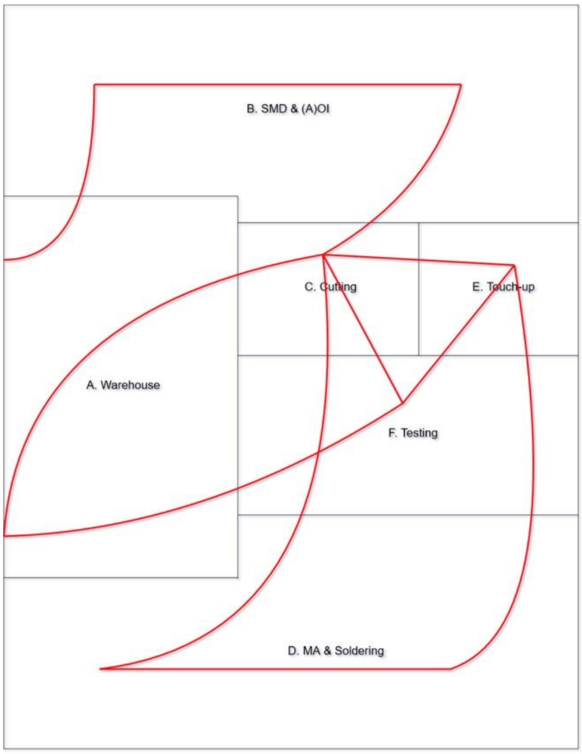


Figure 5-19 Spaghetti diagram new facility

6. SUMMARY OF THE INTERACTION OF ACTIVITIES IN THE SIMULATION

This chapter is a confidential summary of the report. In this chapter, the researched process steps are integrated to the whole process to see how the flow between the different departments behaves and how the alternative investments perform in terms of the KPIs. The process steps are put in the layout as has been determined in Chapter 5 and put into a simulation. The simulation is made in Tecnomatix Plant Simulation. The simulation is used to answer the research question: *"How do the activities interact with or support one another within the boundaries of the facility in a simulation?"*

6.1. SUMMARY OF ALTERNATIVE CONCEPTS

To compare the alternative technologies and see what their impact is on the facility, several potential concepts are made. The concept from the base evolves to a higher level of potential concepts over time. The base concept uses the same processes an in the current situation, but uses the layout as determined in Chapter 5. The base concept is therefore used for the validation against the current situation. The current situation is not further used for the comparison of performance of the concepts. Each concept adds a technique that is discussed in Chapter 4.

These alternative concepts are tested with a simulation. The simulation is briefly discussed in Section 6.2 and in more detail in Appendix A.

6.2. SUMMARY OF THE SIMULATION

In the simulation, a quarter of a year (13 weeks) of production will be replicated. 13 weeks have been chosen for easier simulation purposes. The demand has to be produced within these 13 weeks.

The simulations include the different concepts as discussed previously. To accurately present the concepts, the simulation includes:

- Three different shifts are used, which can vary per department.
- Production times that are either measured in the current situation, or assumed based on the research conducted in chapter 4.
- An availability of a working station which depends on it being a manual or automated task.

For the verification of the simulation, the settings of the simulation were altered. If the expected changes in the simulation could be seen, it was concluded that the simulation was verified.

6.3. SUMMARY OF PERFORMANCE OF THE CONCEPTS

In this section, the performance of the five concepts is discussed. The first concept, the base concept, is used to validate the model as it is the closest representation of the current situation. For each concept the utilization, throughput and size of the buffers are determined. In the conclusion of this section the performance of the concepts is compared.

The KPIs that are used for the performance of the concepts are divided into three categories, which are translated into a cost measurement.

- Cost of personnel
- Cost of space requirements of buffers
- Cost of investment

6.3.1 Base concept

The base concept is used for the validation of the simulation. It measures if the time it takes to produce 13 weeks' worth of demand, is equal to or less than 13 weeks. Since this is the case, the simulation is concluded to be valid.

Next to this, the performance of the base concept is researched based on the beforementioned cost measurements. The stations where the largest buffers are required, are bottlenecks. Next to this, the utilization of all stations are determined.

6.3.2 Cobot testing

For the second concept, the production times, availability and working shift are changed, wherever necessary, according to the added technology. The results of the simulation show what the impact of this added technology is on the production time, utilization of the stations and the size requirements for the buffers.

6.3.3 Automatic wheel cutting

For the third concept, the settings are again changed accordingly. Again the results of the simulation are used to see what process is the new bottleneck and what the impact of adding this technology is on the total required production time. Stations where no improvements are made for this thesis can increase throughput by adding an employee to the station.

6.3.4 MA and soldering in-line

After the settings are changed for the fourth concept, the results of the simulation are analysed. The same method is used as for the previous concepts. The total required production time, utilization, and buffer size requirements are considered.

6.3.5 All processes in-line

For this concept, the input is almost equal to the fourth concept. The difference lies in the reduction of material handling in-between some of the workstations. Placing all the machines in-line also impacts the utilization rates, which is concluded from this section.

6.3.6 Comparison of all concepts

In this section, the five concepts are compared based on the average production time of five simulation runs, average utilization of workstations, and buffer size requirements. The percental change in production time clearly shows if there is an improvement compared to the previous concept or not. The utilization rates can be used to determine how the bottleneck shifts from one station to another if one of the processes is improved. The same can be said for the buffer size requirements. If there is a change in the required buffer size, conclusions can be drawn about the workstation being a bottleneck or not.

6.4. SUMMARY OF COSTS OF THE CONCEPTS

As mentioned in the previous section, there are three costs that are considered.

For the cost of investment, an expected economic useful life is determined. With the investment costs and this expected useful life, the depreciation cost per year are calculated. Then, for each product of customer 75 is determined what their share is in depreciating the machines. This is based on the processing time per product as a percentage of the total time that the machine is used. With these percentages, the costs can be determined per product per concept.

The cost of personnel is determined by calculating the total number of hours personnel is required to produce thirteen weeks of demand. For each concept, the total share in production time per product is determined, which is then used to calculate the cost of personnel per product for each concept.

The costs of buffers is determined by the area that is required in each concept and the costs that are involved in renting this required space. Again, for each product is determined for each scenario what their share is in the required space.

These costs show what the financial impact is of the five researched concepts. The concept with the lowest costs, is concluded to be the most economically attractive concept, based on the three chosen cost factors.

For each of the concepts, the present worth and payback-period are determined. If the PW is above 0 within the lifecycle of the machine, the investment is justified. For the payback period it holds that the period is calculated for which the investment has been paid back with the saving. The savings are determined by subtracting the costs from each concept from the costs of the base concept. An assumption is made for the MARR.

6.5. SUMMARY OF SENSITIVITY ANALYSIS

In order to see how sensitive the results are to changes, a small sensitivity analysis is done. This is done by looking at the impact of an increase or decrease in the production time. Therefore, the production time is simulated when the processing time is 10% lower, 10% higher, or 20% higher. This is chosen because assumption are made about the processing times.

The results show the minimum, maximum and average production time from five simulation runs, and the total production times with increased or decreased processing time. If the production time with increased or decreased processing time fall outside of the minimum or maximum, the solution is sensitive. If this is not the case, the solution is not sensitive to small changes in the data.

6.6.SUMMARY OF CONCLUSION

In the concluding section of this chapter, the results of previous sections are combined. The total cost during production time for each concept is determined. This shows what the financial impact is of the different investment, and what would be the most ideal concept when looking at the beforementioned three cost factors.

7. SUMMARY OF ROADMAP FOR IMPLEMENTATION

This chapter is a confidential summary of the report. In the previous chapter, the improvements and their impact on the production time and costs are evaluated. Now that this information is known, a roadmap is made which shows which improvement can be made at which point in time. In this roadmap IT requirements are added as well, as discussed in Section 4.8. For the roadmap three scenarios are considered, depending on if demand increases, decreases, or remains the same.

7.1. SUMMARY OF ROADMAP

Since this thesis researched both technologies and briefly the IT requirements, both are shown in the roadmap. For the technologies, several scenarios are made. Demand is chosen as an uncertain factor. Many more uncertainties are present and can be added, but the roadmap is based on rough estimations. Adding more uncertainties will make the roadmap false specific. For each of the scenarios, a milestone can be added. This is a point in time where a certain goal has been achieved. The roadmap shows for each scenario when a certain technology can be implemented. The roadmap shows a short, medium and long term.

The IT requirements show when a module of the MES can be implemented. This is based on Section 4.8., where the relevance and need for each module is discussed.

7.2. SUMMARY OF DISCUSSION

In the discussion is discussed that there is a lot of uncertainty, and estimations in the roadmap. This means that to use the roadmap, the scenarios have to be evaluated. If there are changes, the impact on the roadmap must be discussed.

Further discussed in this section is whether concepts are valuable for the company to implement or not. It is discussed if the concepts fit the needs and wishes of GE and whether the concepts could be implemented or if further research is required. If a concept does not add value with the current products and/or demand, it is discussed when this concept does become valuable.

8. SUMMARY OF CONCLUSION

This chapter is a confidential summary of the report. This chapter provides a conclusion to the research problem. Section 8.1 provides the conclusion of the research. Section 8.2 is divided into two subsections. The first section described the relevance of the research to the organisation, after which the contribution to the academic field is discussed. The conclusion is finalised with a recommendation for further research and limitations of this research.

8.1. SUMMARY OF CONCLUSION OF THE RESEARCH

The research question that has been answered during this research is:
What is the feasibility of investing in a new facility for the production of high volume PCBAs?
This question was raised because of several encountered problems at Global Electronics:

- Increasing order volumes and higher demand
- Lack of space in the facility
- Not enough capacity to keep up with the growth
- Behind in market innovations, which means: no traceability of components, no integration of sub-processes, and a lot of manual tasks

Alternative state-of-the-art equipment was researched, of which a few methods and technologies were found to be promising. These potential concepts were further evaluated using a simulation. The evaluation is done using three cost factors:

- Investment of the machines
- Space requirements of the buffers
- Cost of personnel during the production time

The simulation researches five concepts. Each concept adds a new method or technology compared to the previous concept.

1. The first concept uses the same processes as in the current facility, but an AGV is used for material handling between departments in the newly designed layout.
2. Then, instead of manual testing as in the first concept, a cobot is used for the testing.
3. Added to the second concept, is the automatic wheel cutting machine.
4. In concept 4, MA and soldering are placed in-line using a conveyor belt.
5. The fifth concept places all investigated technologies in-line.

The results of the simulation show what the impact is of the concepts on the three cost factors as mentioned before. The percental change in production time for each concept is discussed as well. This shows that there is a trade-off between fastest production time and lowest costs.

Next, the payback periods of the concepts are discussed. With the payback period can be concluded if the investment is justified. If the investment is justified, a more thorough market research can be executed after which they can be implemented.

During the course of this research, the viewpoint of the company changed. They realised that there is a lot more room for improvement in the current facility. They are therefore also interested in the possibilities of these investments in the current facility. Since the effect of these new technologies have not been researched with a simulation, only advices are given. These advices are concerned with what concepts are advised to research further and which to not consider further or on a longer term.

This research shows its relevance in the strategic conclusions that can be drawn by the company. They gained insight in the possibilities of a new facility, but also in what can still be done to expand capacity in the current facility. The testing cobot and automatic wheel cutting machine can increase the capacity, but research in the current facility is required for this. Further research is therefore recommended for the improvement of the current facility. The layout can be evaluated with the approach used in this thesis, and the suggested technologies require further market research.

8.2. SUMMARY OF CONTRIBUTION

The relevance of this research can be found in the knowledge that is gained about the feasibility of opening a new facility. Technologies are researched and a systematic approach is given for this problem and other facility planning problems. Next to this, this research gives strategic insights in the possible technologies and IT requirements that can be implemented and when this implementation is advised.

In the academic field, this thesis shows that facility planning can also be used as a strategic tool for a company. Also, a facility in which a mix of products is manufactured can benefit from the use of facility planning, which is not shown in literature. SMEs are mentioned limited in literature on facility planning. However, the approach can also be used for SMEs. Since the budget may differ, some extra market research is required for suggested machines and equipment in literature to match the budget.

8.3. SUMMARY OF FURTHER RESEARCH

Further research is recommended on two topics. First, the market research for the advised concepts should be extended. This thesis shows a brief market research, and more information must be gathered. Next, the approach for the layout as used in this thesis for the new facility can be adapted in the current facility as well. This is recommended.

8.4. SUMMARY OF LIMITATIONS OF THE RESEARCH

A limitation of this study, is that it is based on a non-existing facility. Therefore, assumptions are made about processing times, space requirements and other input for the simulations. Comparison of the current facility and this new facility is beyond the scope of this research and therefore the advice that is given about the current facility, is limited.

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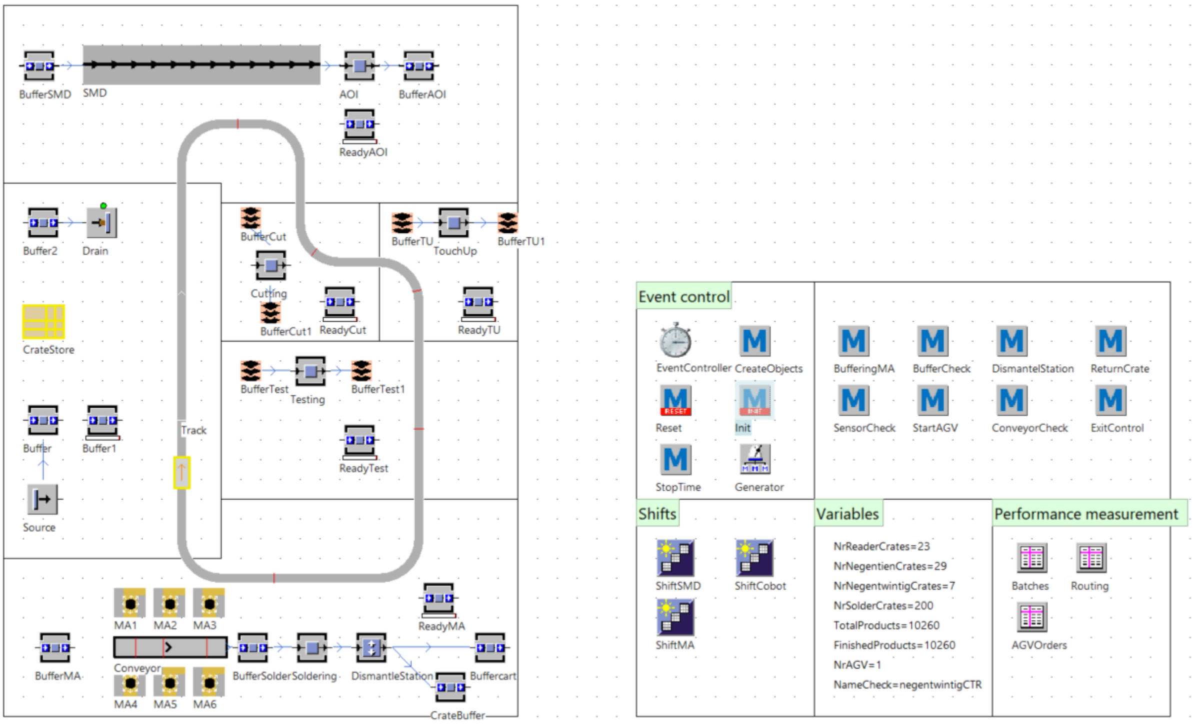
A. APPENDIX

A.1 DETAILED EXPLANATION OF THE SIMULATION

In Figure A-1 a screenshot is shown from the simulation. On the left, the production floor can be seen, using the layout as determined in Section 5.3. On the right, the controls for the simulation are shown. This is the concept in which MA and soldering are placed in-line. First, an explanation will be given on the objects that are in the simulation, after which the methods to move the products are explained.



NrReaderCrates=23
NrNegentienCrates=29
NrNegentwintigCrates=7
NrSolderCrates=200
TotalProducts=10260
FinishedProducts=10260
NrAGV=1
NameCheck=negentwintigCTR

Figure A-1 Production flow in the simulation

The first thing that can be seen in the simulation is the track on which the AGV drives. This track goes from the warehouse through all the departments. The AGV can be moved forward and backwards. The red lines that can be seen on the track are sensors, there is one sensor per department. At this point, the products are loaded or unloaded. The speed of the AGV is 1.6 m/s, based on information provided by WEWO Techmotion (2022).

The process starts and finishes in the warehouse. The Source makes the products according to the table Batches in the controls as shown in **Fout! Verwijzingsbron niet gevonden.**. The source places all the products in the Buffer with an infinite capacity. This Buffer makes a PCB cart ready with 30 PCBs and places them in Buffer1. This Buffer1 is then ready to be picked up by the AGV. When products are finished, the AGV unloads the products at the warehouse again. These products are placed in the infinite Buffer2, after which they move to the Drain.

The Drain represent the shipping of the products. The last object that is seen in the warehouse is the CrateStore. Here, the crates, or carriers, are stored upon which the PCBAs go from the MA department, on the conveyor belt, through the soldering machine.

The next department is the SMD & AOI department. When the AGV unloads its products, the products are moved to the infinite BufferSMD. From here, the product moves through SMD to the AOI, after which an infinite BufferAOI is placed. This buffer makes 30 products ready to get picked up by the AGV and places them in ReadyAOI.

The departments Cutting, Touch-Up and Testing have the same structure. There is an infinite buffer before the machine or workstation (BufferCut, BufferTU and BufferTest), then the machine or workstation (Cutting, TouchUp and Testing), and then an infinite buffer after the machine or workstation (BufferCut1, BufferTU1 and BufferTest1). These last infinite buffer prepare a PCB cart with 30 products to be picked up by the AGV and places them in the buffers (ReadyCut, ReadyTU and ReadyTest).

The last department is the MA and Soldering department. In this concept, these two departments are placed in-line. The products that are unloaded from the AGV are placed in BufferMA. From this buffer, the products are moved, per 30 PCBs, to the MA workstations. There are six workstations shown in the simulation (MA1, MA2, MA3, MA4, MA5 and MA6). These workstations exist of four objects, as shown in Figure A-2. In PCBRack, the 30 products are placed after which one product moves to MAstation. Once the PCB is assembled at the MAstation, the product is placed onto the carrier at the station FillCates. This carrier is stored in the CrateBuffer.

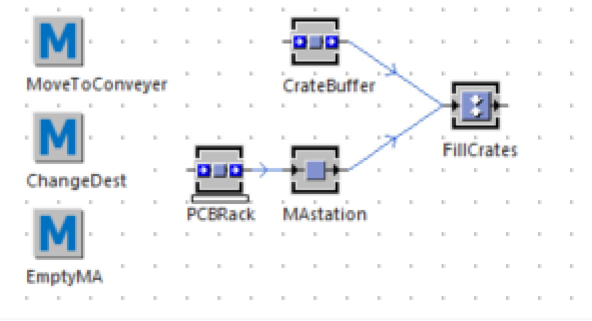


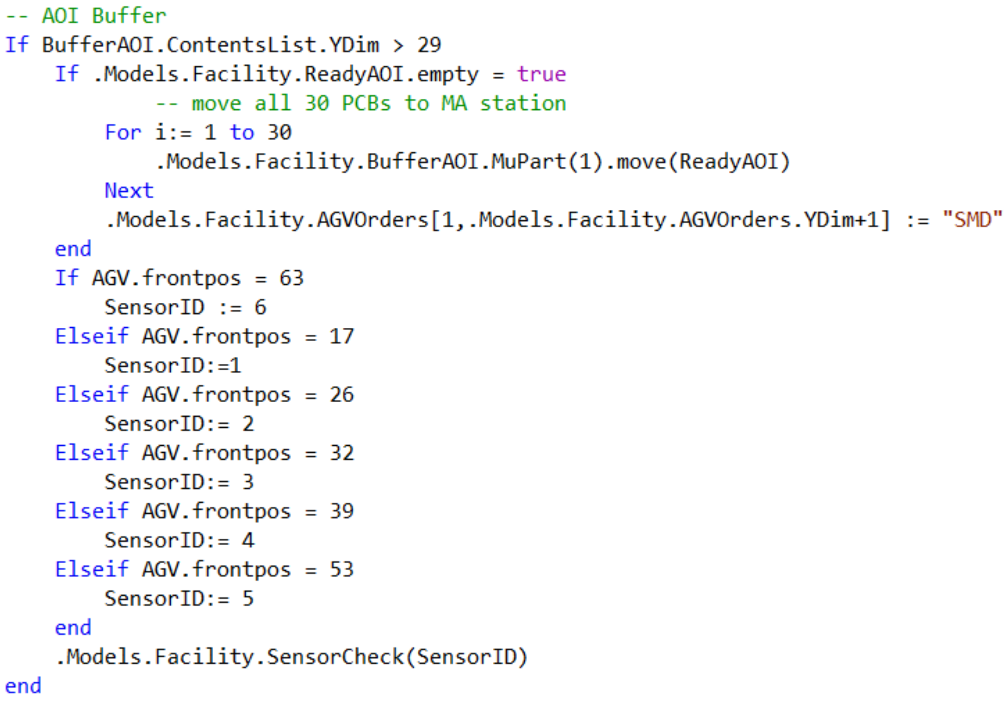
Figure A-2 MA workstation

A.2 METHODS IN THE SIMULATION

Next, the methods that are used to move the products and the AGV are explained in detail. The most important methods are BufferCheck, SensorCheck and ExitControl.

The method BufferCheck ensures that if there are enough products in a buffer, a cart is made ready and that the AGV is called to pick up the cart. This is done for the buffers at AOI, Cutting, Touch-Up, and Testing. In Figure A-3 is shown that the length of the buffer is checked. If the content (ContentsList.YDim) is more than 29, and the cart is empty, 30 products are moved from the buffer to the cart. Then, an order is placed in the table “AGVOrders”, so the AGV knows that a cart is ready to be picked up. Then, the method SensorCheck is called to call the AGV. This method depends on the current location of the AGV, which is why first is determined on which sensor the AGV is.

A comparable method is used for the buffer before MA. The difference is that BufferingMA also ensures that the products at the MA stations are all the same.

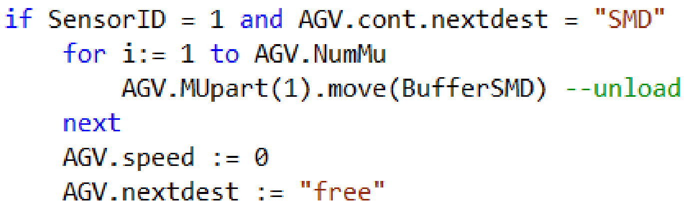


```
-- AOI Buffer
If BufferAOI.ContentsList.YDim > 29
    If .Models.Facility.ReadyAOI.empty = true
            -- move all 30 PCBs to MA station
        For i:= 1 to 30
            .Models.Facility.BufferAOI.MuPart(1).move(ReadyAOI)
        Next
        .Models.Facility.AGVOrders[1,.Models.Facility.AGVOrders.YDim+1] := "SMD"
    end
    If AGV.frontpos = 63
        SensorID := 6
    Elseif AGV.frontpos = 17
        SensorID:=1
    Elseif AGV.frontpos = 26
        SensorID:= 2
    Elseif AGV.frontpos = 32
        SensorID:= 3
    Elseif AGV.frontpos = 39
        SensorID:= 4
    Elseif AGV.frontpos = 53
        SensorID:= 5
    end
    .Models.Facility.SensorCheck(SensorID)
end
```

Figure A-3 BufferCheck

The method SensorCheck is a long code and is therefore cut into three parts. This method is based on a few scenarios: the AGV carries products, the AGV is empty and has no destination, or the AGV is empty but has a destination.

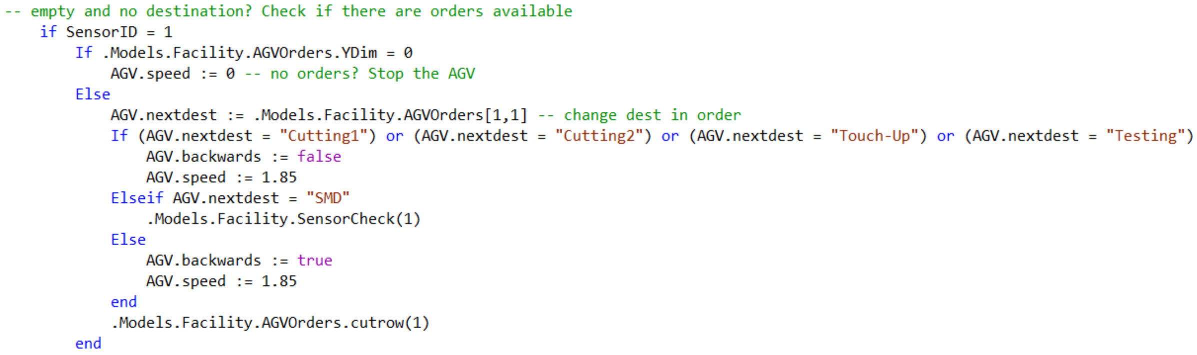
If the AGV carries a product, the method checks if he is at the sensor that corresponds to the destination of the AGV. If this is the case, the products are moved from the AGV to the buffer. Then, the speed is set to 0 and the destination to “free”.



```
if SensorID = 1 and AGV.cont.nextdest = "SMD"
    for i:= 1 to AGV.NumMu
        AGV.MUpart(1).move(BufferSMD) --unload
    next
    AGV.speed := 0
    AGV.nextdest := "free"
```

Figure A-4 SensorCheck: AGV has products

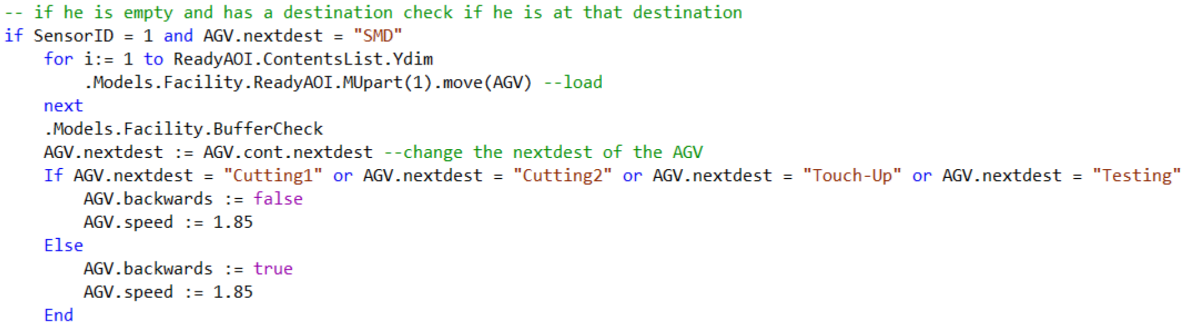
Then, the method part in Figure A-5 checks if there are orders available if the AGV is empty and the destination is “free”. If there are no order available in “AGVOrders”, the AGV is stopped. If there are orders available, the destination of the AGV is changed to the destination of the order. Depending on the current location of the AGV and the new destination of the AGV, the AGV is either send forward or backwards. The order is removed from the table “AGVOrders”



```
-- empty and no destination? Check if there are orders available
    if SensorID = 1
        If .Models.Facility.AGVOrders.YDim = 0
            AGV.speed := 0 -- no orders? Stop the AGV
        Else
            AGV.nextdest := .Models.Facility.AGVOrders[1,1] -- change dest in order
            If (AGV.nextdest = "Cutting1") or (AGV.nextdest = "Cutting2") or (AGV.nextdest = "Touch-Up") or (AGV.nextdest = "Testing")
                AGV.backwards := false
                AGV.speed := 1.85
            Elseif AGV.nextdest = "SMD"
                .Models.Facility.SensorCheck(1)
            Else
                AGV.backwards := true
                AGV.speed := 1.85
            end
            .Models.Facility.AGVOrders.cutrow(1)
        end
```

Figure A-5 SensorCheck: AGV is empty and has no destination

Last, if the AGV is empty and has a destination, the method part in Figure A-6 checks if he is at the right sensor. If the AGV is at the right sensor, the products are moved from the cart to the AGV. Then, BufferCheck is called again to see if the cart can be filled again. The destination of the AGV is changed to the next destination of the products he has just picked up. According to this next destination and the current location of the AGV, the AGV is send forward or backwards.

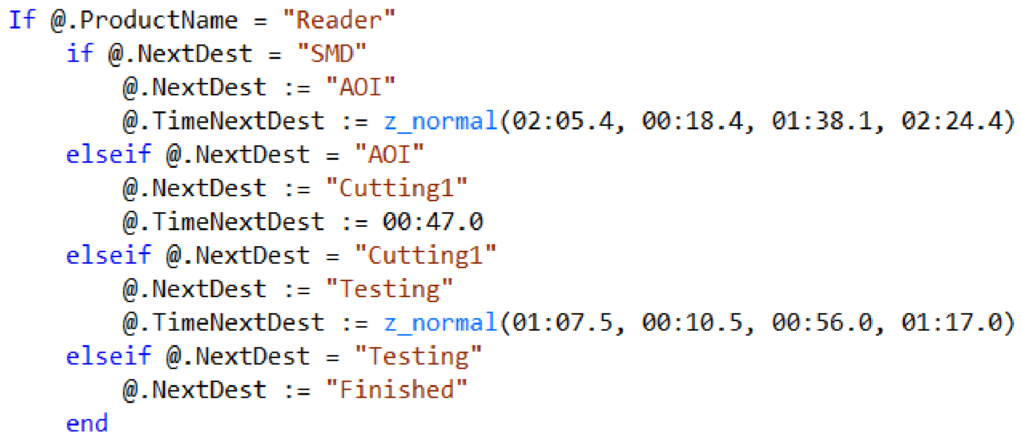


```
-- if he is empty and has a destination check if he is at that destination
if SensorID = 1 and AGV.nextdest = "SMD"
    for i:= 1 to ReadyAOI.ContentsList.Ydim
        .Models.Facility.ReadyAOI.MUpart(1).move(AGV) --load
    next
    .Models.Facility.BufferCheck
    AGV.nextdest := AGV.cont.nextdest --change the nextdest of the AGV
    If AGV.nextdest = "Cutting1" or AGV.nextdest = "Cutting2" or AGV.nextdest = "Touch-Up" or AGV.nextdest = "Testing"
        AGV.backwards := false
        AGV.speed := 1.85
    Else
        AGV.backwards := true
        AGV.speed := 1.85
    End
```

Figure A-6 SensorCheck: AGV is empty and has a destination

The method SensorCheck is called every time the AGV passes a sensor.

The third method is ExitControl and is used every time a product leaves a processing station. In this method the product receives a new destination, and a new processing time. In Figure A-7 the method is shown if the name of the product is reader. Depending on the current next destination, a new destination is given. The time of the next destination is normal distributed. The function z_normal draws a processing time according to the normal distribution with a mean, standard deviation, lower bound and upper bound, respectively.



```
If @.ProductName = "Reader"
    if @.NextDest = "SMD"
        @.NextDest := "AOI"
        @.TimeNextDest := z_normal(02:05.4, 00:18.4, 01:38.1, 02:24.4)
    elseif @.NextDest = "AOI"
        @.NextDest := "Cutting1"
        @.TimeNextDest := 00:47.0
    elseif @.NextDest = "Cutting1"
        @.NextDest := "Testing"
        @.TimeNextDest := z_normal(01:07.5, 00:10.5, 00:56.0, 01:17.0)
    elseif @.NextDest = "Testing"
        @.NextDest := "Finished"
    end
```

Figure A-7 ExitControl

A.3 TRAVEL DISTANCE OF AGV

Table A-1 Distance by AGV

	Warehouse	*SMD & (A)OI*	*Cutting*	*MA & Soldering*	*Touch-up*	*Testing*	*Total*
Warehouse	-	19	28	10	31	41	132
SMD&(A)OI		-	9	29	15	22	75
Cutting			-	27	6	13	46
MA & Soldering				-	21	14	35
Touch-up					-	7	7
Testing						-	
Total							295

In Table A-1 the distances between departments are shown as travelled by the AGV with one track through the facility. The weighted travel distance, using the same method as in Section 5.3, is shown in Table A-2. As can be seen, the total weighted travel distance is a lot higher than when using the rectilinear distance, an increase of 15.4%. This method of using a single track has been chosen for easier programming, however. To compensate for this increase of travel distance, the speed of the AGV has been increased by 15,4%. So, a speed of $1{,}6\ m/s * 1.154 = 1.85\ m/s$ is used for the AGV.

Table A-2 Weighted distance by AGV

	Warehouse	SMD & (A)OI	Cutting	MA & Soldering	Touch-up	Testing	Total
Warehouse	-	9500	0	5000	0	20500	35000
SMD&(A)OI		-	4500	2900	0	0	7400
Cutting			-	13500	1500	6500	21500
MA & Soldering				-	0	3500	3500
Touch-up					-	700	700
Testing						-	
Total							68100

A.4 LIMITATIONS OF THE SIMULATION

For programming reasons, the simulation does always represent the actual process. The simulation is therefore limited. To give insight in the validation of the simulation, the limitations are listed here.

- The batches in the simulation are a factor 10 smaller than in the real situation. This reduces the number of products that must be simulated and thus increases the simulation time drastically. The processing times are therefore a factor 10 larger.
- In the simulation, the PCBAs are always moved in batches of 30. In truth, the PCBs are moved in batches of 300 before they are manually assembled and in batches of 200 after the manual assembly.
- For the manual assembly stations, it is assumed that all stations must be empty before they can move to the next type of product. This is done to make sure that products will not get mixed. If the product in the buffer is different that the product at the manual station, it must wait until the station is empty again. In real life the other working stations could already begin to assemble the next type of product.
- In the simulation, two PCBAs are placed on a carrier to move to the soldering machine. In reality, the 910PWR are placed per four in a carrier. The production times are adjusted to this.