Process Design of the Flexarm Assembly Line at VDL ETG Almelo

Strength through cooperation

VDL & UNIVERSITY OF TWENTE.

Ieke Schrader
July 2019

Master Thesis

Process Design of the Flexarm Assembly Line at VDL ETG Almelo

Student

Ieke M.W. Schrader

Student number:	S1280716
University:	University of Twente
Faculty:	Behavioral, Management and Social Sciences
Programme:	Msc. Industrial Engineering & Management
Specialization:	Production & Logistics Management

Graduation company

VDL ETG Almelo
Bornsestraat 345
Postbus 176
7601 PB ALMELO
The Netherlands
+31 546 54 00 00

University Supervisors

First supervisor

Peter Schuur
University of Twente

Second supervisor

Nils Knofius
University of Twente

Company Supervisors

First supervisor

Wouter Sleiderink
VDL ETG Almelo

Second supervisor

John Nijhuis
VDL ETG Almelo

Foreword

Dear reader,

While writing the last chapter of my thesis, I am rethinking the road that I have travelled. As teenager, I became enthusiastic about technology due to a grumpy old teacher. He taught me to create things, while thinking about it. From that moment on I knew, I am going to work in technology. And so it went, after 12 years I propose this master thesis focussing on the process design of the flexarm assembly line at VDL ETG Almelo.

The period of conducting my master research has its ups and downs. When looking back on the period, if feel satisfaction because of my perseverance during bad days and enthusiasm on good days. I got to know myself a little better, something nobody takes away from me anymore.

VDL ETG Almelo is a big company with the family feeling. The mix of people made a wide range of conversations possible. From small funny chats to in-depth conversations about my research topic, everything has passed. Hence, I want to thank my colleagues at VDL ETG Almelo for everything, especially the many visits to the Lidl for the lunch snacks. Besides this, I want to thank Mart Koertshuis for being the initiator of my internship and my carpool buddy. Last but not least, I want to thank Wouter Sleiderink and John Nijhuis for the many feedback sessions and support.

The other player in this project is the University of Twente. Therefore, I would like to extend my gratitude towards my University supervisors Peter Schuur and Nils Knofius. I appreciate it that they read every last word of my thesis, thereby providing useful feedback and being good discussion partners. Furthermore, I enjoyed our informal conversations, through which I got to know you better.

At last, I would like to express some thanks towards my parents for being endless patiently with me and being the main sponsors during my education, to Thom Oldemaat for the many peer review sessions during our graduation period, and to all others who supported me.

I wish you a lot of reading pleasure.

Yours Sincerely,
Ieke Schrader
July 2019

Management Summary

VDL ETG Almelo is specialized in the manufacturing of (sub)systems and modules for a broad range of clients. Therefore, VDL ETG Almelo can be considered as a system supplier with the possibility to co-design, produce parts and execute quality checks. One of the projects executed for a current client is Flexarm. The goal of this project is the assembly of 7 subsystems. After delivery, the client puts all subsystems together to form an x-ray machine. For ordering the subsystems (called the VB, HB, LC, FDR, CORO, CD and CDS), a make-to-order policy is used. When VDL ETG Almelo receives a sales order, the manufacturing process is initiated. The first step is purchasing parts, executing sheet metal work and producing parts in a parallel process. Thereafter the assembly starts. Around January 2019 the design phase of the subsystems was completed. Hence, the assembly of subsystems gradually started. During the design phase, the demand was on average 1.67 x-ray machines per month. One expects that within 2 years the demand will rise to 25 x-ray machines per month. In order to achieve a well-controlled volume production, a standardized assembly process is needed. This thesis focusses on designing such standardized assembly process. The scope includes development of a layout, workforce planning and employee management. The research question in line with this focus is as following:

*How can the assembly process be (re-) designed in terms of layout design and employee capacity such that a standardized efficient line is obtained, with robustness for the increasing demand and a Committed Line Item Performance of at least **Confidential**%?*

This research is divided into multiple phases to answer the main question. First, the current assembly process and layout are evaluated. Next, the knowledge obtained from analyzing the data is used to give insight in the performance of the assembly process and layout. Afterwards, a literature research is executed to obtain the necessary information about layout development, data analysis and planning methods. Finally, all knowledge obtained in the previous phases contributes to the development of the layout and Discrete Event Simulation model (DES). The goal of the DES model is to find a suitable planning strategy and employee settings.

Project Flexarm concerns the assembly of the aforementioned subsystems. For the VB, HB and LC mechanical assembly is executed. Besides mechanical, the FDR and CORO need also electrical assembly. However, for the CD and CDS gathering of parts is only executed. The subsystems do not only differ in assembly method but also in dimensions. Some decisions concerning the assembly have already been made by VDL ETG. Their decisions are based on a monthly demand of 20 subsystems.

The current layout of the assembly process is based on experience of VDL ETG. This layout contains 7 workstations, so each subsystem has its own workstation. The workstation for the VB, HB, LC, CD contains 5 site locations, which are arranged serially. The workstations for the remaining subsystems are not arranged in predefined alignment. Two disadvantages concerning the layout are the obstruction due to the small available assembly space and the unnecessary movement of subsystems.

The assembly process is divided in the order process, assembly activities and the expedition process. The delivery time and order quantity are pre-defined by VDL ETG on 1 week and 5 subsystems,

respectively. Based on data analysis and literature, we selected Poisson arrivals to represent the order process. Besides the actual assembly, multiple internal activities are executed to support the assembly process. Furthermore, process disruptions occur due to quality issues and mistakes in material handling. To represent the internal activities and process disruptions, we examined a similar project called ***Confidential***. Specifically, we employed the empirical distribution of the efficiency used in ***Confidential***. For performing the activities, a differentiation is made between new and experienced employees. The new employees are restricted to only handle the VB, HB, CD and CDS. The differences between both employees is shown in Table 1. Furthermore, the minimal required number of employees without considering efficiency is 3 for a constant demand of 20.

Employee Type	Hourly Rate	Efficiency
New	**Confidential**	
Experienced		

Table 1: Average Efficiency and Hourly Rate for New and Experienced Employees

Expedition of the subsystems to the client is scheduled in such way that the delivery date is met. If a production order is not finished on time, expedition cannot ship them. The Committed Line Item Performance (CLIP) measures the frequency the production order is delivered on time over a certain time period. The CLIP for Project Flexarm is ***Confidential***% and for Project ***Confidential*** is ***Confidential***%.

A rough-out layout and relationship diagram (inspired by Systematic Layout Planning) are the literature-based methods used for layout development. Furthermore, workstations are approached as product family departments. A u-shaped arrangement is suitable for the workstations. This all lead to a layout with 4 workstations in a u-shaped arrangements and subsystems dedicated to one of those workstations, see Table 2.

Workstations	Subsystems
1	VB, HB
2	LC
3	FDR, CORO
4	CD, CDS

Table 2: Groups of Subsystems

Multiple planning strategies were found in literature. The 'Max Task Time' strategy is evaluated in the DES model. Besides this, the current planning strategy 'First In, First Out' is evaluated. At last, we developed and evaluated our own strategy, called 'Smallest Dimension'. For each strategy, 108 experiments are executed, in which the number of experienced and new employees changes. Other experiment factors are the dedication of experienced employees to LC, FDR and CORO and the settings based on the new layout. The DES model is validated with data obtained from Project ***Confidential***.

After analyzing the experimental results and the sensitivity results, it is concluded that experiment 9 significantly outperforms (***Confidential***%) the other experiments. The number of experienced and new employees on the assembly are 3 and 1, respectively. Furthermore, the annual costs are € ***Confidential***.-. When the monthly demand reaches 21, VDL ETG violates the CLIP threshold of ***Confidential***%. However, VDL ETG is able to fulfill the demand of 21, when the stack height is increased to 3. When demand keeps increasing, we recommend on the base of our results the following settings: 4 experienced employees, 1 new employee, a stack height of 3, and storage area of 5.562 by 14.4251 meter. For a monthly demand of 25, the CLIP and costs for these settings are ***Confidential***% and €***Confidential***. -, respectively.

Despite the insignificant difference between the experiments, we recommend the sequencing of orders according to the strategy 'First In, First Out'. This strategy is already commonly known within VDL ETG. Furthermore, the smallest decrease in CLIP is observed when 2 experienced employees remain for assembly.

Since certain assumptions are taken concerning the data, the current and new layout (cf. Figure 1) are not comparable. We were not able to include the disadvantages of the current layout in the DES model, so advantages concerning the current layout are more relaxed. Furthermore, the other assumptions induce high variation in the simulation, causing a low performance for the new and less flexible layout. The new layout, however, solves the disadvantages such as unnecessary moment of subsystems with the current layout. Therefore, we believe that the new layout contributes to a standardized assembly line. In order to give this layout a fair chance, as further research we propose to redo our simulation for empirical distributions based on larger data sets and for assumptions including the disadvantages of current layout.

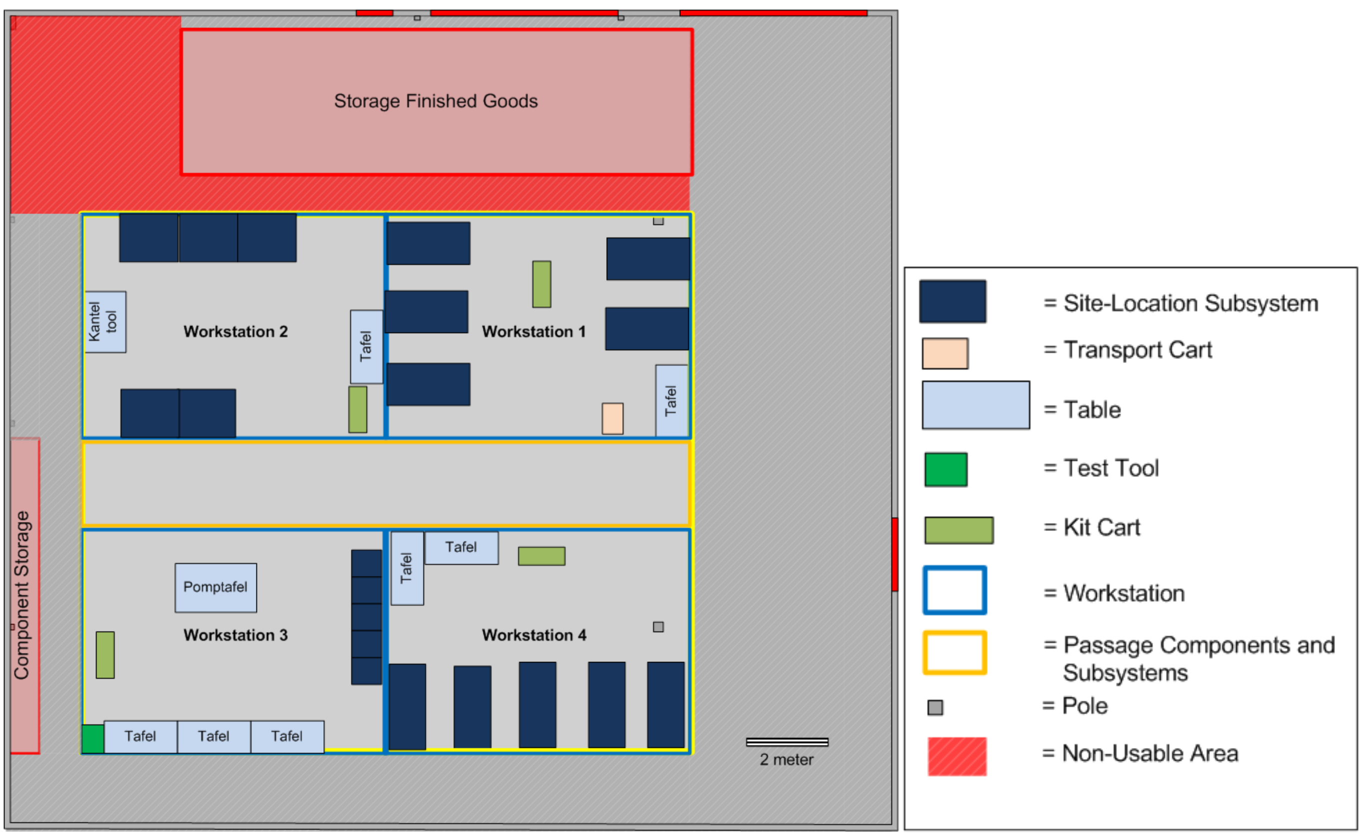

Figure 1: New Layout (Left) and Legend (Right)

List to Support the Report

List of Definitions

Abbreviation	Definition	Introduced
ATO	Assemble-to-order	Page 6
Avg.	Average	Page 31
BOM	Bill of Material	Page 11
CD	Cable Duct	Page 1
CDS	Cable Duct Short	Page 1
CLIP	Committed Line Item Performance	Page 4
CORO	Collimator Rotation Unit	Page 1
Dedicated Pallet	Specially design pallet used for packaging	Page 11
DES	Discrete Event Simulation	Page 8
FDR	Flat Detector Rotate	Page 1
FG	Finished goods, complete end product, 1 x-ray machine	Page 5
FTE	Full Time Equivalent	Page 21
HB	Horizontal Beam	Page 1
Internal Activities	Activities part of the assembly of the subsystems	Page 8
KPI	Key performance indicator	Page 29
LC	Longitudinal Carriage	Page 1
MTO	Make-to-order	Page 1
PERT	Program Evaluation and Review Technique	Page 8
PO	Production Order	Page 21
Site Location	The location of a subsystem	Page 16
SLP	Systematic Layout Planning	Page 39
Subsystem	One of the end products belonging to project FlexArm	Page 1
VB	Vertical Beam	Page 1
VBL	Vertical Beam Long	Page 12
VBS	Vertical Beam Short	Page 12
Workstation	Arrangement of multiple site location and necessary equipment	Page 16
WS	Workstation	Page 44

List of Figures

List of Tables

Contents

1. Introduction

To obtain my Master of Science degree in Industrial Engineering & Management a research is executed. This chapter introduces the research. In Section 1.1, VDL ETG Almelo is introduced. Section 1.2 gives a short description of the problem context. Thereafter, in Section 1.3 a scope is introduced which excludes some parts described in Section 1.1 and 1.2. The resource questions in Section 1.5 support the main question introduces in Section 1.4 problem statement. Finally, the planning and method used to answer the questions is described in Section 1.6 and the deliverables are discussed in Section 1.7.

1.1. VDL Group

The foundation of the VDL group, Van der Leegte, is established in 1953 by Pieter van der Leegte. During the past years the VDL group has extended itself into an international family firm with 99 companies and more than 16.000 employees. Part of this large firm is the VDL Enabling Technology Group, ETG, which is a tier-one contract manufacturing partner. VDL ETG delivers services in the semiconductor industry, solar industry, medical industry and aerospace & defense industry. Clients originating from all over the world can be served from the 4 production locations, located in Eindhoven, Almelo, Singapore and Suzhou (China).(VDL Groep, 2017)

A daily activity of VDL ETG is the manufacturing of high-complex products with low-volume demand. This is also an activity of the site in Almelo. VDL ETG Almelo is specialized in the manufacturing of (sub)systems and modules for a broad range of manufacturers. Therefore, VDL ETG Almelo can be considered as supplier with the possibility to design systems, produce parts and execute quality checks. This all can be done due to several in-house facilities, like electrical assembly, clean room assembly, precision grinding, high-speed milling, product certification, testing and on-site installation. Due to the service they deliver, VDL ETG Almelo must deal with warehousing, purchasing and scheduling.(VDL ETG, 2010) Besides the manufacture-to-order (MTO) policy described above, VDL ETG Almelo also offers an engineer-to-order (ETO) policy. In case a client neither has the capacity nor the competences to design a product himself, VDL ETG Almelo can engineer a certain system or module.

Many departments keep the company running. Two of them, Department 'Projects' and 'Systems', are the executive branches within VDL ETG Almelo. 'Systems' only manufactures systems for one client. Department 'Projects', however, is responsible for projects done for different clients. Project Flexarm is one of these projects and is central in this research proposal. The goal of this project is the assembly of subsystems and the delivery of those to the client. Afterwards, the client puts all subsystems together to form an x-ray machine. A picture of the machine is shown in Figure 2. The subsystems assembled by VDL ETG Almelo are called the Vertical Beam (VB), Horizontal Beam (HB), Longitudinal Carriage (LC), Flat Detector Rotate (FDR), Collimator Rotation Unit (CORO), Cable Duct (CD), and Cable Duct Short (CDS). The design phase started in April 2018. Since January 2019, volume production gradually started.

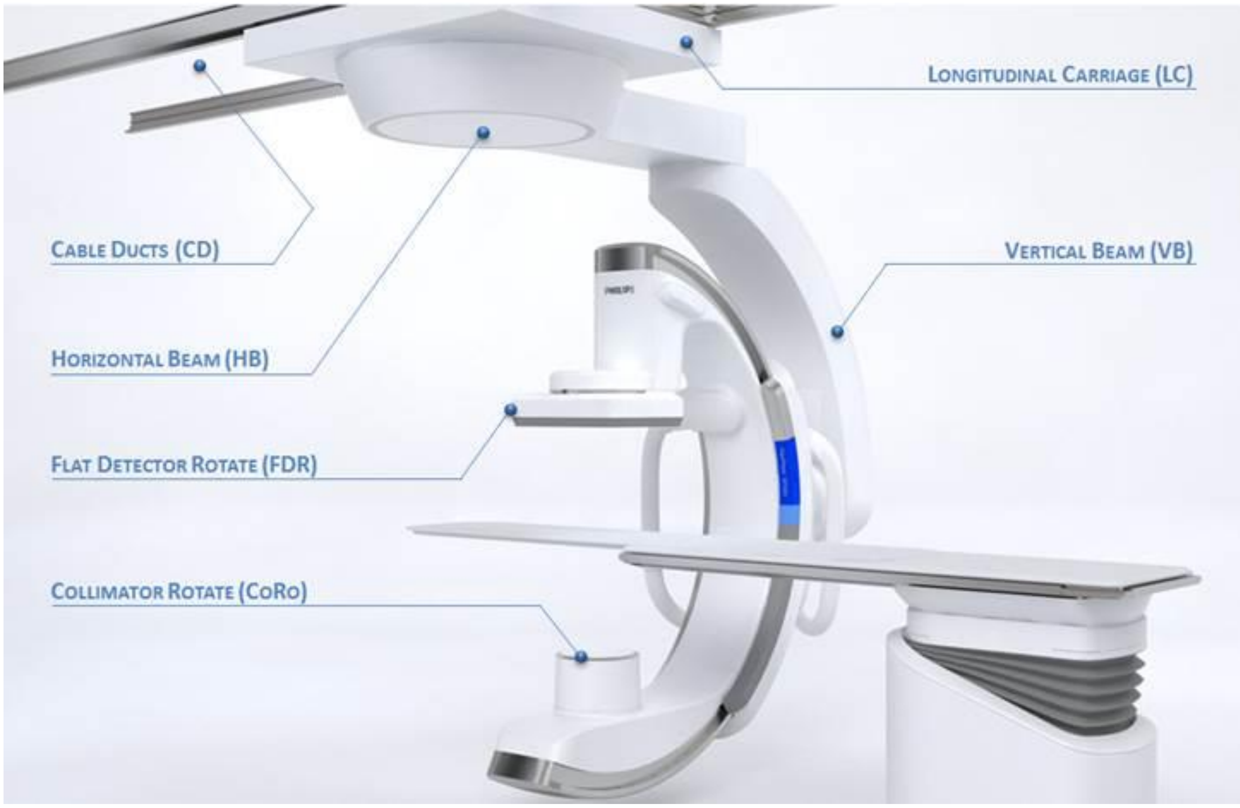

Figure 2: X-ray Machine with 7 Subsystems

For ordering the subsystems, a make-to-order policy is used. When VDL ETG Almelo accepts a sales order, the process described in Figure 3 is initiated. In the flowchart a separation between the departments 'Plaat', 'Parts' and 'Projects' has been made. The legend in the figure describes the differences between the box shape and colours.

First, a parallel process in which purchasing parts, executing sheet metal works and producing parts is started. These are activities executed respectively by the departments 'Projects', 'Plaat' and 'Parts'. The main activity executed within department 'Plaat' is sheet metal work, which includes cutting, joining and forming of metal in different kind of ways. The department 'Parts' can buy parts in addition to production. The decision to outsource production is volume dependent. Components produced in both departments are dedicated to the product, so failure or rejection due to quality checks can induce delay. All the parts of a subsystem must be available before assembly can start, therefore the production planning of these parts, including the failure and rejection rates, must be aligned with the assembly. In the current situation, VDL ETG Almelo starts production early enough to be assured that it does not affect the assembly.

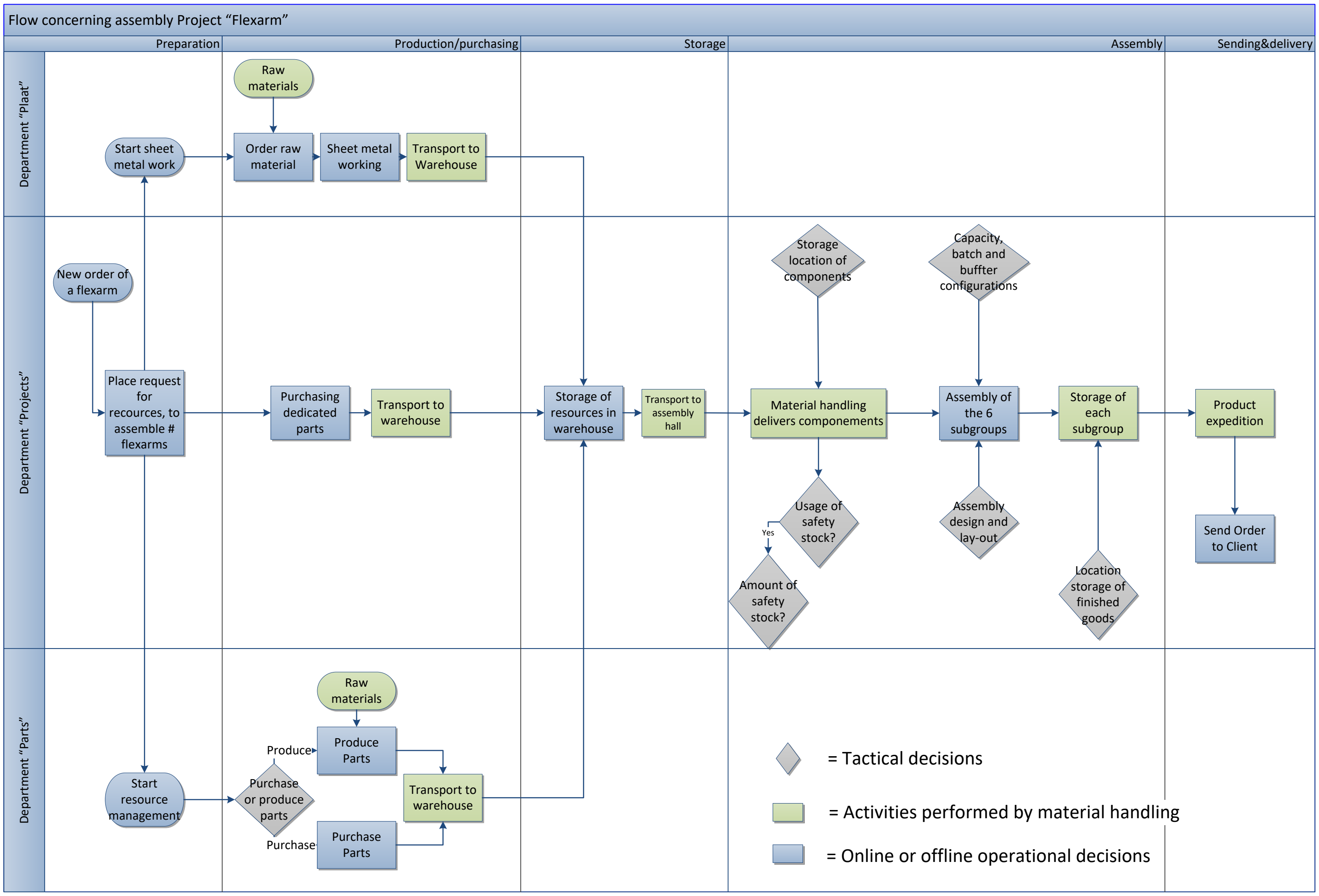

Figure 3: Process to be Completed for Assembly of the Subsystems

After completion of the activities mentioned in the paragraph above, department "Material handling" needs to move the intermediate components to the warehouse. In some cases, the intermediate component is needed right away, then the component will be delivered directly to the assembly floor. Besides component delivery, department "Material handling" is also responsible for the other activities mentioned in the green boxes in the flow chart. All these activities can strongly influence the cycle time and lead time of the process, which affects the efficiency.

Assembly starts when all components are produced, purchased and delivered to the work floor. The configuration of each subsystem is known. Furthermore, the chosen location for the assembly line is hall M3 (cf. Appendix A). Next, a layout is known and shown in Figure 4. The number of components to pick and the number of employees used are based on intuition. All the decisions concerning the assembly process are experience-based and are changed if they are not giving the desired result. Due to the experienced-based decision making and the employee behavior, the assembly process changes a lot. A detailed description of the made decisions are explained Chapter 2 and 3.

Figure 4: The Assembly Hall

The assembly process described above is effective with a current demand of 1.67 x-ray machines per month. However, starting from January 2019 the demand will experience a structural increase, therefore a more standardized design of the assembly line tuned with all the in-house facilities, warehousing, purchasing and scheduling is required. VDL ETG Almelo is responsible for meeting the rising demand and uses the Committed Line Item Performance (CLIP), to measure the performance of the project. CLIP measures the fraction of the agreed sales orders that are assembled and delivered before the due date. Therefore, the main goal of the process is to meet a CLIP of ***Confidential***%, but simultaneously to design and establish an efficient supply chain in order to ensure continuity for this assembly line.

1.2. Problem Context

The main reason for VDL ETG to redesign the assembly process is the failure to meet demand. Besides this, VDL ETG Almelo is interested in the scientific approach behind designing an assembly process. In this paragraph, we discuss why demand cannot be met if VDL ETG Almelo proceeds with the current situation. Multiple reasons are summarized in Figure 5.

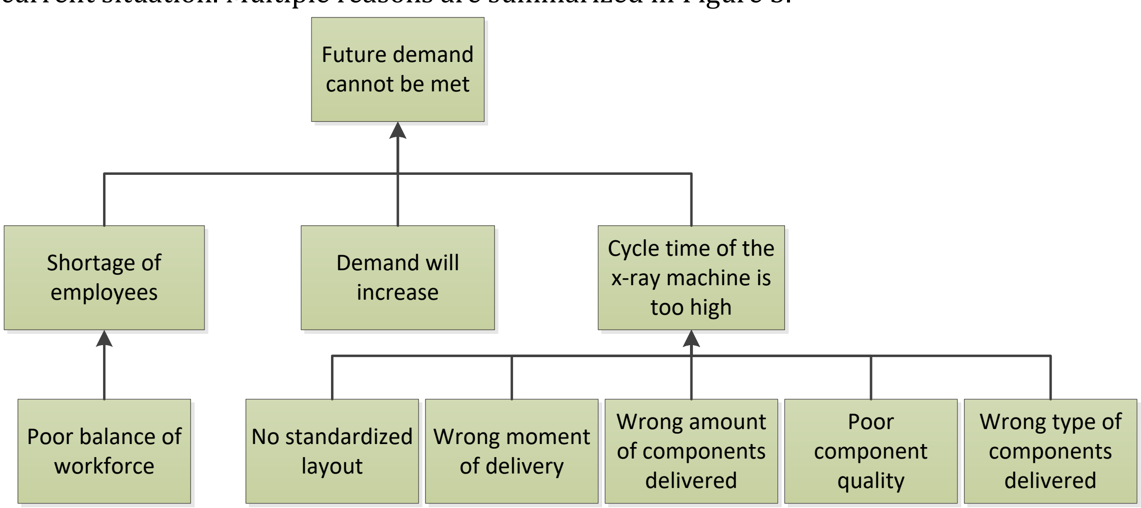

Figure 5: Problem Clusters

Based on forecast received from the client, VDL ETG Almelo expects an increase of the monthly demand till 25 over a time period of 2 years. During the design phase the demand was on average 5 FG per 3 months, which corresponds with 1.67 x-ray machines (FG) per month (cf. Formula 1). VDL ETG Almelo uses a cycle time of ***Confidential*** weeks for assembly of 1 FG, which leads to an assembly rate of ***Confidential*** FG per month (cf. Formula 2). Since the assemble rate is too low for the demand rate, a low CLIP is obtained. The performance of the CLIP is ***Confidential***%, which is below the desired CLIP of ***Confidential***%. VDL ETG Almelo tries to meet demand by increasing the amount of labour force when necessary. The number of employees is still based on intuition.

$$Demand\ Rate\ \ per\ Month = \frac{Demand\ over\ x\ Time}{x\ Time} \qquad (1)$$

$$Assemlby\ Rate\ per\ Month = \frac{1}{Cycle\ Time} \qquad (2)$$

In the past, this low CLIP was still accepted, because the focus was on obtaining a good subsystem design. However, during the phase of volume production the demand can increase in a structured manner to a maximum of 25 FG per month. When continuing in this manner the increased demand scenarios cannot be met.

Fortunately, there is room for improvement. The processing time for the assembly of an individual subsystem varies from 1 to 4 hours. In theory this can lead to a maximal cycle time of 24 hours for 1 FG or 3 days when an eight-hour workday is considered, which is lower than the current cycle time of 3 weeks. There are several aspects that influence the current cycle times. The lack of decision-making concerning material handling, leads to a lot of problems, such as errors in the moment of delivery, right amount, quality and type of the components. This will result in increased waiting times.

Besides the high cycle time, VDL ETG Almelo is also struggling with balancing the number of employees. The problems occurring in material handling will lower the efficiency due to idle time and increase the required employee capacity due to poor workforce balancing. These problems make it even more difficult to cope with employee planning and workforce balancing.

At last, this study provides new insights into shaping assembly processes within VDL ETG Almelo. In the past, the design of assembly lines was a shared responsibility within the project team. Due to the workload on the project group and low priority compared to other activities, the design of an assembly process has never been investigated thoroughly. Furthermore, the designs previously used in assembly processes were based on practical experience. Hereby, making decisions concerning the layout, supply, capacity and planning of the assembly process based on literature can provide more insight into designing the complete assembly process.

The structural increasing demand, problems in material handling, the unbalanced labour force and lack of insight in designing assembly lines makes the research relevant for the company. However, the research is not manageable when all topics are included. Therefore, a scope is defined in the next section.

1.3. Research Objective and Scope

The above described problem context is too complex for executing a thoroughgoing research. Due to the scope in Figure 6, the problem statement in Section 1.4. can be stated using the research scope described below. The scope includes design of the assembly process. All activities prior to assembly are excluded and assumed to encounter no problems (cf. Figure 3). Therefore, we assume that the MTO policy discussed in Section 1.1 is an assembly-to-order (ATO) policy. So, when a sales order is placed by the client, arrival of the components and parts is initiated. In the paragraphs below, the reasons for including and excluding certain parts are discussed.

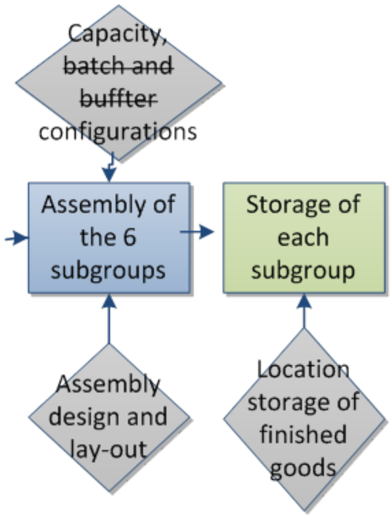

Figure 6: Research Scope

The design of the assembly process includes layout design and decisions concerning the assembly type, for example serial assembly. Furthermore, the configuration for employee capacity are included.

The decision to exclude the internal processes of department 'Plaat' and 'Parts', is made because these activities are hard to adjust. The problems concerning component quality will therefore not be solved. Department 'Projects' has also little influence on the internal processes at 'Material Handling', so improvement on their activities is also excluded

Within the chosen scope there are several limitations that can influence the research results. First of all, the amount of workforce is limited. Furthermore, the basis of the assembly process is weak and frequently changing due to the few decisions that already had been made and the short timespan the project is ongoing. The latter has a great influence on the data quality. Besides the shortage of data, there is also a learning curve which affects the data quality. In Section 1.6. Method and planning it is discussed how these limitations can be handled.

After defining the scope, the problem statement in Section 1.4. is formed.

1.4. Problem Statement

As mentioned above, demand for the Flexarm will structural rise till 25 FG per month, within 2 years. Continuing in the current situation is not an option, because demand cannot be met. Therefore, the assembly design and its configurations must be revised. An efficient layout and a number of employees fitting the rising demand scenarios can contribute to a fine-tuned supply chain in order to ensure continuity for this assembly line. From the problem addressed, the following research question can be extracted:

*How can the assembly process be (re-) designed in terms of layout design and employee capacity such that a standardized efficient line is obtained, with robustness for the increasing demand and a committed Line Item Performance of at least **Confidential**%?*

In Section 1.5. multiple sub-questions are introduced to eventually answer the research question.

1.5. Research Questions

The main research question is based on (re-) designing the assembly process and therefore broadly defined. For answering this research question, it is necessary to divide the design steps in multiple sub-questions.

Questions concerning the current situation

SQ1 What is the technical composition of each subsystem?
SQ2 What are the processing times, waiting times and failure rates of the assembly process?
SQ3 Which tools are used in the assembly process?
SQ4 What is the current layout and where is it based on?
SQ5 How is storage of each subsystem and the component handled?

Questions concerning the current performance

SQ6 How is the performance currently measured?
SQ7 What is the quality of the performance measurement?
SQ8 What is the current performance of the assembly process?

Questions concerning the layout development

SQ9 How can the process of layout development be handled?

Questions concerning model development

SQ10 How can the problems concerning the data availability be solved?

Questions concerning model optimization

SQ11 Which layout fits best for different demand scenarios?
SQ12 How can planning be arranged so that its robust under different demand scenarios?
SQ13 What is the sensitivity and the robustness of the results found?

1.6. Method and Planning

The steps introduced in Section 1.5 contain multiple sub-questions. For each step a method is defined for answering the questions.

Current situation and current performance

To obtain a detailed overview of the current situation and its performance question 1 till 9 must be answered. These questions are solved by monitoring the process, interviewing others and the investigation of company data.

Layout development

For (re-)designing the assembly process a new layout must be developed. To obtain this layout a literature study is conducted.

Model development

Based on the information collected over the current situation and its performance a model will be developed. However, it is plausible that some assumptions concerning the current situation must be made, due to the frequently changing assembly process. To substantiate the assumptions, opinions of experts in combination with literature are used. By preliminary data exploration it is presumable that a data deficiency is present. Therefore, no statistical distributions concerning processing times for internal activities can be determined. However, 2 options suggested by experts are possible to cope with the lack of data:

1) The PERT method can be used to calculate a mean and variance based on the worse, best and expected value (P. Schuur, personal communication, October 23, 2018).
2) Extract data from a project resembling with Project Flexarm (W. Sleiderink, personal communication, November 2, 2018).

It is wise to conduct a literature study to support either option 1 of the 2 or to find new possibilities for data extension. Therefore, the used method for SQ12 will be a combination of a literature study and ideas from experts.

In discrete event simulation (DES) model a certain system is represented by a model. Several events in time will change the state of the system(Law, 2015). For example, the arrival of a product or the end of a painting process. DES model is commonly used for high complex systems, when a mathematical model is missing or when multiple scenarios must be explored(Bangsow, 2016; Banks, 1998). These applications of a DES model are useful for reaching the goals set in this proposal. First of all, the combination of multiple assembly configurations with different layouts, increasing demand and the unexpected behavior of employees creates a high complex process with many factors. Furthermore, no applicable mathematical model was found during preliminary literature study. At last, due to the rising demand and lack of decision making, multiple scenarios need to be examined. Therefore, the decision to use DES for model development has been made. This decision is embraced by management, due to the possibility of multiple scenario analysis.

Model optimization

After model development, optimization of the model is necessary to answer the last sub-questions. An experimental design will be developed to obtain results and analysis will be used to examine the robustness and sensitivity of the found results

The flowchart in Figure 7 is made to give insight in the required research steps to answer the research question. Chapter 2 and 3 treats the current situation and its performance, respectively. In chapter 4, the literature review is written. The developed model and layout are described in Chapter 5. Chapter 6 gives insight in the different experiments and their performances. Eventually, Chapter 7 is used to answer the main question under different demand scenarios. Furthermore, Appendix B contains a time planning.

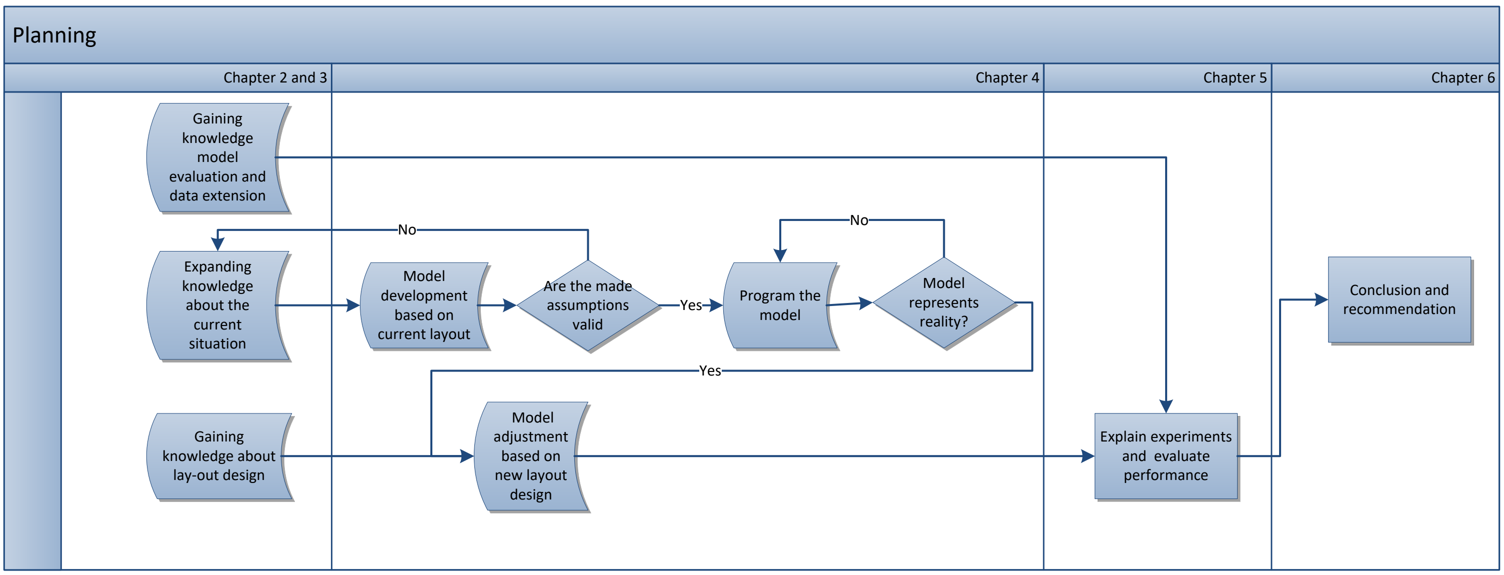

Figure 7: Flowchart of the Research Steps

1.7. Deliverables

This research will deliver different products. Firstly, a simulation model. This model is only available if VDL ETG Almelo possesses a license for Tecnomatix Plant simulation. Secondly, a layout arrangement. At last, a description of (near-)optimal assembly configurations fitting the layout robust under different demand scenarios.

2. Description of Current Situation

Currently, Project Flexarm is in the phase of volume production (cf. Section 1.1). The transition from the design phase to volume production has started gradually in January 2019. During the design phase a prototype is manufactured to test on functionality and is corrected if needed so. If the client and VDL ETG Almelo (hereinafter referred to as VDL ETG) give a mutual approval for the design, the phase of the project becomes volume production. To make volume production feasible, decisions concerning the assembly process are taken and a layout is developed by VDL ETG. Despite the forecasted increase of the demand till 25, all the decisions made by VDL ETG are based on a monthly demand of 20. Therefore, this research uses a demand of 20 as initial value. To describe the current situation in more detail, we divided it in the following sections:

1. Design of the subsystems;
2. Layout developed by VDL ETG;
3. Process executed to assemble the subsystems;
4. Problems encountered since the start of Project Flexarm.

2.1. Design of Subsystems

The end product of the process is an x-ray machine for medical use (cf. Figure 2). VDL ETG delivers 7 subsystems of this x-ray machine, called the Vertical Beam (VB), Horizontal Beam (HB), Flat Detector Rotate (FDR), Collimator Rotation Unit (CORO), Longitudinal Carriage (LC), Cable Duct (CD), and Cable Duct Short (CDS). The development of other parts is executed by other, external, parties. The sections below describe these subsystems one by one, in the following steps:

1. Picture of the subsystem on the floor, exploded view, and pallet used for packaging;
2. Needed assembly tool;
3. Expected process time;
4. Variations within the design.

When reading the information concerning each subsystem, keep the following side notes in mind:

- The design of the VB, HB, LC, and FDR consists of a base frame and components. During assembly the components are mounted on the base frame.
- A dedicated pallet is specially designed to provide support during assembly and shipment. The purpose of VDL ETG is to minimize damage and assembly time. The footprint of each subsystem depends on the dimensions of those pallets. Some pallets have a hard cover.
- VDL ETG calculates the expected process time with the Bill of Material (BOM). The BOM contains all components and subassemblies on multiple levels. The expected process time of each subsystems is based on the kind and the amount of parts. The FDR is used as an example for determining the expected process time in Appendix C;
- To keep the exploded view clear, not all components are separated from each other;
- It is only possible for the VB and CD to add certain variations in the design;
- Needed assembly tools are not mainstream tools. Furthermore, all subsystems are heavy and therefore moved with a hand truck;

Vertical Beam

The first subsystem that is explained is the Vertical Beam (VB). This system connects the HB with an arc produced by the client (cf. Figure 2). The exploded view in Figure 8 shows all the components. The yellow part is the base frame and the purple parts are mounted on this frame. Besides the exploded view, the figure shows a picture of finished subsystems and the dedicated pallet for the VB.

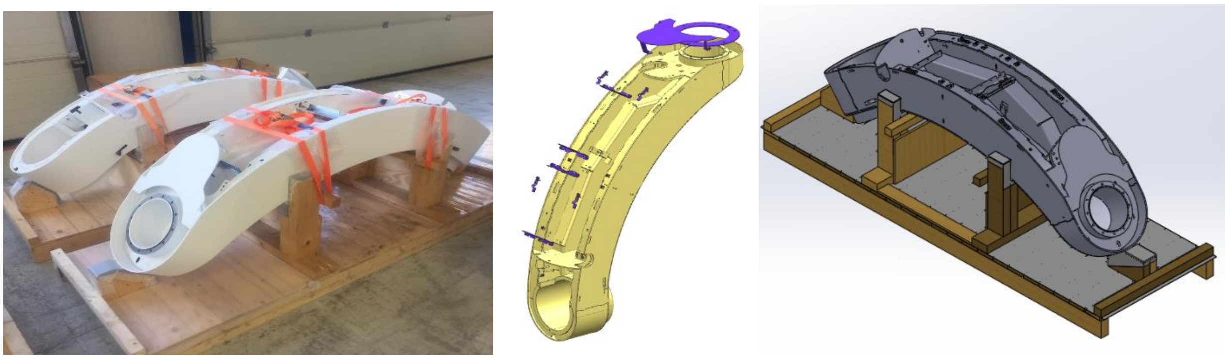

Figure 8: VB: Picture (Left), Exploded View (Middle), On Dedicated Pallet (Right)

As mentioned in the introduction of this section, the VB is one of the subsystems that has multiple variants that substitute each other. The VB has 2 variants which differ only in the length of the subsystems. Both variants are given in Table 3. The order ratio between VBL and VBS is 2:1.

Product Details	Vertical Beam Long	Vertical Beam Short
Expected Process Time (min)	Confidential	
Number of components	105	103

Table 3: Product Details of the VB Long and Short

Horizontal Beam

The second subsystem is the Horizontal Beam (HB). The HB is connected with the LC to the roof of a hospital room (cf. Figure 2). The HB allows the x-ray machine to make a turn of 360 degrees. In Figure 9 a picture, the exploded view and the dedicated pallet are shown.

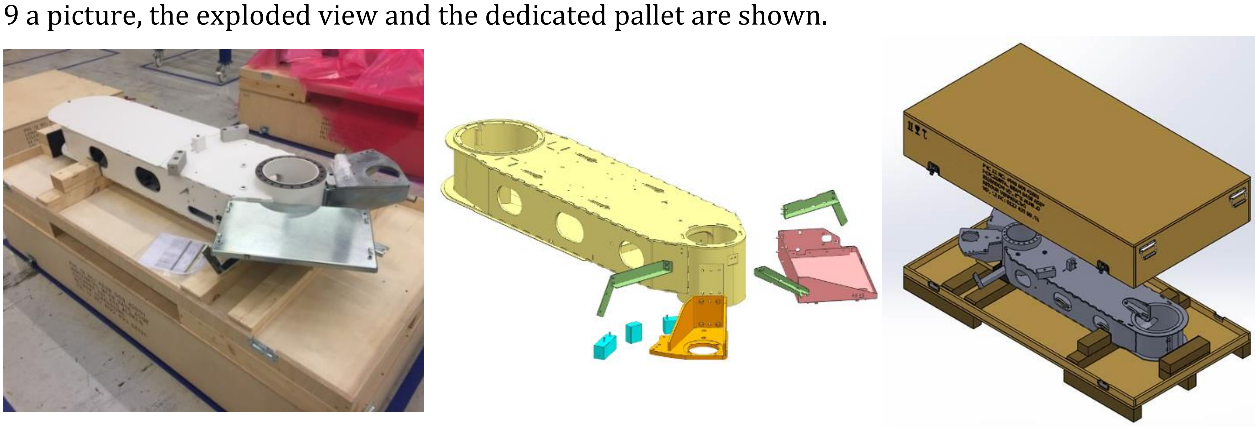

Figure 9: HB: Picture (Left), Exploded View (Middle), On Dedicated Pallet (Right)

The details of this system are given in Table 4. This system is a bit more complex than the VB, because more components are needed.

Product Details	Horizontal Beam
Expected Process Time (min)	**Confidential**
Number of Components	203

Table 4: Product Details of the HB

Longitudinal Carriage

The Longitudinal Carriage (LC) fixates the x-ray machine to the roof of the room (cf. Figure 2). Due to the LC, the x-ray machine can move in horizontally directions. From the exploded view in Figure 10, it can be seen that a sub assembly is placed on every corner point. These 4 sub-assemblies are made by employees before attaching them to the LC. A picture, an exploded view and the dedicated pallet are also shown in the figure.

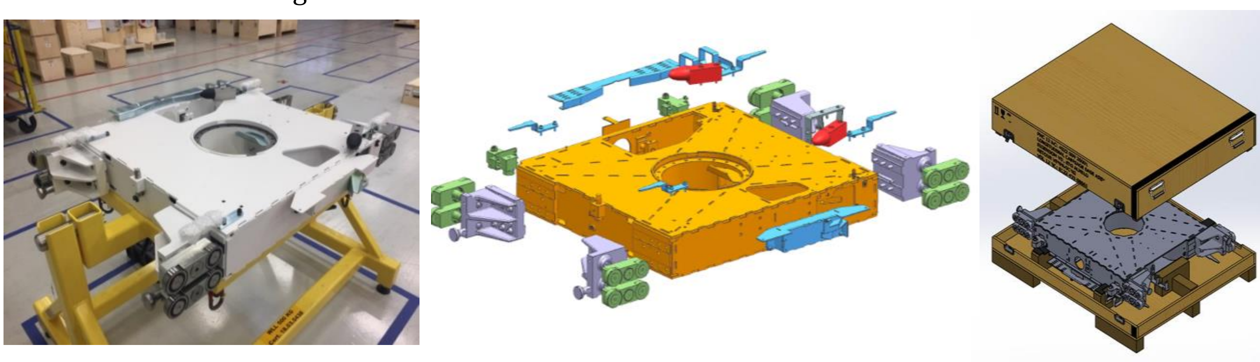

Figure 10: LC: Picture (Left), Exploded View (Middle), On Dedicated Pallet (Right)

During assembly, the LC needs a crane, a press tool and a tilt tool. All these tools are shown in Figure 50 and Figure 53 in Appendix D. The expected process time in Table 5 is ***Confidential*** minutes, which is the longest process time for the subsystems within Project Flexarm.

Product Details	Longitudinal Carriage
Expected Process Time (min)	**Confidential**
Number of Components	293

Table 5: Product Details of the LC

Flat Detector Rotate

The Flat Detector Rotate (FDR) is responsible for detecting x-ray beams. It is located opposite the CORO (cf. Figure 2). Figure 11 shows a picture, exploded view and the dedicated pallet. In contrast to other subsystems, the FDR needs electrical and mechanical assembly, which complicates the assembly for the FDR. On the other hand, the figure shows that the FDR is one of the smallest subsystems. Therefore, is the subsystem easier to move during assembly.

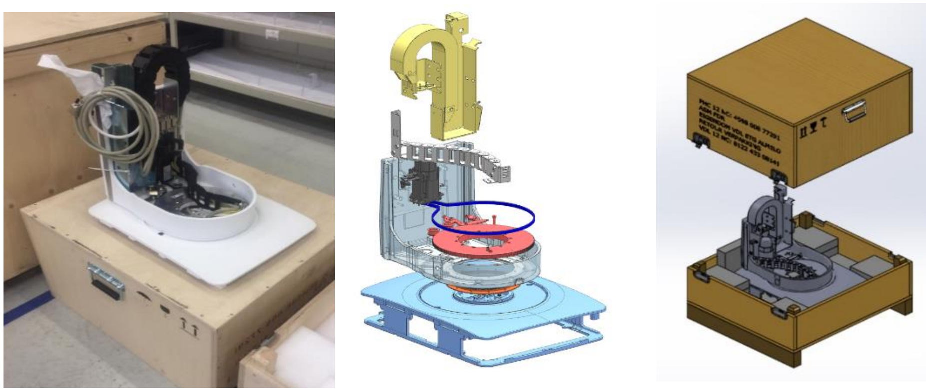

Figure 11: FDR: Picture (Left), Exploded View (Middle), On Dedicated Pallet (Right)

Product Details	Flat Detector Rotate
Expected Process Time (min)	**Confidential**
Number of Components	173

Table 6: Product Details of FDR

After assembly of the FDR, the subsystem is functionally tested with a test tool. The testing process is further elaborated in section 2.3.2.

Collimator Rotation Unit

A system that shows some resemblances with the FDR is the Collimator Rotation Unit (CORO), but the resemblance is not in the design. The difference in design is obvious, when comparing Figure 11 with Figure 12. A similarity in the subsystems is that both subsystems need electrical assembly. Furthermore, the CORO is also tested in functionality. The test tool for the FDR is also used for testing the CORO. Figure 12 shows on the left a picture of the subsystem, in the middle the exploded view and on the right the dedicated pallet.

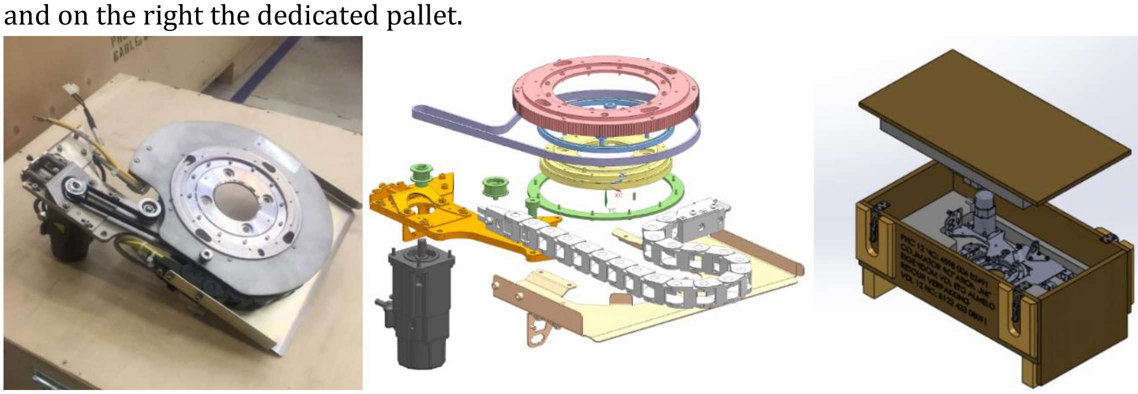

Figure 12: CORO: Picture (Left), Exploded View (Middle), On Dedicated Pallet (Right)

The details of the CORO are given in Table 7.

Product Details	Collimator Rotation Unit
Expected Process Time (min)	**Confidential**
Number of Components	166

Table 7: Product Details of CORO

Cable Duct

The function of the Cable Duct (CD) is to cover the cables on the floor and roof in the hospital room. This subsystem is exceptional, because only gathering of components is needed to complete this subsystem. Figure 13 shows a picture, an exploded view and a big box with different components. Despite no hard cover is shown in the figure, the box can be closed.

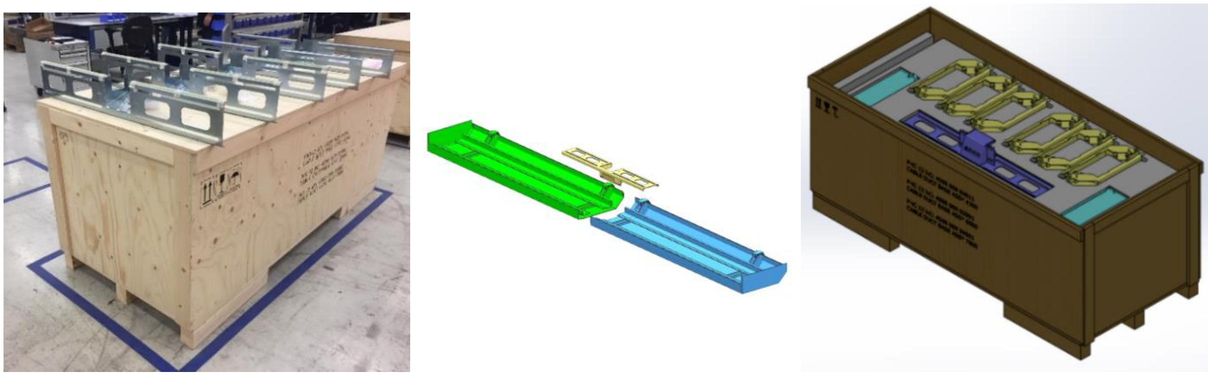

Figure 13: CD: Picture (Left), Exploded View (Middle), On Dedicated Pallet (Right)

As mentioned in the introduction of this section, the CD is one of the subsystems for which variations are possible in the design. There are 3 variants which differ in length and expected process time. These variations are requested by the client because the size of the hospital room determines the required cable duct. The order ratio between CD1, CD2 and CD3 is 1:2:2

Product Details	Cable Duct 4300 (CD1)	Cable Duct 6000 (CD2)	Cable Duct 7800 (CD3)
Expected Process Time (min)	Confidential		
Number of Components	164	211	321

Table 8: Prodcut Details of the 3 CDs

Cable Ducts Short

The last subsystem that VDL ETG delivers to the client is the Cable Duct Short (CDS), its function is covering the cables originating from a certain cabin. Just like the CD, the CDS only contains gathering of the components. The main part of the CDS is shown in the exploded view in Figure 14.

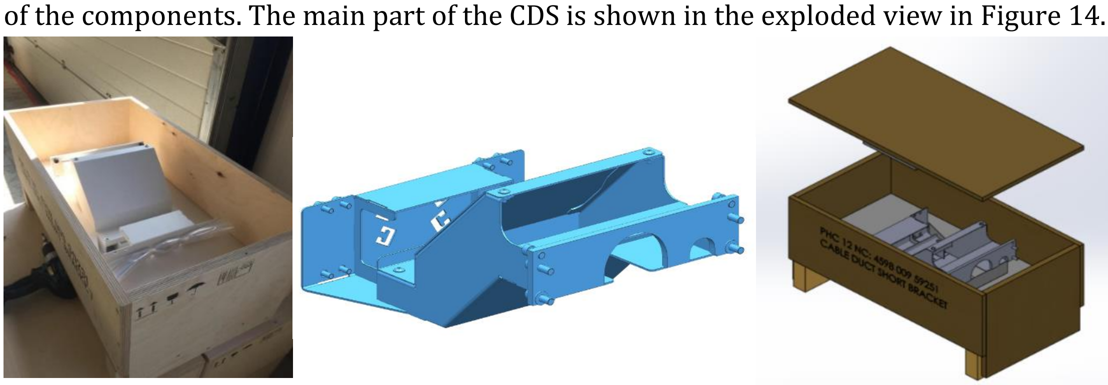

Figure 14: CDS: Picture (Left), Exploded View (Middle), On Dedicated Pallet (Right)

The Cable Duct Short is a small subsystem, as shown in the figure. The time needed for gathering the required components is ***Confidential*** minutes.

Product Details	Cable Duct Short
Expected Process Time (min)	**Confidential**
Number of Components	49

Table 9: Product Details of CDS

Now that all the subsystems for the x-ray machine have been discussed, it is known for each subsystem what the dimensions are, what the number of components is, which tools are required during assembly and what the expected processing time is. This information is useful for explanation of the layout developed by VDL ETG and the process currently executed to assemble the subsystems.

2.2. Layout Overview

Since Project Flexarm is in the phase of volume production, VDL ETG developed a layout. In this section, we elaborate on the developed work floor and the layout. First, the different functional areas are discussed. Afterwards, the workstations for the multiple subsystems are explained. At last, the functionality of the layout is evaluated

2.2.1. Functional Areas Work Floor

VDL ETG divides every hall in the plant in 3 areas, assembly area, site locations, and non-usable area. In the paragraphs below, the division of these areas for Project Flexarm is explained.

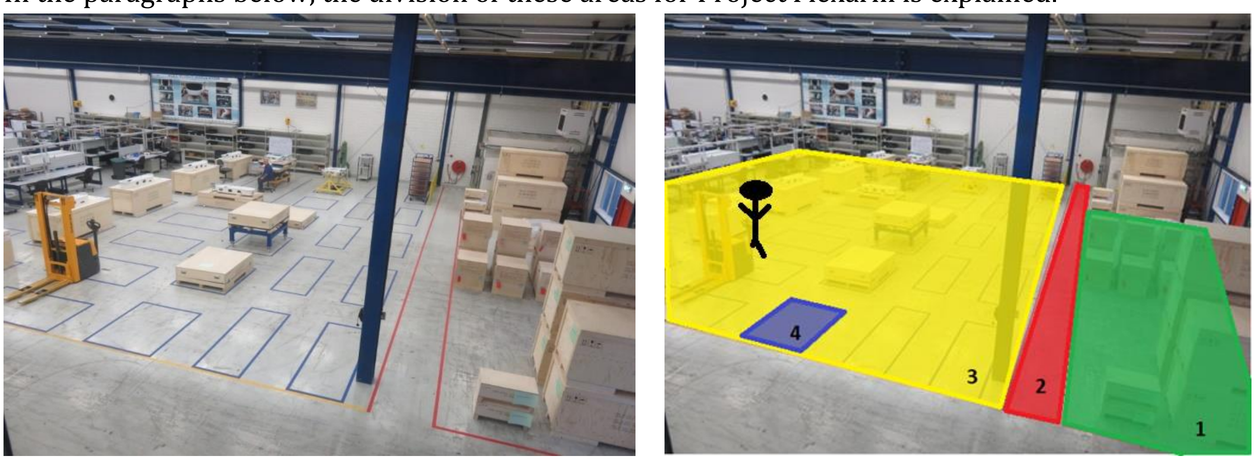

Figure 15: Assembly Hall (Left) and Assembly Hall divided in Functional Planes (Right)

The assembly area that is surrounded by yellow lines and can be recognized in the figure by the yellow plane (3). The size of this area is measured with a laser distance meter. The area and costs per square meter are given in Table 10. The assembly area contains site locations for certain object. Each site location of a subsystem, kit cart, stock cart, or a table is surrounded by a blue line. A kit cart contains packages with components per subsystem and a stock cart contains small components, for example bolts. Plane 4 in the figure is an example for the site location for a LC. Furthermore, a picture of a kit cart and a stock cart is given in Appendix E. The space outside the blue areas is the working area for the employees and contains most of the movement.

Normally the red lines only surround non-usable floor, but in the case of Project Flexarm it also surrounds the storage area. These areas are in the figure distinguished by a red (2) and a green (1) plane respectively. Non-usable floor is necessary for safety reasons and to keep passageways free. The storage area is used for finished subsystems. Normally, the blue lines are used for storage, instead of the red lines.

Area	Length (m)	Width (m)	Costs per square meter
Assembly area	14.973	13.196	**Confidential**
Storage area	12.332	3.562	

Table 10: Dimensions of Assembly and Storage Area

The combination of multiple site locations within the assembly area creates workstations. In the paragraphs below, these workstations are discussed with help of a detailed map of the layout.

2.2.2. Layout Design

In this section, we elaborate on the detailed layout developed by VDL ETG. This layout and its components are on scale in Figure 17. The dimensions of the subsystems are shown in Table 11.

Measurement	VBL	VBS	HB	LC	FDR	CORO	CD1/CD2/CD3	CDS
Length (m)	2.10	1.99	2.04	1.44	0.73	0.74	2.10	0.74
Width (m)	0.70	0.70	1.04	1.19	0.66	0.39	0.70	0.37
Height (m)	0.74	0.74	0.49	0.43	0.75	0.34	0.90	0.35

Table 11: Dimensions Subsystems

In the layout, the site locations for the subsystems have distinctive colours and numbers. Furthermore, all the necessary tools for assembly can be recognized by is light blue colour. Like mentioned in the paragraphs above, these objects are surrounded by blue lines. Figure 16 contains the legend of the detailed layout.

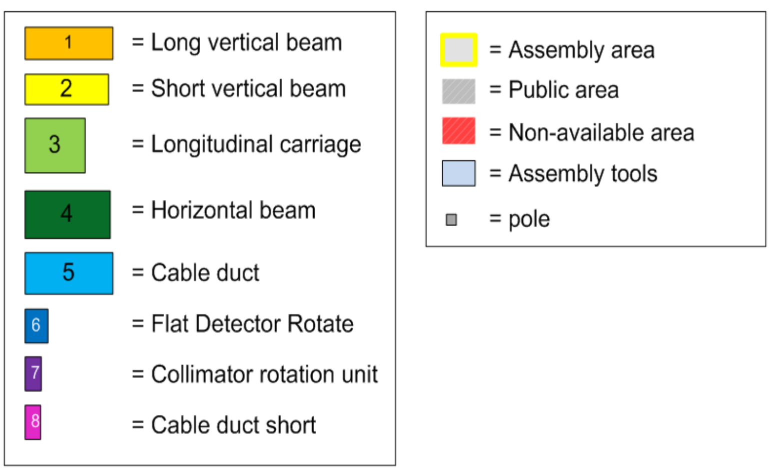

Figure 16: Legend for General Equipment (Left) and Subsystems (Right)

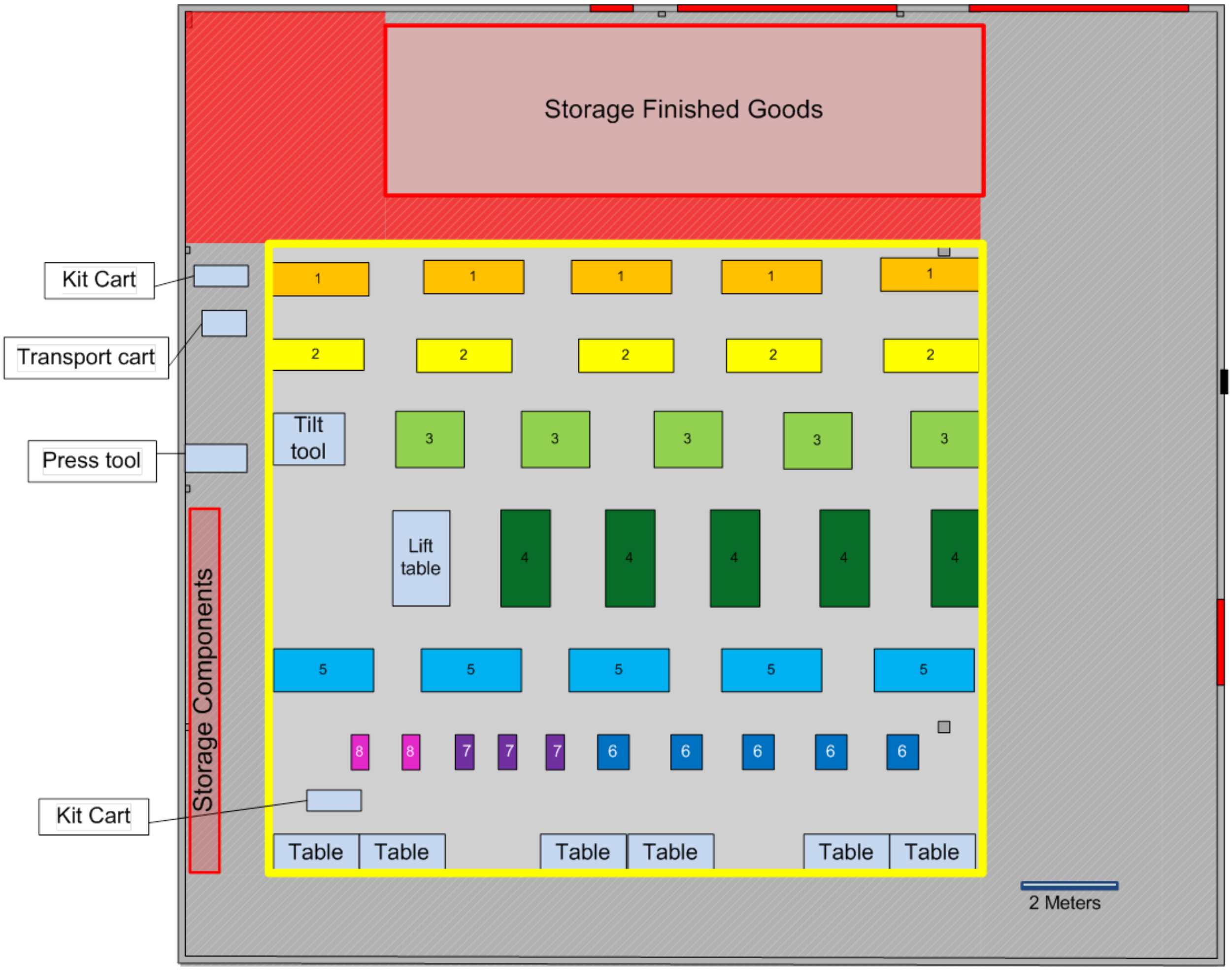

Figure 17: Detailed Map of the Assembly Hall

Nine workstations are distinguished in the layout. Subsystem 1 till 5 have a workstation with 5 site locations for subsystems. A serial arrangement is used for these workstations, because it gives a structured overview and it is commonly used by VDL ETG. In this layout, the long and short variant of the VB have a separate workstation. Subsystem 6 till 8 are not arranged serially, because the dimensions of these system are small, and the remaining assembly area is too small.

VDL ETG chose a serial arrangement, because it is beneficial for the assembly. The employees start with the nearest site location inside the workstation and continues with subsequent site locations. With the help of a transport cart, components are moved between each site locations. It is experienced by VDL ETG that due to serial arrangement an employee only needs to prepare its work once. Besides the one-time preparation, it causes a learning curve whereby the employee gets faster after completing a subsystem within the workstations. Furthermore, the transport cart reduces walking distance. This all benefits the assembly process. In the next section, we evaluate the decisions concerning the layout made by VDL ETG.

2.2.3. Layout Functionality

VDL ETG developed the current layout to create a well-arranged assembly process which supports volume production. In this section, the layout is evaluated on practical functionality. The layout is evaluated by monitoring the behavior of the employees. This section is discussed in two parts, first the assembly area is evaluated and afterwards the storage area.

Assembly Area

During monitoring the behavior on the work floor, 2 things were striking:

1. The space used per workstation is too small;
2. More movement occurred than necessary.

Since each subsystem has its own workstation, a small assembly space per workstation is available and workstations are sometimes empty. From monitoring and conversations with employees, it is observed that the small available space induces placement of subsystems on wrong site locations. Furthermore, when all site locations are filled, the waiting batches block an efficient movement of subsystems with for example the hand truck. In Figure 18, the wrong placement is indicated by the red circle. The left picture shows placement of the vertical beams on the workstation for the Longitudinal Carriage and the Cable Ducts on the workstation for the short vertical beams. The pallets of the cable ducts are randomly placed on the work floor in the right picture.


Figure 18: CDs placed on Workstation for VBS (Left) and Randomly placed CDs on the Work Floor (Right)

Another notable thing is that subsystems are unnecessarily moved. Employees indicate that this movement is caused by the serial arrangement of the site locations. This arrangement induces unnecessary long movement of the LC to the tilt tool. Furthermore, the non-ergonomic height of the VB and HB and the serial arrangement, creates unnecessary long movement of these systems. These useless movement is executed with crane, which is more time due to the distance and extra activities necessary to prepare movement with the crane.

Storage Area

The goal of the storage area is freeing a workstation for a new batch. A workstation is only emptied if the remaining storage area is large enough for the complete batch. In the paragraphs below the storage is evaluated on the stack height of the subsystems and the number of batches in the storage. The 2 pictures in Figure 19 are used to sketch examples.

Figure 19: Several Subsystems in Storage Example 1 (Left) and Example 2 (Right)

Stack Height

The stack height differs but is has never been higher than 3 subsystems. A stack of 2 occurs more frequently than a stack height of 3. In example 1 and 2 mentioned below, both stack heights are observed.

The number of batches

The factors that influence the storage capacity is the sum of the dimension of subsystems in a batch (cf. Section 2.2.2) and the fact that there is a space of on average 30 centimeter in between the subsystems. The capacity of the storage varies between the 3 till 5 batches depending on the dimensions of the batches within the storage, 2 examples are given below.

Example 1: The storage in example 1 contains 13 CDs. The remaining area is large enough for 2 more rows of these subsystems. The total number of CDs become 18, with a batch size of 5 the number of batches in storage is then 3. If the storage contains only 1 batch of CD, there is seemingly more space. When it is filled with smaller subsystems, the number of batches becomes 4 or 5.

Example 2: The red square in the storage in example 2 contains 8 pallets that are not stacked. Two of them are the VB, which cannot be stacked. Imagine that all 8 pallets are VB, if 2 more VBs are added in the storage, the storage contains 2 batches. Behind the red square, there are 4 small subsystems positioned and 1 other pallet. The remaining available space is small, and a complete batch of a random subsystems does not fit. In this case, the total number of batches in the storage is 3. If the storage only contains 1 batch of VBs instead of 2, there is seemingly more space. When it is filled with smaller subsystems, the number of batches becomes 4.

2.3. Process Description

Now the subsystems and assembly layout has been discussed, we continue with evaluating the complete process from ordering of the subsystems until delivery of the finished subsystems to the client. The topics addressed in the following sections are:

1. The order process of the subsystems;
2. The activities concerning the actual assembly;
3. Expedition of the subsystems;
4. Possible disruptions.

2.3.1. Order Process

In this section, the order process for the client is explained first, as this is relevant for the assembly process. Afterwards we discuss briefly which activities are started by VDL ETG when a sales order is received. At last, the arrivals of a production orders on the work floor are explained.

For manufacturing of the subsystems in Project Flexarm a make-to-order (MTO) policy is used. Sales orders are not placed for complete x-ray machines, but only for separated subsystems. The order quantity for the subsystems in Project Flexarm was fluctuating in the design phase. In the second phase, volume production, the order quantity of 5 is agreed between the client and VDL ETG. VDL ETG desires this quantity, due to the serial production of 5 in department 'Plaat'. Therefore, the several workstations in the layout contains 5 site locations. The client accumulates the individual requests from its customer till the agreed quantity is reached.

After receiving a sales order from the client, VDL ETG initiates the manufacturing process. First, a parallel process starts in which purchasing of parts, executing sheet metal work and producing of parts is executed. These activities are not part of the scope (cf. Section 1.3), so we assume that these activities encounter no problems. After finishing the parallel process, a production order (PO) for assembly is made. Due to the PO, all the required components are released on the work floor 1 week before the due date. Because of this time period and excluding the parallel process of purchasing, sheet metal work and parts production, we assume a delivery time of 1 week.

Now that the order process has been discussed, it is known that the desired order quantity is 5 and the delivery time is 1 week. This knowledge is used for construction of the Discrete Event Simulation model in Chapter 5.

2.3.2. Assembly Activities

When the order process is finished the assembly can start. The assembly process contains multiple activities which contribute to finishing a production order (PO). In this section, we elaborate on these activities. However, first information is given about the employees responsible for the activities.

Employees

To execute and finish the assembly process work force is necessary. In this section, the employees are discussed by introducing their behavior, the differences between them, and the number deployed by VDL ETG.

In this research an employee is considered as 1 FTE (Full Time Equivalent). Therefore, each employee works on average 8 hours per day and 5 days per week. After monitoring the behavior of the employees, it is notable that most of the time only 1 employee is working on a PO. Though some extra employees help occasionally, we assume that only 1 employee executes a PO. Furthermore, an employee completes a PO first, before starting a new one.

After discussing the behavior of the employees, the differences between them are elaborated. The employees differ on skill level and therefore efficiency. In this research, 2 type of employees are considered, new and experienced employees. The new employees can only handle POs concerning the VB, HB, CD and CDS. The experienced employee is more flexible and can assemble all subsystems.

The costs for both employees are shown in Table 12. The efficiency of those employees is explained in Section 3.3.2

Employee Type	Hourly Rate
New	Confidential
Experienced	

Table 12: Cost Difference between New and Experienced Employee

To meet demand in a certain month a certain number of employees is needed. The number of employees working on project Flexarm is not balanced.

For example: In the beginning of a PO, 2 employees mount the subsystems. When the due date comes close this number is doubled to increase the chance of delivery to the customer.

We executed a calculation to determine the number of employees per week to fulfill a monthly demand of 20 per subsystem. The expected process time per subsystem (cf. Section 2.1) is used to calculate the required working hours necessary to fulfill demand. To calculate the number of employees required, a workweek of 40 hours is used. This results in a required number of employees of 3. Table 13 shows the required number of employees per subsystem and in total.

Subsystem	Required Working Hours per Month	Required Number of Employees
VB Long	Confidential	
VB Short		
HB		
LC		
CORO		
FDR		
CD 1		
CD 2		
CD 3		
CDS		
Total Required Number of Employees		2.93

Table 13: Calculation of Required Number of Employees

For the next sections it is important to remember that the employees finish a PO before starting a new one. Furthermore, new employees can only handle the VB, HB, CD and CDS. At last, 3 employees are required to fulfill a monthly demand of 20 per subsystem. This information is used for development of the DES model in Section 5.2.

Activities Containing Assembly

The employees discussed above are responsible for the assembly of the subsystems. In this section, these activities are explained. The following activities are part of the assembly process:

1. Positioning the base frame on the designated workstations;
2. Storage of dedicated components;
3. Preparation of the assembly;
4. Whiteboard meeting;
5. Assembly of a subsystem;
6. Visual Quality check;
7. Functional Testing on FDR and CORO;
8. Storage of a finished subsystems.

A precedence chart of the general activity 1 till 7 is shown Figure 20. Because activity 8 is only necessary for the FDR and CORO, it is not included in the figure. Activity 8 is always executed after assembly. In the sections below each assembly activity and testing is explained briefly, starting with the positioning of the base frames on the designated workstation.

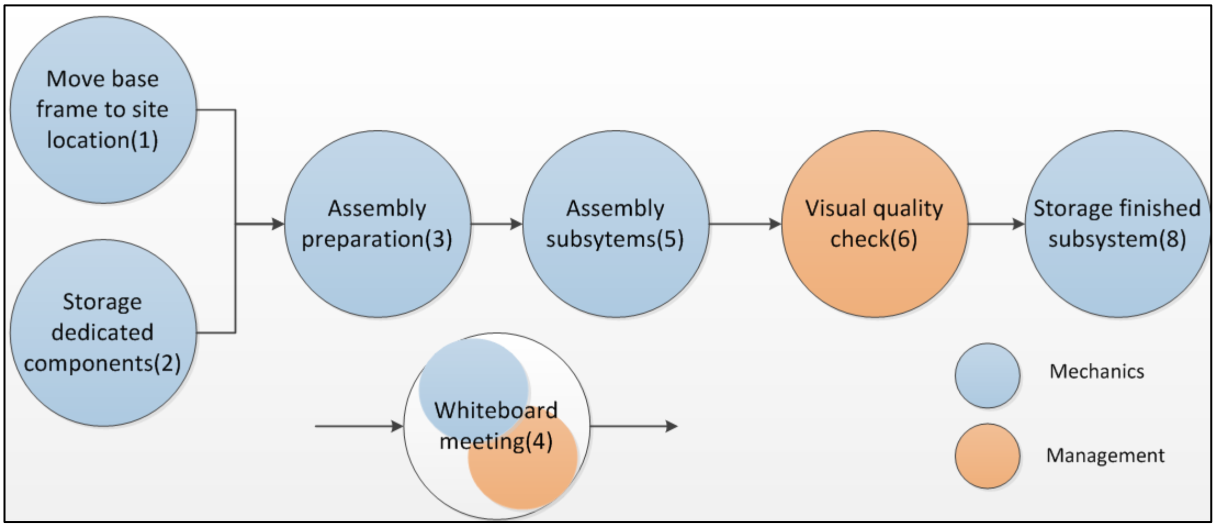

Figure 20: Activities Distributed over 3 Processes

Positioning the Base Frame on the Designated Workstations

One of the activities the employees take care of, is positioning the 5 base frames in a batch on the designated site locations by using a hand truck. Moving base frames is executed multiple times.

> *For example: In Figure 21, 2 LC are waiting for movement on location D1 and D2 within section H to respectively site location E1 and E2.*

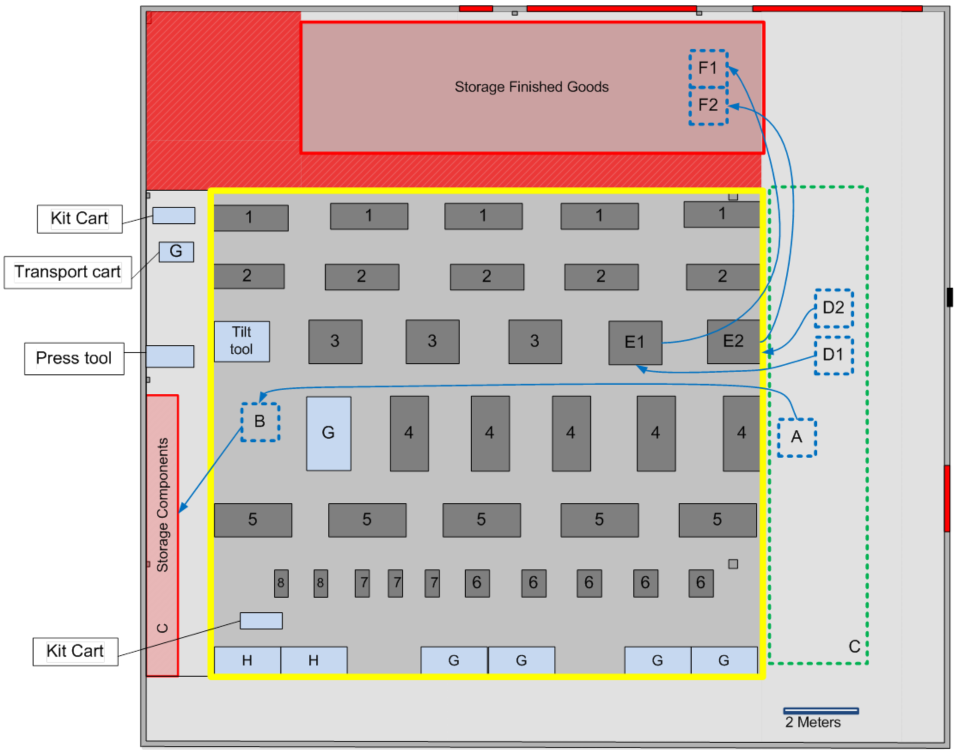

Figure 21: Movement of Employees on the Work Floor

Storage of Dedicated Components

The job of an employee also involves the storage of dedicated components. Arrival of the components occur in a pallet box, see Figure 22.

> *For example: Section H in Figure 21 is the arrival location of the pallet. The employees move the pallet form location A to location B. Afterwards, the components are packed away in the storage 2, indicated with the letter C.*

Figure 22: Pallet Box with Dedicated Components

Preparation of the Assembly
Besides displacement of multiple objects, the employees are also responsible for preparing the assembly. Preparation consists of collecting the necessary components and equipment for the next PO. The G in Figure 21 indicate locations used for preparation.

Assembly of a Subsystem
Assembly of the subsystems is the most important activity for the employees. To assemble a subsystem, employees combine the information on a technical drawing and a parts list. Besides these 2 documents, there is also a PowerPoint available which shows photos of the assembly. Sometimes the mechanic decides that it is beneficial to divide the subsystem in smaller units, which will be assembled first. The goal is to realize assembly within the expected process time (cf. Section 2.1).

Visual Quality Check
To obtain a certain quality, a visual quality check is executed. This activity is executed by management. A subsystem will pass the check if the subsystem is not damaged or grubby. Furthermore, the subsystems must be complete. No subsystems will be delivered to the customer without the visual check.

Functional Testing on FDR and CORO
Besides the general activities, the FDR and CORO are tested. A subsystem passes the test, if its functional behavior is within the predefined specifications. When a subsystem has not passed the test, rework is done by finetuning the certain settings of the subsystems. The yield of the test tool is currently 80%. However, management desires a yield of 99% and tries to improve it. After discussion with management, it is found that the test time is ***Confidential*** minutes, preparation of the test is ***Confidential*** minutes and rework is ***Confidential*** minutes. Letter I in Figure 21 shows the location of the test tools. Figure 52 in Appendix D is respectively the test tool for the ASM Flat Detector Rotate and the Collimator Rotation Unit displayed. The figure also shows the communal test cabinet, which is used by 1 test tool at the time.

Storage of a Finished Subsystems.
After finishing the visual quality check and the functional quality check, the subsystem moves to the next step: storage. Storage is not always possible, because sometimes no available space is left in the storage. All the subsystems are moved by means of a hand truck.

> *For example: After finishing assembly, the LCs on location E1 and E2 in Figure 21 are moved to location F2 and F1, respectively. Due to the serial arrangement and the resulting available space, it is necessary to move E2 before E1.*

Whiteboard Meeting
The last activity to address, is the whiteboard meeting. The goal of this meeting is to evaluate the progress of the POs on the work floor. It occurs thrice a week. Both management and employees are present during this meeting.

2.3.3. Expedition Process

Now the order process and assembly process has been explained, only the expedition process is left for discussion. Expedition is the shipment of finished subsystems to the client. VDL ETG schedules expedition in such way that the delivery date is met. For Project Flexarm, VDL ETG strives to ship all POs once a week on the same day.

2.3.4. Process Disruptions

Above the order process, assembly activities and the expedition process are explained. In an optimal world these have no disruptions. However, several events can disrupt and therefore delay the overall process. All the processes and activities are influenced by human labour, therefore human behavior can induce delay. In the case of project Flexarm the following disruptions have occurred:

1. *Unplanned breaks:* The employees are allowed to have a total break time of 3 quarters of an hour. They, however, drink often coffee outside break time. Sometimes, workforce is redistributed because another project has a higher priority.
2. *Mistake in material handling:* It happens regularly that a delivery contains a wrong component. Furthermore, it occurs often that the employees do not have the right number of components.
3. *Out of general stock:* Despite the daily checks, the stock level is sometimes too low. This can happen because a check is skipped or that the replenishment quantity is too low.
4. *Illness under the employees:* Another event that disrupts the assembly is the illness of a mechanic.
5. *Arrival of base frame on general pallets:* In the current situation it still occurs that base frames are delivered on general pallets instead of the dedicated pallets. As solution the mechanic displaces the base frames to the dedicated pallets with the help of a crane, which delays the assembly.
6. *Unavailability of tooling*: The employees need several tools during assembly. If a tool is unavailable for a mechanic because it is in use, the mechanic waits until the tool can be used. This induces delay in the assembly process.
7. *Flow of employees*: New employees are getting more experienced over time, but they are often relocated to more complex assembly designs. Hence, new employees replace them.

Besides process disruptions, the design of the subsystems encountered quality issues. The following section elaborates on this.

2.3.5. Quality Issues

In this Section, we discuss the quality issues that have occurred in Project Flexarm. It is important to discuss these issues because they have an influence on the quality of the data.

First of all, the test tool for the CORO the FDR often gave the test result “outside specifications”. After rework and a second test, the problem within these subsystems were not solved. The problem originates probably from the quality of the engines and specifications determined by the client. The quality of the engines is too low to be able to meet the specifications. The problem is still not solved because the engine is a high impact part, which cannot be replaced without permission of the client.

Another problem with the test tool was that it responded badly when connected to the test subjects. The mechanic solved this problem by repeatedly plugging the test subject in and out until there was a connection. This induces delay in the assembly process.

Furthermore, there were problems with the paint of the subsystems. After investigation, it was found that the subsystems were damaged during shipment. The dedicated pallets, which support the subsystems during shipment, damaged them. Rework at the supplier, which paints the subsystems, must be done. This also increases the cycle time of the subsystems.

At last, the quality of the bearing used in of the subsystems was too low. A lot of subsystems needed rework due to rejection after testing.

The above described problems had a lot influence on the assembly process, resulting in a decrease in efficiency of the overall process. The employees often paused the assembly during the past months. The influence of the quality issues on the assembly process is considered when examining the available data about the assembly process.

2.4. Conclusion

Chapter 2 describes the current situation. First, volume production for Project Flexarm is explained. Secondly, the design of the subsystems is shown. Thirdly, the layout developed by VDL ETG is discussed. At last, the assembly process is described. The most important knowledge obtained from these sections are summarized here.

Concerning the volume production, it is wise to remember that VDL ETG expect a structurally rise in demand till 25. VDL ETG decided to base the current design of the assembly process on a monthly demand of 20 subsystems. The demand of 20 subsystems is the starting point in this research.

After explaining the design of the subsystems, the dimensions, the expected process time and the required tools are known. The crane, hand truck and test tool are frequently used equipment. Furthermore, knowledge about the complexity and differences between the subsystems is obtained. This information is used for development of the new layout and the DES model in chapter 5.

The dimensions obtained in Section 2.1. are used to develop a detailed map on scale. The map shows the serial arrangement used for the VB long, VB short, HB, LC and CD. This arrangement is not used for the FDR, CORO and CDS. The functionality of the layout is monitored. The first notable thing was the unnecessary movement of certain subsystems. Furthermore, the workstations are not used by the designated subsystems. Also, the space available per subsystem is small. Moreover, the number of batches that fit in storage vary between 3 till 5 subsystems, depending on the dimensions of the systems in storage and the stack height has a maximum of 3. Besides this, there is a small aisle in between 2 adjacent subsystems. The information concerning the layout are used for development of the new layout. Knowledge obtained concerning the storage is used for the DES model.

To describe the assembly process, a division is made in the order process, assembly activities and the expedition process. The following enumeration gives the important information obtained:

- A delivery time of 1 week and order quantity of 5 is used.
- Each employee finishes a PO before starting a new one and new employees can only handle the VB, HB, CD and CDS. Furthermore, the required number of employees to meet demand is 3. The hourly rate for a new and experienced employee is €***Confidential***.- and €***Confidential***.-, respectively.
- The expected process time contains only the time required per component of the subsystem.
- The yield of 80%, test time, preparation time, and rework time are input parameters for the DES model.
- Storage of finished subsystem is only possible if the remaining storage space is sufficient.
- Expedition is scheduled in such way that the delivery is on time.

The assembly process is affected by process disruptions and quality issues. The disruptions that may occur during the processes delay the assembly process. We strive to obtain a time for delay and frequency of the delay in Chapter 3. The quality issues are taken into consideration when evaluating the data in Chapter 3.

3. Further Analysis on Current Situation

For construction of the DES Model in Chapter 5, information concerning the arrival process, individual assembly activities, process disruptions and the Key Performance Measure (KPI) CLIP is necessary. Project Flexarm contains enough data to extract the arrival process. The information gap for the remaining 3 datasets is filled with data from Project ***Confidential***. We explain the reason for the information gap of Project Flexarm in Section 3.1. Next, in Section 3.2. we introduce Project ***Confidential***. At last, the useful data from both projects is analyzed in Section 3.3.

3.1. Information Gap Project Flexarm

This section is used to discuss the reasons for an information gap. First, the gap concerning the realized process times and process disruptions are explained, afterwards the quality of the Committed Line Item Performance (CLIP) of Project Flexarm is discussed.

To be able to implement the general internal assembly activities (cf. Section 2.3.2), the process time per activity must be known. For including the process disruptions in the DES model, a delay and frequency must be known. However, the employees use a punch-in clock to track the start and end time of a production order (PO), therefore no data is available over the individual assembly activities. All the disruptions of the process are monitored by VDL ETG, but no delay or frequency is recorded due to the short length of the projects.

A possible solution for this is determining the efficiency of the assembly process. Since the expected process time is determined on the number of components, it excludes the process disruptions and the general internal activities. The realized process time is tracked with a punch-in clock, so it contains the influence of the process disruptions and general activities on the assembly time. Therefore, the difference between the expected and realized process time gives insight in the time consumption of those activities. This difference is converted into an efficiency curve.

The realized process times for Project Flexarm cannot be used for the efficiency curve, because the quality issues and the short time span of the project pollutes the data (cf. Section 2.3.5). The quality issues increase the realized process times and the short timespan induces just a few POs. This leads to a small data set with high averages. Furthermore, the variation of the process time fluctuated between the subsystems, see Table 14. When comparing the expected process time with the realized process times in the table, a maximal ratio of ***Confidential*** is found. The high realized process times induce a low CLIP, which is further explained in Section 3.3.3. Due to the above reasons, the realized process times is an unsuitable representation of the reality.

Hereby the expected data insufficiency is confirmed. Therefore, Project ***Confidential*** is introduced in the next section. Based on Project ***Confidential***, the efficiency and CLIP are calculated in section 3.3.2 and Section 3.3.3, respectively.

Subsystem	Expected Process Time	Realized Process Time	Variation Process Time	Ratio between Realized and Expected	Sample size
Long Vertical Beam (VBL)	Confidential				0
Short Vertical Beam (VBS)					2
Horizontal Beam (HB)					2
Longitudinal Carriage (LC)					3
Collimator Rotation Unit (CORO)					3
Flat Detector Rotate (FDR)					3
Cable Duct 4300 (CD1)					3
Cable Duct 6000 (CD2)					2
Cable Duct 7800 (CD3)					2
Cable Duct Short (CDS)					3

Table 14: Comparison between Realized Process Times and Expected Process Ttimes

3.2.Project *Confidential*

After discussion with management, we chose to solve the information gap in the data with the related Project ***Confidential*** instead of the PERT-method explained in the literature research. Project ***Confidential*** is preferred above PERT-method, because it contains real data and the PERT method which is commonly used when no data is available (cf. Section 4.2). First, we describe Project ***Confidential***, afterwards resemblances with Project Flexarm are explained.

Description

The orders for Project ***Confidential*** are posted via a make-to-order policy. Sales orders are places for 4 different subsystems, Drive A, Drive C, Selector and Frame. Since the dimensions of the subsystems are small, no special tooling is necessary, and storage is no problem. Drive A and Drive C require electrical and mechanical assembly, unlike the Selector and Frame which only need mechanical assembly. The configuration used are given in Table 15. Due to the long time that Project ***Confidential*** is in the phase of volume production, we were able to extract data from 2016 till 2018.

Configuration	Drive C	Drive A	Selector	Frame
Arrival Rate per Month	9.83	10.33	7.41	6.66
Average Expected Process Time per Subsystem (hours)	Confidential			
Delivery Time (days)	5	5	5	5
Number of Employees	4			

*Table 15: Configurations Project **Confidential***

Resemblances with Project Flexarm

Project ***Confidential*** is used because it shows resemblances with Project Flexarm. For both projects a medical product is assembled, so before it is allowed on the medical market, it needs to meet strict quality requirements. Besides this, electrical and mechanical assembly is executed. Furthermore, the individual general activities (cf. Section 2.3.2) are executed for both projects. At last, new and experienced employees are employed on both projects. Due to the resemblances, the data of Project ***Confidential*** is used to calculate an efficiency. Additionally, the CLIP for Project ***Confidential*** is used to validate the DES model. The efficiency and the CLIP are discussed in the section below.

3.3. Analysis of Useful Data

Now the useful data is identified, we analyse it in this section. First, the arrival process based on Project Flexarm is explained. Next, the extraction of the efficiency for Project ***Confidential*** is discussed. At last, the CLIP containing to Project ***Confidential*** is given.

3.3.1. Arrival Process Project Flexarm

To obtain the arrival rate per subsystem we proceed as follows. First of all, the inter arrival time of the production orders (PO) is calculated. After proving Poisson arrivals, the monthly arrival rate per subsystem is calculated with the inter arrival time. The CORO is used as example in the calculation of the arrival rates. When the example is completed, the arrival rates for the 8 subsystems are given. At the end of this section, the influence of the low sample size on the arrival rate is discussed.

Calculation of Inter Arrival Time

For calculation of the inter arrival time several steps are taken. First of all, all the POs in 2017 and 2018 are extracted from a database and summarized in Table 16. The arrival date is the moment in time that employee can start assembly of the subsystems. If employees are still on another job, then the subsystem is waiting until an employee is available. The arrival date is therefore interpreted as the arrival moment of a batch of subsystems. The inter arrival time between 2 orders is calculated by subtracting the accompanying arrival date, see the table. For the first PO the start date of the project, 1-4-2018, is used.

Order Number	Order Quantity	Order Released	Inter Arrival time (real days)
Start project		1-4-2018	-
530227	3	2-5-2018 07:58	31
530896	4	12-7-2018 13:21	71
532212	1	2-8-2018 08:28	21
532901	4	19-9-2018 15:13	48
533367	4	11-10-2018 16:56	22
533978	4	30-10-2018 11:16	19
Avg. Order Quantity	**3.33**	**Avg. Inter Arrival time**	**35.33**

Table 16: Extraction of POs

Proof of Poisson Arrivals

If Poisson arrivals are proven, the arrival rate is calculated with the inter arrival time. Since exponential distributed inter arrival times is a characteristic of Poisson arrivals, a goodness-of-fit test is executed on the empirical distribution of the inter arrival time and the exponential distribution.

The empirical distribution of the inter arrival time is compared with the theoretical distribution with an average of 1/35.33. The Chi-Square test compares the observed values with the theoretical values X_i belonging to a $X \sim EXP\ (1/35.33)$ distribution. Table 17 shows the result of the test. The null hypothesis states that the data is consistent with the exponential distribution specified above. The null hypothesis is not rejected, because calculated test statistic of 0.63 is seemingly lower than the found Chi-Square Value of 5.99

UNIVERSITY OF TWENTE.

Chi-Square Test	Value
Degree of Freedom	2
Confidence Level	95%
Chi-Square Value	5.99
Test Statistic	0.63

Table 17: Chi-Square Test

The inter arrival time is proven to be exponential distributed. Therefore, it is concluded that the arrivals of the POs occur according a Poisson process.

Calculation of the Arrival Rate

After proving Poisson arrivals for Project Flexarm, the individual arrival rate for the subsystems are calculated. Formula 3 is used to convert the arrival of the PO to the arrival of individual subsystems (Zijm, 2012). The individual monthly arrival rate is λ. Furthermore, $E(N)$ is the average order quantity and λb is arrival rate of PO per month, which is calculated with formula 4.

$$\lambda = \lambda b * E(N) \qquad (3)$$

$$Batch\ Arrival\ Rate = \frac{Total\ Number\ of\ Batch\ Arrivals}{Total\ Time\ in\ Months} \qquad (4)$$

The $E(N)$ is an average value of the fluctuating order quantity since April 2018. Table 18 shows that the arrival rate per month for the CORO is 2.87

Components Formula 3	Value
$\boldsymbol{E(N)}$	3.33
$\boldsymbol{\lambda b}$	0.86
$\boldsymbol{\lambda}$	2.87

Table 18: Calculation Arrival Rate CORO

As mentioned earlier there is one of each subsystem necessary to complete an x-ray machine, therefore the average arrival rates must be close to each other. Table 19 shows a similarity between the arrival rates. The small differences, however, are caused by rework due to failures. Furthermore, the demand for each subsystem is equal. Therefore, the assumption is made that the all the subsystems arrive according to Poisson arrivals.

Subsystem	Arrival rate per month
VBL	2.67
VBS	2.15
HB	3.59
LC	2.41
CORO	2.87
FDR	2.68
CD	3.51
CDS	3.93
Average Arrival Rate per Month	**2.98**
Variance Arrival Rate between Subsystems	**0.40**

Table 19: Monthly Arrival Rate based on Average Order Quantity

Influence of data quality on arrival rates

The risk that comes with a low sample size is that the obtained parameters do not reflect the reality properly. After discussion with management the assumption is made that the parameters reflect the assembly process, because the found arrival rate corresponds with the expectation of VDL ETG. The Chi-Square test and the literature research (cf. Section 4.1) provide proof for this statement. Poisson arrivals are used as input variable for the DES model.

3.3.2. Efficiency Project *Confidential*

The goal of this section is to extract the efficiency curve for Project ***Confidential*** as solution for the information gap. First, we explain the calculation of the efficiency. Afterwards, we discuss the found efficiency distribution

Calculation of Efficiency

The difference between the expected process time and realized process time gives information about the process disruptions and process time for individual general activities (cf. Section 3.1). To obtain the efficiency curve, we calculated for each PO from July 2016 till December 2018 the ratio between the expected process time and realized batch process time (cf. Formula 5).

$$Efficiency = \frac{Expected\ Process\ Time\ per\ PO}{Realized\ Process\ Time\ \ per\ PO} * 100\% \qquad (5)$$

The efficiency is below 100% when the realized process time is bigger than the expected process time. In that case the assembly was not as efficient as expected. The efficiency per PO is converted to the efficiency curve in the paragraph below.

Evaluation of Efficiency Data

After calculating the efficiency for all POs, several steps are taken to extract the efficiency curve. First, we evaluate the dataset with all the efficiency values. Afterwards, we discuss the difference in efficiency for the employees. At last, we fit a distribution to the efficiency.

Before evaluating the data, the outliers are identified with the scatterplot in Figure 23. The datapoint above 160% and below 50% are excluded from the data set.

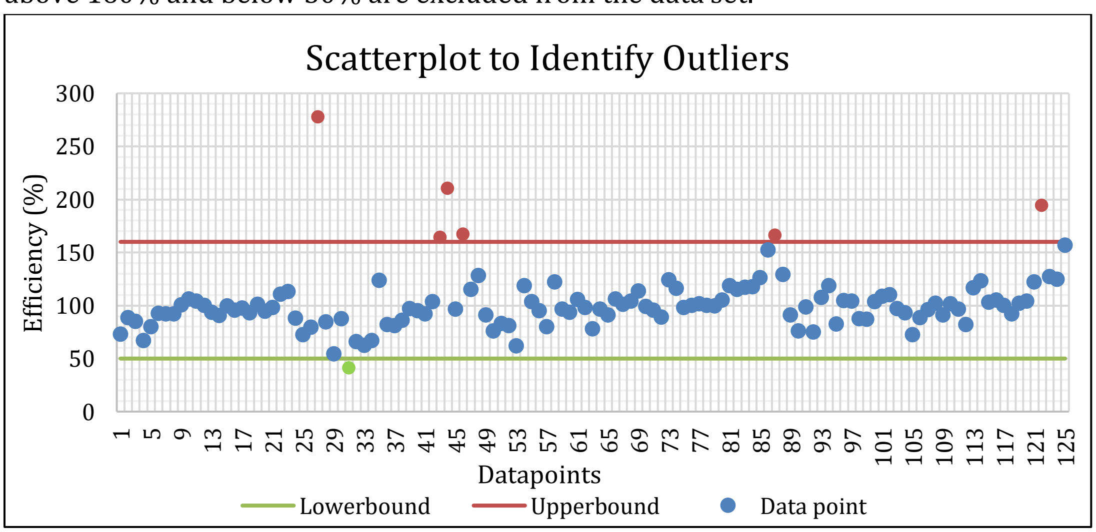

Figure 23: Scatterplot to Identify Outliers

The average efficiency for the separate subsystems is shown in Table 20. We observe a difference between each subsystem. The efficiency for Drive C and Drive A are above 100%. The Selector and Frame have efficiency below 100%. Management suggested that the Selector & Frame are below 100%, because less experienced employees assemble those most of the time. The Drive C & Drive A are more complex and therefore often assembled by experienced employees.

Subsystem	Average Efficiency (%)
Drive C	100.59 %
Drive A	103.82 %
Selector	92.29 %
Frame	86.39 %

Table 20: Average Efficiency per Subsystem

We assume that Drive C & Drive A is assembled by experienced employees and Selector & Frame by new employees. Therefore, it is tested if the data can be merged. The Chi-Square test on homogeneity evaluates if under the null hypothesis the 2 datasets have the same distribution(Meijer, 2016). The test statistic is for both cases smaller than the Chi-Square value, so the null hypothesis is not rejected, see Table 21. Therefore, the data is merged to increase the overall sample size and extract an efficiency curve for the new and experienced employee.

Chi-Square Test	Selector & Frame	Drive C & Drive A
Degree of Freedom	6	8
Confidence Level	95%	95%
Chi-Square Value	12.59	15.51
Test Statistic	8.35	3.80

Table 21: Values Chi-Square Test

Now for each kind of employee a data set is obtained, the efficiency curve per employee is determined based on the descriptive statistics. Potential distributions are found based on the skewness, coefficient of variation and the variance-to-mean ratio. These distributions are (Law, 2015):

1. The negative binominal due to a variance of mean greater than 1;
2. Log Normal due to positive skewness to the right;
3. Gamma due to positive skewness to the right;
4. Weibull due to positive skewness to the right.

When compared with the descriptive statistics in Table 22, no fit is found for the efficiency of new employees, because a negative skewness is found in the table and in the histogram in Figure 24.

Descriptive statistics	New Employee	Experienced Employee
Mean	89.49	102.20
Standard Deviation	14.45	16.85
Skewness	-0.33	0.52
Coefficient of Variation	0.16	0.16
Variance-to-Mean	2.33	2.78

Table 22: Descriptive Statistics Data Set New and Experienced Employees

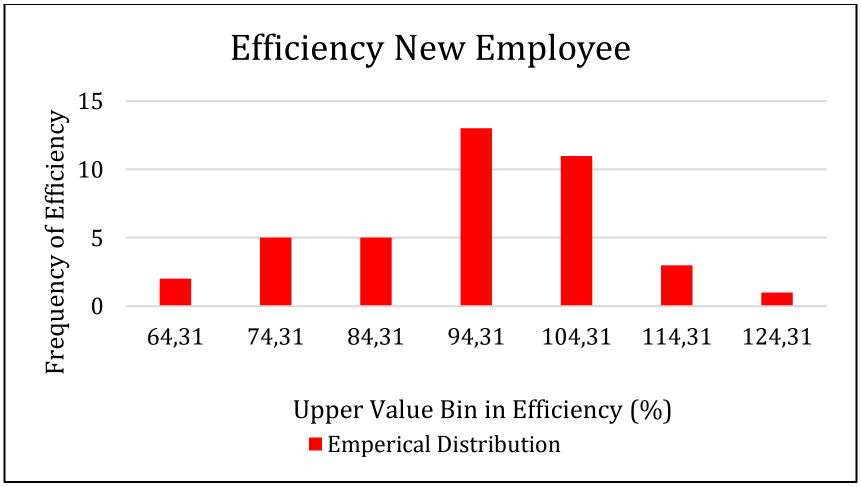

Figure 24: Emperical Distribution Experienced Employee

The gamma distribution is the best choice for the efficiency of experienced employees, because it has as possible application the determination of the distribution for the completion of certain tasks (Law, 2015). The negative binomial is not chosen because it is a discrete distribution. The Log Normal and Weibull are applicable as model when there is no data available(Law, 2015). There is however plenty data concerning the efficiency, so we try to fit the gamma distribution with the data, see Figure 25.

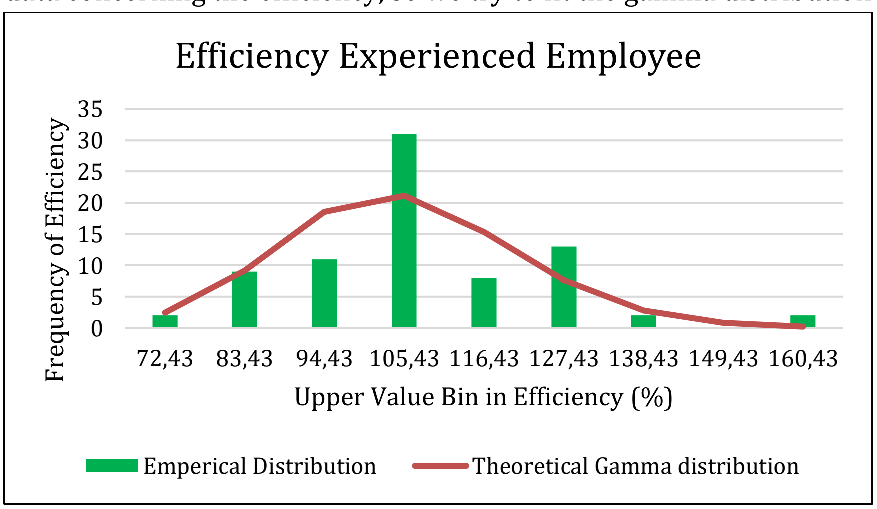

Figure 25: Comparison Emperical and Theoretical Gamma Distribution

However, when executing a goodness-of-fit test (Law, 2015) a significant difference between the gamma distribution and the empirical distribution is found for Drive C & Drive, see Table 23. Since, no fitting distribution is obtained, the efficiency of the new and experienced employees is represented with the empirical distribution based on the data.

Chi-Square Test	Value
Degree of Freedom	8
Confidence Level	95%
Chi-Square Value	15.51
Test Statistic	16.65

Table 23: Chi-Square Test on Goodness-of-Fit

3.3.3. Calculation of CLIP

Besides determining the efficiency curve, the data from Project ***Confidential*** is also used for validation of the DES model developed in Section 5.1. For validation, the performance of the model is compared with the performance of Project ***Confidential***. The performance measure frequently used at VDL is the Committed Line Item Performance (CLIP). The fraction on-time deliveries of the total amount of deliveries is the CLIP, see Formula 6.

$$CLIP\ within\ time\ period\ i = \frac{Number\ of\ production\ order\ that\ are\ on{-}time\ within\ time\ period\ i}{Total\ number\ of\ production\ orders\ within\ time\ period\ i} \quad (6)$$

The performance measure does not include the extent to which an order is late. The due date of a PO is the sum of the date that the sales order is placed and the delivery time agreed between the client and VDL ETG. The delivery time for Project Flexarm is 5 days and for Project ***Confidential*** is also 5 days.

Table 24 shows the CLIP for both projects. The CLIP of Project Flexarm is collected since April 2018 and the CLIP of Project ***Confidential*** is calculated from July 2016 till December 2018. Project Flexarm has a CLIP of ***Confidential*** %, which is low as mentioned earlier (cf. Section 3.1). The CLIP is that low, because the quality issues increased the assembly time, causing late delivery. Project ***Confidential*** has a CLIP of ***Confidential***%, this value is used for validation of the DES model

Project	CLIP
Flexarm (%)	***Confidential***%
***Confidential* (%)**	***Confidential***%

Table 24: CLIP per Project

3.1.Conclusion

In this chapter a data analysis was executed to obtain an overview of data required for the DES model. Due to the data concerning Project Flexarm, an arrival process with a Poisson distribution is found. Since Project Flexarm contains little data, Project ***Confidential*** is used as replacement for extracting an efficiency curve belonging to the internal activities and process disruptions. Also, the average CLIP is calculated based on Project ***Confidential***. The data is collected over a time period of approximately 3 years, from July 2016 till December 2018

In the end, it is concluded that the subsystems arrive according a Poisson process. Therefore, the arrivals in the DES are also according a Poisson process. Furthermore, the CLIP of Project ***Confidential*** is ***Confidential***%. and the efficiency of new and experienced employees is on average 89.49% and 102.20% respectively.

4. Literature Overview

The topics discussed in this section support decisions made in data analysis and layout development. In Section 4.1 a literature review is executed, to substantiate the Poisson arrivals extracted from the data (cf. Section 3.3.1) Furthermore, in Section 1.3 and 1.6 the suspicion is raised that there is data insufficiency. The PERT method is a possible solution for this problem and is therefore discussed in Section 4.2. Besides the data analysis, distinguished priority rules for planning are discussed in Section 4.3. At last, decisions for layout development are based on the found literature described in Section 4.4.

4.1. Arrival Process and Distribution

The most applicable arrival process is the Poisson process (cf. Section 3.3.1). The Poisson process is a stochastic process in which the Poisson distribution predicts the arrival of a new customer with a constant average arrival rate. In case the arrivals come from independent sources with variation in usage of the system, the Poisson process is applicable (S.-H. Kim, Vel, Whitt, & Cha, 2015). The process is used as representation for multiple stochastic phenomena.(Najim, Ikonen, & AÏt-Kadi, 2004)

> *Several examples: For prediction of the stock prices a double stochastic Poisson process is proposed (Bening & Korolev, 2002). Besides this, failure of systems with many components occur due to time-independent and random causes. Therefore, Poisson processes are commonly used in reliability manufacturing. (Nakagawa, 2011)*

The properties of a Poisson process are (Medhi, 2003):

- Additivity;
- Decomposition;
- Exponential distributed inter arrival times;
- Memoryless property;
- Randomness.

The a*dditive property* illustrates that conversion of batch arrivals to individual arrivals is possible, because it states that a sum of n independent Poisson processes with parameter λ_i (i = 1,2,…, n) is a Poisson process with sum over the parameters(Medhi, 2003). Besides this, the Poisson process is substantiated because the *property of exponential distributed inter arrival times* is proven from data. At last, it is likely that the client experiences independent requests for subsystem with a certain uncertainty in the timing, which substantiates the applicability of Poisson process

4.2. PERT Method for Time Analysis of Internal Activities

Program evaluation and review technique (PERT) is a method used for planning and control of certain tasks. Besides manufacturing, the method is also applicable in other areas, examples are movie and stage productions, construction, and training programs. The PERT method consists out of:

1. Construction of a work breakdown structure;
2. Construction of a network;
3. Estimation of activity times.

Element 1, construction of a work breakdown structure, is development of a tree structure in which the main goal is subdivided in smaller sub goals. Furthermore, activities to reach certain goals are added to the structure. Element 2, construction of a network, gives insight into the relations between the goals and activities described in the work breakdown structure. The last element covers the estimation of the activity times described in the network. (Kadet & Frank, 1964) Particularly this element is of interest for this research due to the lack of data regarding the process time of the separated internal activities, discussed in Section 1.6 and 2.3. Estimation of the mean activity time, E(T), and the variance, D^2(T), is done with Formula 7 and Formula 8:

$$E(T) \approx \frac{a+4M+b}{6} \qquad (7)$$

$$D^2(T) \approx \frac{(b-a)^2}{36} \qquad (8)$$

The input parameters for these formulas are an optimistic time (a), a pessimistic time (b) and a most likely time (M). The output value T is assumed to be beta distributed. (Kamburowski, 1997)

PERT gives insight in the work that must be done with the help of visualization. Furthermore, PERT is easy in use for time calculations and includes the uncertainties in the time planning. Without any data, PERT enables the expression of time under a beta distribution. Therefore, this technique is especially useful for uncertain and non-repetitive work. (Kadet & Frank, 1964)

Kim, Hammond and Bickel (2014) give an overview of the questions placed concerning the validity of the PERT method. Some of the reasons to question validity are:

- Error sensitivity
  The assumption of a beta distribution, the formulas for the mean (5) and for the variance (6) and the experienced based time estimates are sources for inaccuracy of the output. Changes in 1 of these 4 aspects can induce significant absolute errors in the outputs.
- Wrong estimation of input values
  The optimistic value and pessimistic value need to be the extreme values of the distribution. The chosen values are however based on experience and experienced value are often not extreme values of the distribution. (S. D. Kim, Hammond, & Bickel, 2014)

4.3. Priority Rules

Priority rules use certain information belonging to the tasks that need to be planned. The information needed is called the priority value. Two types of priority rules are possible, a maximization or minimization rule. The first one has priority for the task with the largest priority value and the latter one has priority for the task lowest priority value. A task may only be chosen, if it is available. Therefore, the constraints are considered when choosing the next task. Some priority rules are time related; others are precedence orientated. Furthermore, it is possible to mix certain priority rules into one. An elementary rule is based on a single attribute, however a composite rule is based mis of attributes. (Otto & Otto, 2014)

The priority rules explored in this research are (Otto & Otto, 2014):

1. Shortest Processing Time First, job with smallest process time has highest priority;
2. Max Task Time First, job with largest process time has highest priority;
3. Most Work Remaining First, the machine which has the most work remaining has highest priority;
4. First In, First Out, job that enters first the system.

Hunsucker and Shah (1991) found that 'First In, First Out' outperforms 'Most Work Remaining First', 'Max Task Time First' and 'Shortest Processing Time First' on the mean tardiness criterion. However, no difference has been found between the rules on number of tardy jobs. (Hunsucker & Shah, 1992)

4.4. Layout Development

After a literature research, we obtained information concerning the differences between departments, Systematic Layout Planning (SLP), and workstation arrangement. These topics are separately discussed below.

4.4.1. Different Assembly Departments

The characteristics of the assembly process determines the choice between the fixed material location department, production line department, product family department and process department. The first one is often used when the product to assemble is heavy and large. The second one is commonly known, because it is applicable within high volume and low-variety production. The third department is used when the product volume is low, but the variety between products is high. For the last department, product families are grouped on common process steps, required tools and/or handling requirements. It combines features of a product and a process layout, because groups are based on the processes, but within the groups a fixed product or production line layout is used. The advantages of the last department are higher machine utilization, shorter travel distance for materials and better understanding concerning the exploitability of tools. (Tompkins, John, Yavuz, & Tanchoco, 2003).

4.4.2. Systematic Layout Planning as Development Method

Systematic Layout Planning (SLP) is introduced by Muther and can be used for layout development of the following levels of layout design:

1. Site layout, which revolves around decisions concerning locating the facility;
2. Block layout, which is about the size and arrangement of different departments in a facility;
3. Detailed layout, which is the arrangement of equipment and workstation within a department;
4. Workstation layout, which goal is to arrange every part of a workstation. (Muther, 1967)

Level 3 of layout design is important for this research, because it concerns the allocation of workstation within the assembly hall. SLP consists out of many procedures which are executed to obtain a layout. Two procedures part of SLP are identifying the space requirements and the development of a relationship diagram.

Identification of the space requirements can be determined in multiple ways. One of these is the rough-out layout, in which the space requirements are based on known dimensions of the area and required equipment. With this knowledge, an estimation is made concerning arrangement inside the available space.

An example of the development of a relationship diagram is given in Figure 26. Between each set of activities, a reason for a relationship is determined. Furthermore, a priority to support this relationship must be indicated. Eventually, this diagram shows the strength of the relation between each activity. Activity is the expression used to designate beside activities also equipment and certain functional areas, like the storage area. (Muther, 1967)

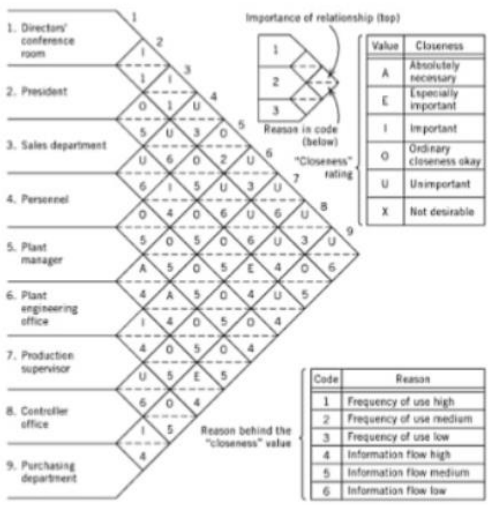

Figure 26: Relationship Diagram with Closeness Rating and Reasons (Batljan. B, Topaloglu, Georgadakis, & Alan)

4.4.3. Workstation Arrangement

After evaluating methods part of SLP, we investigate which arrangements inside the workstations are possible for the assembly process. U-shaped, s-shaped, and straight-lined arrangements for flow assembly were found (Roser, 2016). The advantage of u-shaped and s-shaped lines over a straight-lined arrangement is the increased flexibility for the employees. The employees in Figure 27 can easily access non-adjacent workstation, unlike straight lined arrangements in which only the neighbor workstations are easily accessed.(Chand & Zeng, 2001) Despite its applicability to flow assembly, the advantage of close workstations is useful for this research.

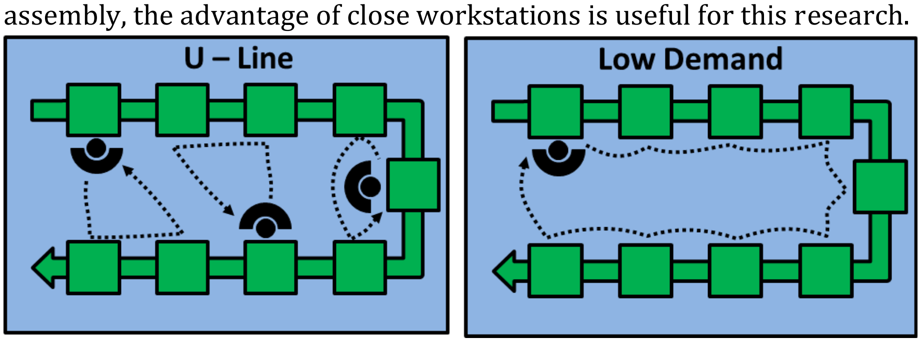

Figure 27: U-shaped Assembly Line (Roser, 2016)

4.5.Conclusion

In the above literature research several facets are investigated. First, the Poisson process is evaluated to substantiate the Poisson arrivals obtained from data analysis. Secondly, the usability of the PERT-method for the individual assembly activities introduces is examined (cf. Section 2.3.2). Besides this, multiple priority rules for planning are found in literature. At last, Systematic Layout Planning (SLP) is explored as possible method for layout development.

The *additive* and *exponential distribution inter arrival times* are 2 properties which substantiate the Poisson arrivals found (cf. Section 3.3.1). Besides that, the client receives independent requests for subsystem with a certain uncertainty in the timing, which also substantiates the applicability of Poisson process.

The PERT- method is easy in use for time calculations and includes the uncertainties in the time planning. Without any data, PERT enables time to be expressed under a beta distribution. Therefore, this technique is especially useful for uncertain and non-repetitive work. (Kadet & Frank, 1964). Error sensitivity and the wrong estimations of input values are reasons to question the validity of the PERT-method. (S. D. Kim et al., 2014) The PERT-method is useful for this research because it can be used to determine the times of the individual assembly activities.

The priority rules found through literature are the 'Shortest Processing Time First', 'Max Task Time First', 'Most Work Remaining First', and 'First In, First Out'. When comparing these, it is found that 'First In, First Out' outperforms the other priority rules on the mean tardiness criterion. However, no difference has been found between the priority rules on number of tardy jobs. (Hunsucker & Shah, 1992) In the assembly process, 'First In, First Out' is identified as the currently used priority rule. The strategy 'Max Task Time First' is evaluated as substitute for the current priority rule in Section 6.1.

Systematic Layout planning (SLP) is a method developed for layout design. SLP contains multiple sub procedures to create a final layout. However, not all procedures are useful for this research. The relationship-diagram and rough-out layout method are used to reconsider the number of workstations of the current layout. When comparing different shapes for flow assembly on performance, it is found that u-shape and s-shape lines increases the flexibility for the employees. These methods found in SLP and the u-shaped lines are used in Section 5.1 for layout development.

5. Model Development

To answer the main research question, a layout and a discrete event simulation (DES) model is built. In Section 5.1 we introduce the new layout and in Section 5.2 we explain the DES Model.

5.1. Layout Development

The problems identified in the current layout are the small available space per workstation and the unnecessary movement of the subsystems (cf. Section 2.2). The first one arose because the layout contains 8 workstations, 1 for each batch of subsystems. The latter one is induced by the serial arrangement and working height. In this section, we introduce a new layout to solve these problems.

The 3 steps taken to develop a new layout are based on the literature study in Chapter 4. First, a substitute for the serial arrangement is chosen. Next, the rough-out layout method is used for determining the space requirements. Furthermore, the relationship-diagram is used for exploring strong relationships between different activities within assembly. At last, the information obtained during the steps is used to develop a new layout.

Best Assembly Arrangement

Since a serial arrangement is not convenient for this assembly process, a u-shaped arrangement is proposed based on literature. Within this assembly process, the u-shaped arrangement reduces distance between the site location of the subsystems. Therefore, the movement of the employees is reduced.

Space Requirements

Because of the small space available for each workstation, it is evaluated with a rough-out layout how many workstations could fit in the available space. With an on-scale print of the work floor and the subsystems, rough-out layouts are tried. The u-shaped arrangement, desired batch size and the dimensions limit the possibilities. If a batch size of 5 subsystems is arranged in a u-shape, the maximal number of workstations is 4. When trying more workstation, the number of 5 site locations cannot be retained. An example of non-feasible layout is given in Appendix F.

Strong and Weak Relations

The advantages of the product family department awaken the idea to subdivide the products in 4 groups with similar characteristics. First, the possible relations between the subsystems and the closeness value are given in Figure 28 and Figure 29.

CODE	Reason
1	Same type of assembly (Electrical vs. Mechanic vs. Gathering)
2	Same employee (New vs. Experienced)
3	Size (Similar, Big, Small)
4	Number of components
5	Same equipment (Tilt tool, Crane, Press tool, Test Tool)

Figure 28: Reasons for Relations

Value	Closeness	Description
A	Absolutly necessary	More than one reason
E	Expecially important	More than one reason, but some weak reasons
I	Important	Beneficial for efficiency of process, but only one reason
O	Ordinary Case	Nice to have close, but only one reason
U	Unimportant	No reasons
X	Undesirable	Negative effect on process

Figure 29: Closeness Value based on Number of Reasons and Kind of Reasons

Thereafter, between each combination of subsystems the relations are identified. The number of relations between the subsystems determines the closeness of between the two. The method behind the relationship-diagram is used iteratively. Step 1 determines the product families. Step 2 determines the best-suitable location of the workstation on the work floor with consideration to the storage locations and access area for base frames. This is a variation on SLP, in which only 1 reason for a closeness value and no iterative procedure is used. The information needed is summarized per subsystem in Table 25 and the results of the steps are below the table.

	VB	HB	LC	FDR	CORO	CD	CDS
Assembly type	Mechanic	Mechanic	Mechanic	Electric & Mechanic	Electric & Mechanic	Gathering	Gathering
Employee type	Both	Both	Experienced	Experienced	Experienced	Both	Both
Size (L x H) (m)	Long: 2.10 x 0.70 Short: 1.99 X 0.70	2.04 x 1.04	1.44 x 1.19	0.73 x 0.66	0.74 x 0.39	2.10 x 0.70	0.74 x 0.37
Number of components	Long: 105 Short: 108	203	293	173	166	CD1: 164 CD2: 211 CD3: 321	162
Equipment	-	-	Crane, Tilt tool, Press tool	Test tool	Test tool	-	-

Table 25: Information Needed to Construct Relationship Diagram

Step 1: On the left in Figure 30, the relations between subsystems are shown. The resulting closeness values are given on the right. The groups found are FDR&CORO, HB&VB, CD&CDS and LC.

	Groepen	FDR	CORO	LC	HB	VB	CD	CDS
1	WS FDR							
2	WS CORO	1,2,5						
3	WS LC	2	2					
4	WS HB	-	-	1				
5	WS VB	-	-	1	1,2,3			
6	WS CD	-	-	-	2	2		
7	WS CDS	-	-	-	2	2	1.2	

	Group	FDR	CORO	LC	HB	VB	CD	CDS
1	WS FDR							
2	WS CORO	A						
3	WS LC	O	O					
4	WS HB	X	X	O				
5	WS VB	X	X	O	A			
6	WS CD	X	X	X	O	O		
7	WS CDS	X	X	X	O	O	A	

Figure 30: Relationship Diagram used for WS Aggregation, Reasons (Left) and Resutls (Right)

Step 2: On the left in Figure 31, the relations between locations are shown. The closeness values are given on the right in the figure. FDR&CORO is close to the component storage. The other groups are close to both storage types. Besides this, for the CD&CDS and VB&HB a closeness to the access area is preferred. In consultation with management, we decided that the CD&CDS is only close to the access area due to gathering. Therefore, the HB&VB is close to the storage for finished goods and the access area. Furthermore, the LC is located near the storage for finished goods and components.

	Group	WS FDR/CORO	WS LC	WS HB/VB	WS CD/CDS	FG Storage	Component storage	Acces Area Base Frames
1	WS FDR/CORO							
2	WS LC	2						
3	WS HB/VB	-	-					
4	WS CD/CDS	-	-	-				
5	FG Storage	-	3	3	3			
6	Component storage	4	4	-	4	-		
7	Acces Area Base Frames	-	-	3	3	-	-	

	Group	WS FDR/CORO	WS LC	WS HB/VB	WS CD/CDS	FG Storage	Component storage	Acces Area Base Frames
1	WS FDR/CORO							
2	WS LC	O						
3	WS HB/VB	X	X					
4	WS CD/CDS	X	X	X				
5	FG Storage	X	I	I	I			
6	Component storage	I	I	U	I	U		
7	Acces Area Base Frames	U	U	I	I	U	U	

Figure 31: Relationship Diagram used for Clossenes of the WS, Reasons (Left) and Results (Right)

New Layout

Now the layout requirements have been identified, the layout is designed. The next page contains Figure 32, which shows the result of the above used methods. Four workstations can be identified:

- Workstation 1 is dedicated to VB&HB, which is close the storage for finished goods;
- Workstation 2 is dedicated to LC, which is close to both storage areas;
- Workstation 3 is dedicated to FDR&CORO, which is close to the component storage;
- Workstations 4 is dedicated to CD&CDS, which can easily reach the storage of finished goods.

The new developed layout is evaluated with the DES model. The number of workstations and the groups of subsystems formed are used as an intervention in the experimental phase in Section 6.1. In upcoming section, we specify the construction of the DES model.

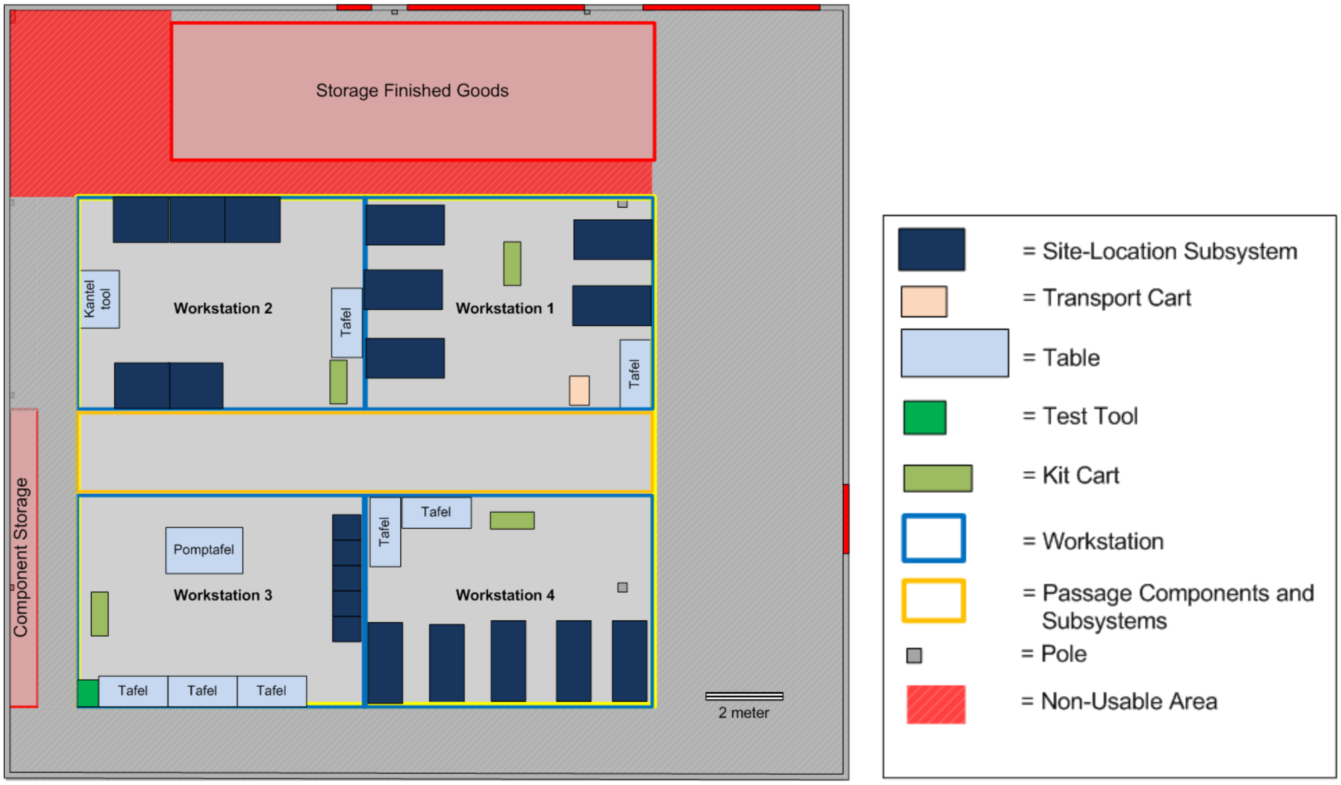

Figure 32. Developed Layout (Left) and Legend (Right)

5.2. Construction of Simulation Model

To find the best suitable employee configuration and evaluate the new layout, a DES model is constructed. The assembly process is divided in several sub processes and those are implemented in the DES mode, see Figure 33. The assembly process is subdivided into:

A. Arrival and batching process;
B. Assembly process;
C. Test process;
D. Storage process;
E. Expedition process.

Each sub process is controlled by the control panel shown in Figure 34. First, we explain the control, input parameters, and, verification & validation of ach sub process. Next, we discuss the overall data collection and calculation of the performance.

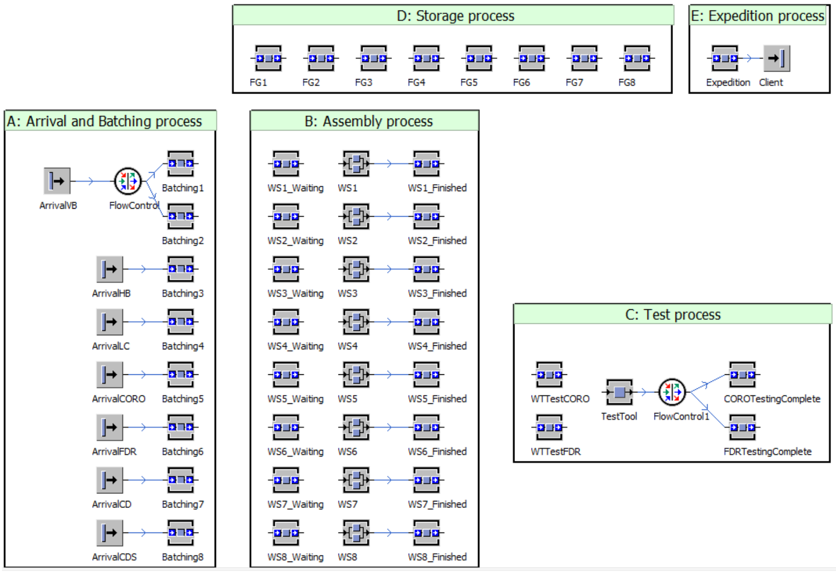

Figure 33: Assembly Process

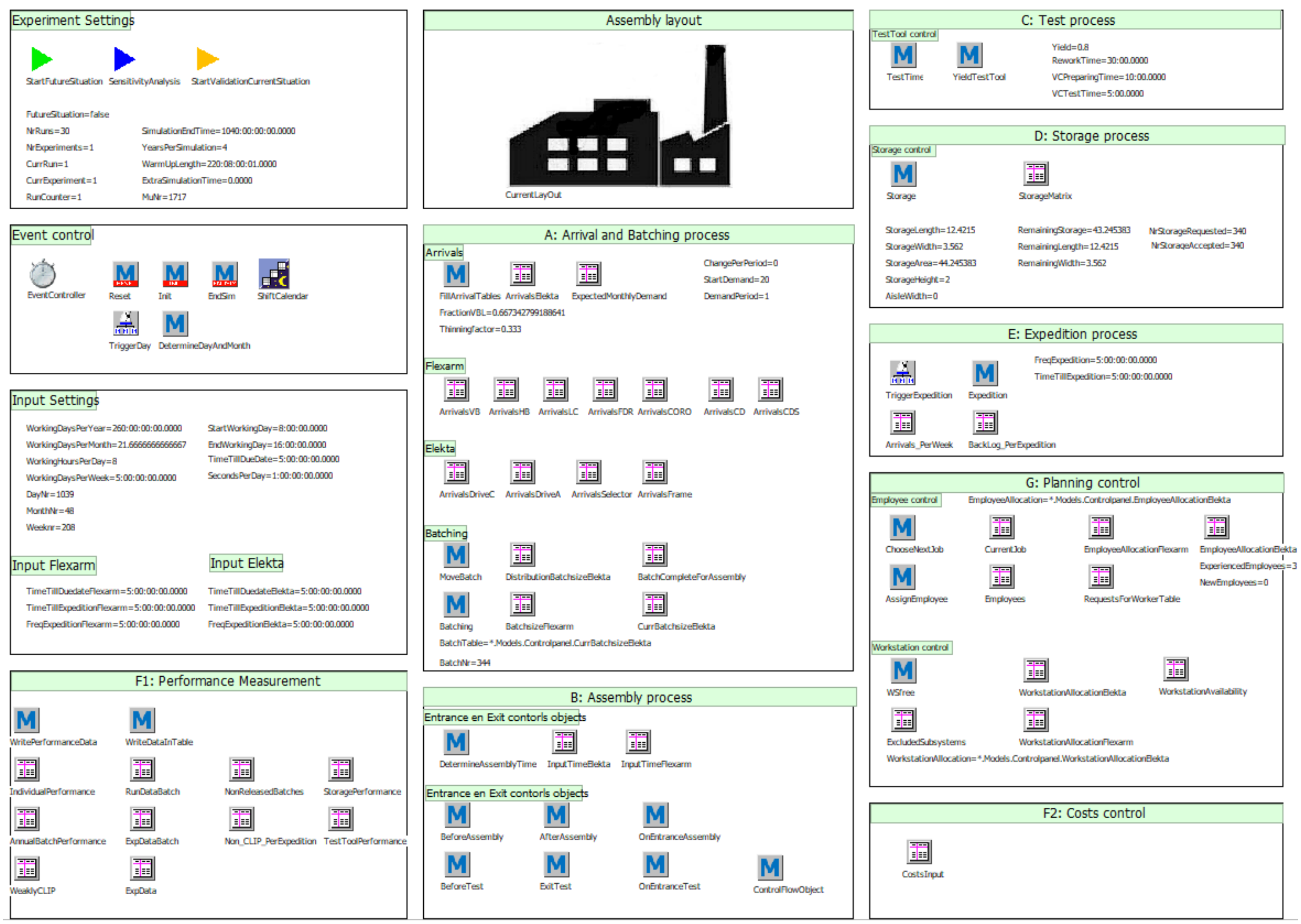

Figure 34: Controlpanel

5.2.1. Arrival and Batching Process

Control

The arrival process of the customers is Poisson distributed, substantiated with data analysis (cf. Section 3.3.1) and literature research (cf. Section 4.1). The client accumulates these arriving customers until the agreed order quantity of 5 subsystems is reached, subsequently the client orders 5 pieces of that subsystem. In the DES model this process is handled as a batching process with individual Poisson arrivals. Three different steps are executed within the simulation, which are enabled by segment A in the control panel in Figure 34:

1. Determining the arrival time of the subsystem and adding them to the table, before the simulation time starts. An arrival is only possible during working hours.
2. During the simulation the individual arrivals become a sales order, when the number of arrivals exceeds the order quantity of 5.
3. In case a workstation is available, a sales order moves to it. Otherwise, a request is placed to enter a certain workstation.

Input Parameters and Decision Variables

For determining the arrival time, an inter arrival time between subsequent arrivals is calculated. The exponentially demand rate induces variability in the inter arrival time. The necessary parameters are summarized in Table 26. The calculation of the inter arrival time is given by Formula 9 and the working days per month is calculated with Formula 10.

Input Parameter	Value
Working hours per Day	8
Working Days per Week	5
Number of Weeks per Year	52
Demand Rate per Month	Exp (20)
Batch Size	5

Table 26: Input Parameters Arrival and Batching Process

$$Inter\ Arrival\ Time = \frac{1}{Demand\ per\ Month} * Working\ Days\ per\ Month * Working\ Hours\ per\ Day \quad (9)$$

$$Working\ Days\ per\ Month = \frac{Working\ Days\ per\ Week * Number\ of\ Weeks\ per\ Year}{Months\ per\ Year} \quad (10)$$

Verification and Validation

Due to the requirement that arrivals only occur during working days, it is verified if the total number of arrivals is correct. This is done by counting all the arrivals under a constant demand rate. This number corresponds with an arrival rate per month of 20 over a time period of 2 years.

5.2.2. Assembly Process

Control

The assembly process is implemented as one activity with a certain efficiency depending on the kind of employee (cf. Section 3.3.2). One of the restrictions in this process is that, a workstation is only occupied by 1 batch at a time. Besides this, assembly can start if an employee is available. Also, a batch remains at the workstation if there is no space available in the storage area. (cf. Section 2.3).

To support these restrictions, workstation with 3 objects is build, see Figure 35. These objects are controlled by element B shown in Figure 34. The functions of the objects are:

1. In case no employee is available the waiting room is used and a request for an employee is placed. Currently, a ‘First In, First Out’ approach is used to determine which batch is assembled.
2. For starting the assembly on the parallel station, an efficiency is determined to calculate the process time. Only 1 employee assembles a batch and finishes it before starting a new one.
3. In case the storage is occupied, a batch waits in the finished room and the new batch cannot enter the workstation. Otherwise, a workstations and employee are available for a new batch.

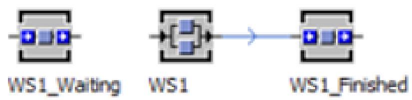

Figure 35: Three Objects forms a Workstation

Input Parameters and Decision Variables

Before the assembly process starts, the number of workstations is set on 8, since the current layout contains 8 workstations. The realized process time is calculated based on the input parameters in Table 27 (cf. Section 2.1 and 3.3.2).

Input parameter	VB	HB	LC	FDR	CORO	CD	CDS
Batch size	5						
Expected Process Time (min)	**Confidential**						
Efficiency New Employee	Empirical Distribution with avg. of 89.49%						
Efficiency Experienced Employee	Empirical Distribution with avg. of 102.20%						

Table 27: Input Parameters for Calculation Realized Process Time

The calculation of the realized process time (cf. Formula 11) is based on the procedure for determining the efficiency curve (cf. Section 3.3.2). Every time an employee is assigned to a request, this calculation is executed, and the parallel station is updated with this process time. process time for the CD and the VB is a weighted average, because these have complementary subsystems with different expected process times (cf. Section 2.1).

$$Realized\ Processing\ Time = Expected\ Process\ Time * Batchsize * \frac{100\%}{Efficiency} \qquad (11)$$

Since the efficiency of the employees represents the internal assembly activities and process disruptions, we can include them in the simulation. However, we were not able to develop a representation for the disadvantages of the layout, so the consequences originating from the small available assembly space and the unnecessary movement are not included in the DES model.

Verification and Validation

The assembly process is verified and validated on 4 levels:

1. The difference in time between the start time and finish time of assembly;
2. The efficiency for each employee generated in the DES model;
3. The processing times calculated in the DES model;
4. Placing and satisfying requests for employees and workstations.

The time difference between the start time and finish time corresponds with the summation of the effective batch processing time and the time outside working hours.

When comparing the real efficiency with the simulated efficiency for both employees in Table 28, an acceptable difference is found.

Employee Type	Real Efficiency	Simulation Efficiency
New	89.49 %	89.10%
Experienced	102.20 %	102.26%

Table 28: Comparison Real and Simulated Efficiency

Besides the efficiency also the process times within Project ***Confidential*** are verified. The simulated process times per subsystem differ from the average processing times found in the data, see Table 29. This difference is a consequence of merging the data of the subsystems mainly assembled by one kind of employee. Table 30 shows that the real efficiency per subsystems differs from the average efficiency used for the employees. Below the tables, the frame is used as example explain the difference.

Subsystem	Drive A	Drive C	Frame	Selector
Real Process Time (hours)		Confidential		
Simulated Process Time (hours)				
Percentage Difference (%)	0.44%	1.51%	-4.29%	4.02%

Table 29: Difference between Real and Simulation Process Time

Subsystem	Drive A	Drive C	Frame	Selector
Real Efficiency (%)	100.59	103.82	86.39	92.29
Average Efficiency (%)	102.26	102.26	89.10	89.10

Table 30: Real Efficiency per Subsystem and Average Efficiency

> *For example; The average efficiency for the frame obtained from the data is 86.39%. Within the simulation, a new employee assembled the frame with an efficiency of 89.10%, which is higher. Therefore, the simulated process time, is lower than expected. This induces a negative difference between the real and simulated process time, as shown in Table 28.*

We expect that the simulated process times for Project Flexarm also differ. After discussion with management it is decided to ignore the difference described above, because it cannot be estimated to what extend the difference occurs for certain subsystems.

At last, it is verified if requests for workstations and employees are satisfied in the right order. Furthermore, it is examined if systems on workstations are allowed to be assembled on them. At last, it is checked if the number of busy employees corresponds with the number of batches that are processed. The employee control is well implemented in the DES model.

5.2.3. Test Process

Control

After completing assembly, only the FDR and CORO are functionally tested (cf. Section 2.3.2.) Each subsystem is tested separately, and not in batch form. The probability that a subsystem is approved after testing is 80%. When rework is required, the employee fine-tunes the subsystem and restarts the test.

All the objects necessary to program this in the DES mode are shown Figure 36. This alignment corresponds with the workstation arrangement introduced in Section 5.2.2, because the functionality of the waiting rooms and finish rooms correspond. A subsystem waits in the waiting room when an employee is unavailable and in the finish room when the storage is full. However, a serial workstation instead of a parallel workstation is used, because the test tool can only handle one subsystem at a time. In case rework is necessary, the subsystem moves to the waiting room again. When a batch of FDRs and COROs are waiting for testing, the batch with the earliest arrival time is first. In Section 6.1.2, other priority rules are introduced. The test process is controlled by segment C in Figure 34.

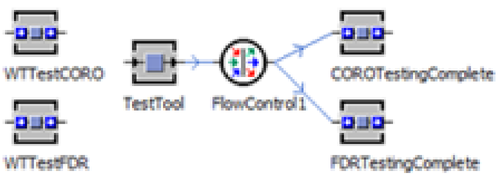

Figure 36: Test Tool with Waiting Rooms and Finish Rooms for the FDR and CORO

Input Parameters and Decision Variables

The input parameters required for the control of the test process are summarized in Table 31. The employee efficiency (cf. Section 5.2.2) is used to induce variation in the preparation time and fine-tune time. In contrast to the test time, which is assumed to be constant because there is no human interaction.

Input Parameter	Value
Yield (%)	80
Test Time (min)	**Confidential**
Preparation Testing (min)	
Fine-tune Time (min)	

Table 31: Input Parameters Test Process

Verification and Validation

The yield for the test tool is compared with the fraction of all subsystems that need rework. The rework fraction is 25.02%. So, it is higher than allowed. When comparing results this will be taken into consideration.

5.2.4. Storage Process

Control

The goal of the storage is to empty workstations and make them available for a new batch. Therefore, only whole batches may move to the storage area. Furthermore, the subsystems within a batch are stapled and the subsystems cannot be placed exactly next to each other. Since the storage area is small compared with the size of the subsystems, the storage influences the whole assembly process.

The storage in the DES model consists out of 8 storage areas for the 8 subsystems, see Figure 37.

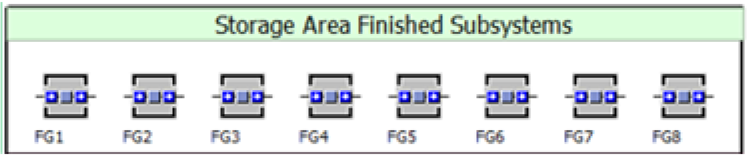

Figure 37: Objects Storage Process

To limit the maximal number of batches in storage, a table with a storage matrix is created. The cells of the matrix are filled when a batch enters the storage. The matrix consists of cells with a size of 0.2x0.2 meter. A batch fits if the length and width of connected cells in the matrix is greater than or equal to the length and width of the batch size. Subsystems cannot be divided in smaller parts, so the complete length and width of it must fit in the remaining length and width of storage.

Input Parameters and Decision Variables

To be able to fill the storage matrix the dimensions for the storage and the 8 subsystems must be known. These dimensions are summarized in Table 32 and Table 33.

Input Parameters Storage	Values
Width (m)	3.56
Length (m)	12.42
Aisle Width (m)	0.3
Cell Dimensions Storage Matrix (m)	0.2 x 0.2

Table 32: Dimensions of the Storage

Subsystem	VBL	VBS	HB	LC	CORO	FDR	CD	CDS
Length (m)	2.10	1.99	2.04	1.44	0.74	0.74	2.1	0.74
Width (m)	0.7	0.7	1.04	1.19	0.39	0.66	0.90	0.37

Table 33: Dimensions of the Subsystems

Verification and Validation

The number of batches of different subsystems in the storage fluctuates between 3 and 5 (cf. Section 2.2.3). When pausing the DES model randomly and investigating the storage, the number of batches within the simulation corresponds with the expected values.

5.2.5. Expedition Process

Control

The last step in the assembly process is expedition of the finished subsystems to the client. Expedition delivers weekly the subsystems that where ordered that week. In case more systems are finished than ordered, the storage remains occupied with several batches.

This is implemented in the DES model with the use of a generator that triggers a method with an interval of 5 days. The method compares the amount of arrivals in that current week, which is the amount of systems that needs to be delivered. This amount of systems is exported from the storage and workstations

Input Parameters and Decision Variables

The width of the interval is 5 days, because expedition happens once a week.

Verification and Validation

To verify the process, the simulation is paused multiple times on different expedition times. During a pause the number of requested values is compared with the total finished subsystems. These values correspond with the number of systems that are moved and stayed in the storage.

5.2.6. Data Collection and Performance Calculation

Control

The performance measures used within VDL ETG is the Committed Line Item Performance (cf. Section 3.3.3). This performance measure is calculated with Formula 12.

$$CLIP\ within\ Time\ Period\ i = \frac{Number\ of\ Production\ Order\ that\ are\ On-time\ per\ Time\ Period\ i}{Total\ Number\ of\ Production\ Orders\ per\ Time\ Period\ i} \qquad (12)$$

Element F in the control panel in Figure 34 is responsible for the data collection and the calculation of the CLIP. To calculate the CLIP in the DES model several steps are taken.

1. Save completion time of batch forming;
2. Calculate due date with Formula 13. Recall that VDL ETG and the client agreed with a delivery time of 5 days.
$$Due\ Date = Completion\ Time\ Batch\ Forming + Maximal\ Delivery\ Time \quad (13)$$
3. Save the finish time of each batch. A batch is finished after the assembly process, except for the FDR and CORO, which are finished after testing.
4. At last, count the frequency that the finish time exceeds the due date (cf. formula 14). In the formula is I all batches in the simulation. The CLIP status is 1 or 0, depending on comparison between finish time and due date.
$$CLIP = \frac{\sum_{i=1}^{I}\left(\begin{cases} CLIP\ Status(i)=1, & Finish\ time<Due\ date \\ CLIP\ Status\ (i)=0, & Finish\ time>Due\ date \end{cases}\right)}{|I|} \qquad (14)$$

As trade-off to the CLIP, the annual costs are used in the DES model. The annual employee costs and storage costs are calculated.

Input Parameters

As mentioned in the paragraph above there are several input parameters necessary for CLIP and costs calculation. Table 34 gives insight in the used costs per unit and the delivery time.

Input Parameter	Value
Hourly Rate Experienced Employee	**Confidential**
Hourly Rate New Employee	
Storage costs per Square Meter	
Delivery Time	

Table 34: Input Paramters for Performance Calculation

Verification and Validation

The costs and CLIP are verified and/or validated in this section. Verification of the costs is executed by comparing the costs obtained from the simulation with a cost calculation executed in excel. Both corresponds with each other.

For validation the CLIP of Project ***Confidential*** is compared with the CLIP obtained from the simulation. When using the input parameters in Table 35 corresponding with the project, a CLIP of ***Confidential***% is obtained.

Input Parameter	Drive C	Drive A	Selector	Frame
Arrival Rate per Month	9.83	10.33	7.41	6.66
Average Expected Process Time per Subsystem (hours)	Confidential			
Delivery Time (days)	5	5	5	5
Number of Employees	4			

*Table 35: Input Parameters Project **Confidential***

Table 36 shows the average CLIP from the DES model, the realized CLIP and the absolute difference between those two. To evaluate if this difference is significant a paired-t test is performed on the absolute difference between the realized CLIP and CLIP per simulation run. The confidence interval is [-0.18701; 4.32912]. This interval contains zero, so there is no significant difference. Therefore, it is possible that the average CLIP calculated with the simulation is equal to the realized CLIP.

	Simulation Value	Real Value	Absolute Difference
CLIP	***Confidential***%	***Confidential***%	2.15

*Table 36: Comparison CLIP Project **Confidential** from Simulation and Realized CLIP*

However, there are some remarks on the validation. First of all, the test tool for Project FlexArm is not used for Project ***Confidential***. Secondly, the storage within the DES model is not included in validation, because Project ***Confidential*** has no storage limitations. Both parts are validated and verified for Project Flexarm in Section 5.2.3 and 5.2.4, respectively. Therefore, it is assumed that these components combined with the complete assembly process are representing the reality.

5.3. Conclusion

Chapter 5 contains the development of the layout and the DES model. For layout development is a rough-out layout is used to determine the number of workstations. Besides this procedure, a relationship diagram is used to identify the relations between several subsystems. The new layout contains 4 workstations, each workstation is used to assemble one of the groups in Table 37. The serial arrangement used for the site locations is replaced with a u-shapes arrangement.

Groups	Subsystems
1	VB, HB
2	LC
3	FDR, CORO
4	CD, CDS

Table 37: Groups of Subsystems determined for Layout

Construction of the DES model is explained by dividing the simulation process in 5 subprocesses, arrival and batching, assembly, testing, storage, and expedition. Besides explaining these subprocesses, also the input parameters are discussed. Based on verification and validation, we obtained a realistic DES model.

In Chapter 6, the DES model is used for experimentation. Besides this, the 4 workstations and groups determined for the layout are evaluated in the DES model.

6. Simulation Study

Now that the structure of the DES model has become clear, a study for the best suitable settings for the assembly process is explored. The study is divided in the experimental phase and the sensitivity phase. The purpose of the experimental phase is evaluating certain strategies for different interventions. Afterwards, in the sensitivity phase the best-found experiment is evaluated on robustness and sensitivity.

6.1. Experimental Phase

In Section 6.1.1. we introduce the experimental design. Afterwards, Section 6.1.2 is used to introduce the experiments executed for all the strategies. In Section 6.1.3. the intermediate results of the experiments are evaluated and discussed.

6.1.1. Experimental Design

The experimental design explains the required settings for each experiment within the simulation study. The settings are the warm-up period, run length, and the number of runs per experiment.

Run Length

The run length used for the simulation is 4 years for Project Flexarm and Project ***Confidential***. This run length is sufficient for the found warm-up length for both projects, and it induces a computation time that is not too time consuming.

Warm-up Period

The warm-up period of the simulation depends on the type of simulation created. A terminating simulation models a system that has a naturel event which indicates the end of the simulation. However, a non-termination simulation has not such event. Non-terminating simulation are often applicable when the researcher is interested in the behavior of the system when it is operating normal. In the latter one, the outcomes of the simulation are of interest when the system is in its steady state. (Law, 2015) The assembly process modelled in this research is non-terminating, because no natural terminating event can be identified. Furthermore, the steady state of the system is of interest for this research, since then the performance of the systems describes the normal expected behavior when using a certain strategy.

Because the simulation shows non-terminating steady state behavior, the warm-up period is determined with the Welch's method. This method is a graphical procedure in which a moving average is calculated. Due to the moving average the high frequency oscillations are filtered, therefore the long-term trend becomes visible. (Law, 2015) The cycle time per batch is the output measure used for the method. This method is executed for all the subsystems in Project ***Confidential*** and Project Flexarm. Due to the multiple subsystems per project, the critical subsystem determines the warm-up period. A system is critical, if its warm-up period is highest of all compared with the other subsystems is.

The graphical result from the Welch's method for Project ***Confidential*** and Project Flexarm is shown in Figure 38 and Figure 39. The critical subsystem in Project ***Confidential*** and Project Flexarm is the Drive A and LC, respectively. The graphs shown, belong to the critical subsystems.

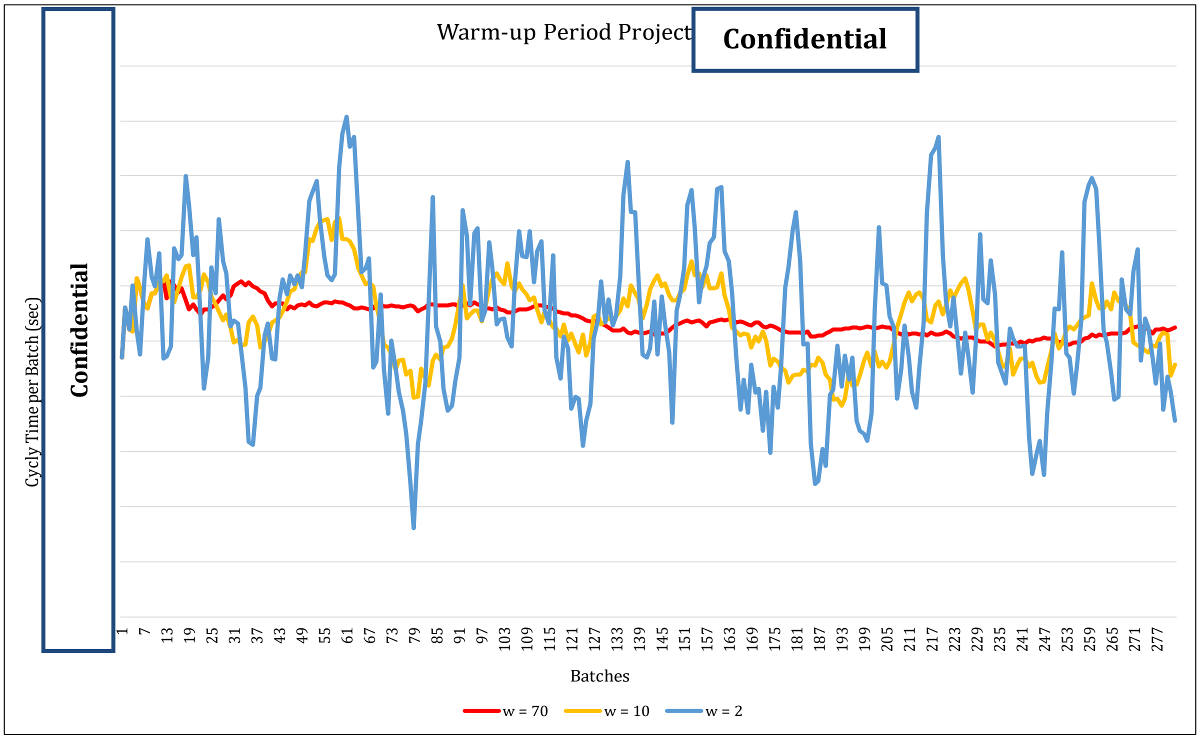

*Figure 38: Graphical Result to determine Warm-up **Confidential***

The graph above is used to determine the warm-up period for Project ***Confidential***. The graph is obtained by executing an experiment of 12 years and extracting the cycle time for each batch in the simulation. A run length of 12 years is used, because 4 years were not enough to notice a trend in the line. When examining the graph, it is noticed that a warm-up period of 21 batches is sufficient to obtain a steady state. The period of 21 batches corresponds with a period of 220 days. A rule of thumb of Welch's method is that warm-up period must be smaller than a quarter of the chosen run length. The warm-up period of 220 days is smaller than the 260 days, which is one-fourth of the proposed run length in the previous section. Therefore, a run length of 4 year and a warm-up of 220 days is used for Project ***Confidential***.

Besides Project ***Confidential***, a warm-up period is determined for Project Flexarm. Since there are 3 strategies, the warm-up period for each strategy is compared which each other and the critical one is chosen. The strategy with the critical warm-up is 'First In, First Out'. The warm-up period is 13 batches, which is equal to 75 days. To be able to find a trend in the graph, a run length of 6 years is used. When using the proposed run length on 4 years, a small increase of the trend at the end is noticed. However, this increase is coincidence, because afterwards the trend returns in a general manner.

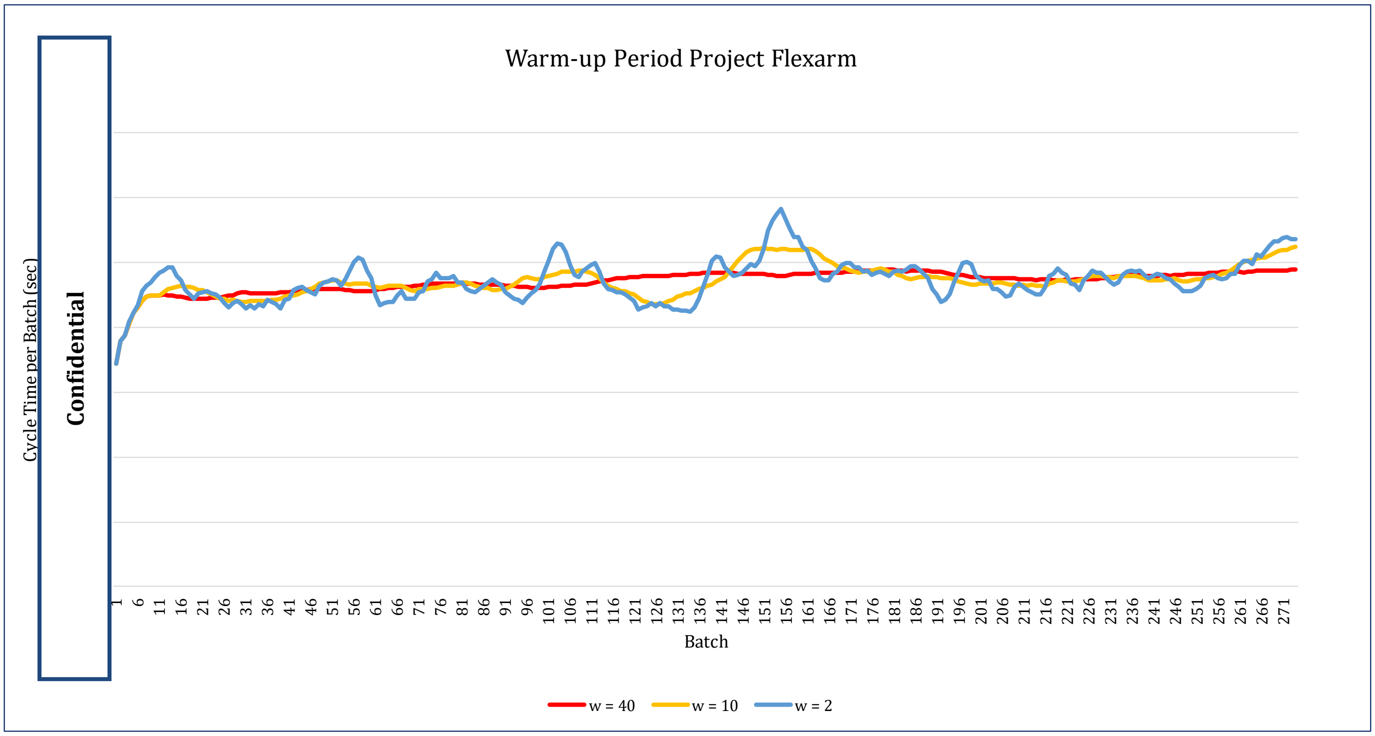

Figure 39: Graphical Result to determine Warm-up Flexarm

Number of Runs per Experiment

Next, the number of runs per experiment is determined. The number of runs is important for the precision of the model, as a simulation model creates outcomes based on variable input values. For determining the required number of runs a sequential procedure is used. First, this procedure is explained and afterwards the required number of runs is given for Project ***Confidential*** and Project Flexarm.

For execution of the sequential procedure, an allowed relative error and the confidence-interval half-length is necessary. The left-hand side of Formula 15 is the confidence-interval half-length and the right hand- side is the allowed relative error. (Mes, 2017)

$$\frac{t_{n-1,1-\alpha/2}\sqrt{S^2/n}}{\overline{X}} < \gamma' \qquad (15)$$

$$\gamma' = \frac{\gamma}{1+\gamma} \qquad (16)$$

The precession of the experiments is specified with the allowed relative error. The allowed relative error determines the maximal value for the confidence-interval half-length. The formula for the allowed relative error, Υ', is given in Formula 16. For this formula the relative error, Υ, is necessary. This error is the ratio of the difference between the absolute error and the average value of the population. The absolute error is the difference between the average value of population and a random value within the population. Therefore, a small relative error is useful, because it gives insight in the maximal allowed deviations between the average value and a random value in the population. (Law, 2015)

Now the procedure has been explained, the allowed and obtained relative error for various number of runs is calculated and given in Figure 40 and Figure 41. For both projects the average cycle time per run is used for calculation of the relative error. This variable is an important output variable for the DES Model, because it determines if a certain sales order is pass the due date. The relative error chosen is 5%, which leads to an allowed relative error of 0.047619. Recall that when the obtained relative error is below the allowed relative error, the number of runs is found. For Project ***Confidential*** 7 runs for each experiment is enough. The number of runs required for Project Flexarm is 21.

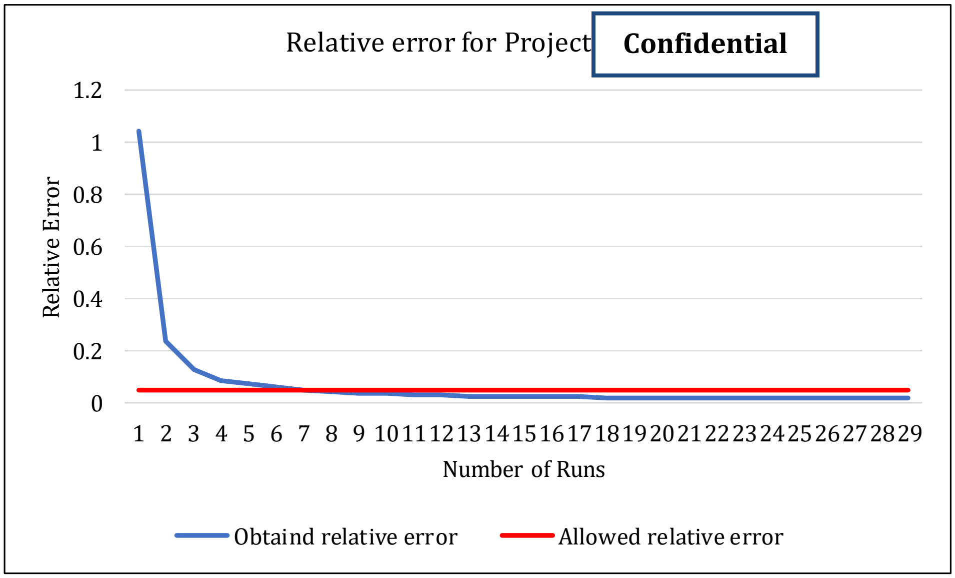

Figure 40: Relative Error for Project ***Confidential***

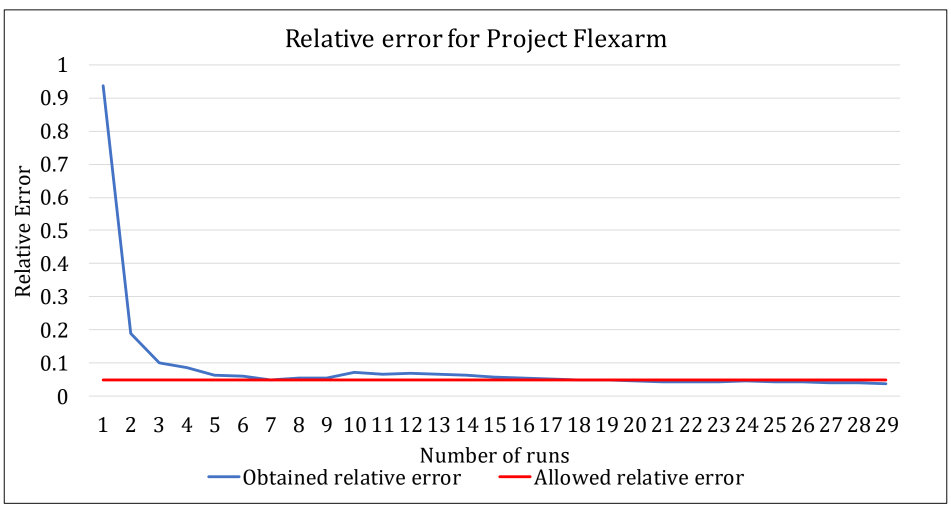

Figure 41: Relative Error for Project Flexarm

Determining the run length, warm-up period and number of runs is important for obtaining reliable output of the simulation model. The values for Project ***Confidential*** and Project Flexarm are used for validation of the DES model and for executing the experiments, respectively. Now the experimental design for the strategies has been acquired, the experiments for each strategy is determined in Section 6.1.2

6.1.2. Experiments

The goal of this section is to describe multiple experiment for the chosen planning strategies. First, we introduce the planning strategies used for this research. Afterwards, the experiments for each strategy is explained.

In this research, 3 planning strategies are chosen. First of all, the strategy 'First In, First Out' is chosen, because this strategy represents the current situation. Besides that, the strategy 'Max Task Time' is found in literature. This strategy is chosen because it is promising. Employees finish the time-consuming batches first, so the workforce is balanced over the employees. At last, we developed an own planning strategy, based on preliminary simulation research about the limitations of the subsystems and the storage area. Therefore, we expect that the area is a bottleneck in the process. To minimize the effect of the bottleneck, the average area over time occupied is minimized. Goetschalkckx and Ratliff (1991) propose a space-time objective in which the average area over time is calculated by multiplying the area required with the time it occupies the area (Goetschalkckx & Ratliff, 1991). When prioritizing on the batch with the 'Smallest Dimension', the average area occupied is low due to a low space-time objective. We refer to this new strategy by 'Smallest Dimension'.

Now the strategies have been chosen, it is time to introduce the interventions for the strategies. For each strategy 5 types of interventions are used. Three of them are the maximal number of employees, the number of new and number of experienced employees. The sum of the experienced and new employees is equal to the maximal number of employees. Since a wide range for the interventions induce a long computation time, it is important to choose the value range well. The values for the interventions are shown in Table 38. A lower bound of 3 employees is used, because the service rate with 2 employees is below the arrival rate. Otherwise, the system will explode.

Intervention	Lower Bound	Upper Bound	Step Width
Maximal Number of Employees	3	8	1
Number of Experienced Employees	1	8	1
Number of New Employees	1	8	1

Table 38: Values of Interventions

Besides the numerical interventions, 2 Boolean interventions are part of the experiments. First, 2 possible situations are evaluated for the experienced employees. In the first one, the experienced employees may assembly all kind of subsystems. In the latter one, it is only allowed to assemble the LC, CORO and FDR. This decision has been made after discussion with management. Next an intervention is executed for the new developed layout in Section 5.1. Recall that a dedication of subsystems to certain workstations is based on the relationship-diagram. Furthermore, the number of workstations is 4. The dedication of the subsystems for the new layout and the current situation is repeated in Table 39. Each possible combination of the numerical interventions is executed with the dedication belonging to the new layout and with the dedication belonging to the current situation.

Subsystem	New Layout	Current Situation
VBL	Workstation 1	Workstation 1
VBS	Workstation 1	Workstation 2
HB	Workstation 1	Workstation 3
LC	Workstation 2	Workstation 4
FDR	Workstation 3	Workstation 5
CORO	Workstation 3	Workstation 6
CD	Workstation 4	Workstation 7
CDS	Workstation 4	Workstation 8

Table 39: Dedication of Subsystems to Workstation

Now all strategies and interventions are introduced, a full-factorial design is used to generate experiment. The total number of experiments is 108, this leads to a computation time of 2.5 hours per strategy. In the next section, the intermediate results of the experiments are discussed. Afterwards these results are used for the sensitivity analysis.

6.1.3. Intermediate Results

Now the experiments described in section 6.1.2. are implemented in the DES model, the results are generated and described in the section. First, we discuss experiment settings which induce similar CLIP value, despite the strategy. Afterwards, we describe and compare the settings, which induce a CLIP of above ***Confidential***% in at least one of the strategies. At last, we evaluate the best-suitable settings for each strategy based on comparison between CLIP and Costs. All results are given in Appendix G, H, and I.

Similar CLIP Value

Table 40 shows that certain experiment settings induce a CLIP within the same range for each strategy. These settings are explained below the table.

Experiments containing:	CLIP Range Strategy		
	First In, First Out	Max Task Time	Smallest Dimension
1 Experienced Employee	**Confidential**		
1 New Employee and Dedication of the Experienced Employee			
New Layout			
None of the above settings			

Table 40: Relations between Experiment Settings and CLIP

All the strategies obtain a CLIP below ***Confidential***%, if 1 experienced employee is part of the experiment. The CLIP is low because labour force necessary for assembly of the LC, FDR and CORO is larger than 1 FTE. Furthermore, the experiments with 1 new employee and dedication of the experienced employees induce for all strategies a CLIP below ***Confidential***%. The low CLIP is induced, because the capacity of the new employee only available for the CD, CDS, and VB is not sufficient to meet the required labour force.

In both cases described above, the modelled assembly system explodes because the service rate is smaller than the arrival rate. Table 41 shows the arrival and service rate corresponding with those cases. When the arrival rate exceeds the service rate, the system cannot handle the incoming orders fast enough and the orders are piled up. The service rate is calculated by dividing the monthly workhours of 1 employee with the sum of the expected process times for the systems the employee is allowed to handle.

Experiment Setting	Arrival Rate	Service Rate
1 Experienced Employee	20	**Confidential**
1 New Employee and Dedication of the Experienced Employee	20	

Table 41: Arrival and Service Rate

Next, when using the settings containing to the new layout (cf. Section 5.1.), the CLIP for these strategies is maximal ***Confidential***%. Recall that the new layout has 4 workstations and that every subsystem is dedicated to 1 of the 4 workstations. One reason for this CLIP range is that the flexibility of the system decreases due to the dedication of subsystems. The Poisson process in the DES model induces a variability in the arrivals of the subsystems. In some cases, multiple sale orders arrive right after each other. Since various subsystems are dedicated to the same workstation, the subsystems in one of the sales orders need to wait until the workstation is available. Another reason for the CLIP range is the grouping of the subsystems based on the relationship-diagram. Since the relationship-diagram does not consider the expected process times of the subsystems, it is possible that a critical group arises due to merging. This assumption is verified by evaluating the systems that CLIP often during the experiments. Table 42 shows the number of CLIP per subsystem. The subsystems that have the most influence on the CLIP percentage are the CD and CDS. These systems are dedicated to the same workstation and have expected process times that are critical when merged.

Subsystem	Number of CLIP
CD	169
CDS	158
CORO	31
FDR	32
HB	37
LC	67
VBL	27
VBS	15
Total Clipped	**Confidential**
Total Orders	
CLIP Percentage	

Table 42: Overview of Number of CLIP per Subsystem

At last, all the remaining experiments results in a CLIP within a range of ***Confidential***% till ***Confidential***%. None of the experiments exceeds this ***Confidential***%. We expect that the factor that limits the CLIP is the available storage area. This is further evaluated in the sensitivity analysis in Section 6.2.1.

In the end, it is observed that the CLIP doesn't exceed ***Confidential*** % when 1 experienced employee or 1 new employee in combination with dedication of experienced employees is used. Besides this, a range ***Confidential***% till ***Confidential***% is obtained when the new layout is evaluated. At last, the remaining experiments are within a range of ***Confidential***% till ***Confidential***%. All those experiments are further evaluated per strategy in the paragraphs below.

*Comparing Settings with a CLIP above **Confidential**%*

All the experiment settings which induce a CLIP above the threshold for each one of the strategies, are shown Figure 42. The horizonal axe of the figure describes the experiment numbers in an increasing order of costs. Furthermore, the primary axis shows the CLIP and the secondary axis shows the costs.

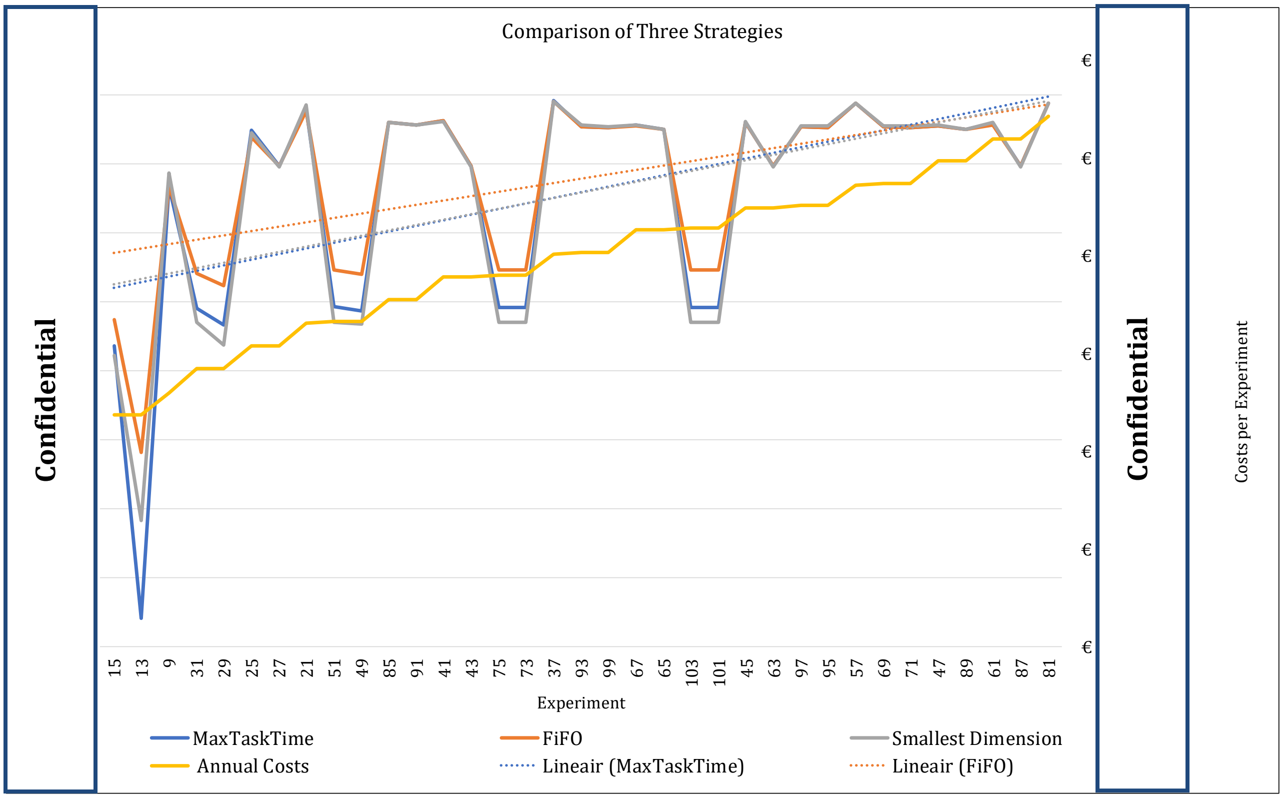

Figure 42: CLIP Comparison between Strategies

Since the CLIP varies, a linear trend line in inserted. The trend line is positive, which indicates that CLIP increases when the costs increase. This is as expected because the variable component of the costs is the employee costs. Since more employees increases the chance on meeting the due date, the CLIP increases. Even though, the trend rises linearly, the CLIP shows variation. Experiment 13, 31, 29, 51, 49, 75, 73, 103, 101 are below the trend line, despite the used strategy. When examining the settings for these experiments, it is notable that the number of experienced employees is for every experiment two, despite the number of new employees. Therefore, we expect that 2 experienced employees limit the increase of the CLIP due to their dedication to the FDR, CORO and LC.

> *For example: The experienced employees assemble a batch of CD and VB. Moreover, the new employees are not allowed to assemble the FDR, CORO or LC. In this case, no employee is left to assemble a batch of FDR, CORO or LC if these arrive.*

Besides this, it is striking that 'First In, First Out' has a better CLIP for each experiment below the trendline. Therefore, it seems that First In, Firs Out is less sensitive for the number of experienced employees. The difference in CLIP for equal experiments is in a range of 0 till 0.98. This difference is however not significant.

*An example of the difference is: The CLIP for experiment 29 in strategy 'First In, First Out' is **Confidential**% and for 'Smallest Dimension' this experiment results in a CLIP of **Confidential**%. The difference is not significant, since [-2.47872; 0.757055] contains zero.*

Best Suitable Experiment Per Strategy

Now the overall CLIP results and the experiments with a CLIP of at least ***Confidential***% have been discussed, we evaluate the best-suitable assembly setting for each strategy. To find these settings, all the experiments with a CLIP exceeding ***Confidential***% are sorted on ascending order. First, these settings are discussed per strategy, afterwards the strategies are compared.

The best-suitable setting is experiment 9 for each strategy. For experiment 9, 4 employees are used (3 experienced and 1 new). Furthermore, the experienced employees are allowed to assemble all kind of systems. At last, the experiment is not based on the new layout, so it is executed for 8 workstations. The total annual costs for these settings are € ***Confidential***. –.

To examine if experiment 9 is significantly better than the other experiments, it is compared with the experiment with lower costs. Experiment 15 has annual costs of € ***Confidential***.-. If experiment 15 does not differ significantly from experiment 9, it may be beneficial to use those experiment settings because there is no certainty that experiment 9 is better than 15. The settings for experiment 15 are 4 employees, 2 experienced and 2 new employees. Furthermore, experienced employees are dedicated and therefore assemble only an FDR, CORO or LC. When comparing experiment 9 with experiment 15 for all strategies in Table 43, a significant difference is found.

Strategy	First In, First Out	Max Task Time	Smallest Dimension
CLIP Exp 15	***Confidential***%	***Confidential*** %	***Confidential*** %
Confidence Interval	[0.006616; 3.872243]	[0.426427; 4.199042]	[0.240668; 5.050833]

Table 43: Results Paired-t Test for Comparing Experiment 9 with 15

Besides comparing experiment 9 with experiment 15, we also compared it with a better performing experiment (cf. Table 44). Experiment 25 differs from experiment 9, because it uses 1 new employee more. All the confidence intervals obtained, show insignificance difference with experiment 9. So, using an extra employee has no influence in increasing the CLIP performance.

Strategy	First In, First Out	Max Task Time	Smallest Dimension
CLIP Exp 25	***Confidential*** %	***Confidential*** %	***Confidential*** %
Confidence Interval	[-1.12726; 2.538368]	[-1.16939; 2.771604]	[-1.02947; 2.564477]

Table 44: Results Paired-t Test for Comparing Experiment 9 with 25

In Table 45 is shown that the CLIP for strategy 'Smallest Dimension' is approximately 0.2% higher than the other two. Since the difference between strategies for experiment 9 is quite small, we expect there is no significant difference. To be sure, the paired-t test is executed to compare 'First In, First Out' and 'Max Task Time' with 'Smallest Dimension'. The table shows that no significant difference has been found between the strategies for experiment 9.

Strategy	CLIP Value	Confidence Interval
First In, First Out	**Confidential**	[-1.10525; 1.495451]
Max Task Time		[-1.23663; 1.609811]
Smallest Dimension		-

Table 45: Difference in CLIP for the Best Experiment

To summarize the experimental phase, the best-suitable settings for all strategies are obtained from experiment 9. The number of employees used within this experiment is 4. Three of them are experienced and 1 is new. Besides this, the settings obtained from the new layout are not used for this experiment. Also, the experienced employees are allowed to assemble al 7 subsystems. Furthermore, no significant difference is found between the strategies, therefore we execute the sensitivity analysis only for strategy 'First In, First Out'. This strategy is already implemented and the decrease of the CLIP in case 2 experienced employees are used is the smallest. The best suitable experiment is in the sensitivity phase evaluated on robustness and sensitivity.

6.2. Sensitivity Phase

The sensitivity analysis is explained in Section 6.2.1 and the results after the sensitivity analysis are given and discussed in Section 6.2.2.

6.2.1. Sensitivity Analysis

In this section, we motivate the scenarios studied in the sensitivity analysis. Primarily, our focus is motivated by questions posted by management and observations that we made during the experimental phase (cf. Section 6.1.3). For the sensitivity analysis, we apply the settings of experiment 9 (cf. Section 6.1.3). Before we further specify the studied scenarios, we first motivate each sensitivity factor separately.

Since the demand is increasing over time (cf. section 1.2), VDL ETG prefers settings robust for the increase. Therefore, *demand increase* is considered as a sensitivity factor. It is expected that a demand increase will lead to a CLIP decrease.

Because management has the goal to increase the yield of the test tool, *test tool yield* is also a factor in the sensitivity analysis. An increase of the CLIP is expected when the yield increases.

Besides these factors, management suggest evaluating the influence of a *learning curve* on the performance of the system. Management recommends implementing a learning period of 8 weeks for the new employees in the model. When these weeks are passed by, the efficiency of those employee is like that of an experienced employee. A new employee is only experienced in assembly of the VB, HB, CD and CDS. As experienced employees can assemble all subsystems, we expect the CLIP to rise when new employees gain efficiency, especially after finding the limitation due to the difference in the employees(cf. Section 6.1.3).

Recall that besides the experienced employees, the storage area also restricts the CLIP (cf. Section 6.1.3). Since we expect an increase of the CLIP due to increased area, *storage area* is one of the sensitivity factors. An increase of the storage area is obtained by increasing the width, length of stack height. The latter one is cost-free, because floor costs are based on square meter.

The 4 sensitivity factors proposed in the paragraphs above are given in Table 46 given. For 3 factors a value range is chosen. For the efficiency, the efficiency of the experienced employees is used. Whit these values, the analysis is executed in the DES Model. The found results are discussed in the upcoming Section 6.2.2.

Sensitivity factor		Lower Bound	Upper Bound	Step Width
Demand		10	30	1
Yield		0.8	0.99	0.02
Learning Curve (Avg. Efficiency)		89.49%	102.20% (after 8 weeks)	Boolean
Storage Area	Stack Height:	2	3	1
	Length:	8.42	16.42	1
	Width:	2.56	4.56	1

Table 46: Value Range for Sensitivity Factors

6.2.2. Results Sensitivity Analysis

In this section, we discuss the observations for each sensitivity factor introduced in the previous section. The best- suitable settings obtained during the experimental phase are 4 employees, whereof 3 experienced and 1 new employee. The experienced employees can assemble all subsystems and the settings of the current lay-out is used.

Storage Area

The first sensitivity factor to discuss is the storage area. As introduced in Section 2.2.3, we first evaluate the influence of the stack height on the CLIP. Next, the different used storage areas are compared. At last, the difference in robustness between the strategies is evaluated.

Table 47 shows how the stack height influences the CLIP of experiment 9. In particular, we observe that a stack height of 3 subsystems achieves a better CLIP performance. These results are confirmed with a paired-t test. The confidence interval of the difference between a height of 2 and 3 ([0.625071; 4.061724]) indicates a significant difference between both stack heights.

Stack Height	CLIP
2	**Confidential**
3	

Table 47: Influence of Stack Height on CLIP of Experiment 9

Figure 43 shows how the different storage area configurations influences the CLIP. The difference between green and the orange line is the stack height. Furthermore, the storage setting of experiment 9 correspond with the experiment indicated by the black triangle. As already observed, there is a difference between the stack height of 2 and 3. However, when the storage area increases, the influence of the stack height declines. This phenomenon is logical because when increasing the area, the storage is becoming a bottleneck less and less. Therefore, each extra square meter yields less benefit.

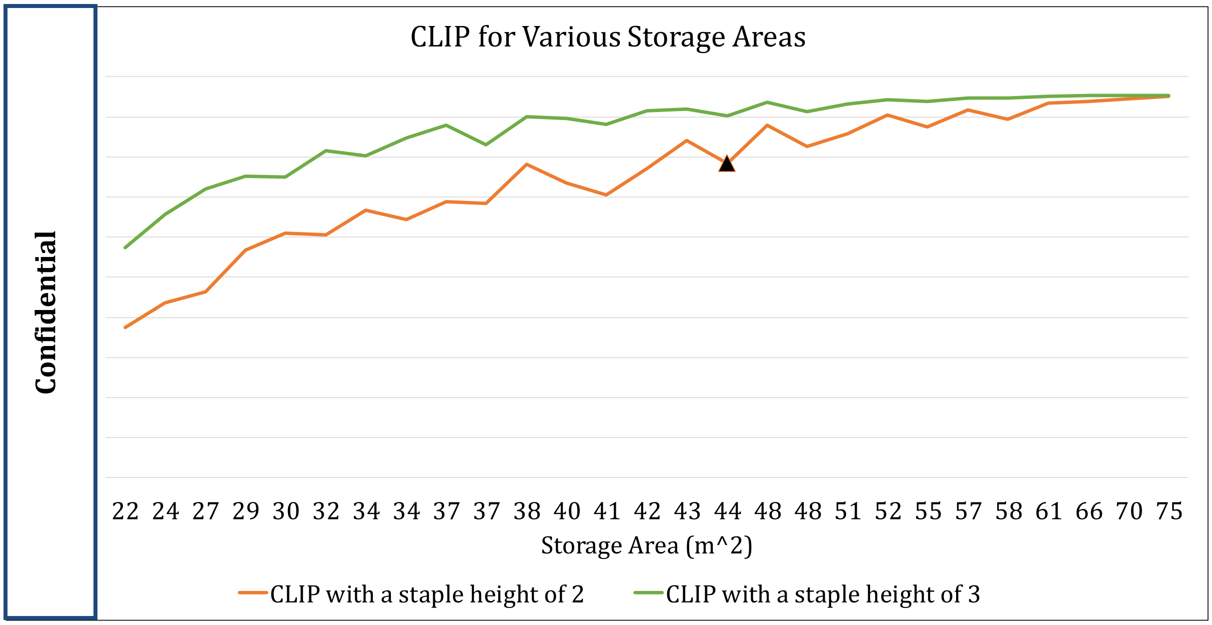

Figure 43: CLIP for Various Storage Areas

In summary, the storage area increases the CLIP. A stack height of 3 instead of 2 induces a significant CLIP improvement to ***Confidential***%. This change induces no additional costs, therefore both stack heights are considered in the sensitivity analysis in the next sections.

Test Tool Yield

The second sensitivity factor is the yield of the test tool. Figure 44 shows the behavior of the CLIP when varying the yield. Recall that the best experiment found in section 6.1.3 has average CLIP of ***Confidential***% for strategy 'First In, First Out'. When changing the yield, the CLIP remains more or less unchanged.

Due to no additional costs and the influence of the storage area, we also executed the sensitivity analysis of the test tool on experiment 9 with a stack height of 3. Therefore, the figure also contains influence of the yield on the CLIP when a stack height of 3 is used. When examining the lines in the graph, it is also observed that the CLIP for both stack heights stays about the same.

The prediction that the CLIP increases in line with the yield is not confirmed. It is likely that no increase has been found, because it is possible that the CLIP performance is not limited by the FDR and CORO. In case the FDR and CORO need rework multiple times, their total cycle time will probably be below 5 days because, the process time of the FDR and CORO are 211 and 165, respectively (cf. Section 2.1).

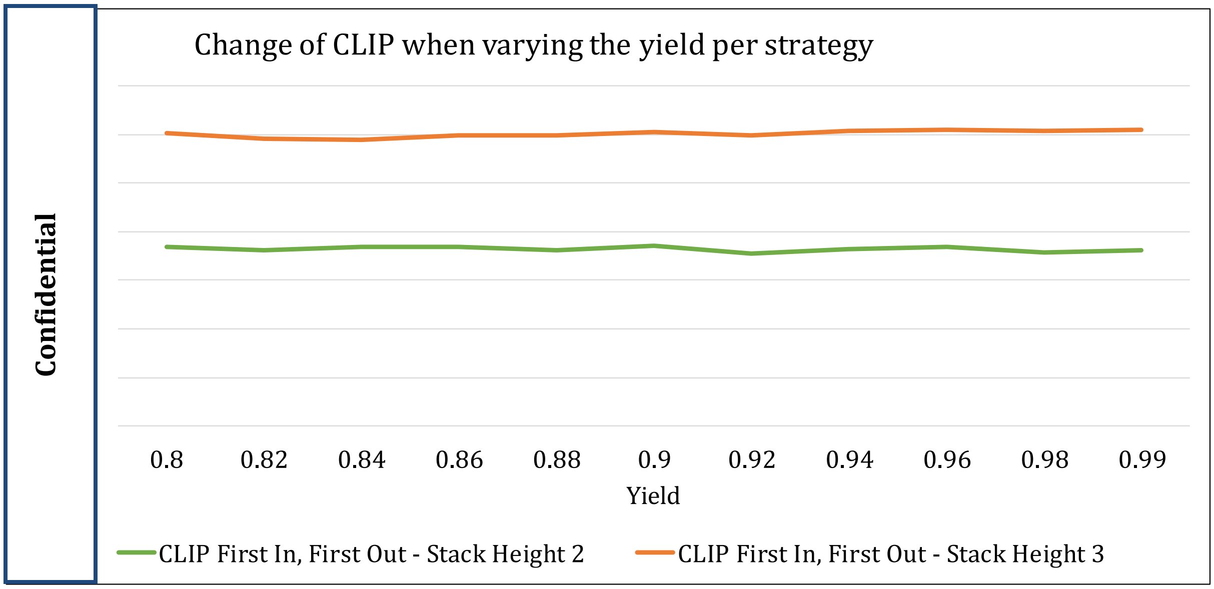

Figure 44: Change in CLIP for Various Yield and Distinguished over Stack height

Learning Curve

Learning Curve is the third factor to discuss. Recall that this factor is chosen because management is interested in its influence on the system.

When running an updated DES model in which new employees are experienced after 8 weeks, we obtain a CLIP of ***Confidential***%. This is larger than the CLIP of ***Confidential***% corresponding to the best-found experiment. However, using a paired-t test, it is found that the learning curve does not result in a CLIP that differs significantly from the situation without learning curve. The interval obtained is [- 0.47736; 1.643255]. Despite the insignificance, the increase in CLIP can be explained. The efficiency of the new employee is higher after the 8 weeks, therefore this employee's ability to foresee in on-time delivery is better. However, due to the high CLIP already resulting from the simulation system, the needed effort to increase the CLIP must be larger.

Demand Increase

Since Project Flexarm expects to experience an increase in demand, we examine if experiment 9 is robust enough to handle the change. In case experiment 9 cannot meet a monthly demand of 25 subsystems, it is investigated if other settings are more robust under reasonable annual costs.

Figure 45 shows the change in CLIP when increasing the monthly demand from 10 till 30. The blue line indicates the current situation. As we observe, starting from a demand of 21, VDL ETG would violate the CLIP constraint of ***Confidential***%. The yellow line in the figure shows the results when using a stack height of 3. When the demand is 22, the CLIP is ***Confidential*** %. This improvement in robustness however, is not sufficient.

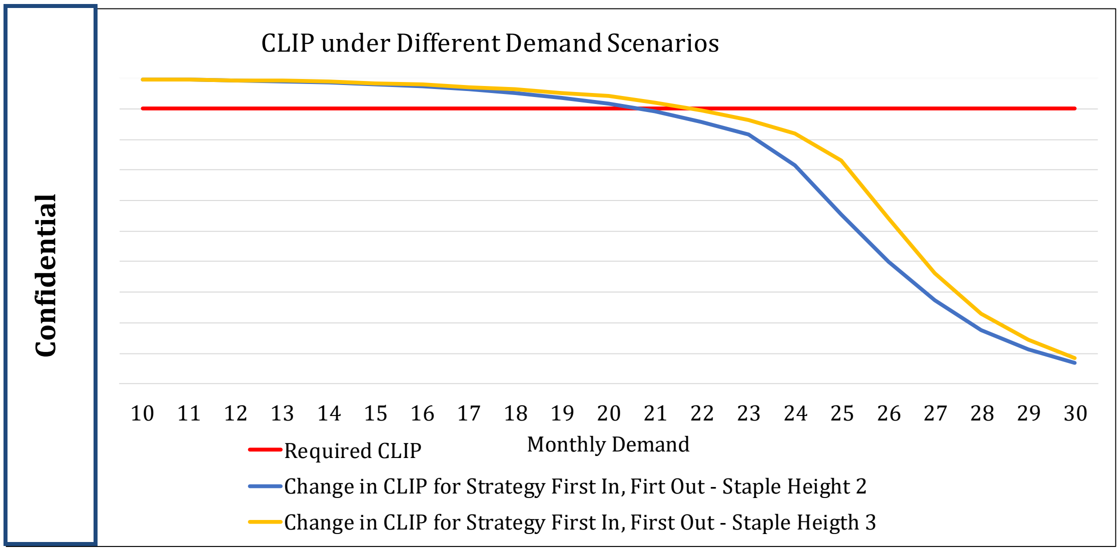

Figure 45: CLIP under Different Demand Scenarios for a Stack Height of 2 and 3

Since the demand is expected to rise to 25 subsystems per month, we studied whether different setups may comply with the CLIP constraint. Experiment 21 is chosen, because 1 extra experienced employee is deployed (cf. Section 6.1.3). The flexibility of an experience employee is larger than of a new employee (cf. Section 2.3.2), which is beneficial when a scale-up for another project is necessary. The above analysis is repeated and results in Figure 46. Besides a stack height of 3 and a larger storage area, an extra experienced employee results in a more robust CLIP Performance. However, the maximal obtained CLIP of ***Confidential*** % still violates CLIP constraint.

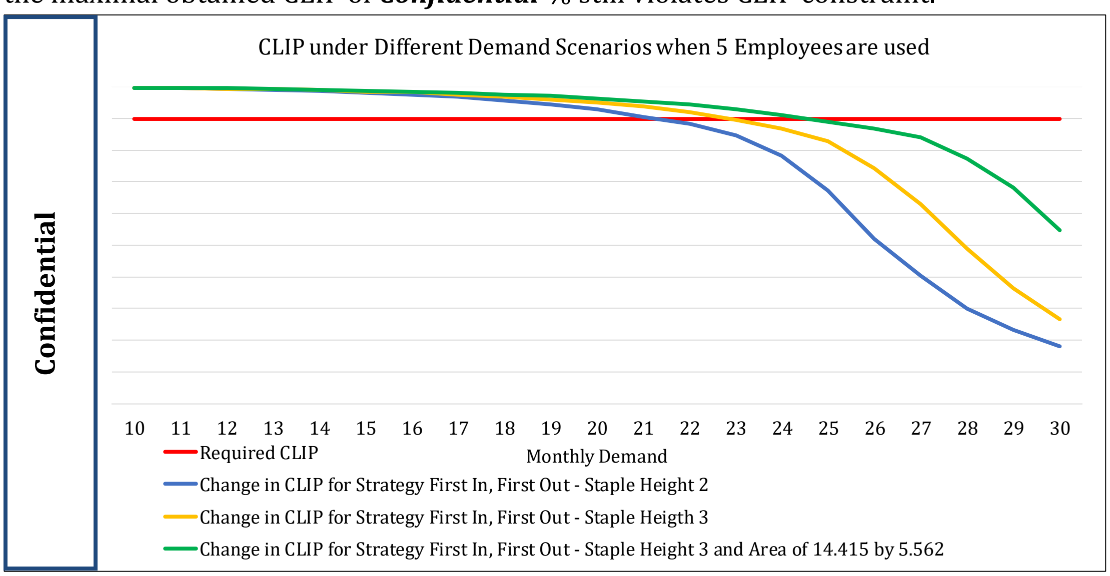

Figure 46: CLIP under Different Demand Scenarios when 5 Employees are used

To ensure that the CLIP of ***Confidential*** % obtained from an experiment with 5 employees and an increased storage is reliable, a paired-t test is performed. The CLIP is compared with the CLIP belonging to a demand of 24 and 26. The results of the test are given in Table 48.

Comparison	Confidence Interval	Conclusion
Demand 24-25	[0.349374; 3.876467]	Significant different
Demand 25-26	[0.077553; 4.821637]	Significant different

Table 48: Paired-t Test for Comparising a Demand of 24 and 26 with 25

Due to the 5 employees and the increased storage space the costs are higher compared with the best-suitable settings found for a demand of 20. The costs for both situations are summarized in Table 49.

Number of employees	Experienced Employees	New Employees	Storage Area	Annual Employee Costs	Floor Costs	Annual Costs
4	3	1	3.562 by 12.4215	**Confidential**		
5	4	1	5.562 by 14.4215			

Table 49: Cost Comparison between 2 Cases

Given the above points, it is found that the settings obtained from experiment are robust until a demand of 22. To be able to fulfill this demand, a stack height of 3 is used. To be able to fulfill demand and comply as best as possible with the CLIP of ***Confidential***%, we propose the settings of 4 experienced employees, 1 new employee and a storage area of 14.4 by 5.6 meter.

6.3. Conclusion

To summarize the important observations, first the experimental phase is handled, afterwards the sensitivity phase is discussed.

In the experimental phase, the experimental design and experiments are defined. For Project Flexarm, a run length of 4 year, a warm-up period of 75 days and 21 runs are used. The strategies evaluated are 'First In, First Out', 'Max Task Time' and 'Smallest Dimension'. For each strategy, experiments are done to determine the best suitable setting and to evaluate the new layout.

Observed first from the experimental phase is, when using 1 experienced or 1 new employee with dedicated experienced employees the service rate is too low for the arrival rate. Therefore, the system explodes, and sales orders are not met on time. The CLIP of these experiments is below ***Confidential*** %.

Secondly, the setting containing to the new layout has a CLIP below ***Confidential***%. The flexibility of the system is limited due to the dedication of the subsystems to workstations. The stochastic behavior of the Poisson process makes it possible that 2 sales orders arrive shortly after each other. When the systems in both sales orders are dedicated to 1 workstation, one of the two must wait. Due to waiting time, the sales order can lower the CLIP. Besides less flexibility as limiting factor, another factor is that some subsystems with relative long expected process times are united. Therefore, the waiting time of a certain sales order before it can be handled is larger. Both factors decrease the CLIP.

The remaining experiments have a CLIP between the ***Confidential***% and ***Confidential***%. Each experiment above ***Confidential***% is sorted on the lowest annual costs. For every strategy, experiment 9 is the best, see Table 50. The number of employees used for this experiment is 4. Three of those are experienced and the last one is a new employee. After performing a paired-t test executed for each strategy, it is observed that the experiment 9 is significantly better than a cheaper experiment. When comparing the experiments with each other, it is observed that the CLIP for the 'Smallest Dimension' exceeds the CLIP of the other two. With a paired-t test is found that there is no significant difference between the strategies.

Strategy	CLIP Value	Annual Costs	Number of employees	Experienced Employees	New Employees	New Layout	Dedicated Experienced Employees
First In, First Out	**Confidential**		4	3	1	False	False
Max Task Time			4	3	1	False	False
Smallest Dimension			4	3	1	False	False

Table 50: Best Found Settings for Each Strategy

After the experimental phase, the sensitivity phase is started. The best suitable settings are evaluated on robustness and sensitivity when changing the storage, yield and demand. Furthermore, it is evaluated what the effect of a learning curve is on the CLIP.

The storage has a lot of influence on the CLIP. When a stack height of 3 is used, the CLIP rises significantly with approximately 2%. Furthermore, an increase of storage area is more effective for a lower CLIP, because the graph shows a decreasing rise.

When increasing the yield in the DES model, the CLIP remains approximately the same. No rise of the CLIP has been found, which is contradicting with the expectation that the CLIP rises due to an increase of yield of the test tool.

The assumptions that the new employees experience a learning curve induces a yield from ***Confidential***% till ***Confidential***% for the CLIP. This increase is not significant.

It is important to test the best-suitable settings on robustness under an increasing demand. Starting from a demand of 21, VDL ETG violates the CLIP constraint, see Table 51 . Since the demand forecast expects a rise till 25, it is investigated how the rise from 21 to 25 can be handled. Therefore, an experiment with 4 experienced employees, 1 new employee, stack height of 3, and enlarged storage area is executed. The CLIP of this experiment is ***Confidential*** % for a demand of 25. This found CLIP differs significantly from the CLIP corresponding with the demand of 24 and 26.

Number of employees	Experienced Employees	New Employees	Storage Area	Stack Height	Annual Employee Costs	Floor Costs	Annual Costs	Comply with CLIP till
4	3	1	3.562 by 12.4215	2	**Confidential**			21
5	4	1	5.562 by 14.4215	3				25

Table 51: Best-Suitable settings to Foresee in Demand Increase

7. Conclusion, Discussion and Recommendations

The goal of this research is to answer the following research question:

*How can the assembly process be (re-) designed in terms of layout design and employee capacity such that a standardized efficient line is obtained, with robustness for the increasing demand and a committed Line Item Performance of at least **Confidential**%?*

To answer this question multiple project phases are executed. First of all, the current situation is explored and necessary data is analyzed. Secondly, a literature review is executed. After, obtaining the required information in the past phases, a layout and a DES model is developed. The DES model is used to compare the performance for different assembly process settings. In this Section, the conclusion, discussion, and recommendation are described based on the research.

7.1. Conclusion

The deliverables of this research are in twofold: the layout and the best suitable assembly settings. For both deliverables, we summarize the findings per project phase separately. To that end, we first elaborate on the current situation and performance. Next, we describe the findings of the literature study. The first subsection below, contains the best suitable assembly settings. Finally, the new layout is given and explained.

Best Suitable Assembly Settings

Project Flexarm concerns the manufacturing of 7 subsystems, the VB, HB, LC, FDR, CORO, CD and CDS. The manufacturing process is initiated, when a sales order is placed by the client. The last step in this process is the assembly of the subsystems. For the VB, HB and LC, VDL ETG performs mechanical assembly. For the FDR and CORO, mechanical and electrical assembly is necessary. Finally, for the CD and CDs it is only required to gather parts from storage. Activities necessary for assembly are executed by experienced and new employees. The experienced employees are allowed to assemble all kinds of subsystems, while the new employees only assemble the VB, HB, CD and CDS. The overall assembly process is measured with the CLIP, which represents the fraction of all POs that are delivered on-time. This KPI is commonly used within VDL ETG.

Project Flexarm contains only limited data concerning internal activities. To overcome this shortcoming, we estimated various parameters from comparable projects. Hence, we derived an efficiency distribution for employees. The average efficiency of the employees is given in Table 52. For an efficiency of 100%, the realized process time equals the expected process time.

Employee Type	Efficiency
New	89.49 %
Experienced	102.20 %

Table 52: Average Efficiency for New and Experienced Employees

Data concerning the frequency of sales orders is available and we found that they are described best with a Poisson arrival process. Furthermore, we found that sales orders are processed using a 'First In, First Out' strategy. Besides this, we also tested the effect of employing 2 other strategies: 'Max Task Time', which is obtained from the literature and 'Smallest Dimension', which is developed within this thesis. However, later it turned out that neither of the strategies has a significant effect on the CLIP. Hence, we recommend continuing using 'First In, First Out'.

Strategy	CLIP Value	Annual Costs	Number of employees	Experienced Employees	New Employees	New Layout	Dedicated Experienced Employees
First In, First Out	**Confidential**		4	3	1	False	False

Table 53: Best Suitable Setting for Chosen Strategy

Experiment 9 contains the best-suitable assembly setting obtained for 'First In, First Out' (cf. Table 53). With these settings, the CLIP constraint of ***Confidential***% is fulfilled up to a demand level of 20 systems per month. However, if VDL would additionally decide to use a staple height of 3, the CLIP constraint would be met up to a demand of 21 systems per month. To be able to fulfill a demand higher than 21 systems per month, different employee and storage settings become necessary.

> *For example: when using 4 experienced employees, 1 new employee, a stack height of 3 and a storage area of 14.4215 by 5.526, a demand of 25 can be fulfilled with a CLIP of **Confidential** %. This setting is more expensive than the first one, but a possible solution when demand increases to 25 systems per month.*

New Layout

The current layout of the assembly process developed by VDL ETG is based on experience. This layout contains 7 workstations, for each subsystem one. The workstation for the VB, HB, LC, CD contains 5 serially arranged site locations. The current layout is not functioning properly, due to the small space available per workstation and the serial arrangement within the workstations.

Literature is used to solve both problems. The problem concerning the available space is solved with the rough-out layout which determines the number of workstations and the relationship diagram which is used for the assigning subsystems to certain workstations. Due to a rough-out layout, it is determined that within the available space, 4 workstations fit. With the relationship diagram, the groups of subsystems are determined and the location of these groups according the fixed storage areas are chosen. Table 54 shows the groups created by the relations. Group 1, 2, and 4 are close to the storage area for finished goods and group 2 and 3 are close to the component storage. The serial arrangement is replaced by a u-shape arrangement, so the movement of the employees is limited. The new layout is shown in Figure 47.

Groups	Subsystems
1	VB, HB
2	LC
3	FDR, CORO
4	CD, CDS

Table 54: Groups of Subsystems based on Relations

The performance of this layout is evaluated in the simulation model by implementing the groups of subsystems. None of the experiments executed on the new layout exceeded the threshold of ***Confidential***%, they are in the range of a CLIP from ***Confidential***% till ***Confidential***%. The CLIP obtained for experiment 9 is ***Confidential*** %

This is lower than we expected but appears to relate to the stochastic nature of the assembly process. To counteract this effect, a layout with higher flexibility is required. Our layout has less flexibility since each subsystem is dedicated to a certain workstation. Furthermore, since the relationship-diagram does not consider the expected process times of the subsystems, it is possible that a critical group arises due to merging.

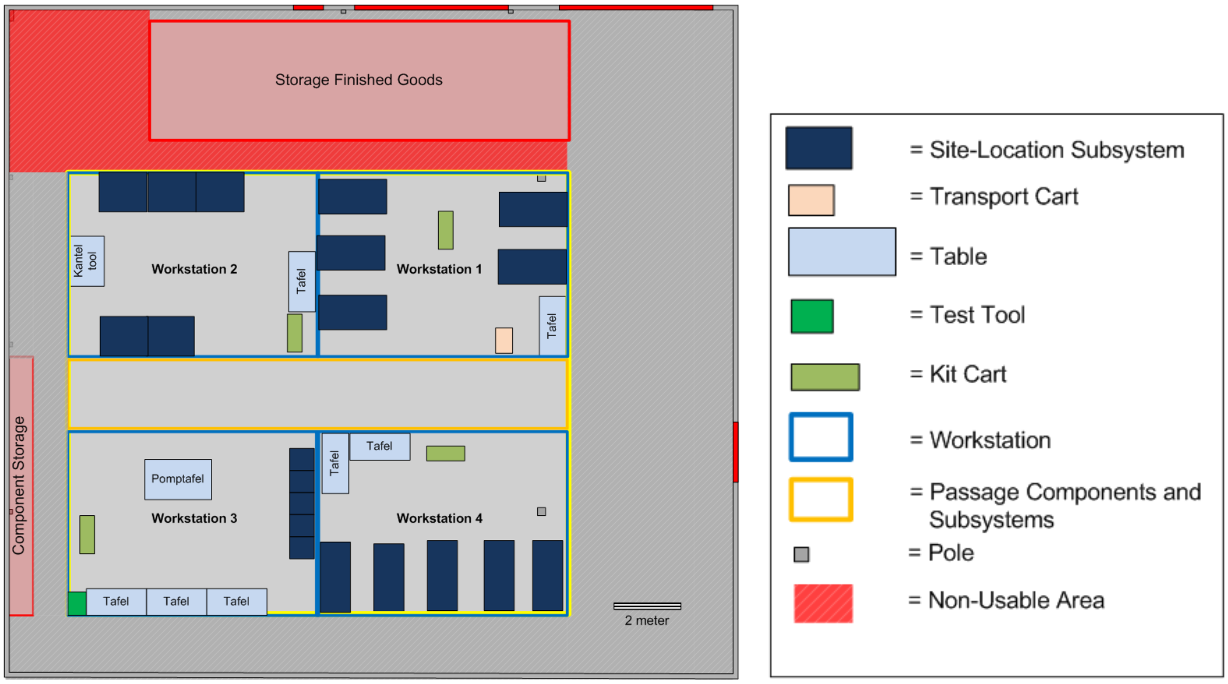

Figure 47: New Layout (Left) and Legend (Right)

7.2. Discussion

This section is used to discuss the conclusions and limitation of the research. In the paragraphs below the following aspects are discussed:

1. The influence of the Poisson arrivals;
2. Efficiency of Project ***Confidential*** and employees;
3. Comparison between current and new lay-out;
4. Increasing the storage area;

The assumption concerning Poisson arrivals is substantiated by literature and the available data. In the simulation model, however, it induces a lot of variation in the arrival rate. Due to a stochastic process, 2 sales orders can arrive almost simultaneously, or with a long time period between them. We expect that this creates the contradiction between the idle percentage of the employees and the CLIP. For the best suitable settings, the idle percentage is 72% and the CLIP is ***Confidential***%. An idle percentage lower than 100% indicates that employees have time left, and therefore a CLIP of 100% is expected. But because of a long inter arrival times, it is possible that an employee needs to wait. This results in an increase of the idle percentage. Furthermore, short inter arrival times increase the likelihood of missing the due date, because a sales order needs to wait before the assembly process can be started. This increases the CLIP. For the subsystems LC and CD this happens most frequently, since their expected process time is the largest compared to others.

Another limitation is the non-availability of data concerning the activities and disruptions of the assembly process. The solution is using data from the related Project ***Confidential***. The internal activities and process disruptions within project Flexarm (cf. Section 2.3) are generic, so must also executed for Project ***Confidential***. However, there is no certainty that these activities correspond directly in time duration. To reduce this uncertainty as much as possible, the efficiency curve is verified and validated with CLIP data from Project ***Confidential***. However, after evaluation of the results we expect that the gamma distribution and the empirical efficiency distributions extracted are not fully applicable. Due to the random numbers, the distributions sometimes generate large realized process times for subsystems with high expected process times, like LC and CD. Therefore, certain sales orders could not be finished before the due date, because the realized process time was already higher than the delivery time. The maximal obtained CLIP from the system is ***Confidential*** %, due to long realized process times.

The research is also limited by the relaxed assumptions concerning the current layout, because of the relaxation the new and current layout cannot be compared on their CLIP performance. The small assembly space and the unnecessary movement is not implemented in the DES model. However, in the new lay-out these disadvantages are solved. So, we cannot determine the benefit of the new layout versus the current layout.

Another assumption is that the storage area can increase. However, the area is located in such way that it cannot be increased. The location of the storage for finished goods is in between the assembly area and an overhead door. VDL ETG however recommended to assume flexibility for the storage area, because in the assembly hall there are possibilities for placement of the Finished goods. If necessary, even other storage facilities within VDL ETG can be used.

7.3.Recommendations and Implementations

Based on the conclusions and discussions in the previous sections, we come to multiple recommendations.

Firstly, we recommend obtaining a more exact forecast from the client and monitoring realized arrivals. This gives more insight in the arrival process and makes it possible to adjust the assembly process on time to meet the requested demand. Furthermore, the assumption concerning the Poisson arrivals can be revalidated.

Secondly, no data is available concerning the internal activities and process disruptions part of the assembly process. We recommend collecting this data, so it can be used to calculate the expected process times. Furthermore, the resulting process disruptions and delay can give more insight in the bottlenecks of the assembly process.

Thirdly, due to time restrictions we did not manage to develop a detailed layout for each workstation. Improvements can be done on the ergonomics of the workstations and the locations of small equipment and tools. This will probably result in a clear and standardized workplace for the employees.

Within the scope of this research, we recommend using current layout as intended, with 3 experienced and 1 new employee. The experienced employees are allowed to handle all kind of subsystems. In order to compare the new layout with the current layout, we propose as further research to find an approach for including the disadvantages of the current layout in the DES model and to redo our simulation for better empirical distributions based on larger data sets. With less variation in the assembly process, the flexibility of the current layout is not necessary which will probably lead to a better performance. Besides revising the empirical distribution, implementing the disadvantages of the current situation leads to CLIP performances that can compared. Therefore, the influences of the disadvantages on the process can be evaluated.

References

Bangsow, S. (2016). Basics. In *Tecnomatix Plant Simulation: Modeling and Programming by Means of Examples* (pp. 1-15). Cham: Springer International Publishing.

Banks, J. (1998). *Handbook of simulation, Principles, Methodology, Advances, Applications and Practice*. New York: John Wiley & Sons.

Batljan. B, Topaloglu, F., Georgadakis, N., & Alan, S. *Facilities Planning and Production Management*. Retrieved from https://www.slideshare.net/serkan1989alan/facility-planning-and-production-management

Bening, V. E., & Korolev, Y. K. (2002). Generalized Poisson Models and their Application in Insurance and Finance. In *Modern Probability and Statistics* Zeist - The Netherlands: VSP BV.

Chand, S., & Zeng, T. (2001). A Comparison of U-Line and Straight-Line Performance Under Stochastic Task Times. *Manufacturing & Service Operation Management, 3*(2), 138-150. doi:https://doi.org/10.1287/msom.3.2.138.9990

Goetschalkckx, M., & Ratliff, H. D. (1991). Optimal Lane Depths for Single and Multiple Products in Block Stacking Storage Systems. *IIE Transactions, 23*(3). doi:0740-81X/91/$3.00x.00

Hunsucker, J. L., & Shah, J. R. (1992). Performance of priority rules in a due date flow shop. *Omega, 20*(1), 73-89. doi:https://doi.org/10.1016/0305-0483(92)90057-E

Kadet, J., & Frank, B. H. (1964). PERT for the engineer. *IEEE Spectrum, 1*(11), 131-137. doi:10.1109/MSPEC.1964.6500471

Kamburowski, J. (1997). New validations of PERT times. *Omega, 25*(3), 323-328. doi:https://doi.org/10.1016/S0305-0483(97)00002-9

Kim, S.-H., Vel, P., Whitt, W., & Cha, W. C. (2015). Poisson and non-Poisson properties in appointment-generated arrival processes: The case of an endocrinology clinic. *Operations Research Letters, 43*(3), 247-253. doi:https://doi.org/10.1016/j.orl.2015.02.008

Kim, S. D., Hammond, R. K., & Bickel, J. E. (2014). Improved Mean and Variance Estimating Formulas for PERT Analyses. *IEEE Transactions on Engineering Management, 61*(2), 362-369. doi:10.1109/TEM.2014.2304977

Law, A. M. (2015). Basic Simulation Modeling. In *Simulation Modeling and Analysis* (5e ed. ed.). New york, NY: McGraw-Hill Education.

Medhi, J. (2003). CHAPTER 1 - Stochastic Processes. In J. Medhi (Ed.), *Stochastic Models in Queueing Theory (Second Edition)* (pp. 1-46). Burlington: Academic Press.

Meijer, D. (2016). Statistiek voor INF-BIT-TBK. In. Enschede: Faculteit Elektrotechniek, Wiskunde en Informatica - University Of Twente.

Simulation: L5 - Data analysis, warmup period & comparing models, (2017).

Muther, R. (1967). *Systematic Layout Planning* (Eighth ed.). Bosten, Massachusetts: Industrial Education Institute.

Najim, K., Ikonen, E., & AÏt-Kadi, D. (2004). Chapter 1 - Stochastic Processes. In K. Najim, E. Ikonen, & A.-K. Daoud (Eds.), *Stochastic Processes* (pp. 1-92). Oxford: Kogan Page Science.

Nakagawa, T. (2011). Poisson porcesses. In *Stochastic Processes.* Londen: Springer.

Otto, A., & Otto, C. (2014). How to design effective priority rules: Example of simple assembly line balancing. *Computers & Industrial Engineering, 69*, 43-52. doi:https://doi.org/10.1016/j.cie.2013.12.013

Roser, C. (2016). Line Layout Strategies – Part 2: I-, U-, S-, and L-Lines. *AllAboutLean.com.* Retrieved from https://www.allaboutlean.com/line-layout-i-s-u-l-lines/

Tompkins, J. A., John, A. W., Yavuz, A. B., & Tanchoco, J. M. A. (2003). *Facilities Planning* (W. Anderson Ed. Third ed.). Danvers: John Wiley & Sonsi.

VDL ETG. (2010). VDL Enabling Technologies group. Retrieved from http://www.vdletg.com/?page/780232/Profiel.aspx

VDL Groep. (2017). Over VDL. Retrieved from https://www.vdlgroep.com/nl/vdl-groep/over-vdl

Zijm, W. H. M. (2012). *Manufacturing and Logistic Systems Analysis, Planning and Control*. Study Reader. University of Twente. Enschede.

Appendix

A. Layout of the Area

Figure 48: Layout of the Area

B. Time Planning Master Thesis

Time planning master thesis.

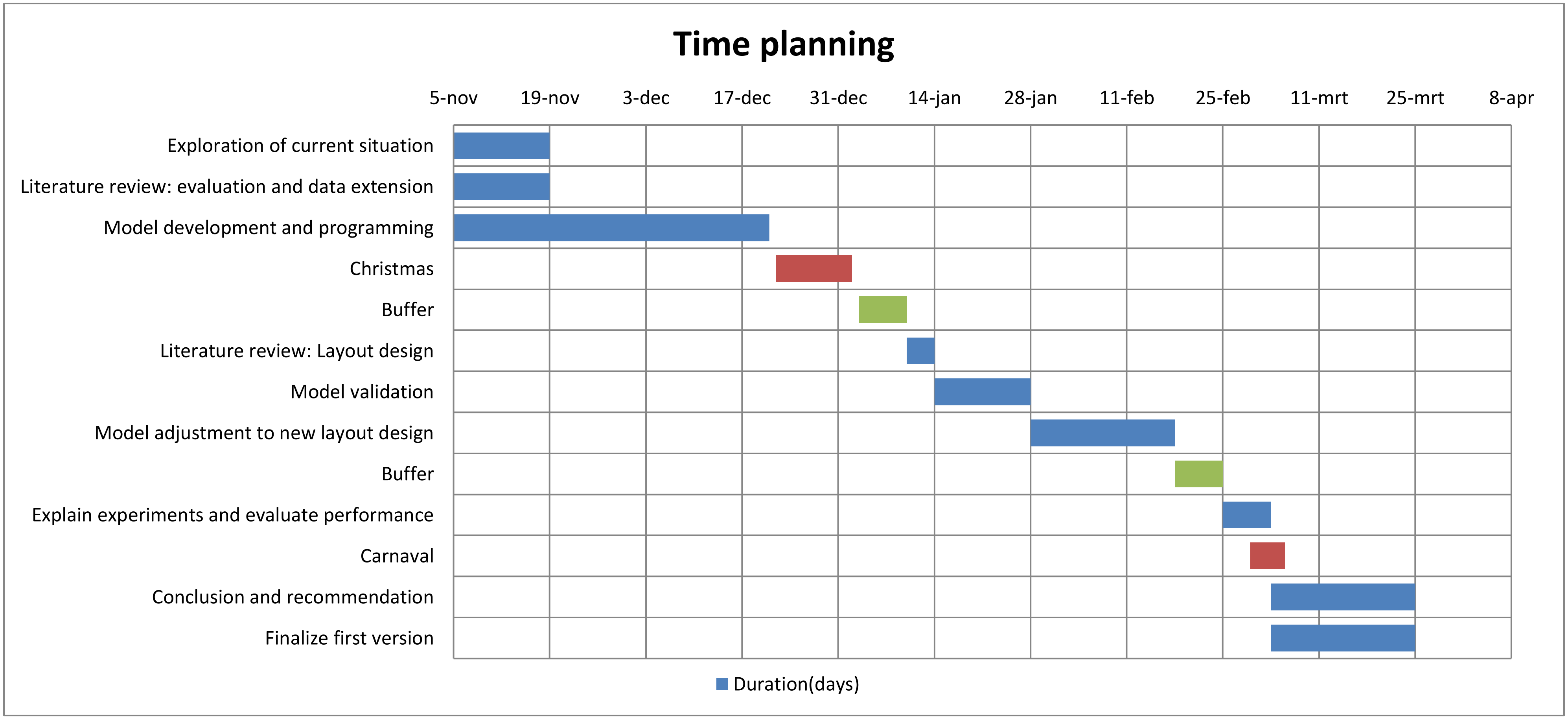

Figure 49: Time Planning of the Research Project

C. Calculation Expected Process Time

A part of the estimation of the assembly time for the ASM Flat Detector Rotate is given in Table 55. The estimation is based on the bill of material and the time per part. The bill of material is a list of all the parts en components in a finished product. It is of hierarchical nature, with a the top level the finished product. In Table 55 the FDR is the finished product. Every part that is put together with the hands of a mechanic is being taken into acount to calculate the assembly time. There are also parts that are not part of the assemlby and therefore nog included. These parts are recognized by the combination of selection number 603 or 601 with the definition “maakdeel”. The former indicates respecitvely department ‘Plaat’ and ‘Parts’, the latter is a part that is produces or assembled internal at the indicated department. This kind of activity not influence the assembly time direclty. All the parts below this level is also nog included, because activities concerning these parst are executed on also department ‘Plaat’ or ‘Parts’. Besides excluding parts belonging to other departments, phantom parts are also excluded. A phantom part consist out of multiple parts, but is not a the top level. The time necessary for that part consists completely out of the time necessary for the multiple parts on the lower level.

Level	Description	Quantitiy	Definitions	Selection	Time per Unit	Total time (min)	Total time incl. ensat (min)
1	FDR SUB ASSY	1	Maakde	605			
.2	FDR L-FRAME ASSY	1	Maakde	601			
..3	FDR LOWER FRAME	1	Inkoop	601			
..3	DOWEL H6 ST 10X24 NLN	2	Inkoop	605			
..3	INSERT ST ZN BLUE PAS	6	Inkoop	669			
..3	LOCTITE 603	0	Inkoop	669			
.2	ASSY FDR SUSPENSION P	1	Maakde	601			
..3	FDR SUSPENSION PLATE	1	Inkoop	601			
..3	ENSAT302 M/F THRD M4X	8	Inkoop	601			
..3	ENSAT302 M/F THRD M5X	4	Inkoop	605			
.2	FDR LARGE PULLEY ASSY	1	Maakde	605		**Confidential**	
..3	FDR LARGE PULLEY	1	Inkoop	605			
..3	DOWEL H6 ST 3X12 NLN-	1	Inkoop	669			
..3	ENDSTOP BUMPER USBKS	1	Inkoop	669			
..3	LOCTITE 243	0	Inkoop	669			
.2	MOTOR BRACKET ASSY	1	Inkoop	605			
.2	FDR TENSIONER ASSY	1	Maakde	603			
..3	FDR TENSIONER	1	Maakde	603			
...4	INKOOPDUMMY TBV PHANT	0	Inkoop	601			
..3	LASMOER ST M6 DIN 929	1	Inkoop	669			
..3	PLAAT ST 3.0 DC01-A-m	0	Inkoop	603			

.2	BELT ROLLER AXIS	2	Inkoop	605	**Confidential**
.2	BELT ROLLER ASSY	2	Maakde	605	
..3	BELT ROLLER	2	Inkoop	605	
..3	GROOVE BALL BEARING 6	2	Inkoop	669	
..3	RETAIN RING INT ST PH	2	Inkoop	669	
.2	FD20 INTERFACE PLATE	2	Inkoop	605	
.2	FDR MOTOR CABLE BRACK	1	Maakde	603	
..3	FDR MOTOR CABLE BRACK	1	Maakde	603	
...4	INKOOPDUMMY TBV PHANT	0	Inkoop	601	
..3	FDR MOTOR CABLE BRACK	1	Maakde	603	
...4	INKOOPDUMMY TBV PHANT	0	Inkoop	601	
..3	LASMOER ST M4 VLG UN	2	Inkoop	669	
..3	DSOS-UNC440-275	6	Inkoop	605	
..3	PLAAT ST 1.5 DC01-A-m	0	Inkoop	603	
..3	PLAAT ST 3.0 DC01-A-m	0	Inkoop	603	
.2	FD20 SIDE PLATE ASSY	2	Maakde	605	
..3	FD20 SIDE PLATE	2	Inkoop	605	
..3	DOWEL H6 ST 3X12 NLN-	6	Inkoop	669	
.2	FD20 SIDE PLATE	2	Inkoop	605	
.2	SCREW HEX BUT.HD FL M	2	Inkoop	669	
.2	BG &FD FILTER CON. BR	1	Maakde	603	
..3	DSOS-UNC440-275	2	Inkoop	605	
..3	STANDOFF TH. H. THR.	4	Inkoop	669	
.....	....	....	....	....	
Total Assembly time					

Table 55: Part of the Estimation of the Assembly Time

Due to human decision making there occur differences in the total assembly time. The black rectangle surrounds a sub assembly which is eventually outsourced. When including it in the calculation a time of ***Confidential*** minutes is obtained, in contrast to a time of ***Confidential*** minutes.

D. Assembly Tools

Figure 50: Tilt Tool for LC (Left) and Press Tool for the LC (Right)

Figure 51: Hand Truck (Left) and Stacker (Right)

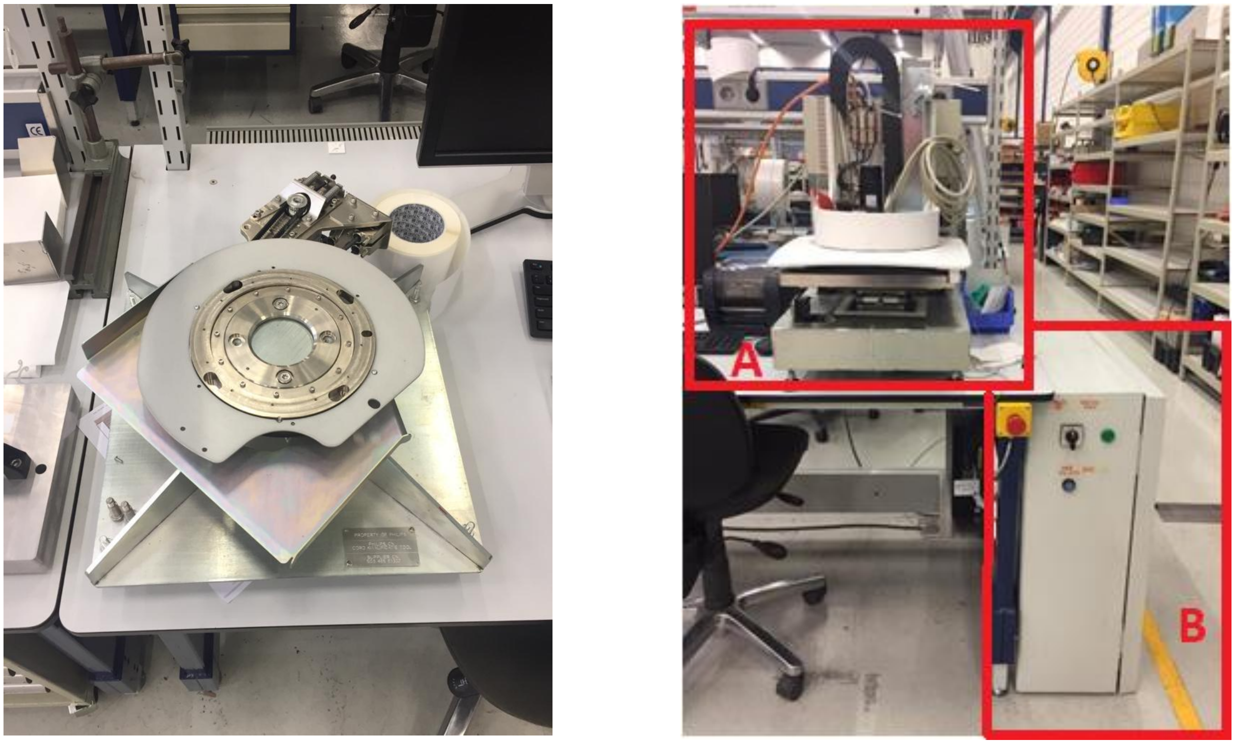

Figure 52: Test Unit CORO (Left), Test Unit FDR (Right, A) amd Test Cabinet (Right, B)

Figure 53: Crane

E. Multiple Carts

Figure 54: Stock Cart (Left) and Transport Cart (Right)

Figure 55: Kit Cart

F. Non-Feasible Layout

The layout shown in Figure 56 is an example for a non-feasible solution obtained from the layout development in Section 5.1. However, when using 5 site locations, the space within each workstation is too small for easy movement of the subsystems to the storage. Subsystems within workstations 1, 2, and 3 are moved through the passage for components and subsystems when placed in the storage area instead of directly moved to the storage area. Furthermore, workstation 1 and 3 contain 4 site locations instead of the requested 5.

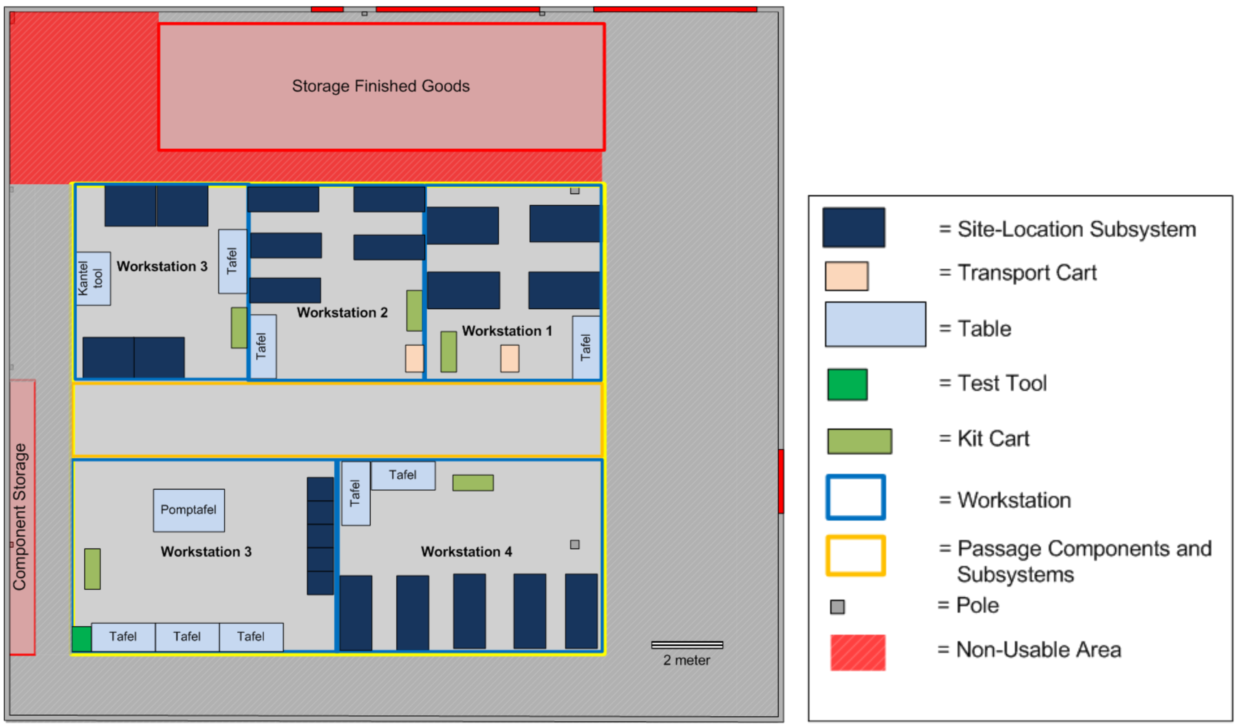

Figure 56: Non-feasible Layout (Left) and Legend (Right)

G. Results 'First In, First Out'

Exp Nr	Total Employees	Experienced Employees	New Employees	Experienced Employee Dedication	New Layout
37	6	5	1	False	False
57	7	6	1	False	False
81	8	7	1	False	False
21	5	4	1	False	False
41	6	4	2	False	False
61	7	5	2	False	False
85	8	6	2	False	False
45	6	3	3	False	False
93	8	4	4	False	False
69	7	3	4	False	False
97	8	3	5	False	False
71	7	3	4	True	False
95	8	4	4	True	False
99	8	3	5	True	False
47	6	3	3	True	False
67	7	4	3	True	False
91	8	5	3	True	False
65	7	4	3	False	False
89	8	5	3	False	False
25	5	3	2	False	False
27	5	3	2	True	False
43	6	4	2	True	False
63	7	5	2	True	False
87	8	6	2	True	False
9	4	3	1	False	False
51	6	2	4	True	False
73	7	2	5	False	False
75	7	2	5	True	False
101	8	2	6	False	False
103	8	2	6	True	False
49	6	2	4	False	False
31	5	2	3	True	False
29	5	2	3	False	False
15	4	2	2	True	False
13	4	2	2	False	False
24	5	4	1	False	True
40	6	5	1	False	True
60	7	6	1	False	True
84	8	7	1	False	True
12	4	3	1	False	True
28	5	3	2	False	True
44	6	4	2	False	True
64	7	5	2	False	True
88	8	6	2	False	True
14	4	2	2	True	True
26	5	3	2	True	True
30	5	2	3	True	True
32	5	2	3	False	True
42	6	4	2	True	True
46	6	3	3	True	True
48	6	3	3	False	True
50	6	2	4	True	True
52	6	2	4	False	True

Confidential

62	7	5	2	True	True
66	7	4	3	True	True
68	7	4	3	False	True
70	7	3	4	True	True
72	7	3	4	False	True
74	7	2	5	True	True
76	7	2	5	False	True
86	8	6	2	True	True
90	8	5	3	True	True
92	8	5	3	False	True
94	8	4	4	True	True
96	8	4	4	False	True
98	8	3	5	True	True
100	8	3	5	False	True
102	8	2	6	True	True
104	8	2	6	False	True
16	4	2	2	False	True
1	3	2	1	False	False
4	3	2	1	False	True
53	6	1	5	False	False
55	6	1	5	True	False
77	7	1	6	False	False
79	7	1	6	True	False
105	8	1	7	False	False
107	8	1	7	True	False
19	4	1	3	True	False
17	4	1	3	False	False
33	5	1	4	False	False
35	5	1	4	True	False
5	3	1	2	False	False
7	3	1	2	True	False
11	4	3	1	True	False
23	5	4	1	True	False
39	6	5	1	True	False
59	7	6	1	True	False
83	8	7	1	True	False
3	3	2	1	True	False
2	3	2	1	True	True
10	4	3	1	True	True
22	5	4	1	True	True
38	6	5	1	True	True
58	7	6	1	True	True
82	8	7	1	True	True
6	3	1	2	True	True
18	4	1	3	True	True
20	4	1	3	False	True
34	5	1	4	True	True
36	5	1	4	False	True
54	6	1	5	True	True
56	6	1	5	False	True
78	7	1	6	True	True
80	7	1	6	False	True
106	8	1	7	True	True
108	8	1	7	False	True
8	3	1	2	False	True

Confidential

Table 56: Experimetal Results for Strategy 'First In, First Out'

H. Results 'Max Task Time'

Exp Nr	Total Employees	Experienced Employees	New Employees	Experienced Employee Dedication	New Layout
37	6	5	1	False	False
57	7	6	1	False	False
81	8	7	1	False	False
21	5	4	1	False	False
41	6	4	2	False	False
61	7	5	2	False	False
85	8	6	2	False	False
45	6	3	3	False	False
69	7	3	4	False	False
93	8	4	4	False	False
97	8	3	5	False	False
71	7	3	4	True	False
95	8	4	4	True	False
99	8	3	5	True	False
47	6	3	3	True	False
67	7	4	3	True	False
91	8	5	3	True	False
65	7	4	3	False	False
89	8	5	3	False	False
25	5	3	2	False	False
27	5	3	2	True	False
43	6	4	2	True	False
63	7	5	2	True	False
87	8	6	2	True	False
9	4	3	1	False	False
31	5	2	3	True	False
73	7	2	5	False	False
75	7	2	5	True	False
101	8	2	6	False	False
103	8	2	6	True	False
51	6	2	4	True	False
49	6	2	4	False	False
29	5	2	3	False	False
15	4	2	2	True	False
13	4	2	2	False	False
24	5	4	1	False	True
40	6	5	1	False	True
60	7	6	1	False	True
84	8	7	1	False	True
12	4	3	1	False	True
44	6	4	2	False	True
64	7	5	2	False	True
88	8	6	2	False	True
28	5	3	2	False	True
30	5	2	3	True	True
32	5	2	3	False	True
50	6	2	4	True	True
52	6	2	4	False	True
74	7	2	5	True	True
76	7	2	5	False	True
102	8	2	6	True	True
104	8	2	6	False	True
14	4	2	2	True	True
46	6	3	3	True	True
48	6	3	3	False	True

Confidential

66	7	4	3	True	True
68	7	4	3	False	True
70	7	3	4	True	True
72	7	3	4	False	True
90	8	5	3	True	True
92	8	5	3	False	True
94	8	4	4	True	True
96	8	4	4	False	True
98	8	3	5	True	True
100	8	3	5	False	True
16	4	2	2	False	True
26	5	3	2	True	True
42	6	4	2	True	True
62	7	5	2	True	True
86	8	6	2	True	True
1	3	2	1	False	False
4	3	2	1	False	True
11	4	3	1	True	False
23	5	4	1	True	False
39	6	5	1	True	False
59	7	6	1	True	False
83	8	7	1	True	False
3	3	2	1	True	False
17	4	1	3	False	False
33	5	1	4	False	False
35	5	1	4	True	False
53	6	1	5	False	False
55	6	1	5	True	False
77	7	1	6	False	False
79	7	1	6	True	False
105	8	1	7	False	False
107	8	1	7	True	False
19	4	1	3	True	False
7	3	1	2	True	False
5	3	1	2	False	False
2	3	2	1	True	True
10	4	3	1	True	True
22	5	4	1	True	True
38	6	5	1	True	True
58	7	6	1	True	True
82	8	7	1	True	True
18	4	1	3	True	True
20	4	1	3	False	True
34	5	1	4	True	True
36	5	1	4	False	True
54	6	1	5	True	True
56	6	1	5	False	True
78	7	1	6	True	True
80	7	1	6	False	True
106	8	1	7	True	True
108	8	1	7	False	True
8	3	1	2	False	True
6	3	1	2	True	True

Confidential

Table 57: Experimental Results Strategy 'Max Task Time'

I. Results 'Smallest Dimension'

Exp Nr	Total Employees	Experienced Employees	New Employees	Experienced Employee Dedication	New Layout
37	6	5	1	False	False
57	7	6	1	False	False
81	8	7	1	False	False
21	5	4	1	False	False
41	6	4	2	False	False
45	6	3	3	False	False
61	7	5	2	False	False
85	8	6	2	False	False
47	6	3	3	True	False
67	7	4	3	True	False
91	8	5	3	True	False
93	8	4	4	False	False
69	7	3	4	False	False
97	8	3	5	False	False
71	7	3	4	True	False
95	8	4	4	True	False
99	8	3	5	True	False
65	7	4	3	False	False
89	8	5	3	False	False
25	5	3	2	False	False
27	5	3	2	True	False
43	6	4	2	True	False
63	7	5	2	True	False
87	8	6	2	True	False
9	4	3	1	False	False
51	6	2	4	True	False
73	7	2	5	False	False
75	7	2	5	True	False
101	8	2	6	False	False
103	8	2	6	True	False
31	5	2	3	True	False
49	6	2	4	False	False
29	5	2	3	False	False
15	4	2	2	True	False
13	4	2	2	False	False
24	5	4	1	False	True
40	6	5	1	False	True
60	7	6	1	False	True
84	8	7	1	False	True
12	4	3	1	False	True
28	5	3	2	False	True
44	6	4	2	False	True
64	7	5	2	False	True
88	8	6	2	False	True
14	4	2	2	True	True
26	5	3	2	True	True
30	5	2	3	True	True
32	5	2	3	False	True
42	6	4	2	True	True
46	6	3	3	True	True
48	6	3	3	False	True
50	6	2	4	True	True
52	6	2	4	False	True
62	7	5	2	True	True

Confidential

66	7	4	3	True	True	Confidential
68	7	4	3	False	True	
70	7	3	4	True	True	
72	7	3	4	False	True	
74	7	2	5	True	True	
76	7	2	5	False	True	
86	8	6	2	True	True	
90	8	5	3	True	True	
92	8	5	3	False	True	
94	8	4	4	True	True	
96	8	4	4	False	True	
98	8	3	5	True	True	
100	8	3	5	False	True	
102	8	2	6	True	True	
104	8	2	6	False	True	
16	4	2	2	False	True	
1	3	2	1	False	False	
4	3	2	1	False	True	
19	4	1	3	True	False	
33	5	1	4	False	False	
53	6	1	5	False	False	
55	6	1	5	True	False	
77	7	1	6	False	False	
79	7	1	6	True	False	
105	8	1	7	False	False	
107	8	1	7	True	False	
35	5	1	4	True	False	
17	4	1	3	False	False	
7	3	1	2	True	False	
5	3	1	2	False	False	
8	3	1	2	False	True	
6	3	1	2	True	True	
18	4	1	3	True	True	
20	4	1	3	False	True	
34	5	1	4	True	True	
36	5	1	4	False	True	
54	6	1	5	True	True	
56	6	1	5	False	True	
78	7	1	6	True	True	
80	7	1	6	False	True	
106	8	1	7	True	True	
108	8	1	7	False	True	
11	4	3	1	True	False	
23	5	4	1	True	False	
39	6	5	1	True	False	
59	7	6	1	True	False	
83	8	7	1	True	False	
3	3	2	1	True	False	
2	3	2	1	True	True	
10	4	3	1	True	True	
22	5	4	1	True	True	
38	6	5	1	True	True	
58	7	6	1	True	True	
82	8	7	1	True	True	

Table 58: Experimental Results Strategy 'Smallest Dimension'