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## Eindhoven University of Technology

## MASTER

# The design of an automated hybrid manufacturing system using a discrete-event simulation for an additive manufacturing facility 

Knipping, Julie

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# TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY 

## Eindhoven University of Technology

Department of Industrial Engineering \& Innovation Sciences

# (s)ignify 

## Master Thesis

March 23, 2023

The design of an automated hybrid manufacturing system using a discrete-event simulation for an additive manufacturing facility

## J. (Julie) Knipping

BSc. Industrial Engineering
Student Number: 1015553

## Supervisors:

dr. ir. R.J.I. (Rob) Basten

Eindhoven University of Technology
dr. Q.V. (Vinh) Dang
Eindhoven University of Technology
prof. dr. ir. I.J.B.F. (Ivo) Adan
Eindhoven University of Technology
ir. K. (Koen) van Os
Signify Research
ir. C. (Chris) Damkat
Signify Research

## Abstract

With big global changes, like the introduction of Industry 4.0, increasing demands and fast market needs, manufacturing systems need to continuously evolve. These reasons caused Signify to start thinking about $24 / 7$ automation in manufacturing. To become more automated, Signify introduced a new automated hybrid manufacturing system in the winter of 2022, which includes a machine known as the box handler. The box handler is an automated manufacturing and storing machine. Due to this change, a few challenges have arisen: there is no clear view of the new system design, it is still in the prototype phase, and there is no clarity about the number of required storage spaces. This study aims to determine the design of an additive manufacturing (AM) facility when using Signify's new automated hybrid manufacturing system. We define hybrid manufacturing as the combination of AM and conventional manufacturing (CM). To evaluate the system's performance based on cost, service level, box handler capacity, and cycle time, we create a model that uses discrete-event-simulation (DES). The model includes three production units: box handler, quality control, and assembly \& packaging. This study shows that the low yield of some items leads to a high percentage of failed parts, requiring reprinting which results in high waiting times at the AM machines. Because of this, the other parts of the order need to wait in the box handler until everything is printed and checked. This causes the box handler capacity to become full and block the system. Furthermore, we compare the current and automated systems, and the results suggest that the automated system is cheaper, since fewer workers are needed. We recommend that Signify should consider automating its production process, increasing its box handler capacity, and focusing on increasing the yield of its items to improve the overall efficiency of the new manufacturing system.

## Executive Summary

## Introduction

Changes like Industry 4.0 and increasing market demands have led to the rise of intelligent manufacturing. As a result, organizations are turning to $24 / 7$ automated manufacturing systems, with the implementation of 3D printers becoming increasingly popular. 3D printing, also known as Additive Manufacturing (AM), has many advantages for manufacturing, such as fast production, mass customization, and enhanced sustainability. Signify, the world leader in lighting, has announced its focus on AM with its venture, Signify 3D Printing, which creates 3D-printed luminaires. Signify 3D Printing (further referred to as Signify) has introduced a new automated hybrid manufacturing system. Challenges have arisen and Signify is interested in designing a printing facility that takes into account demand, service, and cost levels. Hence, Signify's interests lead to the following problem statement: Signify intends to expand its operations by incorporating automation into its business strategy. As a result, the company is transforming its manufacturing process. This transformation raises questions regarding the required planning capacity of the AM facility and the level of efficiency that can be achieved compared to the current manufacturing approach.

## Research Design

Based on the interests of Signify, the main question of this study is: How to design and analyse an automated hybrid additive manufacturing facility? To answer this question, several steps need to be made: identifying the KPIs to evaluate the system, modelling the system, performing numerical experiments to optimize the system's design, and comparing the current manufacturing process to the manufacturing process with the automated system. The methods that are used in this study consist of a literature review, interviewing experts, and using simulation modelling to calculate KPIs.

## The Automated Hybrid Manufacturing System

An automated hybrid manufacturing system is defined as: "a manufacturing system that consists of additive manufacturing in combination with conventional processes, where the transfer of work parts between the machines are done without human operations" (Crooymans, 2022; Morris \& Morris, 1988; Savolainen \& Collan, 2020). Signify's automated hybrid manufacturing system consists of three production units (PUs), storage places, and production flows (Figure 1). The completed product, a customized luminaire, consists of several parts that are created from raw materials. The printed parts are stored in the box handler's storage until needed for the PU quality control where parts are checked on their quality. After checking, the parts arrive at the PU assembly \& packaging, where the completed product is assembled and packaged. Signify manufactures with a Make-To-Order system, which means that the products are made when an order arrives.

The PUs can be divided into several steps. The box handler PU can be divided into three steps: preparing AM machine, AM, and retrieving the printed parts. The print jobs are assigned to an AM machine based on the availability and the filament reel colour/material of that machine. After printing, the box handler robot removes the box containing printed


Figure 1: Process diagram of the automated hybrid manufacturing system of Signify
parts and delivers it to the quality control PU. A worker checks all the parts required for an order for defects, if the part is defective a rework is requested at the AM machines. Each box handler has two quality control stations. The assembly \& packaging PU is divided into the assembly, testing of the product, and packaging. If a product fails at the testing, the product needs to be checked again. If the product does not pass the test the second time it goes back to the assembly and a check is performed to see where the defect lies.

We decided that due to the complex system, a simulation model is the best approach for this study, specifically Discrete-Event-Simulation (DES). The Tecnomatix Plant Simulation software is used to create the simulation model. Figure 2 shows the simulated automated hybrid manufacturing system. Next, we identify the appropriate Key Performance Indicators (KPIs) for evaluating the automated hybrid manufacturing system of Signify. The KPIs are identified through examining relevant literature, consulting experts from Signify, analyzing the initial design of the print facility and comparing with the research of Crooymans (2022). The four KPIs of this study are: Cycle Time ( $C T$ ), Service Level ( $S L$ ), Total Manufacturing Costs (TC), and Box Handler storage Capacity.


Figure 2: Signify's automated hybrid manufacturing system model in Plant Simulation

## Results

To get results, we perform a numerical experiment. In the base experiment, we simulate a realistic input scenario approved by Signify employees. The base experiment showed the average $C T$ of the model is 16 days and an $S L$ of 0.73 . The average cost per manufactured luminaire is around $\in 43$. The maximum occupancy and thus the required capacity of the box handler is 668 places. Additionally, per product 1.73 kg of filament reel is needed. This is a large amount due to throwing away items after quality control, throwing away items due to printer failures, and throwing away leftover filament due to premature changeovers. Finally, the utilization rate of the assembly line is $32 \%$, which is quite low. This probably happens due to the box handler controlling the arrival of the parts. Hence, the
utilization rate of the AM machines in the box handler is high $(86 \%)$. It is found that the box handler, particularly the AM machines, is the bottleneck due to high utilization rates and long waiting times. The AM machines are slow compared to the rest of the system due to the rework required when a printed part does not pass quality control. From the results, we can conclude that the original box handler capacity needs to be increased to fulfil the demand, and the high percentage of failed parts in quality control and long waiting time at the AM machines are attributed to the low yield of some items.

Next, we perform experiments to understand the behaviour of the model. The experiments aim to investigate the impact of changes in different aspects of the model on the four KPIs. The first experiment is decreasing the lead time. We perform this experiment to see how increasing the item yield will impact the system. Increasing yield improves costs, service level, cycle time, and capacity. Higher yield means fewer failed parts, less waste, and more orders fulfilled with the same cost. This leads to better system performance and customer satisfaction. The next experiment is increasing the number of filament colours/materials. This experiment is performed because in the real-world Signify uses more than 40 different types of colours/materials. Introducing more filament colours and materials has a small impact on KPIs. Differences between values for each number of colours/materials used are small and do not significantly affect SL, box handler capacity or CT. However, adding more colours/materials increases total costs per product due to the need for more filament reels. Finally, we tested the amount of AM machines. This results in a trade-off between costs and CT that affects the service level. Increasing the number of AM machines improves service level and filament reel changeovers while decreasing the number of machines reduces service level due to longer waiting times and higher CT.

## Discussion, Recommendations \& Conclusion

In conclusion, this study has presented a comprehensive examination of the implementation of automated hybrid manufacturing systems in Signify's AM facilities. The research questions focused on identifying the characteristics of the manufacturing system and the key performance indicators for the model, modelling the system using a DES model, and analysing the AM facility's capacity using numerical experiments. The study also compared Signify's current manufacturing system to its new automated hybrid system.

The study has the potential to make significant contributions to both Signify and the existing literature on the topic. For Signify, the study and simulation model can provide valuable insights into the benefits of using automated hybrid manufacturing systems compared to their current manufacturing system, including increased efficiency of their lead time, reduced costs, and improved cycle time. The report can also serve as a guide for Signify looking to adopt modelling with Plant Simulation in other manufacturing systems. Plant simulation is a useful tool for manufacturers to optimize production processes and reduce costs. By making the model more realistic, the model could eventually become a digital twin of the real-world system.

The report provides valuable insights into the benefits and challenges of using automated hybrid manufacturing systems, as well as guiding companies looking to adopt these systems and identifying areas for future research. Designing an AM facility that incorporates an automated hybrid manufacturing system requires careful consideration of various factors, including box handler capacity, the number of AM machines, demand, yield optimization, and cost optimization. By addressing these factors, it is possible to design a facility that is efficient, productive, and cost-effective.

## Preface

It is with great pleasure that I present my master's thesis. The completion of this master's thesis marks the culmination of my academic journey in Operations Management \& Logistics at the Eindhoven University of Technology. This project represents the peak of two years of hard work and intensive research. I hope that this work will contribute to a deeper understanding of automated additive manufacturing systems and that it will serve as a valuable resource for future scholars in the field. This thesis would not have been possible without the support and guidance of many individuals, to who I would like to express my heartfelt gratitude.
First and foremost, I would like to thank my supervisor, Rob Basten, for his invaluable guidance and expertise throughout the two years of my master's. His constant support and encouragement helped me navigate through the challenges of my master, and his insightful feedback and advice were instrumental in shaping my research. I would also like to express my sincere appreciation to my second supervisor, Vinh Dang, for his time and assistance when I was facing difficult situations during my thesis. His willingness to help and his expertise in the field were crucial in enabling me to overcome the hurdles I encountered.

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Julie Knipping
Eindhoven, March 23, 2023

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## List of Abbreviations

## Table 1: List of Abbreviations

|  | Description |
| :--- | :--- |
| AGV | Automated Guided Vehicle |
| AM | Additive manufacturing |
| CAD | Computer-aided design |
| CI | Confidence Interval |
| CM | Conventional manufacturing |
| CT | Cycle time |
| DES | Discrete-event simulation |
| FCFS | First-Come-First-Serve |
| FGI | Finished goods inventory |
| GHG | Greenhouse gases |
| JIT | Just-in-time |
| KPI | Key performance indicators |
| LED | Light-Emitting-Diode |
| LT | Lead time |
| MTO | Make-To-Order |
| MTS | Make-To-Stock |
| PU | Production unit |
| R\&D | Research \& Development |
| RMI | Raw material inventory |
| SL | Service Level |
| TC | Total Costs |
| TH | Throughput |
| WIP | Work in process |

## List of Variables

Table 2: List of Variables

|  | Description |
| :---: | :---: |
| $\alpha_{o}$ | Indicates if order $o$ is on time |
| $\beta_{i_{b}}$ | Maximum number of items $i \in \mathcal{I}^{p}$ in box $b \in$ $\mathcal{B}$ |
| $\delta$ | Capacity of the Box Handler |
| $\gamma$ | Quality control Yield* |
| $\gamma_{i}$ | Yield of a printed item $i \in \mathcal{I}^{p}$ |
| $\gamma_{i}$ | Yield of a non-printed item $i \in \mathcal{I}^{n}$ |
| $\lambda$ | Total Demand Rate* |
| $\lambda_{o}$ | Arrival rate of an order $o \in \mathcal{O}$ |
| $\omega^{\text {r }}$ | Weight of a new filament reel |
| $\omega_{i}$ | Weight of a printed item $i \in \mathcal{I}^{p}$ |
| $\rho^{\text {b }}$ | Processing time of the Box Handler Robot |
| $\rho^{\mathrm{p}}$ | Processing time of the packaging |
| $\rho^{\mathrm{np}}$ | Processing time of a non-printed item |
| $\rho_{i}$ | Processing time of a printed item $i \in \mathcal{I}^{p}$ |
| $\theta_{w}$ | Time worked by a worker $w \in \mathcal{W}$ |
| $\xi_{p}$ | Inspection time of a product $p \in \mathcal{P}$ |
| $\xi_{i}$ | Inspection time of an item $i \in \mathcal{I}^{p}$ |
| $A_{m}$ | Availability of AM machine $m \in \mathcal{M}$ |
| $b$ | Box, with $b \in \mathcal{B}$ |
| $\mathcal{B}$ | Set of boxes |
| $c^{\text {a }}$ | Assembly line costs |
| $c^{\text {b }}$ | Box handler costs |
| $c^{\text {f }}$ | Facility costs |
| $c^{\text {r }}$ | Filament reel rate |
| $c^{\text {W }}$ | Worker rate |
| C | Number of colours/materials |
| C | Maximum Capacity Filament reel* |
| $C^{\text {operational }}$ | Operational costs |
| $C^{\text {plant }}$ | Plant costs |
| $C F$ | Costs per Production Facility* |
| $C T_{o}$ | Cycle Time of order o |
| $C T$ | Total Costs for Total Demand Area* |
| $F$ | Number of Production Facilities* |
| i | Item, with $i \in \mathcal{I}^{n} \vee \mathcal{I}^{p}$ |
| $\mathcal{I}^{n}$ | Set of non-printed items |
| $\mathcal{I}^{p}$ | Set of printed items |
| $K$ | Number of Possible Colors* |
| $L T$ | Lead Time |

Table 2 - Continued from previous page

|  | Description |
| :--- | :--- |
| $m$ | Machine, with $m \in \mathcal{M}$ |
| $M$ | Maximum number of boxes that fit into the |
| $\mathcal{M}$ | box handler |
| MTTR | Met of machines |
| $o$ | Mean-time-to-repair of an AM machine |
| $\mathcal{O}$ | Set of orders |
| $p$ | Product, with $p \in \mathcal{P}$ |
| $\mathcal{P}$ | Set of products |
| $P^{3 \mathrm{DP}}$ | Average Processing Time on AM machine* |
| $P^{\text {AL }}$ | Average Processing Time on Assembly Line* |
| $Q_{o}$ | Number of products in an order $o \in \mathcal{O}$ |
| $R$ | Total amount of material used |
| $s$ | Changing time of a filament reel* |
| $S$ | Threshold for Latest Time to Start Assign- |
|  | ment of Filament reel of AM machine* |
| $S L$ | Service Level |
| $\mathcal{T}$ | Modelling time |
| $t_{o}^{\text {end time }}$ | End time of an order $(o)$ |
| $t_{o}^{\text {start time }}$ | Start time of an order $(o)$ |
| $T^{\text {change-over }}$ | Change-over Time for AM machine* |
| $T^{\text {check }}$ | Intermediate Time Step to Check Status of |
| $\mathrm{U}^{\text {AM }}$ | Filament reel* |
| $\mathrm{U}^{\text {AL }}$ | Utilization of the AM machine* |
| $w$ | Utilization of the Assembly Line* |
| $\mathcal{W}$ | Worker, with $w \in \mathcal{W}$ |
| Average $\mathrm{W}^{\text {AM }}$ | Set of workers |
| Average $\mathrm{W}^{\text {AL }}$ | Waiting time of the AM machine* |

[^0]
## Chapter 1

## Introduction

With big global changes, like the introduction of Industry 4.0, increasing demands and fast market needs, manufacturing systems need to continuously evolve. Over many decades, manufacturing systems have been evolving with advances in production, technology and new materials (ElMaraghy et al., 2021). Industries all around are adapting to this trend which has led to the rise of intelligent manufacturing. Intelligent manufacturing aims to develop more efficiency, lower costs and more flexible workflows (Ashima et al., 2021; Lu et al., 2020). Nowadays, manufacturing systems have to fulfil requirements to keep up with intelligent manufacturing. At the same time, sensors, robots and 3D printers are becoming more affordable and fewer workers are needed to do the manual work. All these benefits cause organizations to think about $24 / 7$ automated manufacturing systems (Clauer et al., 2021; Guo et al., 2022; Jerman et al., 2020).

A new way to become more automated is by implementing 3D printers into the manufacturing system. In the 1980's the first form of 3D printing was developed: rapid prototyping (Wong \& Hernandez, 2012). As its name suggests, this method was mostly used for creating models and prototypes. Nowadays, additive manufacturing (AM) has many advantages for manufacturing, like the possibility to create complex shapes, fast production, manufacturing in mass customization, and enhancing sustainability (Campbell et al., 2011; Gibson et al., 2021; Kruth et al., 1998). These advantages make AM now a popular option for organizations that want to evolve their manufacturing systems, by creating completed products that are brought to the market with AM. Since AM is still very new, organizations prefer to use AM in combination with conventional manufacturing (CM), which is called a hybrid manufacturing process (Crooymans, 2022).

Currently, Signify is the world leader in lighting. In 2017, it announced to be focusing on AM with the new venture: Signify 3D Printing (Signify, 2022). Signify 3D Printing manufactures 3D-printed luminaires that, in comparison to other luminaires, use fewer materials (Signify, 2022). It also offers a big variety of options by letting its customer personalize the design of the luminaire to their liking. Like other organizations, Signify wants to focus on the emerging trend of changing its manufacturing system from current to automated procedures. The current manufacturing costs Signify a lot of time, while Signify is also facing the problem of having a shortage of workers. Both these reasons caused Signify to start thinking about $24 / 7$ automatized systems. To become more automatized, Signify introduced a new automated hybrid manufacturing system in winter 2022.

Due to the change that Signify wants to make in its manufacturing process, a few challenges have arisen: there is no clear view of the new system design, it is still in the prototype phase, and there is no clarity about storage spaces. Thus, Signify is interested in what output could result from this system and the difference between the current and new manufacturing systems. Hence, Signify wants to know how to design an AM facility which
contains an automated hybrid manufacturing system, taking into account demand, service, and cost levels.

In conclusion, with this research we try to answer the following main question:

> How to design and analyse an automated hybrid additive manufacturing facility?

In the remainder of this chapter, the company Signify in Section 1.1 and its venture Signify 3D Printing (Section 1.2) are discussed. Additionally, in Section 1.3 and Section 1.4, a background on AM and Signify's manufacturing system is provided. Finally, the report structure is outlined in Section 1.5.

### 1.1 Signify

Signify is a Dutch multinational lighting company that manufactures electric lights and light fixtures (Signify, 2023). The company was founded by Philips in 1891, known as Philips Lighting. Eventually, in 2016, Philips Lighting spun off from Philips, and in 2018 was named Signify (Signify, 2021).
Signify is currently leading the world in lighting, providing customers with high-quality energy efficient lighting products, systems and services. In 2022, Signify made sales of 7.5 billion, employed 35,000 people, and had a presence in 70 countries (Signify, 2023). As stated by Signify (2023, para.3), its purpose is to: "unlock the extraordinary potential of light for brighter lives and a better world". This is mainly achieved by innovation in the company. In 2017, the 3D printer imposed a change in Signify's company, a new venture: Signify 3D printing. The venture has now grown into a team with more than 90 workers (Signify, 2022).

### 1.2 Signify 3D Printing

Signify 3D Printing manufactures 3D-printed luminaires. 3D-printed luminaires use fewer screws, fewer items, and no paint (Signify, 2022). Additionally, the 3D printed luminaires are made from $100 \%$ recyclable polycarbonate, are designed to be circular, and reduce the CO2 footprint up to $75 \%$ (Signify, 2022). Therefore as many items as possible are 3D printed. Signify 3D Printing offers a big variety of options, the customer can create and personalize the design of the luminaire to their liking.

The luminaires are only printed when the customer needs them, this helps with avoiding large stock storage. 3D printing also gives the ability to manufacture small numbers of luminaires or even a single luminaire, which is very flexible for customers. At the moment, Signify 3D Printing has a variety of customers: individual consumers, other businesses, and governments. The ability to print in large or small quantities makes the variety of customers possible. Together with a diverse range of items, sustainable benefits and flexible service, 3D printing of luminaires is becoming a big contender (Signify, 2022). For ease of reading, we will refer to Signify 3D printing as Signify hereafter.

### 1.3 Additive Manufacturing

The main manufacturing technique that is considered in this research is 3D Printing, also referred to as AM. AM can be defined as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive/reductive manufacturing methodologies" (Frazier, 2014, p.1924). As stated by Jimo et al. (2019, p.5), AM was first used around the 1980s for concept modelling and prototyping. Nowadays, it offers much more possibilities than only rapid prototyping (Campbell et al., 2011). AM shows
that it has emerged as an innovation-driven technology that can completely change the way of manufacturing. According to Campbell et al. (2011), Rajaguru et al. (2020) and Zhang \& Liou (2021), AM requires a few steps before the completed product is manufactured: creating a computer-aided design (CAD), preparing CAD-file for AM equipment, machine setup, manufacturing, removal from AM equipment, post-processing and application. An example of this technique is shown in Figure 1.1.


Figure 1.1: Example of additive manufacturing (Zhang \& Liou, 2021)

The AM process starts with creating a 3D CAD Model by designing or scanning an item. Next, slicing software is needed to prepare the model for the AM machine. The slicing software slices the CAD Model into cross-sectional layers and turns it into G-codes that an AM machine understands. Next, the AM machine starts printing the item by forming each layer with filament. After the machine has finished printing, the excess material is removed and cleaned. Finally, the item is printed and ready to be further assembled or used.

### 1.4 Signify's Manufacturing System

Currently, Signify has a hybrid manufacturing system, which combines AM and CM techniques. A significant portion of the work in the hybrid manufacturing system is carried out manually by personnel. In the 3D printing area, a large number of AM machines are located in rows next to each other. The AM machines print the necessary parts that are needed for production. Upon completion, the printed parts are accumulated in a cart,
which can be collected by the workers. The carts are stored near the AM machines and when ready brought to a separate quality station where the printed parts are checked and weighed to see if they fit the standard. Next, the printed parts are temporarily stored in a box on the floor. Between stations, workers are responsible for keeping track of the number of printed parts by counting them regularly. Finally, the printed parts are taken to an assembly station where they are combined with the non-printed parts to create the final product, ready for delivery to the customer.

Under the new arrangement, multiple hybrid manufacturing systems, incorporating automation, are located within a single production facility. Signify aims to incorporate robots to automate the hybrid manufacturing system, making the process more efficient.

The primary focus of the new situation is a machine known as the box handler. The box handler is an automated manufacturing and storing machine. Figure 1.2 shows the box handler system and all its main components, displayed within the indicated circles. The box handler consists of 48 AM machines, these machines can all create AM-printed parts. Filament, the material that is needed to create the AM prints, is stored in an oven below the AM machine. When a refill is needed a worker comes to add a new reel of filament into the oven. When the AM machine is finished printing, the parts are disposed of in the box hanging near the 3D printing system. Next, the box with printed parts is stored in the box handler system.


Figure 1.2: The box handler

To make sure that the quality of the printed parts is sufficient, the parts need to be checked. When required, the box containing the printed parts is moved to the quality control desk with the assistance of the box handler robot. There a worker retrieves the parts and checks whether they fit the standard. Afterwards, the box is stored back in the box handler system. Finally, when ready, the box continues to the assembly and packaging line. This line consists of tables with workers that assemble parts of the final product, test them, and puts them into packaging. The final product is then completed.

### 1.5 Report Structure

This study, specifically designed for Signify, is executed with the understanding that its methods, outcomes, and conclusions can be adapted to different settings. In the following chapters, we present the study fitting the context discussed earlier. In Chapter 2, we present the problem statement, the corresponding methodology, the scope of this study and the
contribution to literature. Chapter 3 discusses the manufacturing system at Signify, with the relevant characteristics, and the most important key performance indicators. Next, in Chapter 4, we present the simulated model for the manufacturing system. Then, in Chapter 5, numerical experiments are discussed and executed. Additionally in Chapter 6, we perform a comparison between the study of Crooymans (2022) and ours, to see the difference between a current system and an automated system. And finally, in Chapter 7, the discussion, conclusion and recommendations from this study are provided.

## Chapter 2

## Research Design

This chapter provides the design of the research. First, in Section 2.1 the problem description is given followed by the main question in Section 2.2. Next, we state the other research questions with the corresponding methodology in Section 2.3. In Section 2.4, the scope of this study is described. Finally, the contribution of this research in literature is mentioned in Section 2.5.

### 2.1 Problem Description

From the problem context in Chapter 1, it can be concluded that Signify needs to be supported in the design, analysis and cost-effective configuration of an AM facility with automated hybrid manufacturing systems. Therefore, it is needed to derive the required planning capacity, while also looking at the current demand, service level, and costs. Hence, Signify's interests lead to the following problem statement:

> Signify intends to expand its operations by incorporating automation into its business strategy. As a result, the company is transforming its manufacturing process. This transformation raises questions regarding the required planning capacity of the additive manufacturing facility and the level of efficiency that can be achieved compared to the current manufacturing approach.

### 2.2 Main Question

Based on the problem description, we formulate the main question as:
How to design and analyse an automated hybrid additive manufacturing facility?

To fully understand the main question, a few key terms need to be explained. In Chapter 1, we already give a short introduction to this terminology. For this study, we define additive manufacturing (AM) as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive/reductive manufacturing methodologies" (Frazier, 2014, p.1924). Additionally, the term automated hybrid manufacturing system is defined as: "a manufacturing system that consists of additive manufacturing in combination with conventional processes, where the transfer of work parts between the machines are done without human operations" (Crooymans, 2022; Morris \& Morris, 1988; Savolainen \& Collan, 2020).

### 2.3 Research Questions

To answer the main question, several research questions need to be answered first. For each research question, the research method is explained shortly.

An automated hybrid manufacturing system involves a lot of different aspects. To answer the main question, it is necessary to know what the newly automated hybrid manufacturing system looks like. The first research question is:

## RQ1: What does the automated hybrid manufacturing system look like?

To answer Research Question 1, knowledge and data about the automated hybrid manufacturing system are required. To gain this knowledge and data, we interviewed experts that are part of the project team for the automated hybrid manufacturing system and Research \& Development. Additionally, we visited the system itself in Maarheeze and Turnhout, where we took an in-depth look at the facility. Lastly, relevant literature was reviewed to gather information about automated manufacturing systems, which serve as a reference framework to provide deeper insights. By combining these steps, sufficient knowledge and data are obtained to develop a conceptual model of Signify's automated hybrid manufacturing facility.

In the process of investigating the desired design of the system, it is crucial to identify the key performance indicators (KPIs), which are the variables necessary to evaluate and obtain as an output. We determine these KPIs with the following research question:

RQ2: What key performance indicators should be used to evaluate the automated hybrid manufacturing system?

To determine the appropriate KPIs to use, two steps are taken. The first step involves analyzing the literature on KPIs for automated hybrid manufacturing systems. A comparable analysis, performed by Crooymans (2022), is used to compile a list of crucial KPIs. The second step involved conducting interviews with employees and experts who are part of the project team for the automated hybrid manufacturing system, as well as those in Research \& Development, to determine the KPIs that should be used by Signify.

When we have an output, the values can be used to analyze and give a good representation of the automated hybrid manufacturing system for Signify. We choose to use a simulation model to calculate these KPIs. The study leads to the following research question:

## RQ3: How do we model the automated hybrid manufacturing system?

The model is designed to represent an individual automated hybrid manufacturing system that is formulated in research question 1 (RQ1). There are two methods for modelling a manufacturing system: analytical calculations and data-based simulation. Both methods aim to study the same systems and address similar issues. In Appendix A, we compare these two modelling approaches and determine that simulation modelling is the appropriate method for Signify's manufacturing system. Signify's manufacturing system has many setups, returning orders, and complex processes that are difficult to model analytically, which would make an analytical model less realistic and detailed.

The model returns the KPIs of the automated hybrid manufacturing system that are formulated in research question 2 (RQ2). Each model depends on functional requirements that must be satisfied within the given constraints. These are formulated based on literature and data. Data is needed to gain a realistic view of the situation and to obtain the relevant output. Additionally, the functional requirements were discussed with experts mentioned earlier from Signify. Literature provides ample information on modelling manufacturing systems and automating them, as well as the impact of AM on the supply chain. It is crucial to conduct a thorough literature review to gain a deeper understanding of how to
model the automated hybrid manufacturing system. The literature review delved into this subject in depth, providing insights into various concepts within a manufacturing system. Together with the KPIs we decided upon in RQ2, the model gives thresholds for the design of an automated hybrid manufacturing system.

To gain more knowledge of the behaviour of the automated manufacturing system, we perform numerical experiments. Numerical experiments help validate the model and estimate the value for parameters. Additionally, we use numerical experiments to make the simulation more coherent with the real-world system, by analyzing it under different conditions and viewing its results. Thereby, the following research question is formulated:

RQ4: How can numerical experiments analyse the design of an AM facility with an automated manufacturing system?

In collaboration with Signify's Research department, we design several numerical experiments. These experiments are assessed based on their expected outcome, significance, and feasibility of implementation. Then, a subset of these experiments is carried out using the model developed in Research Question 3.

To assess the efficiency of the automated hybrid manufacturing system, the system needs to be compared to the current hybrid manufacturing system utilized by Signify. The corresponding research question is as follows:

RQ5: How do the current manual and new automated manufacturing systems compare?

This comparison reveals the potential advantages or disadvantages of using the new automated hybrid manufacturing system for Signify. The study conducted by Crooymans (2022) is used to examine the current manufacturing system in Signify. However, different assumptions are made in Crooymans (2022), making it impossible to directly compare the two models. To overcome this, the input parameters from our model are utilized in the model of Crooymans (2022), generating additional outputs. These results are analyzed and compared with the findings from RQ3 in this research. The conclusions from this comparison provide a comprehensive evaluation of Signify's new AM facility, enabling Signify to expand its operations and become $24 / 7$ automated.

### 2.4 Scope

The study focuses on the hybrid manufacturing system for the production of customized luminaires in an automated hybrid manufacturing system. The main research focuses on three processes: 3D printing in the box handler, quality control, and assembly \& packaging. The process of supplying the non-printed parts and supplying the filament are not included in the scope of this research. Hence, we assume that there is an infinite number of materials and non-printed parts.

Signify's 3D luminaires range from downlights, projectors, and pendants to fully customized luminaires. Hence, there are a lot of different products that Signify manufactures (Philips Lighting, 2022a, b). In this research, the focus lies on the Greenspace Downlight, as this is the best-selling luminaire of Signify (Philips Lighting, 2022a). The Greenspace Downlight is a luminaire that is designed for the circular economy while optimizing performance and extending its lifetime by upgrades and integration possibilities (Philips Lighting, 2022a,b). The downlight is easy to customize, recycle and disassemble (Philips Lighting, 2022a). To keep this research specific, we concentrate on a particular type of Greenspace Downlight which has four printed items: the Housing, Front Rim, Mixing Cup, and Mixing Cup Holder. Additionally, we examine the non-printed items, including the LED module, LED driver, and reflector, all of which are supplied by Signify. In Figure 2.1, the Greenspace

Downlight for this research specific is shown.


Figure 2.1: The modelled Greenspace Downlight (Philips Lighting, 2022a)

### 2.5 Contribution to Literature

In the field of AM, a significant amount of research has been conducted, focusing primarily on prototyping, AM materials, and understanding of the concept itself (Gibson et al., 2021; Kruth et al., 1998; Thakar et al., 2022; Wong \& Hernandez, 2012). However, more recent studies show that the implementation of AM in specific industries has become an increasingly important topic (Gibson et al., 2021). When searching for literature on AM in supply chains and AM facilities, there is some literature on hybrid manufacturing, particularly in recent studies (Strong et al., 2018).

Literature shows that several studies highlight the benefits of automated manufacturing systems, but relatively few focus on automated hybrid manufacturing systems (ElMaraghy et al., 2021; Hjorth et al., 2021). These studies tend to focus on small components of manufacturing systems rather than the entire system. To the best of our knowledge, there is limited research available that looks at automated processes in combination with hybrid manufacturing facilities.

The literature is missing a comprehensive examination of the topic, which is what this study aims to address by combining information on automated processes and hybrid manufacturing production.

## Chapter 3

## Analysis of the Automated Hybrid Manufacturing System

Nowadays, nearly all industries are busy applying new technologies to their manufacturing systems (Ashima et al., 2021). Examples of these techniques are automation and hybrid manufacturing. Together these two concepts form the main subject for this chapter: automated hybrid manufacturing systems. In this chapter, we cover the characteristics of this system in Section 3.1, where the three Production Units (PUs) are discussed. In the final section, Section 3.2, the KPIs are presented and considered for this study. Ultimately, the goal of this chapter is to address Research Questions 1 and 2.

### 3.1 System Characteristics

This section presents the PUs and a flow chart which answers the research question (RQ1): What does the automated hybrid manufacturing system look like? Moreover, Section 3.1.2 discusses three PUs: box handler, quality control and assembly \& packaging. This section goes into detail about the manufacturing system's flow, data, and assumptions of these PUs. The whole manufacturing system is presented in Figure 3.4.

### 3.1.1 The Manufacturing System

The manufacturing system of Signify consists of three PUs, storage places and production flows. In Figure 3.1, the general flow chart of the new automated hybrid manufacturing system is displayed. The flow chart is configured after a visit to Signify's AM facility in Turnout and consultation with Signify's experts. The Signify experts' roles are: Project Manager Research \& Development, Manager Research, and Scientists.
The flow chart shows how the completed product, a customized luminaire, is processed from raw materials. First, raw materials arrive and are transformed into filaments. Filament reels are often made from a variety of thermoplastic materials, but could also be recycled (Mikula et al., 2021). Filaments are used as a material by an AM machine to create parts. Non-printed parts are supplied by external organizations as Signify does not construct them, hence this is not included in the scope. The non-printed parts that have arrived are stored until needed for the assembly \& packaging PU.

The filament is supplied to the box handler PU with integrated AM machines, which return printed parts of the product in boxes. The parts then continue to the quality control PU, where the parts, either continue, go back to the box handler or leave the system. Next, the printed parts are stored in the storage of the box handler until needed for the assembly \& packaging PU. After all the parts continue to the assembly \& packaging PU,
the completed product continues to a storage warehouse before being transported to the customer. It should be noted that Signify manufactures a Make-To-Order (MTO) system, which indicates that the products are made when an order arrives.


Figure 3.1: The general automated hybrid manufacturing system of Signify

### 3.1.2 Production Units

To gain a comprehensive understanding of the system, the three PUs are discussed in greater detail. These three PUs are the most important units in the system for Signify and show the biggest change compared to the current manufacturing system. The PUs box handler and assembly \& packaging can both be divided into several steps. Below the steps are elaborated upon and more details are given.

## Box Handler

The box handler PU can be divided into three steps: prepare AM machine, AM, and retrieve printed parts. To perform these steps, an AM machine is needed. One box handler contains 48 AM machines parallel connected, which can create products with measurements no bigger than $250 \times 250 \mathrm{~mm}$. The AM machines require a specific raw material, filament, which is supplied and created in-house by Signify at another plant. As this plant is located in a different place (Maarheeze, The Netherlands), the production of the filament is left out of scope. We assumed that there is an infinite amount of filament reels available for the box handler. The box handler can store up to three filament reels per AM machine and needs one reel to print parts.

In Figure 3.2, the flow chart specific to the box handler is shown. When an order arrives, the AM machines in the box handler are prepared for printing. The filament is already installed beforehand in an oven below the AM machine. The oven heats the filament to a certain degree. Simultaneously, the print file of the part is loaded into the printer, which checks if the settings are right for the AM machine. When everything is prepared, the AM machine is ready to start the printing process. In the AM process, the AM machine prints a part that is required for the order. A failure can happen during this process, such as the first layer not sticking to the base or some other defect. If this happens, maintenance is required and the machine needs to be attended to by a worker. The AM machine is again prepared for the part and printed. When the AM machine completes the part, the part is ejected by an automated system integrated into each of the AM machines, which slides the part from the base into the box next to the AM machine. Since the box handler contains 48 AM machines with 192 storage places in total, this process described in the previous paragraph is performed 48 times in parallel.


Figure 3.2: Flow chart of the box handler PU

Once the parts have been retrieved, the box containing the parts is transported to the storage area of the box handler. The box handler is capable of storing up to 192 boxes, with a maximum of four boxes that can be stored above each AM machine. The fifth slot in the box handler is used to interchange the boxes as needed. The box handler robot can quickly move and swap the containers with the printed parts, at a speed of 500 mm per second in the $x, y$, and $z$ axes. The robot can complete a container change from one location to another in around a minute and a half.

## Quality Control

Once all the parts required for an order have been completed and are ready for assembly, the box with the parts is retrieved from the storage area and transported to the quality control station. In the quality control PU , the printed parts are all checked for defects. This process is quick but very important. It determines if the part needs to be printed again or if it can continue to assembly \& packaging possibly with an intermediate storage time in the box handler before. The box handler has two quality control stations, the box handler robot delivers the box with the parts to one of these stations and lets the workers determine whether the parts are correct. If the part is not correct, the part needs to be printed again. Hence, the print job needs to go back to the preparation of the AM machine. This can cost a lot of time since the whole order needs to wait for the new part to be finished before assembly can start. The defective part is removed from the box and then leaves the manufacturing system. After the part is checked and accepted, the box with parts is ready to continue to the next PU: assembly \& packaging.

## Assembly \& Packaging

The assembly \& packaging PU is divided into four steps: Prepare Assembly stations, Assembly, Testing electronics, and Packaging (Figure 3.3). This process of the manufacturing system is performed in a different area, close to the box handler. This area contains a line of assembly tables followed by a computer system for electronics testing. A big order requires five workers to run the line effectively. When a small order (e.g. one product) is requested, then less than one or two workers are already sufficient for the operation.

The boxes with printed parts arrive from the box handler via an automated guided vehicle (AGV) to the assembly \& packaging area, the boxes are stored here until needed. When the assembly \& packaging process starts, first the assembly stations are prepared. This is done by retrieving the non-printed and the printed parts from the storage and placing them on the assigned spot. Next, the assembly of the product starts. The non-printed and printed parts are combined into the product that is ordered by the customer. After the completed product is assembled, the electronic parts are tested on whether they are performing as intended. The testing takes about 1.5 minutes, if the part does not pass the test the whole product is tested again. If the product does not pass the test the second time it goes back to the assembly and a check is performed to see where the defect is. This defect can only be in the non-printed parts since the printed parts were already checked in the box handler. If a new non-printed part is needed, the worker retrieves a new part from storage. The failed part leaves the system and does not return. When the product passes the test, the product continues to the packaging. The worker can prepare the package during the testing electronics process, hence it only takes a short time to place the completed product and
close the package. After the product is packaged, it is ready to go onto a pallet and wait until the complete order is processed. After the order is finished, the completed products are stored in a warehouse until transportation to the customer has arrived.


Figure 3.3: Flow chart of the assembly \& packaging PU

The final flow chart of the automated hybrid manufacturing system of Signify can be seen in Figure 3.4. The red dotted line displays the scope of this research, inside the three main PUs.


Figure 3.4: Automated hybrid manufacturing system of Signify

### 3.2 Performance Measures

In order to answer RQ2, we need to determine the appropriate KPIs for evaluating Signify's automated hybrid manufacturing system. The first step involves identifying the most critical performance metrics from relevant literature. Afterwards, the performance measures outlined in the research of Crooymans (2022) are examined and compared. Next, we analyse the initial design of the print facility given by Signify. Finally, consultations with experts from Signify were held to gain an understanding of their requirements.

To obtain the fundamental objective of organizations, the performance needed to be measured and evaluated (Hopp \& Spearman, 2000). However, many organizations have been working with the wrong measures or have incorrectly termed them (Hopp \& Spearman, 2000; Parmenter, 2015). Therefore, we must give a clear definition of performance measures that could be used in a manufacturing system. Since there is a broad range of production environments and business strategies, there is not one single set of performance measures for all the manufacturing systems (Hopp \& Spearman, 2000). Hence, we have chosen for KPIs, "A set of measures focusing on those aspects of organizational performance that are the most critical for the current and future success of the organization" (Parmenter, 2015, p.4). These performance measures are measured frequently, clearly indicate what action is required and often have a significant effect on the organization (Parmenter, 2015).

When specifically looking for KPIs for an automated hybrid manufacturing system several terms can be found. Studies about automation measures mention that monitoring and continuous productivity improvement are very important due to the high investment and
operating costs of automating a system (Mathur et al., 2011). While hybrid manufacturing systems more often use sustainability as a KPI, environmental, social and economic performance indicators are mentioned (Taddese et al., 2020). Below, the definition of the KPIs is given with the studies from Groover (2016), Hopp \& Spearman (2000) and Mathur et al. (2011).

- Cycle time (CT): The average time from the release of a job at the beginning of the routing until it reaches an inventory point at the end of the routing (i.e. the time the product spends as work in process). CT is one of the most important KPIs, as it has a big influence on both costs and revenue. A shorter CT indicates less Work-in-process (WIP), better responsiveness, better forecasting, and cost reduction.
- Green House Gas (GHG) emissions: Total direct GHG during manufacturing and post-processing stages which can be estimated as GHG emission per product or per revenue. It also considers strategies or initiatives to minimize GHG emissions through minimized overall energy consumption or utilization of renewable energy sources.
- Inventory: The stock of any part or resource used in an organization. Inventory consists of the Raw material inventory (RMI), WIP and Finished goods inventory (FGI). The ideal situation would have a minimum RMI, everything would be delivered just in time (JIT). Additionally, there would be minimal FGI, and the completed product would be delivered to customer JIT. Only the minimum WIP is needed for the given throughput based on Little's Law.
- Lead time (LT): The time allotted for the production of an order on that routing or line, should be as short as possible. When the organization uses make-to-stock the LT is zero. However, when applying this to an MTO system, a zero target is not realistic.
- (Total) Manufacturing cost (TC): The total costs (TC) of the manufacturing system. Note that the TC consist of the fixed costs and the variable costs in relation to the quantity created. When comparing automated and current production methods, it is typical that the fixed cost of the automated method is high relative to the current method and the variable cost of automation is low relative to the current method. Consequently, the current method has a cost advantage in the low quantity range while automation has an advantage for high quantities.
- Parts quality: The extent to which the parts are correctly made the first time by the system. Hence, the parts quality efficiency can be calculated by the fraction of parts that are made correctly the first time through the system. A scrape or rework will decrease this value.
- Raw material waste: The efficiency or saving during material utilization. In 3D printing, raw materials are used to efficiently build parts layer by layer. For the printed parts, it is assumed that waste does not re-enter the system. Dematerialization is used to increase material efficiency, the higher the efficiency the better the environmental performance.
- Service level (SL): The probability that the CT of an order is smaller or equal to the LT. For an organization with a make-to-stock (MTS) system, this will be equal to the fill rate, for MTO systems the service level is a fraction of the orders that are filled within their LT.
- Throughput (TH): The average output of a production process (machine, workstation, line, plant) per unit time (e.g. parts per hour). Only non-defective parts created per unit of time are included in the TH. The TH can be defined in terms of efficiency, of whether the output is adequate to satisfy demand.
- Transport: Environmental impact of transporting products, other goods, and materials used for the organization's operations and transporting members of the workforce, etc.
- Utilization: The fraction of time the workstation is not idle. This includes the fraction of time the workstation is working on parts or has parts waiting and is unable to work on them due to a machine failure, setup, or other detractor. An ideal situation would be when all the workstations have $100 \%$ utilization since there is then no unused capacity and no excess costs (without variability). Moreover, the ideal situation will also not be plagued by detractors and give a $100 \%$ rate.

When analysing the study of Crooymans (2022), it is noticeable that Porter's Generic Strategies and Treacy and Wiersema's Value Disciplines are used to reason about the performance measures. Crooymans (2022) describes how both suggest choosing one central value discipline to excel at and performing acceptably at the other disciplines. Porter presents the disciplines: cost leadership, differentiation, and a niche market (Porter, 1985). While Treacy and Wiersema suggest: operational excellence, product leadership, and customer intimacy (Treacy \& Wiersema, 1995). With the help of experts from Signify, Crooymans (2022) states that Signify strives for differentiation leadership, cost leadership, and customer intimacy. For these disciplines, it is concluded that the study of Crooymans (2022) focuses on the KPIs service level and total costs.

In Section 3.1.2, we researched and described the design of the automated hybrid manufacturing system. After analysing the current design of Signify's automated hybrid manufacturing system, we think it could be interesting to see what the optimal storage capacity of the box handler should be. Currently, the box handler storage design has a capacity of 192 boxes. We suspect this to be too little capacity for the box handler storage. However, this is uncertain until tested. Hence, it could be interesting to see what optimal value can be found in the design of the box handler storage capacity.

Finally, the concerning interviews for the determination of the KPIs were held with R\&D Project Manager, R\&D Manager, and Scientific Employee. The interviewees were asked to present the most important KPIs for the automated hybrid manufacturing system of Signify, and to discuss the already found KPIs in literature and by Crooymans (2022). The interviews showed that Signify wishes to strive for being cost-competitive, while also always satisfying the needs of the customers as much as possible. Additionally, an interviewee mentioned the interests of Signify lie with sustainability, reducing energy consumption as much as possible. However, as this was only mentioned once, it is chosen that cost competition and customer satisfaction are more important. Customer satisfaction can be reached by aiming for a high service level and fulfilling all orders within the desired LT. However, currently, the LT of Signify is around three weeks. Signify wants to reduce this as much as possible and be able to manufacture even faster. Hence, it was mentioned in interviews that the goal should be less than the current LT, thus minimizing the CT of the manufacturing system.

To conclude, based on literature research, analysis of the study of Crooymans (2022), interviews with experts, and analysis of the system, we have chosen to maintain the following KPIs with corresponding definitions in the remainder of the research:

KPI 1. Cycle Time: The average time from the release of an order at the beginning of the routing until it reaches an inventory point at the end of the routing (i.e., the time the product spends as work in process).

KPI 2. Service Level: The probability that the cycle time of an order is smaller than or equal to the desired lead time. Hence, the number of orders delivered to the customer in time.

KPI 3. (Total) Manufacturing Costs: The total costs of the manufacturing system. Note that the total costs consist of the fixed costs and the variable costs.

KPI 4. Box Handler storage Capacity: The total required storage capacity of the box handler.

## Chapter 4

## Modelling of the Automated Hybrid Manufacturing System

In this chapter, our objective is to address Research Question 3: How do we model the automated hybrid manufacturing system? The most commonly used models for manufacturing systems are prescriptive models (Hopp \& Spearman, 2000; Ansari et al., 2019; Lepenioti et al., 2020). These models are designed to optimize or prescribe a manufacturing system. As mentioned in Section 2.3, we decided that a simulation model is the best approach for this study. The simulation model that we use is Discrete-Event-Simulation (DES). DES is a method in which states or events are changed at discrete points in time, where the events take no time to occur (Banks \& Carson, 1986; Varga, 2001).
The Tecnomatix Plant Simulation software version 2201, from Siemens Digital Industries Software, is used to create the model (Siemens Plant Simulation, 2023). This simulation software solution was recommended by Signify, as it is already used and applied in the organization. Furthermore, Signify requested the simulation to be visual without compromising the simulation, as that shows a realistic representation of the system. Hence, the complete professional package was made available by Signify. Plant Simulation allows for the modelling, simulation, and optimization of logistic systems and processes while analyzing material flow and resource utilization. It also has 3D modelling capabilities and is object-oriented, providing clear visuals. For more complex scenarios, algorithms and script programming can also be applied. Plant Simulation uses the built-in SimTalk 2.0 language for scripting.

The DES in Plant Simulation starts simulation through the Event Controller, by initiating a run, which acts as the timing controller of the simulation model. Signify receives its business orders well in advance (often half a year), thus there is a long lead time. As Signify does not want to deliver its luminaires too early to the customer, it is decided by them to always start production three weeks in advance. In our model, we assume that all orders arrive three weeks before the shipping date, all at the same time, which is 00:00 AM at the start of the day. After running the model for $\mathcal{T}$ time units, the model calculates the desired performance measures. Figure 4.1 shows the automated hybrid manufacturing system modelled in Plant Simulation. Figures 4.2 and 4.3 focus on the different processes in the model.


Figure 4.1: Signify's automated hybrid manufacturing system model in Plant Simulation


Figure 4.2: The box handler and quality control in Plant Simulation


Figure 4.3: Assembly \& packaging in Plant Simulation

We applied the DES method using the Process Interaction modelling perspective, as described by Banks \& Carson (1986). When using Process Interaction in Plant Simulation, our focus is on the processes in the model and their effects on the behaviour. The first step is creating a flow chart or network to clearly understand all the processes in the model. In Figure 3.4, we created a flow chart of Signify's automated hybrid manufacturing system to identify the entities and attributes present in the model. Then, all the processes in the model must be identified, including when they occur and how they change the objects in Plant Simulation. These processes are discussed in Section 4.1.1. Finally, the performance measures calculations can be implemented after finding all the processes, as we do in Section 4.2.

### 4.1 Model Description

This section details the simulation model. First, the processes, decision rules and assumptions of the model created in Plant Simulation are discussed in Section 4.1.1. The decision rules are not known yet as the system is not in production yet, hence we design and implement these ourselves. Finally, the calculation of the KPIs is explained in Section 4.1.2.

### 4.1.1 Production process

The Manufacturing System consists of three production processes: the AM (Additive Manufacturing) of printed parts, quality control, and the assembly of non-printed parts with printed parts. The completed product is then delivered to the warehouse and transported to the customer. In the manufacturing system, we assume that there are no restrictions on the availability of boxes, filament reels, non-printed parts, and packaging materials, ensuring $100 \%$ stock availability for these supplies. Additionally, we assume that the transportation time between the different machines and storage places is negligible with exception of the box handler robot.
The three production processes can be divided into nine processing events, which are shown in Figure 4.4. Additionally, the figure displays the times the event occurs in $\mathcal{T}$. Note that demand generation, creation of order queue, and print job assignment to AM machine all occur at the same time directly after an order arrives. The next paragraphs explain the nine processing events in more detail with the corresponding assumptions.


Figure 4.4: Processing events in the AM facility

## Demand Generation

The first step in the production process is the generation of demand. An order includes the following order characteristics: start date, order number, product type, colour/material, and quantity (e.g. 01-01-2023 00:00:00.00, 1, Down_Light_S, White, 35). The order number is unique to that specific order, while the product type is determined by the type distribution: Down Light S, 0.25 , Down Light M, 0.45, and Down Light L, 0.30. The colour/material is chosen based on the probabilities: White, 0.6 , Black, 0.3 , Blue, 0.025 , Green, 0.025 , Yellow, 0.025 , and Red, 0.025 . Thus, the model consists of six different colours/materials. The product type also specifies which parts need to be printed and which non-printed parts need to be added to complete the product.

Demand generation is an ongoing event in the AM facility depending on the arrival of orders. The number of generated orders at the end of the simulation model depends on the number of days the model is run for. After generating the orders, the print job queue is created, which occurs simultaneously with demand generation as these events do not require simulated time.

## Creation of Order Queue

The next event is the creation of the order queue for the model. The order queue determines the sequence in which orders are processed and converted to print jobs to be sent to the AM machines, as outlined in Figure 4.5. The first order in the queue is processed first. Orders can be created in the normal way (from an order arrival) and the priority way (from quality control). A priority order is created when a printed part is a defect and a new one is required. The quality control creates an order and sends it back to the queue, giving it priority over other orders in the queue. Normal orders are processed based on the First-Come-First-Serve (FCFS) rules. After the order queue is created, the orders are converted into print jobs and distributed to the AM machines.


Figure 4.5: Decision rule for order assignment to the queue

## Print Job Assignment to AM machine

An order consists of multiple print jobs, one for each part that needs to be printed for that order. If an order is for a single product, the number of print jobs is equal to the number of parts needed for that product. If an order is for five products, the number of print jobs is five times the number of parts needed for one product. During the process of converting orders to print jobs, additional characteristics such as item type and item number are created. Item type refers to the type of printed part that the print job creates, and the item number is a unique identifier for the instance of that part. Print jobs also have characteristics such as order number, product type, ID number, and colour/material that are copied from the order. Quality control, priority and corresponding box are additional characteristics added later in the process.

After processing the order into a print job, the print job is assigned to an AM machine in four steps. All the AM machines are checked in accordance with step one, and if that assignment rule is not feasible, step two is applied, followed by step three and finally step four. This decision rule can be seen in Figure 4.6.


Figure 4.6: Decision rule for the assignment of a print job to the AM machine

## Printing Process

When arriving at the machine, the print jobs must be evaluated to determine if they are priority print jobs. If a print job has a priority, it is given priority placement in the machine's queue. However, if an order group with parts that belong together is being printed, it is placed after that order group. Before processing the print job, the AM machine checks if the filament reel has the colour/material and the amount of material available for the part to be printed. In Section 3.1.2, we mentioned that a filament oven consists of three filament reels. However, for the purpose of simplifying the model, we assume the presence of only one filament reel in the filament oven. If the filament reel is not the correct colour/material or there is not enough material, it is switched to a new filament reel and the old one is discarded. This switch requires 10 minutes of setup time and the assistance of a worker.

The model includes three types of skilled workers: Additive Manufacturing (AM) Workers, Quality Control Workers, and Assembly Workers. It is assumed that all workers, regardless of their skill, earn the same salary and that a worker cannot operate more than one machine at a time. In the model, workers are only present on weekdays (Monday to Friday). The AM facility operates on weekends (Saturday and Sunday), but without workers. Public holidays and sick leave are not considered, and remote working is not supported in the model. Workers work in two shifts, each consisting of 8 hours a day, with two breaks. Furthermore, workers remain at their final location until they receive a new job order, thus do not need to return to a specific place to receive one. The workers' travel speed
is assumed to be $1.3 \mathrm{~m} / \mathrm{s}$, based on the average walking speed of an adult, as stated by Mohamed \& Appling (2020).

After the printing process is completed, the part is created by adding all necessary characteristics and saving important information. Once the printing process is complete, the print job is finished and deleted. If the AM machine fails during the printing process, a worker is called to fix the issue and the failed part is reprinted on the same machine. The failure can only occur during processing, not during filament reel changing or when the machine is idle. A failure can be caused by issues with the filament reel supply, printing (misprint), nozzle, and more. The breakdown of the machine itself is not considered as it could occur at any time. These steps of the decision rule are shown in Figure 4.7.


Figure 4.7: Decision rule for the printing process of a part

## Box Assignment and Storage

When a part has been created by an AM machine, it must be placed in a box for storage (refer to Figure 4.8). We assume that the boxes used to transport the printed parts are filled with only one type of printed part. If the part is a priority item, the relevant box
(the box used for the first printing) is retrieved from the box handler and used for the part. If there is no box corresponding to the part (for example, if it is a new part that has not been in the system before), a new box is created. When parts belong to the same order group and are the same item type, they can be stored together in the same box. The boxes also have a maximum number of parts that can fit inside, which is dependent on the type of part. For some types, this could be 100 , while for others it could be 5 . When the box is full (reaches its maximum capacity) or the next part belongs to a different order group, the box is transferred to the box handler. Before the box is removed from the machine, it is assigned the necessary characteristics. The box handler robot then transports the box and its parts to the storage area in the box handler, where it remains until needed for a quality check. In the simulation, the robot is modelled as four separate stations that work as one, due to practicality. Together, the four robots can transport one box at a time, just like the original box handler robot. It is assumed that it takes 1:30 minutes for the robot to store or retrieve a box in/from the storage area. In the model, it is also assumed that a box is first moved to the storage of the box handler and then, when located in the storage, can be moved to another place. It should be noted that a box cannot be moved directly from an AM machine to a quality control station.


Figure 4.8: Decision rule for the assignment of a part in a box

## Quality Control Process

When a box arrives in the storage area of the box handler, it is immediately ready to be transferred to one of two quality control stations (Figure 4.9). The box handler robot
retrieves the box from storage and places it at an available quality control station. Once the box arrives at a quality control station, it must wait for a worker to perform the check. If a part is defective, it is removed and a new print job request is created and sent to the AM machine as a priority print job, while the accepted parts remain in the box. The box and its accepted parts are then returned to the box handler via the box handler robot.


Figure 4.9: Decision rule for the removal of a box from the box handler

## Box Handler Removal

Figure 4.9 shows the decision rule for removing a box from the box handler. A box is ready for assembly when all parts of the order are present in the box handler and have been checked at a quality control station. As discussed and proposed before, the box is conveyed from the box handler to the assembly via an AGV. However, we decided not to include it in the model, as the AGV project still needs to start. Together with the time constraints, we decided not to incorporate it into the model. When the box is ready for assembly, the box is transported to the assembly storage by the box handler robot, where it is stored until all boxes of the order are present and a worker is available to begin assembly. We assume that there is unlimited storage for the boxes before the parts are assembled into the completed product. In reality, this storage space can be seen as the floor in front of the Assembly stations, which can temporarily hold boxes.

## Assembly Process

When all boxes of an order are in the assembly storage, the product is created from all necessary printed items (in this model, four printed items make up a product). It is assumed in the model that once the parts are removed from the boxes, the empty boxes are deleted from the model. The boxes are assumed to have $100 \%$ availability and do not affect the output. A product has the following characteristics: Name, Order Number, and Color. After the printed parts are assembled into the product, non-printed parts must be added to complete the product. The reflector is added first, taking 1:30 minutes, followed by the light-emitting-diode (LED) module (also taking 1:30 minutes), and finally, the LED driver
is installed (taking 1:30 minutes). The completed product is then ready for testing.

## Completed Product Testing

At the testing station, the completed product is evaluated for Reflector Yield, LED Module Yield, and LED Driver Yield. If the product fails the test, it must be inspected again and any failed parts must be repaired or replaced. Note that this failure could block the assembly line. Once the completed product has reached the warehouse, it is stored until delivery (which is outside the scope of this model). The transportation time of the finished goods to the customers is not included in the lead time of this model.

### 4.1.2 Key Performance Indicator Measurements

In Section 3.2, we have selected four KPIs to measure the model's performance. These KPIs are used to evaluate the performance of the box handler and assembly line. This section describes how the KPIs are calculated and modelled. The KPIs are calculated only after the modelling time ( $\mathcal{T}$ in hours), as all the data is available at that point. Note that some of the values required for calculating the KPIs have been agreed upon in consultation with Signify. The following sections provide details about the KPIs' variables and calculations.

## KPI 1. Cycle Time

The CT is calculated based on the time it takes for an order to go through the production process $\left(C T_{o}\right)$. An order is part of a set of orders $(\mathcal{O})$. When all the finished products have completed the production process and arrived at the warehouse, the CT can be calculated by subtracting the start time of the order ( $\left.t_{o}^{\text {start time }}\right)$ from the end time of the order ( $t_{o}^{\text {end time }}$ ), as shown in Equation 4.1.

$$
\begin{equation*}
C T_{o}=t_{o}^{\text {end time }}-t_{o}^{\text {start time }} \quad \forall o \in \mathcal{O} \tag{4.1}
\end{equation*}
$$

## KPI 2. Service Level

As described in Section 3.2, the SL is based on the CT, specifically, the probability that the CT of an order is less than or equal to the desired lead time (LT). An order is considered on time $\left(\alpha_{o}\right)$ if the CT is less than or equal to the LT, as shown in Equation 4.2. The LT is agreed upon with Signify beforehand. The SL can then be calculated as the ratio of the number of orders that are finished on time and the total number of orders finished, as shown in Equation 4.3. Note that if an order is not finished within the modelling time $(\mathcal{T})$, it is not included in the SL calculation, as its completion time cannot be determined.

$$
\begin{gather*}
\alpha_{o}=\left\{\begin{array}{ll}
1, & \text { if } C T_{o} \leq L T \\
0, & \text { otherwise }
\end{array} \quad \forall o \in \mathcal{O}\right.  \tag{4.2}\\
S L=\frac{\sum_{o \in \mathcal{O}} \alpha_{o}}{|\mathcal{O}|} \tag{4.3}
\end{gather*}
$$

## KPI 3. Total Manufacturing Costs

The TC can be divided into plant costs, the fixed costs, and operational costs, the variable costs, as shown in Equation 4.4.

$$
\begin{equation*}
T C=C^{\text {plant }}+C^{\text {operational }} \tag{4.4}
\end{equation*}
$$

The plant costs include all costs related to operating and maintaining the plant, such as the costs of the facility, assembly line, and box handler. The facility costs ( $c^{\mathrm{f}}$ ) encompass expenses such as building, and land costs. The assembly line costs ( $c^{\mathrm{a}}$ ) include costs from assembly stations, packaging stations, testing equipment, and storage space. This cost is variable and dependent on the number of assembly lines if there is more than one in the AM facility. The box handler costs $\left(c^{\mathrm{b}}\right)$ are expressed by the number of AM machines $(|\mathcal{M}|)$, which is fixed at 48. In collaboration with Signify, we assume that the facility, assembly line, and box handler can be amortized after five years, and thus the plant costs are calculated over the modelling time $(\mathcal{T})$, as shown in Equation 4.5.

$$
\begin{equation*}
C^{\text {plant }}=\frac{\left(c^{\mathrm{f}}+c^{\mathrm{a}}+c^{\mathrm{b}}\right)}{5 \cdot 365.25 \cdot 24} \cdot|\mathcal{T}| \tag{4.5}
\end{equation*}
$$

For the operational costs, we consider worker costs and filament reel costs. These ongoing costs are incurred from the normal day-to-day operations of the business and can be found in Equation 4.6. The total worker costs are determined by multiplying the labour rate of a worker $\left(c^{\mathrm{w}}\right)$ by the amount of time worked by that worker $\left(\theta_{w}\right)$ and summing that for all workers in the system. The filament reel costs are expressed as the cost per kilogram of material used $\left(c^{r}\right)$, which must be multiplied by the amount of material used $(R)$. The material used includes all material used to create printed parts, including parts that fail at quality control or fail a breakdown and material that is switched out before it's completely used.

$$
\begin{equation*}
C^{\text {operational }}=\sum_{w \in \mathcal{W}}\left(c^{\mathrm{w}} \cdot \theta_{w}\right)+c^{\mathrm{r}} \cdot R \tag{4.6}
\end{equation*}
$$

In collaboration with Signify, we decided that these costs need to be included in the KPI. Hence, we can assume that the costs included in the model are sufficient enough to conclude the model.

## KPI 4. Box Handler Capacity

The box handler capacity $(\delta)$ is calculated based on the maximum number of boxes that fit into the box handler storage at any point in time (M). When a box goes into the box handler, the box handler stores it until it can continue to the next process in the system. After a while, more boxes are added and the box handler storage fills up. $\varphi^{\mathrm{b}}$ is determined by looking at the maximum number of boxes that is in the box handler within the modelling time. In Equation 4.7 the formula for this KPI is found.

$$
\begin{equation*}
\delta=M \tag{4.7}
\end{equation*}
$$

### 4.2 Model Verification

A model verification must be conducted to determine if the simulation model performs correctly. The verification is performed by performing checks. These checks allow us to assess the model's behaviour and determine whether the model simulates as we expected in Section 4.1. As stated by Kleijnen (1995) and Robinson (1997), the key concept of verifying is sufficient accuracy. Since no model can be $100 \%$ accurate.

Based on the theorem by Robinson (1997), we are performing the method visual checks to verify the model. The method Visual checks proves to be a powerful aid for verification, namely, it can show both the logic and the behaviour of the model by running the model and
watching how each element behaves (Robinson, 1997). A few potential approaches for this method are: stepping through the model event by event, predicting what happens with the model and checking it, and setting up conditions to force certain events. We have chosen to use prediction as a visual check. In Chapter 6, we perform an additional verification technique called: comparison with other models. For the first verification, three checks are performed. We first describe the check, then we predict what happens and afterwards, we check if the model behaves th7098e same way. The following paragraphs summarize the verification checks that we performed:

## 1. Utilization Rates

The utilization rates of the workstations (i.e. the AM machines, box handler robot, quality control stations, and assembly stations) measure the workload and productivity of the model. By adjusting the demand, we can see how the behaviour of the utilization changes. With a low demand, we expect the utilization also to become low, since the workstation needs to produce less. Subsequently, we expect a high utilization rate with high demand, as the workstations need to produce more demand. We can calculate the demand for the expected utilization by using the formula: $u=\frac{r_{a} \cdot t_{e}}{m}$. However, this system is too complicated for this formula, we cannot give an estimation of what the demand would be. Hence, we estimate by increasing the model as much as possible.

The model shows that a low utilization is reached in case of low demand. The utilization rate approaches 0.00 , however, it never becomes 0.00 exactly (the model always keeps producing demand). We do notice that some AM machines are not used at all, because the amount of machines that belong to a box handler is large (48 AM machines). Vice versa, very high demand causes the utilization to become very high. The workstations never reach 1.00 exactly but do approach it. The assembly station's utilization rate does not increase a lot, this happens because the assembly needs to wait until the whole order is completed before it is removed from the box handler. Note that when the demand is too high, the storage of the box handler becomes full and blocks the process.

## 2. Stabilization over Time

The model simulates a certain timespan (i.e., simulation time $\mathcal{T}$ ). There are variables dependent on this simulation time, but not all are. We check if the outcomes change if simulation time $\mathcal{T}$ is altered. We expect that the outcomes that are not timedependent stay stable over time, while outcomes that are dependent on time and the number of orders change. Running the model for several days, months or a year, the time and order independent outcomes stay the same, while the outcomes dependent on time and order amount do change. In conclusion, regardless of the simulation time, a few days or a year, the outcomes stay stable.

## 3. Box Handler AM Capacity changes

Finally, we check how the model behaves when the capacity changes. When the capacity of the box handler increases, it is expected that the orders go quicker through the model. The other way around, if the capacity of the box handler decreases (fewer AM machines, less storage, fewer quality controls), fewer orders are completed on time.

With a higher box handler capacity, all the orders are finished in time, because there are much more AM machines to print a part. However, this also influences the utilization, which becomes lower. If the capacity of the box handler becomes lower, the storage of the box handler becomes full and the boxes become stuck. The demand is too much for the model to handle, hence no order can be processed.

## Chapter 5

## Numerical Experiments

In Chapter 4, we modelled the production facility of Signify with Discrete-event Simulation. In this chapter, we perform four experiments, to gain more knowledge and information about the modelled production facility of Signify and to answer Research Question 4: How can numerical experiments analyse the design of an AM facility with an automated manufacturing system? Generally, numerical experiments are used to get a response of the model over a range of parameters (Bowman et al., 1993). We start with a base experiment followed by a set of numerical experiments. First, in Section 5.1, we discuss the base experiment, what inputs it uses, and how it performs. Next, Section 5.2 shows the setup and the results of the numerical experiments. Lastly, we present a conclusion of the base experiment and numerical experiments in Section 5.3.

### 5.1 Base Experiment

We define a base experiment with which we compare the further numerical experiments. This is done by simulating a realistic input scenario approved by Signify employees. It should be noted that due to randomness in the model, the simulation consists of 100 runs which leads to a $95 \%$ confidence interval that gives valid results of the model. Additionally, a warm-up period is removed from the simulation run to make sure the results are not influenced by waiting times at the start of the simulation. The precise calculations for these values can be found in Appendix B.

In the following sections, the input for the base experiment is discussed in Section 5.1.1. Table 5.1 presents all input parameters and provide a brief explanation. Afterwards, the output measures are displayed and explained in Section 5.1.2. Finally, we discuss the bottleneck of the base experiment in Section 5.1.3

### 5.1.1 Input Parameters

We explain in this section all the input parameters, we give an overview in Table 5.1. These values were discussed with two Signify employees both with the role: Digital Workflow Scientists. These employees actively participated in supporting the simulation model and approving the final values. The input values are not historical data values, as some of them are not yet available (box handler data) and some cannot be disclosed by Signify for confidentiality reasons. In this section, we provide a more detailed explanation of some of the input parameters.

Table 5.1: Input parameters for the Base Experiment

| Symbol | Description | Input Value |
| :--- | :--- | :--- |
| $\beta_{i_{b}}$ | Maximum number of items $i \in \mathcal{I}^{p}$ in box $b \in$ | See Appendix C |
|  | $\mathcal{B}$ |  |
| $\gamma_{i}$ | Yield of a printed item $i \in \mathcal{I}^{p}$ | See Appendix C |
| $\gamma_{i}$ | Yield of a non-printed item $i \in \mathcal{I}^{n}$ | See Appendix C |
| $\lambda_{o}$ | Arrival rate of an order $o \in \mathcal{O}$ | Uniform(8, 12) |
| $\omega^{\mathrm{r}}$ | Weight of a new filament reel | 10 kg |
| $\omega_{i}$ | Weight of a printed item $i \in \mathcal{I}^{p}$ | See Appendix C |
| $\rho^{\mathrm{b}}$ | Processing time of the box handler robot | $1: 30$ min |
| $\rho^{\mathrm{p}}$ | Processing time of the packaging | $1: 00$ min |
| $\rho^{\mathrm{np}}$ | Processing time of a non-printed item | $2: 30$ min |
| $\rho_{i}$ | Processing time of a printed item $i \in \mathcal{I}^{p}$ | See Appendix C |
| $\xi_{p}$ | Inspection time of a product $p \in \mathcal{P}$ | $1: 30$ min |
| $\xi_{i}$ | Inspection time of a item $i \in \mathcal{I}^{p}$ | See Appendix C |
| $A_{m}$ | Availability of AM machine $m \in \mathcal{M}$ | $99.8 \%$ |
| $C$ | Number of colors/materials | 6 |
| $c^{\text {a }}$ | Assembly costs | $€ 10,000$ |
| $c^{b}$ | Box handler costs | $€ 75,000$ |
| $c^{\mathrm{f}}$ | Facility costs | $\in 100,000$ |
| $c^{\mathrm{r}}$ | Filament reel rate | $€ 10 / \mathrm{kg}$ |
| $c^{\mathrm{w}}$ | Worker rate | $€ 25 /$ hour |
| $\left\|\mathcal{I}^{n}\right\|$ | Number of non-printed items | 3 |
| $\left\|\mathcal{I}^{p}\right\|$ | Number of printed items | 4 |
| $L T$ | Lead Time | 21 days |
| $\|\mathcal{M}\|$ | Number of AM machines | 48 |
| MTTR | Mean-time-to-repair of an AM machine | $5: 00$ min |
| $\|\mathcal{P}\|$ | Number of product items | 3 |
| $Q_{o}$ | Number of products in an order $o \in \mathcal{O}$ | Erlang $(0.5625,0.0375)$ |
| $s$ | Changing time of a filament reel (setup time) | $10: 00$ min |
| $\|\mathcal{T}\|$ | Modelling Time | 84 days (12 weeks) |
| $\|\mathcal{W}\|$ | Number of workers | 18 |

As described in Section 4.1, we have assumed that a box filled with parts can continue to the box handler by reaching its box limit $\left(\beta_{i_{b}}\right)$. This limit can range from 10 to 100 parts, depending on the type of part in the box. Hence, a box can hold more smaller parts than larger parts. Note that the box is the same for all types of parts. Table 5.1 also shows two different inspection times: $\xi_{p}$, which is the inspection time of a complete product at the assembly stage, and $\xi_{i}$, which is the inspection time of a printed item at quality control. The inspection time of a product is the same for all products, but the inspection time of a printed item depends on its type.

Table 5.1 displays several cost values, which are used to calculate the KPIs. The assembly $\operatorname{costs}\left(c^{\mathrm{a}}\right)$, facility costs $\left(c^{\mathrm{f}}\right)$, and worker costs $\left(c^{\mathrm{w}}\right)$ are based on the study of Crooymans (2022) performed at Signify 3D Printing and checked with multiple employees at Signify.

We have focused on three types of Greenspace Downlights $(\mathcal{P})$, size $\mathrm{S}, \mathrm{M}$, and L , which consist of four printed items $\left(\mathcal{I}^{p}\right)$ and three non-printed items $\left(\mathcal{I}^{n}\right)$. The number of products in an order $\left(Q_{o}\right)$ is assumed to be an Erlang distribution with $k=0.5625$ and $\lambda=0.0375$, which results in a $\mu$ of 15 and a $\sigma$ of 20 . The Erlang distribution gives an order size distribution with a long tail and many small orders. These characteristics fit the order quantity of Signify. The model has 18 workers, $\mathcal{W}$, present, working in two shifts. Eight
workers are performing tasks related to the AM machine (repair and setup), four are at quality control, and six are assembling the product.
The simulation's box handler storage capacity $(\delta)$ is a high value, to find the minimum required capacity when using the realistic input of Signify. In Section 5.1.2, KPI 4. is discussed and the capacity of the box handler is elaborated upon.

### 5.1.2 Result Measurements

In this section, the results of the base experiment are displayed and discussed in detail. We start by discussing the results on the four KPIs: cycle time, service level, total costs, and box handler capacity which were defined in Section 4.1.2. We also elaborate on results that are not KPIs but provide insight into the behaviour of the model.

## Cycle Time (CT)

We defined the $C T$ as the time from when an order arrives until the moment a completed product leaves the system for the warehouse. Figure 5.1 shows a Gantt Chart of the $C T$ of 100 orders in an example run from the base experiment. It is important to note that the figure displays the start time (when an order arrives in the manufacturing system) and the end time (when an order is completed).


Figure 5.1: Gantt Chart of the start time, end time and $C T$ per order

The Gantt chart shows that the $C T$ of the orders differ a lot. On average the $C T$ is 16.04 days. The average maximum $C T$ is 19.92 days. The example run in Figure 5.1, displays a few orders that take much shorter to process than 16 days. This is especially the case for part $M$ orders, which could be expected as part $M$ occurs the most and also needs a printable item with a $\gamma_{i}$ of 0.43 .

Service Level (SL)
The $S L$ is dependent on the $C T$ and $L T$. The $L T$ needs to be determined beforehand to calculate the $S L$. According to Section 5.1.1, Signify currently has an $L T$ of three weeks.

We run the model for 12 weeks, which displays a $S L$ of 0.73 . We can explain the $C T$ by the variability in demand. With more demand, the system has more difficulty keeping up with all the orders due to the high utilization of the AM machines, which is shown later. This causes some orders to have to wait a long time to be processed. Additionally, the low yield causes more rework parts, which have a priority over the normal parts. The normal parts need to wait longer to be processed and this can again cause an order to delay longer.

## Total Costs (TC)

Next, the output of the costs can be found in Table 5.2. To better understand the cost output, we also present the cost per completed product and the cost per kg. The cost per completed product shows the average cost per created luminaire, which is around €43. In Figure 5.2, a breakdown of the base experiment costs can be seen.

Table 5.2: Cost results of the base experiment

| Total Costs | Total Costs (per completed product) |
| :---: | :---: |
| $€ 351,872$ | $€ 43.16$ |



Figure 5.2: Breakdown of the total costs per product

## Box Handler Storage Capacity

As already mentioned in Section 5.1.1, we simulated the model with an unlimited amount of box handler capacity, meaning that there should be no trouble putting the boxes in the box handler. By doing this, we can now see how much capacity is needed for the demand of Signify. In Chapter 3, we stated that the box handler designed by Signify has 192 storage places for boxes, however, we assumed that this would be too little for the average demand Signify gets. After simulating the base experiment, we have found that the maximum number of boxes at the same time in the box handler for the demand (Table 5.1) is 668. This amount is three times more than the 192 places chosen for the box handler capacity. A box handler capacity of 668 , means that there are 14 places needed above an AM machine ( $668 / 48 \approx 14$ ). Furthermore, we notice that the storage occupancy fills up slowly over time and reaches a steady state. This mainly happens due to large orders that stay stuck in the box handler storage and have a low-yield item, which requires many reworks. Hence, we can say that the original box handler capacity needs to increase to fulfil the demand.

## Extra Results

The extra results provide more insight into the behaviour of the simulation model. On average 8,167 products are completed, which belong to 598 different orders. Additionally, $14,136 \mathrm{~kg}$ of filament reels is used, which means that per product a bit more than 1.73 kg is needed. This is a large amount due to throwing away items after quality control, throwing
away items due to printer failures, and throwing away leftover filament due to premature change-overs. Hence, the average filament reel utilization is 0.44 . Finally, a worker spends 448 hours in the system, however only $29 \%$ of the time the worker is actually busy. When calculating the worker costs: $25 \cdot 448=611,200$ per worker, we notice that this is a large part of the total costs.

Figure 5.3 shows the average number of parts that failed either during printing or quality control. The figure also includes the average number of parts that are completed as a reference. From the figure, we can conclude that half of the parts that are printed fail. Additionally, we see that quality control causes many more failed parts than the other two processes. This is because some parts have a yield lower than $40 \%$, increasing the chance of parts failing.


Figure 5.3: Number of failed parts in the system compared to the number of parts created

The utilization of the AM machines is displayed in Figure 5.4. The data shows that the machines are mostly failing, working or blocking, with some machines having a high percentage of waiting. We expect the failure percentage to be this high, because of failures that happen during the weekend when no worker is around to fix them. Blocking also occurs often, which is attributed to the box handler robot being occupied at the same time as a box moving to storage. From this figure, we can conclude that the machines are frequently busy and have a high utilization rate.


Figure 5.4: Utilization rate per AM machine

The utilization rate of the two quality control checking stations on average is 0.44 and 0.45 . The stations are mostly waiting. The utilization of the assembly line is 0.32 , which is again quite low. This probably happens due to the box handler controlling the arrival of the parts. The assembly stations also show blocking signs. Here, the testing station is the sole cause of blocking. Finally, the box handler robot displays a utilization rate of 0.87 , which means that most of the time it is busy moving boxes from and to the box handler.

### 5.1.3 Bottleneck

For further evaluation of the model, we find the bottleneck. In Section 3.2, we already predicted that a box handler with the storage capacity of 192 places causes trouble. In Section 4.2, we showed that increasing and decreasing the AM capacity of the box handler does change the order flow. Hence, it is interesting to see how the box handler exactly behaves. In cases of high demand, the box handler gets full. Moreover, the higher utilization rates in the box handler compared to the assembly line, even if the demand increases, show that the box handler is a critical point in the model. A normal queuing theory responds with long waiting times and too high utilization. This would mean that the box handler with high utilization rates would cause long waiting times at the AM machines. Which is the case for our model. The print job queue in the AM machines is long, but due to the large amount of AM machines, the print jobs can be distributed over several queues. A reason for the fast filling of the box handler storage is that the boxes need to wait in the box handler until the order is complete and quality checked, before being transported to the assembly line. Because of this, the box handler becomes full and only allows orders to go to the assembly one by one. To make sure that we correctly interpret the trouble in the box handler, we check how the model behaves when shifting the storage place (transporting boxes without waiting on a complete order). Furthermore, we check the cycle times of an order in the box handler and the assembly line. These checks help find the bottleneck of this model.

## 1. Shifting the storage in the system

In the current model, we move the boxes from the box handler to the assembly, when the whole order is checked and complete. This is changed to moving the boxes to
the assembly already when a box is checked. When changing the way the boxes are removed to the assembly line, we can see that the storage place shifts. Instead of filling the box handler storage, the assembly storage is now becoming full. The utilization rate of the assembly line does not increase, since the assembly still needs to wait until all parts have arrived to start producing. If the model would start assembly even though not all the parts of the order are available, the storage shifts to the warehouse, where the completed products are waiting until the order is complete. This test shows that storing the boxes/parts/completed products is a problem in the model since they always need to wait on each other until the order is complete in the model.

## 2. Cycle Time check

To check if the box handler is indeed the bottleneck of the model, we divide the cycle time of an order into the time in the box handler and the time in the assembly line. The division line is the moment the order arrives from the box handler robot to the assembly storage. We observe that the box handler cycle time takes much longer than the assembly line time. The box handler can on average manufacture a part in 5 days, while the assembly takes less than an hour. Thus, we can conclude that the box handler takes longer than the assembly line.

We can conclude, that boxes/parts/completed products are always waiting until the AM machines have finished printing the order. In our model, this happens in the box handler. Thus, the bottleneck is the box handler, in particular the AM machines, on which the system is always waiting. From the model, we can observe that the AM machines are slow compared to the rest of the system, because of the rework that needs to happen when a printed part does not pass the quality control. The rework returns to the AM machines, then needs to wait until it can start printing. After printing on the AM machine, the part goes into the corresponding box and needs to be checked at the quality control again. Since the yield of some printed items is so low, it often happens that a part becomes reworked more than two times. This happens especially with the item: Mixing Cup L, which has a yield of $34 \%$. From this bottleneck research, we can conclude that the AM machines are having trouble keeping up with the number of print jobs because many items have a low yield which requires rework.

### 5.2 The experiments

This section describes the setup of experiments that can be performed to test the limits of the model presented in Chapter 4. Afterwards, we conduct the experiments and discuss the outcomes. We perform a series of four experiments: Increase the item yield, decrease the capacity of the box handler storage, increase the number of filament materials, and adapt the number of AM machines. Each experiment is carefully chosen for its ease of implementation, the potential for achieving valuable outcomes, and overall importance to Signify's business. In Appendix D, four more experiments can be found that could not be executed due to lack of time.

In the experiments, we first explain the experiment itself and its necessity, then we describe the expected outcome, and next, we discuss the implementation of the experiment. Afterwards, we show the outcomes of the experiment and discuss the most important outcomes. Below, the numerical experiments can be found:

### 5.2.1 Increasing the item yield

A finding of the base experiment is that the yield of the items has a big influence on the flow of the system. In Section 5.1.3, we concluded that the yield is one of the reasons
behind the AM machines being the bottleneck of the process. Hence, it is interesting to see what happens with the system when we increase the yield of the items.

We expect that the increase will affect the number of reworks. If the yield of an item is bigger, fewer parts fail at the quality control and this means less rework is needed. The AM machine probably has fewer print jobs than the base experiment, we expect that the utilization of the AM machines will decrease. Additionally, the $C T$ becomes smaller, which decreases the $S L$. Lastly, we expect that there will be fewer filament reels needed, as fewer parts fail and are thrown out. This will also have a decreasing effect on the costs.

This implementation is not complicated since the yield of an item can be easily adjusted. We analyze the model assuming the lowest yield in the base experiment 0.34 to $0.44,0.54$, $0.64,0.74,0.84$, and 0.94 . The other yields increase also increase with a 10 per cent point until 1.00 is reached. Note this is only be done for the printed items since the bottleneck occurs there. In Appendix E, we present the exact yield values of the items.

Table 5.3 presents the outcomes of this experiment. We notice that the costs per product decrease when the yield becomes better. However, after a while, the costs do not change that much anymore, and a steady state is reached. Figure 5.5 shows the Confidence Interval $(C I)$ of the total costs per product. Here, we see the same steady state as shown in the table. Additionally, we notice that the only significant difference happens between the base experiment and the +10 per cent point yield experiment. Hence, not much difference is seen between the increases in the yields in the costs. Next, the table shows that the filament reels per completed product also decreases a little bit. We would expect that this would give a larger difference. We suspect that because the AM machines need to print less rework, there is more place for normal orders, which still cost filament reels of course. Hence, with a higher item yield, more orders can be fulfilled. We do see a small increase of the filament reels for experiment +20 per cent point yield, however, due to the big variability in the system, we expect it to be a stochastic difference. Furthermore, we notice that only after a small increase in the yield of the items, the $S L$ increase immediately to 0.96. Subsequently, this happens for the $C T$ and the box handler capacity. Both decrease a lot after the first yield increase. In Figure 5.6 , we can see the $C I$ of the $C T$, it shows that like the costs the $C T$ goes to a steady state from +30 per cent point, where differences between the yields do not matter much anymore.

Table 5.3: KPIs Experiment 1

| Experiments | Total Costs | Total <br> Costs <br> (per <br> com- <br> pleted <br> product) | Filament reels in kg (per completed product) | Service Level | Average <br> Cycle <br> Time (d) | Box handler Capacity | Completed <br> Prod- <br> ucts |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Base Experiment | €351,872 | €43.16 | 1.73 | 0.73 | 16.04 | 668 | 8,167 |
| +10 per cent point yield | €369,086 | €34.89 | 1.50 | 0.96 | 9.00 | 437 | 10,603 |
| +20 per cent point yield | €389,446 | €34.39 | 1.57 | 1.00 | 3.38 | 229 | 11,333 |
| +30 per cent point yield | €377,373 | €32.62 | 1.44 | 1.00 | 2.75 | 163 | 11,578 |
| +40 per cent point yield | €370,046 | €31.97 | 1.38 | 1.00 | 2.54 | 144 | 11,588 |
| +50 per cent point yield | €363,554 | €31.10 | 1.31 | 1.00 | 2.46 | 137 | 11,700 |
| +60 per cent point yield | €359,972 | €31.00 | 1.29 | 1.00 | 2.42 | 137 | 11,623 |
| 100 per cent point yield | €359,239 | €31.02 | 1.28 | 1.00 | 2.42 | 134 | 11,594 |



Figure 5.5: Confidence Intervals of the Total Costs (per completed product)


Figure 5.6: Confidence Intervals of the Average Cycle Time

### 5.2.2 Original capacity of the Box Handler storage

In Section 5.1.3, we noticed that the storage of the box handler fills up quickly, which could become an issue over a longer period. Therefore we modelled an unlimited amount of box handler capacity in the base experiment. The original box handler contains 192 storage places. Hence, it is interesting to see how much demand can flow through the system with the original capacity. The behaviour of the model could change and with that the results as well. It is interesting to see how the model behaves with a box handler capacity of 192.

We expect that the box handler will fill more quickly since fewer boxes can fit in the storage. Additionally, the quality control will have an easier time checking all the boxes since more parts are available for quality control, thus the utilization of the quality control stations will decrease. Therefore, we think the waiting time will shift more towards the box handler. In general, the capacity decrease is expected to increase the cycle time of a product but decrease the costs (due to additional expenses for the box handler storage).

The implementation of this experiment is not complicated, the model can easily be changed to test this experiment. For this experiment, tests are performed to see the maximum demand that can still fit into the box handler's capacity. This is done by simulating multiple times with different demands until we find the maximum box handler capacity of 192. Table 5.4 shows the results of decreasing the demand to get to 192 storage places in the box handler.

Table 5.4: Maximum capacity of box handler for Experiment 2

| $\lambda_{o}$ | Maximum number of boxes in the box handler |
| :---: | :---: |
| Base experiment | 668 |
| z_uniform $(7,11)$ | 588 |
| z_uniform $(6,10)$ | 323 |
| z_uniform $(5,9)$ | 170 |
| z_uniform $(4,8)$ | 145 |
| z_uniform $(3,7)$ | 141 |



Figure 5.7: Confidence Intervals of the Maximum number of boxes in the box handler

From the results, we can see that the 192 capacity is reached at an arrival rate of z_uniform(5, $9)$. This is nearly half the amount of demand compared to the base experiment. Hence, we can say that the storage of the box handler decreases proportionally with the arrival rate. Figure 5.7 shows the $C I$ of the box handler capacity. We notice a big significant difference between the first three demands, the difference between the final three demands is not that big. In Table 5.5, we present the KPIs of the z_uniform(5, 9) experiment. We notice that the $S L$ is much higher compared to the base experiment, namely 1.00. Hence, we can conclude that, although a 192 storage has a higher service level, it can only handle an average demand of 7 orders per day. If Signify wants to use this box handler capacity, it should be thinking about adding more box handlers to process the larger demand.

Table 5.5: KPIs Experiment 2

|  | Total Costs | Total Costs <br> (per kg) | Service <br> Level | Average <br> Cycle <br> Time (d) | Box han- <br> dler Ca- <br> pacity | Completed <br> Prod- <br> ucts |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| $\mu$ |  |  |  | $€ 47.31$ | 1.00 | 3.66 |
| 170 | 7,781 |  |  |  |  |  |
| CI Left bound | $€ 347,011$ | $€ 399$ | $€ 43.79$ | 1.00 | 3.38 | 114 |
| CI Right bound | $€ 388,222$ | $€ 50.82$ | 1.00 | 3.92 | 226 | 7,581 |

### 5.2.3 Increase the number of Filament Materials

In Signify, the majority of the luminaires are printed in black or white. However, Signify does offer customized luminaires in more than 40 colours/materials. For the base model, we assumed six different colours/materials. For this numerical experiment, we are going to see what happens if we add more colours/materials. By adding more filament colours/materials, Signify can gain insight into the effect of customized luminaires on the supply chain.

The increase in filament colours/materials is expected to influence the number of filament setups that are needed. The AM machines need to change the filament more often, hence more setup time is required and more time from the workers is needed. This could make the cycle time much longer. Additionally, the production costs could increase, as the filament reels are changed more often, which means more useable material is thrown away, costing Signify money and sustainability.

Not many adjustments need to be made to implement this experiment, which makes it an easy experiment to apply. Currently, the base experiment assumes the probabilities of white 0.60 , black 0.30 , and each of the other four colours 0.025 . The model is adjusted by changing the filament colours/materials from 6 (base experiment) to 12,24 , and, 48 colours/materials while keeping the probability ratio the same as the base model. Table 5.6 presents the results of the conducted experiments.

Table 5.6: KPIs Experiment 3

| Colours/ Materials | Total Costs | Total <br> Costs <br> (per <br> com- <br> pleted <br> product) | Filament reels in kg (per completed product) | Filament used for change overs | Service Level | Average Cycle Time (d) | Box handler Capacity | Completed Products |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 6 | €351,872 | €43.16 | 1.73 | 4,150 | 0.73 | 16.04 | 668 | 8,167 |
| 12 | €375,397 | €46.57 | 2.04 | 6,616 | 0.72 | 16.08 | 661 | 8,074 |
| 24 | €389,295 | €48.07 | 2.20 | 7,982 | 0.73 | 15.92 | 651 | 8,108 |
| 48 | Є395,565 | €48.65 | 2.27 | 8,553 | 0.74 | 15.96 | 647 | 8,138 |

The results show that the differences between the values for each number of colours/materials used are relatively small. For example, the difference between the total costs per product for 6 colours/materials and 48 colours/materials is only an increase of $€ 5.49$, which is not a lot given the fact that there are 42 different colours/materials more. Figure 5.8, displays the $C I$ of the cost per product, we can see that the $C I$ overlap does not make it significant. Furthermore, we see that the filament reels increase when more colours/materials are added as we had expected. This is especially evident for the filament used for changeovers. Surprisingly, the $C T$ does not change much. However, in Figure 5.9, we see that the $C I$ overlap a lot, which does not make the $C T$ significant.


Figure 5.8: Confidence Intervals of the Total Costs (per completed product)


Figure 5.9: Confidence Intervals of the Average Cycle Time

### 5.2.4 Adapt the number of AM machines

The occurrence of blocking or starvation has a big impact on the production of Signify. When blocking occurs in the production facility, it is likely that the production comes to a halt and cannot continue until the blocking is solved. While starvation occurs when the production facility is idle and has no jobs to perform. This can cost Signify a lot of money since the workers and the machines are idle. Hence, it is interesting to see how many AM machines are needed to prevent blocking and starvation from happening. We are testing this by increasing and decreasing the number of AM machines in the box handler.

We expect that with fewer AM machines than in the base experiment (48), fewer parts come into the box handler storage at the same time. This prevents the box handler from blocking. However, this will decrease the service level since products will take more time to manufacture. Vice versa, when more AM machines are added to the box handler starvation will occur. If the orders can be easily completed with more AM machines, a few machines will be idle and cost money instead of producing money. By increasing or decreasing the number of AM machines, the whole system changes immensely, therefore it is important to find the balance between AM machines and KPIs.

This experiment mainly requires running the model multiple times with a different number of AM machines to see where the blocking and starvation occur and what the optimal number of machines is. To get a good view of the behaviour of the model, we analyze the model with $12,24,36,48$ (base experiment), 60,72 , and 84 . The results can be seen in Table 5.7.

Table 5.7: KPIs Experiment 4

| AM machines | Total Costs | Total <br> Costs <br> (per <br> com- <br> pleted <br> product) | Filament reels in kg (per completed product) | Service <br> Level | Average Cycle Time (d) | Box <br> Handler <br> Capacity | Completed <br> Prod- <br> ucts |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 12 | €288,383 | €76.26 | 2.57 | 0.32 | 32.42 | 229 | 3,133 |
| 24 | €292,334 | €59.58 | 2.15 | 0.32 | 29.21 | 423 | 3,883 |
| 36 | €357,000 | €53.56 | 2.32 | 0.47 | 21.92 | 541 | 6,363 |
| 48 | €351,872 | €43.16 | 1.73 | 0.73 | 16.04 | 668 | 8.167 |
| 60 | €362,657 | $€ 42.03$ | 2.07 | 0.86 | 12.96 | 756 | 8,629 |
| 72 | €376,641 | €50.33 | 2.19 | 0.88 | 12.42 | 992 | 7,483 |
| 84 | €397,004 | €53.42 | 2.47 | 0.98 | 8.38 | 803 | 7,432 |

The results show a trade-off between the costs and the $C T$ when increasing the number of AM machines. This balance has a big impact on the service level provided to customers. As the number of AM machines increases, so does the service level. This increase is entirely logical, as more machines mean that there are more spots for demand to be printed. The $C I$ of the costs per product and the $C T$ are found in Figure 5.10 and Figure 5.11. We notice that the bounds overlap quite a bit. Therefore it is difficult to say whether the changes are significantly relevant. Finally, we see that the cheapest number of AM machines is 60 . If we compare this experiment with the base experiment, we notice that it shows better results for the total costs, service level, and $C T$. However, when looking at the $C I$ of the costs and $C T$ for these two experiments there is no significant difference.


Figure 5.10: Confidence Intervals of the Total Costs (per completed product)


Figure 5.11: Confidence Intervals of the Average Cycle Time

### 5.3 Conclusion

In this chapter, experiments are conducted on Signify's AM facility to gain valuable insights into how numerical experiments can enhance the base experiment. Through a range of parameter tests in the numerical experiments, a deeper understanding of the system's behaviour is achieved. The base experiment serves as a foundation for exploring numerical experiments and analyzing the additive manufacturing process. The key findings show that the bottleneck is the box handler due to the many reworks on the AM machines.

Four numerical experiments are performed to analyze the effects of different scenarios on the production facility. Increasing the yield of printed items improves all the KPIs, however, after adding the first 10 per cent point there are not many differences between the results that can be seen. The original box handler capacity (192) can handle a maximum of 7 orders on average per day. The lower demand causes a higher service level of 1.00 and $C T$ compared to the base experiment. Increasing the number of filament colours and materials had a relatively small impact on KPIs but did increase the costs and filament per product a bit. Increasing the number of AM machines increased the $S L$, while vice versa decreasing the number of AM machines caused the $S L$ to become low. In both situations, the costs per product increased. Surprisingly, we notice that 60 AM machines give the best results for costs, $S L$, and $C T$.

From this chapter, we can recommend adding more AM machines to the setup to distribute the demand and prevent such issues from arising. Alternatively, a highly impactful solution would be to focus on improving product yield. We noticed a significant amount of rework, which contributes to the demand for AM machines. By improving the yield, fewer parts will fail the quality check, ultimately reducing the demand for AM machines. While this solution may be more challenging to implement, it can lead to significant savings in terms of machinery, material, energy costs, and space in the manufacturing facility.

## Chapter 6

## Comparison of Signify's Manufacturing Systems

In this chapter, we answer research question 4: "How do the current manual and new automated manufacturing systems compare?" Now that we have modelled the new automated hybrid manufacturing system of Signify in Chapter 4, it is important to see how it relates to the current manufacturing system. The study by Crooymans (2022) is used to examine the current manufacturing system in Signify. Crooymans (2022) aimed to determine the desired number of production facilities, while additionally finding the corresponding capacity needed to serve a total demand area for a product that includes AM. The results showed that multiple smaller production facilities are preferred compared to a few big ones to minimize transportation and labour costs, with the capacity of each facility depending on the demand rate. Specifically, the study showed an optimal solution of 10 production facilities, each with 12 AM machines and 1 assembly line capacity. This composition gave the lowest costs while also satisfying the chosen service level and utilization.

Before we start comparing the two systems, it is important that the model of this study is verified, and thus accurate enough to make comparisons with. We already performed some verification tests in Section 4.2. However, we have chosen to do an extra verification by recreating the base model of Crooymans (2022) in our model. After the model is verified, we compare the two manufacturing systems with each other. However, as different assumptions are made by Crooymans (2022), it is not possible to compare the two systems directly. To still make a comparison, the parameters in the study of Crooymans (2022) are estimated to be as close to the situation as described in this study.

First, we verify our model by recreating the model of Crooymans (2022) in Section 6.1. The implementation of this verification is discussed in Section 6.1.1, and the results in Section 6.1.2. In Section 6.2, we adjust the parameters of Crooymans (2022) to represent the assumptions made in this study. Here, we again discuss the implementation (Section 6.2.1) and the results (Section 6.2.2). Finally, a conclusion comparing the models, which answers research question 4 is given in Section 6.3.

### 6.1 Verification by comparison with another model

As previously explained in Section 4.2, the key concept of verifying is sufficient accuracy. We already verified the model based on visual checks, however, a final verification is performed by using the technique comparison with other models (Robinson, 1997). This technique is especially useful when no real system data is available, which is the case in this study.

In the following paragraphs, the model is verified. First, in Section 6.1.1, the implementa-
tion of the parameters of Crooymans (2022) is discussed. Lastly, the results are compared and checked for interesting findings in Section 6.1.2.

### 6.1.1 Implementation

The optimal combination of AM machines, assembly lines and production facilities is 12,1 , and 10 , respectively. This is a completely different manufacturing system than the system we created in this study. Therefore, we use these parameters of Crooymans (2022) in our Tecnomatix Plant Simulation model. By doing so, we can verify our model with the results of Crooymans (2022), and prove that the model in this study is accurate.

First, we changed the number of AM machines, assembly lines, and facilities in our model to match the base model of Crooymans (2022). We also changed some other important parameters of our model, which are discussed next. Because the study of Crooymans (2022) uses a manual system, we removed the box handler and its corresponding attributes. Additionally, we adapted the assumptions by Crooymans (2022) that 6 workers are needed per facility of this size, 1 worker for the AM machines, and 5 workers for the assembly line. We also change the demand input and machine assignment to match Crooymans (2022). The precise input of this model can be found in Appendix F.

A big difference that can be noticed between Crooymans (2022) and our study is the transportation costs and use of demand areas. Crooymans (2022) uses demand areas, with a corresponding total demand rate ( $\lambda$ ) that follows a Poisson distribution and is uniformly distributed within the area. The demand areas are represented by circles with an associated radius with a production facility in the centre. We applied the same demand rate as Crooymans (2022) but we did not account for transportation as this is not included in our study. To make the results of our model and the model by Crooymans (2022) comparable, we excluded the transportation costs from the cost calculation of Crooymans (2022).

Finally, like Crooymans (2022) does, we assume that a year consists of 260 days. This is based on working days (i.e., no weekends and public holidays). Additionally, the workers operate in two shifts, which makes a workday 16 hours. Hence, the model is run for 260 days with 16 hours per day.

### 6.1.2 Results

For final verification of our model, we compare the results of Crooymans (2022) and our recreated model. Table 6.1 shows the results of Crooymans (2022) and the results from our recreated model. We see that all the mean results are very similar to each other. There are, however, a few small differences between the interval bounds of the values. This could be explained by the randomness of the Poisson distribution, as a small change in demand can have quite an effect on this complex model. Additionally, it could be possible that mistakes are made with either the interpretation of the model of Crooymans (2022) or the implementation of the model in Tecnomatix Plant Simulation.

With this verification, we conclude that the model we created in Chapter 4 is, as Robinson (1997) puts it, sufficiently accurate, ensuring that the model meets its requirements and specifications of Signify.

Table 6.1: Comparison of the base experiment results of Crooymans (2022)

|  | Crooymans (2022) |  |  |  | Our model |  |  |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | $\mu$ | $C I$ Left bound | $C I$ | Right bound | $\mu$ | $C I$ |  |
| Left bound | $C I$ Right bound |  |  |  |  |  |  |
| SL | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |  |
| Cycle Time (h) | 50.89 | 46.14 | 54.45 | 52.88 | 50.62 | 54.16 |  |
| $C F(\|\mathcal{T}\|=260) *$ (Thousand $\in)$ | 646 | 646 | 646 | 646 | 646 | 646 |  |
| $C T(\|\mathcal{T}\|=260) *($ Million $\in)$ | 7.46 | 7.46 | 7.46 | 7.46 | 7.46 | 7.46 |  |
| Avg. Costs per Order* (€) | 36.28 | 36.17 | 36.38 | 35.89 | 35.82 | 35.96 |  |
| No. Order Produced | 20,563 | 20,508 | 20,702 | 20,785 | 20,743 | 20,827 |  |
| No. reels Produced | 2,074 | 2,067 | 2,082 | 2,084 | 2,080 | 2,088 |  |
| No. rees Ready if not $C$ | 0 | 0 | 0 | 0 | 0 | 0 |  |
| Average $\mathrm{W}^{\text {AM }}$ (h) | 59.91 | 58.84 | 65.84 | 53.22 | 49.83 | 56.62 |  |
| Average $\mathrm{W}^{\text {AL }}(\mathrm{h})$ | 0.16 | 0.11 | 0.21 | 0.16 | 0.15 | 0.16 |  |
| $\mathrm{U}^{\text {AM }}$ | 0.82 | 0.82 | 0.83 | 0.83 | 0.83 | 0.84 |  |
| $\mathrm{U}^{\text {AL }}$ | 0.82 | 0.82 | 0.83 | 0.83 | 0.83 | 0.83 |  |

### 6.2 Comparison with the current manufacturing system of Signify

To answer research question 4, we want to compare the current and the automated systems with each other. However, the two models that are created for these systems differ too much. The assumptions, parameters, assignment methods and much more, follow different rules in Crooymans (2022) compared to this study. For us to take some kind of conclusions, we adjust the parameters from Crooymans (2022) to be closer to the parameters and assumptions of our study. This estimation is imprecise, therefore we cannot take any hard conclusion from this analysis. However, it does give an idea of how the two systems perform compared to each other. Additionally, an estimation comparison is made of 1 facility against 10 facilities. This comparison can be found in Appendix G. The next paragraphs explain the implementation of the estimation of the parameters in Section 6.2.1. Afterwards, the results are formed and discussed in Section 6.2.2.

### 6.2.1 Implementation

We need to adjust the parameters of Crooymans (2022) to the assumptions of this study. This is done by performing 'back of the envelope' calculations. These are quick and informal mathematical computations that are used to estimate results and get a general idea 'a ballpark estimate' (Widerquist, 2017). To make these estimations of the parameters, we need to know what differences there are between the model of Crooymans (2022) and this study.

The models differ a lot from each other: facility capacity, demand rate, order size, product size, printer assignment, breakdowns, processing times, colour/materials, quality control yields, filament reel assignment, and some other minor differences. Obviously, the two models differ in handling the parts (automated or manually), but this is the thing we want to compare so this is kept as it is. As we cannot change the systems to be exactly the same, there are a few large differences that we want to focus on. Demand has a big influence on the models, as it decides the flow of the model. The order size of the demand is also changed since Crooymans (2022) assumes one part per order, while we assume an Erlang distribution with $k=0.5625$ and $\lambda=0.0375$ for the order size. Additionally, we want to incorporate the multiple product and item types and their characteristics that occur in this study ( 3 products, 4 items). These are, namely, of great importance for the processing of products in the model. Lastly, the quality control check is a big difference that prevents
the comparison of the two models. The study of Crooymans (2022) does not contain a check, thus assuming a $100 \%$ yield.

Equations 6.1, 6.2, 6.3, and 6.4 show the 'back of the envelope' calculations that are made. First, Equation 6.1 calculates the demand rate of the model, we multiply the average orders per day by the average order size with the number of parts in a product. We do this to get an accurate representation of the number of parts that are printed in our system. Finally, we divide it by 16 , to get the number of parts per hour for the Crooymans (2022) model. The second equation (6.2), shows the average yield for the quality control, we first calculate the average yield per product and then take the weighted average over the products, this results in a 0.71 average yield. Next, the average processing time of the AM machines is calculated in Equation 6.3 using the same method as the yield calculations. Lastly, we calculate in Equation 6.4 again in the same manner and look at how many fit in a reel of 10 kg . The final input parameters can be found in Table 6.2.

$$
\begin{align*}
\lambda= & 10 \cdot 7.5 \cdot 4 / 16=18.75 \text { parts.per.hour }  \tag{6.1}\\
\gamma= & 0.25 \cdot\left(\frac{0.98+0.5+0.78+0.64}{4}\right)+0.45 \cdot\left(\frac{0.79+0.43+0.99+0.55}{4}\right) \\
& +0.3 \cdot\left(\frac{0.78+0.34+0.87+97}{4}\right)=0.71  \tag{6.2}\\
P^{3 \mathrm{DP}}= & 0.25 \cdot\left(\frac{60+20+15+80}{4}\right)+0.45 \cdot\left(\frac{90+30+20+100}{4}\right) \\
& +0.3 \cdot\left(\frac{120+45+30+140}{4}\right)=63.2 \text { minutes }  \tag{6.3}\\
C= & 10 /\left(0.25 \cdot\left(\frac{0.1+0.02+0.01+0.2}{4}\right)+0.45 \cdot\left(\frac{0.2+0.04+0.02+0.4}{4}\right)\right. \\
& +0.3 \cdot\left(\frac{0.4+0.08+0.04+0.8}{4}\right)=52 \text { parts.per.filament reel } \tag{6.4}
\end{align*}
$$

Table 6.2: Overview of Input Parameters for estimation comparison

| Parameter | Description | Original input of Crooymans (2022) | Adjusted input of Crooymans (2022) |
| :---: | :---: | :---: | :---: |
| $\gamma$ | Quality control Yield | 1 | 0.71 |
| $\lambda$ | Total Demand Rate (products/hour) | 50 | 18.75 |
| C | Maximum Capacity Filament reel (products) | 10 | 52 |
| $F$ | Number of Production Facilities | 10 | 1 |
| K | Number of Possible Colors | 1 | 6 |
| $L T$ | Lead Time for Customer (days) | 8 | 21 |
| M | Number of AM machines | 12 | 48 |
| $N$ | Number of Assembly Lines | 1 | 1 |
| $P^{3 \mathrm{DP}}$ | Average Processing Time on AM machine (hours) | 2 | 1.05 |
| $P^{\text {AL }}$ | Average Processing Time on Assembly Line (minutes) | 10 | 10 |
| $S$ | Threshold for Latest Time to Start Assignment of Filament reel of AM machine (days) | 1 | 1 |
| $\|\mathcal{T}\|$ | Modelling/Simulation Time (days) | 260 | 84 |
| $T^{\text {change-over }}$ | Change-over Time for AM machine (hours) | 2 | 0.17 |
| $T^{\text {check }}$ | Intermediate Time Step to Check Status of Filament reel (hours) | 1 | 1 |
| W | Amount of Workers in the system | 6 | 11* |

[^1]
### 6.2.2 Results

As mentioned in Section 6.2.1, the new input parameters for the model of Crooymans (2022) are not completely accurate, however, they give a good indication of the current system. We run the model of Crooymans (2022) with the input parameters for two different scenarios: $\lambda=18.75$ and $\lambda=26.41$. The first demand rate is calculated with Equation 6.1, and the second demand rate is calculated by dividing the demand rate by the average yield (0.71). By doing this, we account for the rework that has to be done on the AM machines $(\lambda=26.41)$. For the assembly line, this rework should not be taken into account, thus the results of $\lambda=18.75$ are relevant for the KPIs concerning the assembly line. The results of the adjusted parameters are found in Table 6.3. Here, we had to use the cost calculations as proposed by Crooymans (2022) due to the assumptions made.

From the results, we can see that the current model can easily process all the demand that flows through the system. The utilization rates are low for both the AM process and the assembly line. We expect that the reason behind the higher utilization of the assembly line is the congestion before the assembly line. The parts are printed on multiple AM machines, which then need to go to one assembly line where they are waiting. Table 6.3 also shows the cost resulting from this input. We notice that the cost of workers is quite high, compared to the original results of Crooymans (2022) as more workers are needed for more AM machines (48).

### 6.3 Conclusion

Now that we verified the model completely, we can more strongly confirm that the model from Chapter 4 is sufficiently accurate to retrieve results from and use for experiments. Hence, we can compare our model with the model created in Section 6.2.

Table 6.3: Simulation results of Crooymans (2022) with adjusted input parameters

| KPIs | Results Crooymans (2022) |  |  | Our model results |  |  |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
|  | $\mu$ | $C I$ | Left bound | $C I$ | Right bound | $\mu$ |
| $C I$ | Left bound | $C I$ | Right bound |  |  |  |
| SL | 1.00 | 1.00 | 1.00 | 0.76 | 0.72 | 0.79 |
| Total Costs (Thousand €) | 527.60 | 527.60 | 527.60 | 460.70 | 460.70 | 460.70 |
| Cost Facility (€) | 100,000 | 100,000 | 100,000 | 100,000 | 100,000 | 100,000 |
| Cost AM machines (€) | 48,000 | 48,000 | 48,000 | 48,312 | 48,312 | 48,312 |
| Cost Assembly Line (€) | 10,000 | 10,000 | 10,000 | 10,000 | 10,000 | 10,000 |
| Cost Workers (€) | 369,600 | 369,600 | 369,600 | 302,400 | 302,400 | 302,400 |
| Avg. Costs per Order (€) | 50 | 47 | 53 | 52 | 40 | 63 |
| U $^{\text {AM }}$ | 0.45 | 0.45 | 0.45 | 0.86 | 0.86 | 0.87 |
| U $^{\text {AL }}$ | 0.62 | 0.61 | 0.62 | 0.32 | 0.31 | 0.33 |

The differences between the automatic- and current manufacturing systems can be seen in Table 6.3. For the utilization, we see that all the utilization rates are relatively low and can process the number of orders fairly easily, except for the AM machines on the automatic manufacturing system. This can partly be explained by the downtime an AM machine can have in the automatic system, whereas the current system assumes no downtime of the machines. Additionally, set-up times are expected to be higher in the automatic manufacturing system as this system waits for a worker to be available again before a set-up can be performed. The current system does have more workers decreasing this impact, but nevertheless, we expect this to have some influence as well. Although the actual utilization of the AM machines in the current system is expected to be a bit higher than the given value, the utilization of the AM machines in the automatic system is too high. Furthermore, the utilization rate for the current system displays more issues at the assembly line,
while contrariwise this is the case for the automated system. Presumably, this happens due to the automated system having a storage space in the box handler, which stores all the orders until needed at the assembly and causes congestion at the AM machines.

For the costs, we also notice differences, as fewer costs are made at the automated system. The facility and assembly line costs are equal in both cases as there is 1 facility and 1 assembly line in both cases. The costs of the AM machines are higher in the automated system since the box handler adds a bit more cost, but this difference is very small. The real difference is seen between the cost of workers, which is less in the automated system because fewer workers are needed. This is also the point where we expect the automatic system to outperform the current system.

We tried to make the parameters in the two models as similar as possible, however, the automated model still contains many more details than the current model (e.g. breakdowns, assembly yield, transportation time in the facility). The fact that the automatic system can keep up with the same demand as the current model for lower costs shows the possible benefit of the automatic system. However, the high utilization at the AM Machines should be kept in mind, as this might be problematic if demand has high variability. Finally, we want to note again that this is an estimation comparison, which means that the results are not precisely accurate and therefore we cannot conclude that one system is better than the other.

## Chapter 7

## Discussion, Conclusion \& Recommendations

We have explored the subject of how automated hybrid manufacturing can be implemented in industrial settings to improve production efficiency and reduce costs. A main question and five research questions were identified upfront and answered throughout this study, including the characteristics of an automated hybrid system, the identification of key performance indicators, the modelling of the manufacturing system, numerical experiments to understand the behaviour of the model, and the comparison of an automated to a current manufacturing system.

In this section, we examine the findings from the research about these research questions and the main question. We provide a summary of the key results and explore their implications for future research and industrial practice. This chapter is organized into five main parts. The first part (Section 7.1) gives a conclusion on the main finding of this study, including an answer to the main question we formulated in Section 2.2. In Section 7.2, we examine the contribution of the study to literature and Signify. Next, in Section 7.3 we present the limitations of this study. We then explore several directions for future research in Section 7.4. Finally, the main recommendations established for Signify are discussed in Section 7.5.

### 7.1 Conclusion

In this section, we provide a concise summary of the most significant findings of this study. Additionally, a reflection is given on the outcomes and shortly discussed. Finally, we answer the main question: How to design and analyse an automated hybrid additive manufacturing facility?

In Chapter 3, we addressed two research questions (RQ1 and RQ2): What does the automated hybrid manufacturing system look like? and What key performance indicators should be used to evaluate the automated hybrid manufacturing system? The system consists of three production units (box handler, quality control, and assembly \& packaging), storage places, and production flows. The box handler process involves printing parts from filaments on an AM machine, which are then stored in an automatic system called the box handler. Quality control checks the parts, and assembly \& packaging assembles them into the final product for transport to the customer. We also discuss the process of identifying key performance indicators (KPIs) for the system, including cycle time, service level, and manufacturing costs.

Next, in Chapter 4, we use a simulation model to answer research question 3: How do we model the automated hybrid manufacturing system? We implemented the model using
a discrete-event-simulation (DES) model. The model was created with Tecnomatix Plant Simulation software. We evaluate the model by performing verification tests and identifying bottlenecks, which we determine to be the AM machines.

We discuss the base experiment and numerical experiments in Chapter 5, to understand Signify's AM facility and answer RQ4: How can numerical experiments optimize the design of an AM facility with an automated manufacturing system? We started with a realistic base experiment approved by Signify. Based on the base experiment results, we proposed four experiments to test the AM facility model's limits. Results showed that increasing item yield led to better system performance and customer satisfaction. Decreasing the capacity of the box handler showed how much demand can fit into the system with the original box handler. Introducing more filament colours/materials had a small impact on KPIs but increased total costs per product. Adjusting the number of AM machines showed a trade-off between the costs and the service level.

Finally, in Chapter 6, we compare Signify's current manufacturing system and their new automated hybrid system, addressing research question 5: How do the current manual and new automated manufacturing systems compare? We use Crooymans (2022) to examine the current system, verifying our model's accuracy by comparing it to its base model. By comparing the current and automated systems, we found that the automated system handles the same demand with lower costs due to the reduction of the number of workers, but has a higher utilization rate for the AM Machines.

In conclusion, we answer the main research question we defined in Section 2.2. Designing an additive manufacturing facility that incorporates an automated hybrid manufacturing system can be a difficult task. This can be challenging due to potential bottlenecks, such as the box handler, which we identified as a crucial factor in determining the facility's output. To ensure smooth operations with Signify's demand, a box handler with a capacity of at least 668 boxes is essential. Another factor to consider is the number of AM machines required. If the demand is high, it may be necessary to have more than 48 AM machines to meet production targets. However, it is also important to evaluate the demand and determine if decreasing it is a viable option. Furthermore, increasing yield is the key to maximizing efficiency and productivity, by minimizing waste and improving service levels. Additionally, cost optimization can be achieved by reducing labour and material costs, and by decreasing the number of workers and filament reels used.

Using DES to design the facility provides flexibility in adapting to changes in demand and production requirements. Simulating different scenarios allows for real-time evaluation of the impact of changes and system adjustments. Ultimately, designing an AM facility with an automated hybrid manufacturing system requires careful consideration of various factors, including box handler capacity, the number of AM machines, demand, yield optimization, and cost optimization, leading to an efficient, productive, and cost-effective facility.

### 7.2 Contribution of the study

Overall, the report can contribute to both Signify and the literature by providing valuable insights into the benefits and challenges of using automated hybrid manufacturing systems, as well as providing guidance for companies looking to adopt these systems and identifying areas for future research.

For Signify, the study can provide valuable insights into the benefits of using automated hybrid manufacturing systems compared to their current manufacturing system. The study can help Signify understand the advantages of implementing these systems, including increased efficiency of their lead time, reduced costs, and improved cycle time. Furthermore,
it helps in making design decisions for the system by addressing the bottlenecks and potential problems in the system, such as the limited box handler storage and high utilization of the AM machines. Next to these insights, the methodology used in this study can serve as a guide for Signify, but also for other companies, for creating insights using a simulation, optionally using Plant Simulation. We showed that Plant Simulation offers the possibility to simulate a highly complex manufacturing system, even if the facility does not exist in reality yet. Thanks to this, valuable insight into the behaviour of the system under different scenarios can be created. Plant Simulation can help Signify and other companies to optimize facility operations, reduce costs, and identify potential problems.

As we stated in Section 7.2, the field of Additive Manufacturing (AM) has seen a significant amount of research focusing on prototyping, materials, and understanding of the concept itself. However, recent studies indicate that the implementation of AM in specific industries, particularly in supply chains and AM facilities, has become an increasingly important topic. Despite several studies highlighting the benefits of automated manufacturing systems, there is limited research available that looks at automated processes in combination with hybrid manufacturing AM facilities. This study addresses this gap by providing a comprehensive examination of the topic. This report provides insights into how automated hybrid manufacturing systems can be integrated into existing supply chains and AM facilities and sets possible directions for future research and development in this area.

### 7.3 Limitations

Although effort has been made to ensure that the study was conducted with rigour and accuracy, several limitations should be acknowledged. We can break down the limitations into three different categories, namely general limitations during the study, model limitations, and limitations about the comparison with the study of Crooymans (2022).

### 7.3.1 General Limitations

Firstly, it should be noted that in general all estimates of parameters used in the study were not based on historical data but on assumptions, which may not be entirely accurate. This may cause the model outcomes to be inaccurate in some cases. To prevent this as much as possible, we chose these parameters in consolation with experts within Signify, thus we can define the values as realistic and reliable. However, it is advisable to validate the simulation once the additive manufacturing system is operating in reality.

Secondly, the results from this research are specific to the case of Signify. Therefore, results may be different if there is a different facility setup, different parameter values, different machinery, or different worker schedules. Although this prevents generalizing the outcomes to some extent, this methodology is still reproducible for different situations which would still lead to valuable insights.

Lastly, the use of Plant Simulation can be called a limitation of this research. Plant Simulation clearly showed its worth in simulating a complex manufacturing environment capturing a lot of aspects, benefiting the outcome of this study. This may not have been possible using a common programming language (e.g., Python) or different simulation software. However, we acknowledge that Plant Simulation might not be easily accessible to everybody because of the software costs and necessary skills to use it.

### 7.3.2 Model Limitations

There are some assumptions in the model which determine the way of working or limit the scope of this research. Some ways of working may impact the model outcomes while
limiting the scope means that the model does not account for some parts of the process. The most important of these assumptions are therefore discussed as limitations.

Firstly, stock limitations are out of the scope of this research. In the model, we assumed that there are no restrictions on non-printed parts, boxes, filament reels, and packaging materials. In practice, this cannot always hold, since it could occur that certain parts are not available anymore. This could influence the production flow in the model, thus affecting the model outcomes. However, if inventory control is on point, this should not be a problem.

Secondly, to simplify the model, we assumed that only one part per AM machine could be printed at the same time. In reality, Signfiy can print multiple parts at the same time on a machine. Relaxing this assumption might speed up the printing process, decrease the utilization of the AM machines, and thus improve the cycle time. However, we can not be certain of the exact impact of this assumption.
Thirdly, we assumed a fixed number of workers at the start of this study. In Section 5.1.2, the worker utilization rate was defined as 0.29 . This is very low, which suggests that the number of workers we determined beforehand where too many. The number of workers has a big impact on the costs of this study. When reducing the number of workers, the costs also change. This model with fewer workers should be further researched in the future.

Next, the decision rule of only letting completely checked orders flow through to the assembly line can be changed. Since there were no decision rules, we decided upon this ourselves. This rule can influence the study's findings. Another rule that we could have used was cutting orders into smaller pieces and sending these pieces through the system. This would have caused less blocking in the box handler storage and might also show good results.

Finally, the way print jobs were assigned and scheduled to AM machines could have been done differently, as we used a heuristic. This may have affected the study's findings. The printer assignment is a big decision rule as it determines how efficiently print jobs are distributed over the AM machines. Hence, it is possible that a more efficient scheduling method could give better results, and therefore the study's results may not be as positive as they could be.

We can conclude that we made various assumptions in our model. This makes the outcomes of our study not exact, and the findings may not be entirely accurate. However, by carefully deciding on the assumptions we believe that our findings are still useful and representative of reality, despite the assumptions made.

### 7.3.3 Comparison Limitations

Lastly, we acknowledge that there are a few limitations in Section 6.2 about the comparison with the study of Crooymans (2022). As already mentioned in that chapter, the comparison between the automated and the current system is not very strong. The parameter calculations are based on 'back of the envelope' estimations, therefore it may be difficult to draw valid conclusions from them. We already noted that we cannot make hard conclusions about the comparison. But since the models of the two systems were too different it was difficult to perform a very accurate comparison. However, we can get a valid idea from this estimation, which could be further researched in the future.

Lastly, we used the study of Crooymans (2022) for verification and comparison, however, there is a possibility of implementation errors. For one there is a possibility of errors in the current model made by Crooymans (2022). Since we make conclusions based on the study of Crooymans (2022) if there are any errors they automatically are also implemented in
our study. Furthermore, we could have wrongly integrated the conclusions of Crooymans (2022) study. It is possible that we did not fully understand the study and therefore wrongfully made conclusions which were not intended by Crooymans (2022).

In conclusion, despite the limitations outlined above, this research provides valuable insights into the feasibility of automation and AM in a manufacturing environment. However, the limitations must be taken into account when interpreting the results and drawing conclusions. Future research should address these limitations and further refine the research.

### 7.4 Future Research

Based on the findings and limitations of this master thesis, we present directions for future research. Future research focuses on improving the general understanding of automation in a manufacturing environment, developing more realistic models, and conducting additional experiments to test the system's performance under different scenarios.

Firstly, as the study indicated, an automated AM system can be a more cost-effective option. We saw in this study that a current system relies on workers to perform tasks and transport parts. However, relying on workers has shown to be very expensive. However, a 0.29 worker utilization rate was found, which indicates that the model can easily handle worker reduction. The expenses for operational factors in a manufacturing system easily outway the expenses for the plant itself. Therefore, future research could explore the optimal degree of automation for different manufacturing environments and the cost-benefit analysis of such a system. Additionally, we saw that many filament reels are changed, which cost Signify a lot of money, workers, and production time. Another input for AM machines is pellets, this reduces the setup time as it only needs to be added to the printer and not dried in the oven. Furthermore, pellets are cheaper than filament reels, since the filament reels need to be processed from pellets to reels. The pellet printers also show some disadvantages, only limited details can be printed, and more printing defects could occur. By modelling the pellet printers into the system, Signify could see how the defects way out to the costs that it could save. Hence, it is interesting for Signify to evaluate the possibility of pellet printers in a manufacturing system.

Secondly, plant simulation is a useful tool for manufacturers in this study. It is a valuable tool for engineers and managers as it allows them to optimize production processes and reduce costs. Although the tool is difficult to understand directly, as it can be a complex and time-consuming process. We have shown in this study that it can help identify bottlenecks, find areas where costs can be reduced, implement tests and evaluate different scenarios, and be used to validate the design of a production process. By using this tool, future research could focus on developing a model to become more realistic. This would involve adding more attributes to the model to make them more accurate and reflective of real-world conditions. Relaxing assumptions made during the research could help make the models more accurate. Eventually, after creating a very realistic model, you could even make the model a digital twin of the real-world system.

Thirdly, we saw in this study that the yield is a big cause of the high utilization of the AM machines, the blocking of the box handler storage, and the overall $C T$. Hence, future research should focus on finding ways to increase this yield. Furthermore, the yield could also be increased when considering an additional post-processing machine (like sanding, polishing, or coating) to improve the quality of the print (Zhang \& Liou, 2021). This can help remove defects and fewer printed parts will need to be thrown away. However, the machine will cost an additional amount of money and maybe even workers. We suggest future research to investigate to see if increasing the yield is worth the investment in this system.

Finally, additional experiments could be conducted to test the system's performance under different scenarios. We already explained four potential experiments in Appendix D. These experiments include variations in print job assignment, different box-filling methods, night/weekend print job queues, and including consumer demand. The findings from such experiments would provide additional valuable insights into the system's robustness and help optimize the production process.

In conclusion, the findings of this study provide a starting point for future research into the use of automated AM in a manufacturing environment. Further research in the areas of automation, plant simulation, realistic modelling, and experiments will help refine the findings and optimize the production process.

### 7.5 Recommendations for Signify

In this study, we looked at how automated hybrid manufacturing can be implemented in industrial settings to improve production efficiency and reduce costs. This section provides recommendations for how the findings of this study can be applied to improve Signify's manufacturing systems.

Firstly, plant simulation is a useful tool for optimizing manufacturing systems. Therefore, Signify could consider implementing plant simulation software to model and analyze its production processes. This would allow them to identify bottlenecks, optimize their production line, and improve overall efficiency while offering visual insights into the manufacturing systems.

Secondly, this study highlights the benefits of automated systems over current ones. Therefore, Signify should consider automating its production process wherever possible. This would help reduce labour costs and improve efficiency, while also reducing the risk of manual errors. Using plant simulation, as stated before, can help with the right system design for such automated systems.

Thirdly, the study identifies workers and filament reels as the biggest costs in the 3D printing production process. Therefore, Signify should focus on strategies to reduce these costs. For example, they could implement lean manufacturing techniques to reduce waste and optimize their production line. They could also consider alternative sources for filament reels or explore alternative materials that are more cost-effective.

Finally, from the analysis of the box handler capacity follows that the box handler capacity is insufficient. Because the storage fills up, the system gets blocked and the AM machines stop working as they cannot store the printed parts. Furthermore, the demand for AM machines is too much, which can be derived from the high utilization. Having a high utilization in combination with variable demand leads to high waiting times at the AM machines, which in turn leads to a high cycle time. Therefore, we would recommend adding more AM machines to the setup so the demand can be spread and this is prevented from happening. An impactful alternative would be to focus on increasing the yield of products. In this study, we found that the amount of rework is enormous, increasing the demand for AM machines. If the yield can be improved, fewer parts will fail the quality check, in turn decreasing the demand for the AM machines. This second solution may be harder to implement but would save on machinery costs, material costs, energy costs and space in the manufacturing facility.

In conclusion, the findings of this master thesis provide valuable insights into how manufacturing systems can be improved through the use of automation and AM. By implementing plant simulation, automating the production process, reducing costs, and enhancing the system, Signify can optimize its production line, reduce costs, and improve overall efficiency.

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## Appendix A

## Analytical vs. Simulation Modelling

Both analytical and simulation modelling have important benefits for automated hybrid manufacturing systems but also have critical drawbacks. The main difference between these two modelling methods is complexity. Analytical models are often known to require less effort and are easier to use but have less detail in the model (Hsieh, 2002; Zhou et al., 2012). On the other hand, simulation models are more complex but offer a better representation of the real world (Hsieh, 2002). However, because of their complexity, they require more time and money to create. On the contrary, analytical models are cheaper and take less time to complete. Therefore, an analytical model is a good choice for a simple and quick model, while a simulation model is appropriate for a more complex system with more time available (Banks et al., 2014). Input characteristics also reflect these differences between the two methods. Analytical models require simple input characteristics with a distribution pattern, while simulation models can handle more complex characteristics, but are harder to solve. The choice between the two methods depends on the accuracy needed and the available resources.

For this study, simulation modelling has been chosen for Signify's printing facility. This decision was based on four critical points in the system: filament change-over, preparation of the AM machine, rework/request for a new part, and assembly \& packaging PU. In the following paragraphs, the reasons behind this decision for these four points are discussed.

As noted in Section 3.1.1, the box handler has an unlimited supply of filament reels as the filament is created in-house at a separate facility. Nevertheless, the assignment of filament to the AM machines within the box handler is included in the scope. Each AM machine has an oven to dry the filament reels. Signify creates around 40 different luminaire colours, such as recycled glossy white, transparent lime, or metallic blue (Philips Lighting, 2022c). Additionally, Signify has started producing filaments from recycled fishing nets instead of the traditional polycarbonate material used for luminaire production (Philips: My Creation, 2022). This results in a filament assignment problem within the box handler as there are 40 different colours and materials to choose from for each order. To change the filament reel in the oven, a certain amount of time is required for the reel to dry. This leads to changeover times for filament reels and affects the setup time. Analytical studies do not support setup times that vary per item. Assumptions need to be made to make this possible for an analytical study, which changes the complete representation of the manufacturing system.

Before the AM machine starts printing, the machine needs to be prepared. The setup consists of several setting steps, like material type, layer thickness, and travelling speed.

Subsequently, the base plate of the AM machine needs to be heated up to the right temperature. Since the AM machine needs to be cooled off before removing the printed part, the heating of the base plate needs to happen every time a newly printed part is printed. Again an analytical study requires assumptions for the setup times. These assumptions are not representative of the model.

Another important point is the return of parts to the Automated Hybrid Manufacturing system, which occurs during two stages: the quality check and assembly. If a part fails the quality check, a request for a new part is sent to the box handler and the entire order must wait until the new part is printed and checked. The same process happens during assembly, but with a non-printable part. If the non-printable part fails the test, it returns to the assembly for a check to determine if it was incorrectly assembled. If not, a request for a new part is made and the assembly \& packaging process is stopped until the new part is retrieved. The queuing theory (used for the analytical study) does not support returning parts/orders in the system, which makes it difficult to perform an analytical study.

Lastly, the PU assembly \& packaging is not a deterministic process, this process is fully dependent on the workers. The workers are needed to assemble, test and package the products. However, the workers are only available during the day, require breaks, and also work in shifts. This makes the PU assembly \& packaging a difficult process to analytically calculate. It has many factors that need to be considered, which is difficult for a queuing theory.

Although assumptions can be made to simplify these critical points, such as assuming negligible setup times. However, these would make the model less realistic and detailed, especially when multiple assumptions are used. For this reason, we have decided, together with Signify, that a simulation model is the best approach for this study.

## Appendix B

## Simulation Warm-up Period and Runs

This section gives an overview of the simulation warm-up period and the number of runs $(n)$. First, we discuss the simulation run time. Next, we generate the number of runs needed to receive accurate results.

The simulation run time $(\mathcal{T})$ is the modelling time of the system. At that moment, when the simulation starts modelling some time is needed to reach a steady state. This time can make a big difference in the model since it is a time in which the model does not show accurate results. By determining a warm-up period the effects of the initialization can be diminished and more representative values can result from the simulation. Therefore, we have chosen to remove in the model the time it takes until the steady state phase is reached. Figure B.1, shows the analysis that was performed to find the time to reach a steady state for the simulation. The figure shows that in the first four days, the results are not trustworthy and vary a lot. Hence, we can say that the warm-up period is during the first three days of the simulation. This time is removed from the simulation run time.


Figure B.1: Warm-up period for the Costs

Second, we use the central limit theorem (CLT) to determine the number of runs. The model in this study contains many independent random variables, which causes its normalized sum to tend towards a normal distribution (Boon et al., 2021). The CLT makes
it possible to do a trade-off between execution time and result quality. We base the result quality on the confidence intervals ( $C I$ ) of $95 \%$. Based on the book of Boon et al. (2021), Equation B.1, and Equation B. 2 can calculate the CLT.

$$
\begin{gather*}
C I=\left(\bar{Z}-z_{\alpha} \cdot \sqrt{\frac{S^{2}}{n}}, \bar{Z}+z_{\alpha} \cdot \sqrt{\frac{S^{2}}{n}}\right)  \tag{B.1}\\
\bar{Z}=\frac{Z_{1}+Z_{2}+\ldots+Z_{n}}{n} \quad S^{2}=\frac{1}{n-1} \cdot \sum_{i=1}^{n}\left(Z_{i}-\bar{Z}\right)^{2} \tag{B.2}
\end{gather*}
$$

The software Tecnomatix Plant Simulation, which we use in this study, uses the tool Experiment Manager. This tool can automatically evaluate the number of runs generated for a model based on the $C I$. It applies the same equations of the CLT theory as stated above. In Table B.1, we display the results of the KPI: Total Costs for 5, 25, 50, 75, and 100 runs.

Table B.1: The central limit theorem executed for the Total Costs with numerous runs

| runs $(n)$ | $\mu$ | $\sigma$ | Minimum | Maximum | Left interval bound | Right interval bound |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 5 | 352,096 | 3,840 | 349,254 | 358,784 | 347,327 | 356,865 |
| 25 | 350,940 | 8,541 | 338,134 | 365,064 | 347,449 | 354,430 |
| 50 | 351,108 | 7,941 | 338,134 | 368,267 | 348,762 | 353,455 |
| 75 | 350,027 | 7,356 | 338,134 | 368,267 | 348,239 | 351,816 |
| 100 | 351,872 | 6,871 | 338,134 | 367,389 | 350,420 | 353,324 |

After generating these results for the different runs, we can conclude that the left interval and right interval of the $C I$ do not change a lot after 25 runs. From 5 to 25 runs a big difference in the interval size can be seen, subsequently, this happens from 25 to 50 runs. After the 50 runs, the interval sizes all become a little bit more precise but stay similar. Running the model 100 times costs Plant Simulation 1.17 hours. At 100 runs, the size of the $C I$ is less than $1 \%$ of the mean, which is a good ratio. Therefore, we have chosen to generate the results using the simulation of 100 runs $(n)$. Table B. 2 shows the results of the KPIs with 100 runs.

Table B.2: The central limit theorem executed for $n=100$

| KPIs | $\mu$ | $\sigma$ | Minimum | Maximum | Left <br> interval <br> bound | Right <br> interval <br> bound |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Total Costs |  |  |  |  | 350,420 | 353,324 |
| Cost per completed product | 43.16 | 2.10 | 39.98 | 48.11 | 42.20 | 44.12 |
| Service Level | 0.73 | 0.08 | 0.57 | 0.86 | 0.69 | 0.77 |
| Average Cycle Time (d) | 16.04 | 1.92 | 13.04 | 19.92 | 15.17 | 16.92 |
| Max box handler Capacity | 668 | 54.44 | 582 | 796 | 642 | 694 |

## Appendix C

## Base Experiment Detailed Input parameters

Table C. 1 and Table C.2, both present the detailed characteristics of the printable and non-printable parts.

Table C.1: Detailed Printable Items Input parameters of the Base Model

| Printable Item | Weight <br> in $\mathrm{kg}\left(\omega_{i}\right)$ | Yield <br> $\left(\gamma_{i}\right)$ | Processing <br> Time inspection <br> hours $\left(\rho_{i}\right)$ |  |  |
| :--- | :--- | :--- | :--- | :--- | :--- |
|  |  |  | Time in <br> $\min \left(\xi_{p}\right)$ | Limit <br> $\left(\beta_{i_{b}}\right)$ |  |
| Front_Rim_S | 0.10 | 0.98 | $1: 00: 00$ | $1: 00$ | 75 |
| Mixing_Cup_S | 0.02 | 0.50 | $20: 00$ | $0: 30$ | 100 |
| Mixing_Cup_Holder_S | 0.01 | 0.78 | $15: 00$ | $0: 30$ | 75 |
| Housing_S | 0.20 | 0.64 | $1: 20: 00$ | $1: 00$ | 50 |
| Front_Rim_M | 0.20 | 0.79 | $1: 30: 00$ | $1: 00$ | 50 |
| Mixing_Cup_M | 0.04 | 0.43 | $30: 00$ | $0: 30$ | 75 |
| Mixing_Cup_Holder_M | 0.02 | 0.99 | $20: 00$ | $0: 30$ | 50 |
| Housing_M | 0.40 | 0.55 | $1: 40: 00$ | $1: 00$ | 25 |
| Front_Rim_L | 0.40 | 0.78 | $2: 00: 00$ | $1: 00$ | 25 |
| Mixing_Cup_L | 0.08 | 0.34 | $45: 00$ | $0: 30$ | 50 |
| Mixing_Cup_Holder_L | 0.04 | 0.87 | $30: 00$ | $0: 30$ | 25 |
| Housing_L | 0.80 | 0.97 | $2: 20: 00$ | $1: 00$ | 10 |

Table C.2: Detailed Non-Printable Items Input parameters of the Base Model

| Down_Light_S | Non-Printable Item | Yield $\left(\gamma_{i}\right)$ |
| :--- | :--- | :---: |
|  | Led Module | 0.97 |
|  | Reflector | 0.99 |
|  | Led Driver | 0.83 |
| Down_Light_M | Non-Printable Item | Yield |
|  | Led Module | 0.98 |
|  | Reflector | 0.99 |
|  | Led Driver | 0.57 |
| Down_Light_L | Non-Printable Item | Yield |
|  | Led Module | 0.98 |
|  | Reflector | 0.97 |
|  | Led Driver | 0.66 |

## Appendix D

## Extra Numerical Experiments

Due to a lack of time, we could only conduct four numerical experiments. In Section 5.2, we perform a series of four experiments: Decrease the $L T$, increase the capacity of the box handler storage, increase the number of filament materials, and adapt the number of AM machines. Each experiment is carefully chosen for its ease of implementation, the potential for achieving optimal outcomes, and overall importance to Signify's business. Below we discuss four more experiments that could be performed to get more information about the behaviour of the model.

## Different assignment of Print Jobs

In our model, print jobs are defined as a part of an order that needs to be completed by the AM machine. When an order has arrived, the print job is sent to the AM machine. Currently, the print jobs are assigned to an AM machine through the available filament material on the machine: First, if the AM machine has the same filament material as the print job needs and the AM machine is available, the print job is assigned to this machine. If that is not possible, next the print job is assigned to the AM machine which is available (no matter what filament material is present in that machine). If such a machine is not available, the print job is distributed to an AM machine, which has the right filament material available in the machine (although the machine is not free). Finally, if the first three methods are not possible, the print job is sent to the machine with the lowest amount of print jobs in the queue. This distribution method gives priority to the availability of the machines, it prefers an available machine before no filament material setup.

We predict that this method could decrease the number of idle machines, and possibly decrease the $L T$. However, it also causes more setups, which means more workers are needed. It could be interesting to see what changes in the model when distributing the print jobs differently. This information is very interesting for Signify since it could change the $L T$ and the need for workers.

For this experiment, a distribution method needs to be changed, this will require a few changes in the model's code. For this experiment, we will change the distribution to:

- Filament Material focused assignment (as few setups as possible)
- Production-focused assignment (as few idle machines as possible)


## Different filling method of the boxes

The boxes in the model can be filled in two different ways: per product, or per part. The base model fills the boxes per part, hence with the same type of parts and stops when it is full or when a new type of part is printed. The per-product method fills the box by adding in all the parts that make the product. This method could fill the box with only one product or even more products. The current method causes the boxes to move as a complete order since all boxes are needed for the assembly of a product. While the
per-product method could already start assembling even though a box is still being quality checked. For Signify, it is interesting to see how both filling methods perform because Signify has not determined exactly what filling method it wants to apply.

It is expected that the per-product method could cause blocking at the assembly station. When waiting on the boxes, the assembly needs to stop and cannot continue unless the other products in the box arrive. While the per-part method could have a bigger $L T$ because the boxes need to move in order through the manufacturing system.

This experiment will cost more time to implement, since the method of filling needs to be changed completely. However, the comparison of these methods could show a big difference in performance.

## Night/Weekend queue for Print Jobs

At Signify the workers work during the week from 7:00 AM to 9:00 PM in two shifts. This means that there are no workers present during the night and at the weekends. The AM machines in the production facility need workers during setups of the filament materials and when a breakdown of the machine occurs. A breakdown of the machine is defined by Hopp \& Spearman (2000) as a preemptive outage, the break the own occurs whether we want it or not. A setup of the filament material is defined as a non-preemptive outage, this is a breakdown that occurs, but we can control exactly when (Hopp \& Spearman, 2000). Hence, a preemptive outage cannot be prevented if it happens during the night/weekend. When this occurs, the machine needs to wait until the moment a worker is available and cannot create parts during this time. However, the non-preemptive outage can be planned to not happen or happen as little as possible. A night/weekend queue for the print jobs can be made to ensure this. In this queue only parts can be printed that do not need a filament material change, hence, the model should form a print job queue when the final setups are made by the workers before the night or before the weekend. The print job queue should distribute the print jobs according to the filament material in the AM machine. Another option could be to have only a few workers present at the night/weekend. These workers will probably not be enough to maintain the whole AM facility. However, they could be used to fix failures on the AM machines. Therefore, it is interesting to see how a few workers that can fix AM failures and the night/weekend print job queue combined to influence the system. We can perform four studies: a weekend print job queue, a night print job queue, a night/weekend print job queue, and a few workers with a night/weekend print job queue.

It is expected that the print job queue will cause the AM machines to manufacture during the off hours. However, we expect that a problem will arise the next morning when the box handler storage is full and the AM machines need to wait on space before continuing printing. Additionally, the print job queue will automatically print the parts in the filament material of the machines, which means that parts that need other filament material need to wait until a worker is present, which can cause a long $L T$. Furthermore, we expect that the combination of a few workers and the night/weekend print job queue will give the shortest $L T$.

This experiment could be very interesting for Signify since it could enhance production immensely. However, it would require a lot of changes in the base model, which can take a lot of time. A separate method for creating the print job queue needs to be formed, which is only activated at night and at the weekends. Additionally, the print job assignment method needs to be changed, to a method that assigns a print job according to the filament material.

## Including consumer demand

For Signify, it would be valuable to understand how the model interacts with different types of demand. Currently, the base case performs with only business orders, these orders
are made a half year before being needed. This gives Signify a long $L T$ to manufacture the luminaires. Moreover, the luminaires are less customized and bought in bigger batches. A different type of demand could be individual consumer orders. This differs from business orders because consumers often want only one, but a more customized luminaire. Furthermore, the individual consumer also requests a shorter $L T$. When an order is placed by a consumer, the consumer will want the luminaire as fast as possible. This issue changes the model heavily, the consumer orders need to have a much shorter $L T$, which indicates that they should have priority over business orders. However, often business orders create more money, hence it is not clear how much priority should be given. Even though Signify's consumer orders are not very numerous, it is interesting to see how a change in the market changes the production of 3D-printed luminaires.

We expect that with the additional consumer demand the model's behaviour will change immensely. To fulfil the $L T$ of the consumer demand, the model will need to give priority over those orders. This will decrease the service level of the business demand. Additionally, more filament reel changes will be needed, as the consumer luminaires will use more different colours/materials. We expect that more useable material is thrown away, costing Signify money and sustainability. The reel changes also require workers, which means more workers are needed to keep up with the setups. To conclude, it is expected that costs and service levels will both increase due to the priority and filament reel changes.

Unfortunately, this experiment could take up a lot of time, due to the change in the behaviour of the orders. The order generation needs to be changed completely, while also adding a method to how consumer demand has priority over business demand. We expect that this experiment will be complicated.

## Appendix E

## Yield of items for Experiment 1

Table E.1: Yield of printable Items for experiment 1

| Printable Item | base ex- <br> periment | $+10 \%$ <br> yield | $+20 \%$ <br> yield | $+30 \%$ <br> yield | $+40 \%$ <br> yield | $+50 \%$ <br> yield | $+60 \%$ <br> yield | $100 \%$ <br> yield |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Front_Rim_S | 0.98 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Mixing_Cup_S | 0.50 | 0.60 | 0.70 | 0.80 | 0.90 | 1.00 | 1.00 | 1.00 |
| Mixing_Cup_Holder_S | 0.78 | 0.88 | 0.98 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Housing_S | 0.64 | 0.74 | 0.84 | 0.94 | 1.00 | 1.00 | 1.00 | 1.00 |
| Front_Rim_M | 0.79 | 0.89 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Mixing_Cup_M | 0.43 | 0.53 | 0.63 | 0.73 | 0.83 | 0.93 | 1.00 | 1.00 |
| Mixing_Cup_Holder_M | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Housing_M | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | 1.00 | 1.00 | 1.00 |
| Front_Rim_L | 0.78 | 0.88 | 0.98 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Mixing_Cup_L | 0.34 | 0.44 | 0.54 | 0.64 | 0.74 | 0.84 | 0.94 | 1.00 |
| Mixing_Cup_Holder_L | 0.87 | 0.97 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Housing_L | 0.97 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

## Appendix F

## Input for the verification in Chapter 6

Table F.1: Overview of Input Parameters for the verification model of Crooymans (2022)

| Symbol | Description | Value |
| :--- | :--- | :--- |
| $\lambda$ | Total Demand Rate | 50 orders/hour |
| $\lambda^{\mathrm{F}}$ | Demand Rate per Facility | 5 orders/hour |
| C | Maximum Capacity Filament Reel | 10 orders |
| $c^{3 \mathrm{DP}}$ | Purchase Costs per 3DP | $€ 1,000$ |
| $c^{\mathrm{AL}}$ | Purchase Costs per AL | $€ 10,000$ |
| $c^{\mathrm{F}}$ | Purchase Costs per Production Facility | $€ 100,000$ |
| $c^{\mathrm{L}}$ | Labor Costs per worker | $25 \in /$ hour |
| F | Number of Production Facilities | 10 |
| K | Number of Possible Colors | 1 |
| LT | Lead Time for Customer | 8 days |
| M | Number of AM machines | 12 |
| N | Number of Assembly Lines | 1 |
| $P^{3 \mathrm{DP}}$ | Average Processing Time on AM machine | 2 hours |
| $P^{\text {AL }}$ | Average Processing Time on Assembly Line | 10 minutes |
| S | Threshold for Latest Time to Start Assign- | 1 day |
| $T^{\text {change-over }}$ | ment of Filament Reel of AM machine |  |
| $T^{\text {check }}$ | Change-over Time for AM machine | 2 hours |
|  | Intermediate Time Step to Check Status of | 1 hours |
| $T^{*}$ | Filament Reel | 260 days |
| $W$ | Modelling/Simulation Time | 6 |

## Appendix G

## Comparison of 10 facilities against 1 facility

In this section, we obtain more information about the comparison of producing in multiple facilities or one facility. We perform the comparison by using the base experiment (Section 5.1) and the optimal facility design of Crooymans (2022). According to Crooymans (2022), the optimal number of facilities is 10 with 12 AM machines and 1 assembly line. We use these parameters as input for the comparison.

To simulate the 10 facilities of 12 AM machines and 1 assembly line, we use the input of the base experiment but divide the input over 10 facilities. We adjust the model of the 48 AM machines to 12 and change the number of AM workers to 1 as is done in the study of Crooymans (2022). The model now represents one of the ten facilities. In Table G.1, the results are shown of one facility (from the 10 smaller facilities). Note, that for the 10 facilities together, the results should be multiplied 10 times.

We notice already that having 10 small facilities causes the costs to increase a lot compared to one big facility with 48 machines. This is likely due to there being fewer completed products, but still high fixed costs for the facility ( $€ 100.000$ for the plant, Є25 per worker per hour). Furthermore, the $S L$ of the smaller facility is nearly always 1.00 , because there is much less demand that needs to be fulfilled in one facility. Additionally, less filament per facility is needed, this is again because of the small amount of demand that needs to be finished. However, when looking at the filament reels for all 10 facilities, we see that more is needed than for the base experiment. Finally, the table shows that the box handler capacity is very low, only 20 places for boxes are required at the same time.

The balance between one or ten facilities can be found in the service level vs the costs. On the one hand, by having multiple facilities, the service level becomes a lot better and can even ensure an $L T$ reduction to a few days. This could be a great solution if Signify wants to promise its customers faster production. However, it does cost Signify a lot of money by having more smaller facilities. The major costs are made by the workers needed at all the facilities. Hence, the choice needs to be made between service level and costs.

We would like to add that this comparison is an estimation, as we did not include any transportation costs, which could have a big influence on the results. Additionally, we compared the two situations with the help of the optimal facility design of Crooymans (2022), however, this optimal design might not be a perfect choice. Hence, the results are not precisely accurate.

Table G.1: Results of the model when using Crooymans (2022) optimal number of facilities

| KPIs | $\mu$ | Left <br> interval <br> bound | Right <br> interval <br> bound |
| :--- | :--- | :--- | :--- |
| Total Costs | $1,578,975$ | $1,576,104$ | $1,581,845$ |
| Cost per kg | 91.30 | 89.97 | 92.68 |
| Cost per completed product | 151.46 | 136.97 | 165.94 |
| Filament reels (kg) | 17,294 | 17,006 | 17,581 |
| Service Level | 1.00 | 0.99 | 1.00 |
| Average Cycle Time (d) | 2.27 | 2.25 | 2.29 |
| Max box handler Capacity (per facility) | 19.61 | 19.20 | 20.02 |


[^0]:    *from the study of Crooymans (2022)

[^1]:    *Consists of 4 AM, 5 assembly, and 2 quality control workers

