Increasing the capacity of the consumer packaging lines of Europastry Oldenzaal

May 2024

Master Thesis IEM

Wendie van der Meer s1728113

europastry
We are bakers

UNIVERSITY OF TWENTE.

Document Information

Company:
Europastry Oldenzaal
Coulissenweg 1
7572 PJ Oldenzaal

Research institute:
University of Twente

Study programme:
Industrial Engineering & Management

Specialization:
Production & Logistics Management

Title:
Increasing the capacity of the consumer packaging lines of Europastry Oldenzaal

Student:
Wendie van der Meer, s1728113
Master: Industrial Engineering & Management
Specialization: Production & Logistics management

Supervisory committee:
First supervisor UT: Dr. Ipek Seyran Topan
Second supervisor UT: Dr. Engin Topan
Supervisor Europastry: BJ Hudepohl

Publication date:
16-05-2024

Confidentiality:
To ensure the confidentiality of the company information, all sensitive information is moved to the appendix of this thesis. Next to that, all sensitive numbers shown in the thesis are multiplied by an unknown number.

Management summary

Europastry is a multinational company specialising in producing and distributing frozen bakery products. Europastry Oldenzaal is a part of Europastry central Europe and produces donuts, croissants, and popdots in all forms and shapes. These bakery products are packaged in both bulk and consumer packaging. Bulk packaging is the main type of packaging at the moment. However, the employees of Europastry Oldenzaal noticed a growing desire from customers for consumer packaging, especially for donuts (dots). Since the main type of packaging is still bulk packaging, the packaging lines are not ready for a big shift towards consumer packaging. On lines 1 and 3 several kinds of donuts are baked and packaged, including balldots (filled donuts), crodots (donuts made with croissant dough), minidots (mini donuts) and dots (normal donuts). The consumer packaging used on these packaging lines are flowpackaging (2/4/6 units) and blister packaging (2/4/6/9 units). The production and packaging lines produce and package 24/7 in shifts of 8 hours long. Next to that, there are two consecutive shifts each week for cleaning. Additionally, Europastry Oldenzaal currently has around 2 shifts (16 hours) per week that are scheduled for dots that need consumer packaging. Europastry Oldenzaal expects that the number of shifts will increase to 6 consumer packaging shifts per week. Currently, the average packaging utilization of lines 1 & 3 is 37,11% and 72,73%, respectively. The core problem of this study is that the capacity of the consumer packaging lines 1 & 3 of Europastry Oldenzaal is not high enough for the expected change in packaging preference. This means that not enough dots get packaged per hour. Europastry Oldenzaal wants to increase the utilization of the consumer packaging lines to 95,95%. By increasing the utilization of the consumer packaging lines, the packaging capacity will increase. This utilization is chosen because of other malfunctions at other parts of the line which result in a maximum utilization of 95,95% instead of 100%. Therefore, the main research question of this study is as follows:

How can the utilization of the consumer packaging lines 1 & 3 be increased from 37,11% to 95,95% and 72,73% to 95,95%, respectively?

First, an analysis of the packaging lines 1 and 3 has been performed to determine the problem at hand. Part of this analysis was an inspection of sales and production data. In addition, the output files of the shifts of 2023 have been analysed, and walk-ins on both lines have helped to analyse the current situation. Next to this analysis, a literature study has been conducted. The goal of this literature study was to find ways to improve capacity and solve potential bottlenecks. Next, data was collected to develop a simulation model of both packaging lines. The simulation model enables testing of specific interventions that potentially improve the capacity and was created and validated with a 99% confidence interval paired t-test. Due to a lack of data, not all donuts/packaging are included in the model, the included donuts/packaging are displayed in Table 0.1.

Table 0.1: Overview donuts/packaging included in simulation model

Line	Dot type	Packaging type
Line 1	Crodots	Flowpackaging - 2 units
	Dots	Blister - 4 units
	Minidots	Blister - 6 units
Line 3	Dots	Flowpackaging - 4 units

Next, the interventions were developed based on the analysis and the literature study. The main bottlenecks are the processing time of both packaging types (line 1) and the malfunctions of the flowpacker machine (line 3). These bottlenecks were determined by looking at the active and inactive states of each station in the simulation model (Roser, Nakano, & Tanaka, 2001). In total, 27 different interventions (unique interventions and combinations) were tested. The interventions were evaluated by looking at two performance measures, the utilization (%) and the payback period (years). The results of all interventions were varying, but overall positive. For the flowpackaging (line 1 & 3) and blister packaging (line 1), the most promising interventions are displayed in Table 0.2. In this table, a small description of

the promising interventions is given.

Table 0.2: Overview promising interventions packaging lines 1 and 3

Line (packaging)	**Intervention (combination)**	**Description**
Line 1 - Flowpackaging	3.1	Installing two flowpacker machines to divide the workload
	3.2	Adjusting the speed of the single flowpacker
	1 & 2 & 3.0	Installing a vision system, a buffer and a flowpacker machine
	1 & 3.0	Installing a vision system and a flowpacker machine
	1 & 3.2	Installing a vision system and adjusting the speed of the single flowpacker
	2 & 3.2	Installing a buffer and adjusting the speed of the single flowpacker machine
Line 1 - Blister packaging	4.1	Using cobots instead of employees at the current packaging station
	4.2	Using cobots and an adjusted conveyor belt and placing system
Line 3 - Flowpackaging	3.1	Installing two flowpacker machines to divide the workload
	1 & 2	Installing a vision system and a buffer
	1& 3.1	Installing a vision system and two flowpacker machines

For the flowpackaging of line 1, the most promising interventions are shown in Figure 0.1. For example, intervention 3.1 (line 1) installs two flowpacker machines at line 1. As can be seen in figure 0.1, this intervention increases the utilization by almost 70%. The payback period for the current situation (2 shifts of consumer packaging a week) is around 5 years and the payback period for the expected situation (6 shifts of consumer packaging a week) is around 2 years. For some interventions, only the expected (yellow dots) payback periods are displayed which means that the payback period for such an intervention is similar to the current and expected situation. When taking a look at the biggest utilization improvement, intervention 3.1 is the best option. However, this is also the intervention with the highest payback period. When looking at the payback periods, intervention combination 2 & 3.2 is the most interesting to choose due to having the lowest payback period in both situations. Another interesting intervention is the intervention combination 1& 3.0, this intervention increases the the utilization by approximately 60% while the payback period is around 1.5 years shorter than intervention 3.1.

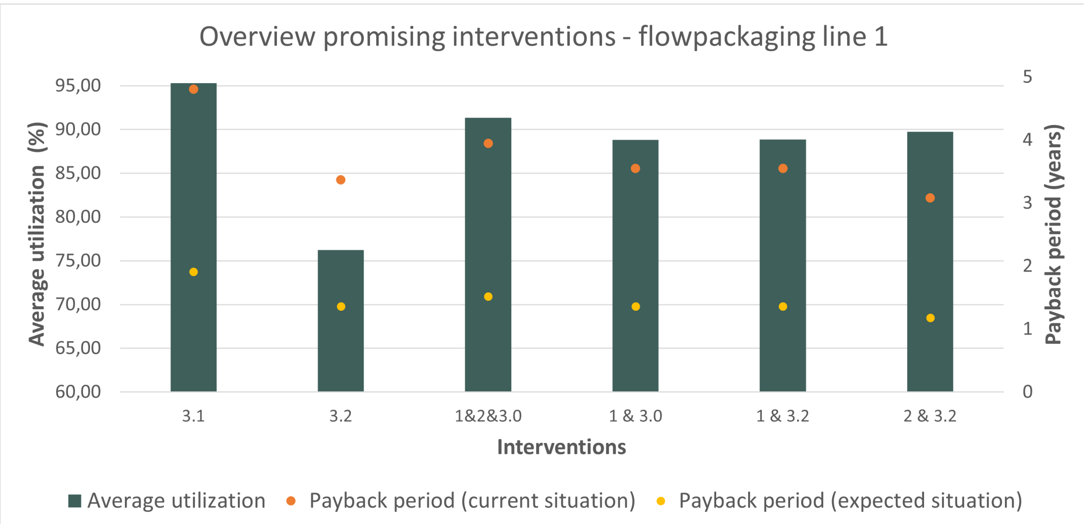

Figure 0.1: Overview performance measures per intervention - line 1 Flowpackaging, (orange/yellow dots are the payback periods, green bars represent the average utilization)

In figure 0.2, the promising interventions are displayed for the blister packaging of line 1, which are intervention 4.1 and 4.2. The graph has the same components as Figure 0.1, so the utilization improvement is represented by green bars and the orange and yellow dots are represented by the payback periods for both the current and expected situations. Both interventions implement cobots in different ways at the packaging line. As can be seen in the figure, intervention

4.1 has a lower utilization improvement, mostly for the minidots, but it does have a better payback period compared to intervention 4.2. So from the utilization improvement point of view, intervention 4.2 would be more interesting. However, when taking into account the payback period, intervention 4.1 could also be implemented due to its lower payback period.

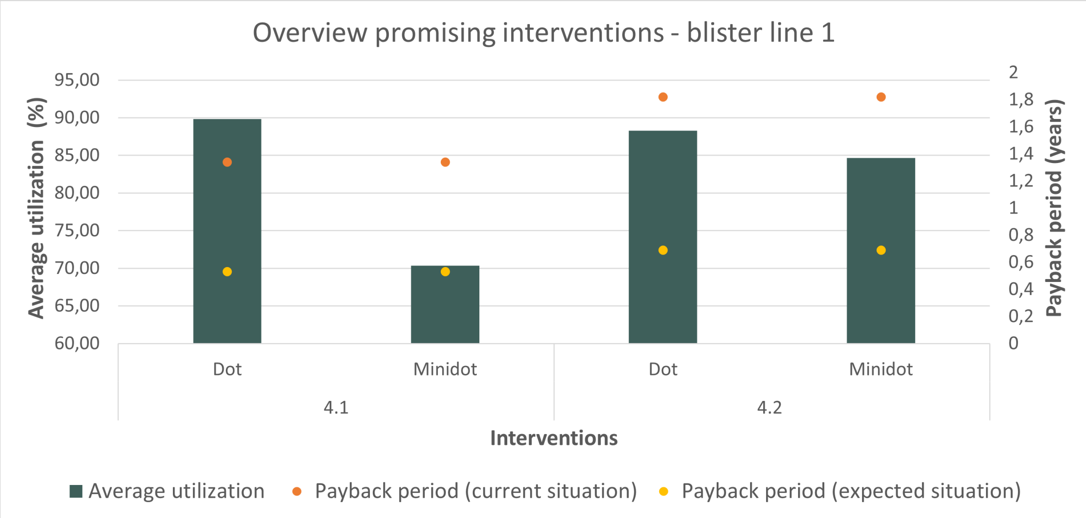

Figure 0.2: Overview performance measures per intervention - line 1 Blisters, (orange/yellow dots are the payback periods, green bars represent the average utilization)

The promising interventions for the flowpackaging of line 3 are displayed in figure 0.3. The biggest improvement in utilization is reached by implementing intervention combination 1& 3.1, as this intervention improves the utilization by around 27%. However, this intervention has a relatively long payback period. When taking a look at intervention 3.1 on its own, the utilization increases almost just as much as intervention combination 1& 3.1, while decreasing the payback period by 1,5 years. The third intervention is intervention combination 1& 2 which improves the utilization by around 17% and which has a payback period for the current situation of just over 5 years and the expected situation of around 2,5 years. Even though this utilization improvement is a little less compared to intervention 3.1 or combination 1 & 3.1, it could still be an interesting intervention to look into further.

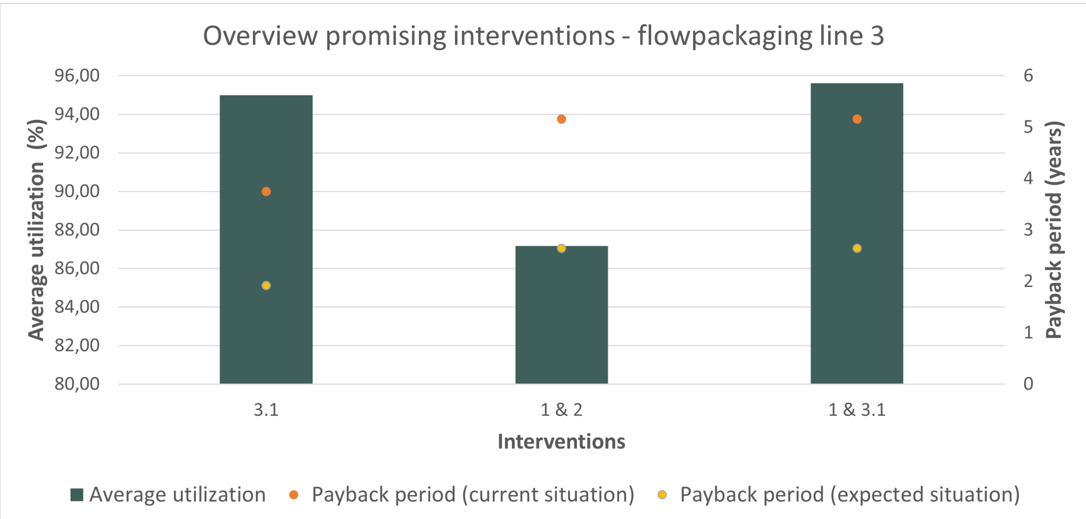

Figure 0.3: Overview performance measures per intervention - line 3, (orange/yellow dots are the payback periods, green bars represent the average utilization)

The promising interventions could all be implemented at line 1 or 3 since there is enough space and it is unnecessary to make big layout changes. The implementation would cause some downtime which could be limited by performing the implementation in multiple steps. This way part of the packaging line could stay operational. If, for example, the decision is made to implement intervention 3.1 at line 3, a second flowpacker needs to be installed at the packaging line. In this case, for a big part of the time the dots can still be bulk packaged due to the bulk part of the packaging line being separate from most of the consumer packaging line. However, when the second flowpacker has to be connected to the main conveyor belt on which the dots arrive, it might cause some downtime for the complete packaging line. Next to making the relevant changes to the layout, the scheduling team needs to take into account the changes that are necessary in their planning strategy according to the new performance of the consumer packaging lines 1 & 3.

In conclusion, this thesis provides several ways of improving the capacity of consumer packaging lines 1 and 3 of Europastry Oldenzaal. Not every promising intervention improves the utilization to 95,95%, but they are a start in the right direction. For line 1 interventions 3.1, combination 1, 2 & 3.0, combination 1 & 3.0, combination 2& 3.0 and combination 1 & 3.1 have experiments that reach the 95,95% utilization rate, but the average utilization is somewhat lower. Intervention 3.1, combination 1& 2 and combination 1 & 3.1 have experiments with a 95,95% utilization for line 3, but also for these interventions, the utilization is somewhat lower. Finding those ways to improve the capacity of the consumer packaging lines 1 & 3 is done by performing an analysis of the packaging lines and conducting a literature study that explores ways to improve capacity and analyse bottlenecks. Following the analysis and literature study, 27 different interventions have been developed and tested using a simulation model. The interventions were evaluated based on two performance measures, the utilization (%) and the payback period (years). There are several promising interventions to look into further, which are shown in figures 0.1, 0.2 and 0.3.

The limitations of this study are the availability of data and the assumptions made for the simulation model. For example, as described in Chapter 4, there are only 19 data points available for the dots in a blister of 4 (line 1). Next to that, the assumptions can influence the output of the simulation model as well. For example, the assumption has been made that the packaging itself is never out of stock. Even though the availability of the packaging is out of scope for this thesis, it could influence the output of the simulation results. The availability of data and the assumptions made might also influence the results, but that is not certain. All in all, the results of the interventions can be used as a guideline for the direction that might be interesting to investigate further to improve the capacity of consumer packaging lines 1 & 3.

Contents

Document Information I

Management Summary II

Glossary XII

1 Introduction 1
1.1 Company background 1
1.1.1 Packaging of EO 1
1.1.2 Customers of EO 1
1.2 Problem statement and research motivation 2
1.3 Research questions 4
1.3.1 Sub-questions 4
1.4 Scope 5

2 Current situation 6
2.1 Products (SKUs) 6
2.2 Sales & production on lines 7
2.3 Packaging 7
2.3.1 Division Consumer vs. Bulk packaging 8
2.4 Scheduling 8
2.5 Current packaging lines 8
2.5.1 Malfunctions 9
2.5.2 Capacity of packaging lines 9
2.5.3 Maintenance 10
2.6 Employees 10
2.7 Current factory layout 10
2.8 Takeaways of the analysis regarding the capacity 11
2.9 Requirements, wishes and limitations 12

3 Literature study 13
3.1 Simulation 13
3.1.1 Discrete event simulation (DES) 13
3.1.2 Simulation study design 14
3.1.3 Conceptual Model 15
3.1.4 Experimental settings 16
3.1.5 Intervention design & analysis 18
3.2 Bottleneck analysis and improvement 18
3.3 Capacity improvement 20
3.3.1 Buffers 20
3.3.2 Layout improvement 20
3.3.3 Maintenance 22
3.3.4 Lean methodology 23
3.4 Manufacturing lines in the food industry 23
3.5 Summary of Chapter 3 26

4 Solution design 27
4.1 Conceptual Model 27
4.1.1 Data collection 27
4.1.2 Inputs 27
4.1.3 Contents 32
4.1.4 Outputs 32
4.1.5 Settings 33
4.1.6 Assumptions and simplifications 33
4.2 Simulation model 34
4.2.1 Verification and Validation 35
4.2.2 Experimental setup 36
4.3 Experimental Configuration 41
4.4 Current bottlenecks and utilization 42
4.5 Interventions 44
4.5.1 Interventions line 1 44
4.5.2 Interventions line 3 53
4.5.3 Combination of interventions 56
4.6 Summary Chapter 4 57

5 Results 59
5.1 Results interventions line 1 60
5.1.1 Intervention 1: Vision system 60
5.1.2 Intervention 2: Buffers 60
5.1.3 Intervention 3: Flowpacker 61
5.1.4 Intervention 4: robots 63
5.1.5 Intervention 1 & intervention 3.0 65
5.1.6 Intervention 2 & intervention 3.0 65
5.1.7 Intervention 1 & intervention 2 & intervention 3.0 66
5.1.8 Intervention 1 & intervention 3.1 66
5.1.9 Intervention 1 & intervention 3.2 67
5.1.10 Intervention 2 & intervention 3.2 67
5.1.11 Intervention 1 & intervention 4.1 67
5.1.12 Intervention 1 & intervention 4.2 68
5.1.13 Intervention 1 & intervention 4.3 68
5.2 Payback period 69
5.3 Comparison of all results Line 1 70
5.4 Results interventions line 3 73
5.4.1 Intervention 1: Vision system 73
5.4.2 Intervention 2: Buffers 73

5.4.3 Intervention 3: Flowpacker . . . 74
5.4.4 Intervention 1 & intervention 2 . . . 75
5.4.5 Intervention 1 & intervention 3.1 . . . 75
5.4.6 Intervention 1 & intervention 3.2 . . . 76
5.4.7 Intervention 2 & intervention 3.2 . . . 76
5.5 Payback period interventions Line 3 . . . 76
5.6 Comparison of all results Line 3 . . . 77
5.7 Recommendation and implementation plan . . . 79
5.7.1 Line 1 . . . 79
5.7.2 Line 3 . . . 81

6 Conclusion **83**
6.1 Conclusion . . . 83
6.2 Limitations . . . 85
6.3 Recommendations . . . 86
6.4 Future research . . . 87
6.5 Theoretical and practical contribution . . . 87

References **88**

7 Appendix **92**
A Packaging Europastry Oldenzaal . . . 92
B Sales Europastry . . . 94
C Overview packaging line 1 and 3 . . . 96
D SKUs Europastry Oldenzaal lines 1 and 3 . . . 97
E Production quantity of SKUs per line . . . 101
F Planning example . . . 105
G Flowcharts packaging line 1 and 3 . . . 108
H Capacity . . . 110
I Layout Packaging floor . . . 111
J State Transition Diagrams Simulation . . . 113
K Python script - distribution fitting . . . 115
L Distribution fitting . . . 116
M Distribution fitting simulation . . . 124
N Results black-box testing . . . 134
O Results paired t-test run length . . . 137

List of Figures

0.1 Overview performance measures per intervention - line 1 Flowpackaging, (orange/yellow dots are the payback periods, green bars represent the average utilization) . . . III
0.2 Overview performance measures per intervention - line 1 Blisters, (orange/yellow dots are the payback periods, green bars represent the average utilization) . . . IV
0.3 Overview performance measures per intervention - line 3, (orange/yellow dots are the payback periods, green bars represent the average utilization) . . . IV
1.1 Products EO . . . 1
1.2 Percentage number of customers per customer category . . . 2
1.3 Percentage Bulk/Consumer per line over time . . . 3
1.4 Problem cluster . . . 3
2.1 Number of SKUs per subfamily SKUs . . . 6
2.2 Packaging flow . . . 7
2.3 Percentage Consumer/Bulk packaging per line . . . 8
2.4 Workflow production and packaging Dots . . . 9
2.5 Current factory layout . . . 11
2.6 The order of the packaging line . . . 11
3.1 Flowchart of ways to study a system, from Law (2015, Chapter 1.2) . . . 13
3.2 Overview of simulation types within different management layers, from Borshchev and Filippov (2004, page 3) . . . 14
3.3 Steps in a simulation study, adapted from Law (2015, Chapter 1.7) . . . 15
3.4 Framework for developing a conceptual model, from Robinson (2004, Chapter 6.2) . . . 16
3.5 Verification, validation and credibility during the steps of the simulation study, from Law (2015, Chapter 5.1) . . . 17
3.6 Black and white box validation, adapted from Nidhra and Dondeti (2012, section 3.2) . . . 17
3.7 Six big losses in OEE, adapted from Sowmya and Chetan (2016, page 557) . . . 19
3.8 Steps of TOC, information from Slack, Chambers, and Johnston (2010, Chapter 15) . . . 19
3.9 Possible layout for various quantity - variety combinations, from Groover (2015, Chapter 2.4) . . . 21
3.10 Example flow line production, Proc: process, from Groover (2015, Chapter 2.3) . . . 21
3.11 SLP procedure, from Yang, Su, and Hsu (2000, Chapter 2.3) . . . 22
3.12 Proposed framework to develop a facility layout within the food production, from Wanniarachchi, Gopura, , and Punchihewa (2016, page 3) . . . 24
3.13 The food industrial robot methodology, from Bader and Rahimifard (2020, page 3) . . . 25
4.1 Conceptual Model . . . 27
4.2 Histogram arrival crodots of line 1 . . . 28
4.3 Histogram arrival dots of line 1 . . . 28
4.4 Histogram arrival mini dots of line 1 . . . 28
4.5 Histogram of the arrival of the dots of line 3 . . . 29
4.6 Histogram of the processing times Crodots Line 1 (flowpack 2u) . . . 30
4.7 Histogram of the processing times Dots Line 1 (blister 4x) . . . 30
4.8 Histogram of the processing times Minidots Line 1 (blister 6x) . . . 31
4.9 Histogram of the downtime of the flowpacker of line 3 . . . 31
4.10 Simulation Line 1 . . . 34
4.11 Simulation Line 3 . . . 35
4.12 Satistics Simulation Model Lines 1 & 3 . . . 35
4.13 Warm up period situations line 1 . . . 37
4.14 Warm up period without waiting time Minidots Line 1 . . . 38
4.15 Warm up period without waiting time Dots Line 1 . . . 38
4.16 Warm up period without waiting time Crodots Line 1 . . . 38
4.17 Warm up period Minidots Line 1 . . . 39
4.18 Warm up period Dots Line 1 . . . 39
4.19 Warm up period Crodots Line 1 . . . 40
4.20 Warm up period line 3 . . . 40
4.21 Bottleneck line 1 (yellow shows the overflow of dots) . . . 42
4.22 Illustration intervention 1: Vision system . . . 45
4.23 Simulation line 1, intervention 1: Vision system . . . 45
4.24 Illustration intervention 2: Buffers . . . 47
4.25 Simulation line 1, intervention 2: Buffers . . . 47
4.26 Simulation intervention 3.0: One Flowpacker . . . 48
4.27 Illustration intervention 3.1: Multiple Flowpackers . . . 49
4.28 Simulation line 1, intervention 3.1: Multiple Flowpackers . . . 49
4.29 Illustration intervention 4.1: Cobots . . . 52
4.30 Illustration intervention 4.2: Cobots . . . 52
4.31 Illustration intervention 4.3: Cobots . . . 53
4.32 Simulation line 3, intervention 1: Vision system . . . 54
4.33 Simulation line 3, intervention 2: Buffers . . . 55
5.1 Avg. Utilization vs. Payback period (current situation) - flowpackaging line 1 . . . 71
5.2 Avg. Utilization vs. Payback period (current situation) - blister packaging Dots line 1 . . . 72
5.3 Avg. Utilization vs. Payback period (current situation) - blister packaging Minidots line 1 . . . 73
5.4 Avg. Utilization vs. Payback period (current situation) - flowpackaging line 3 . . . 78
5.5 Proposed layouts line 1 . . . 80
5.6 Proposed layouts line 3 . . . 82
7.1 Packaging options line 1 . . . 92
7.2 Packaging options line 3 . . . 93
7.3 Consumer/Bulk line 4 over time . . . 94
7.4 Sales per customer category . . . 94
7.5 Sales lines 1,3 and 4 2022 . . . 95
7.6 Overview line 1 . . . 96
7.7 Overview line 3 . . . 96
7.8 SKUs line 1 . . . 97
7.9 SKUs line 1 . . . 98
7.10 SKUs line 3 . . . 99
7.11 SKUs line 3 . . . 100
7.12 Production line 1 2022 - part 1 . . . 101
7.13 Production line 1 2022 - part 2 . . . 102
7.14 Production line 3 2022 - part 1 . . . 103
7.15 Production line 3 2022 - part 2 . . . 104
7.16 Planning week 19 Monday-Thursday line 1 . . . 106

7.17 Planning week 19 Friday-Sunday line 1 . . . 107
7.18 Flowchart packaging line 1 . . . 108
7.19 Flowchart packaging line 3 . . . 109
7.20 Current packaging layout ground floor . . . 111
7.21 Current packaging layout first floor . . . 112
7.22 State Transition Diagram simulation line 1 . . . 113
7.23 State Transition Diagram simulation line 3 . . . 114
7.24 Python script for distribution fitting . . . 115
7.25 Box Plot Arrival Rate Minidots Current Situation . . . 116
7.26 Box Plot Arrival Rate Dots Current Situation . . . 117
7.27 Box Plot Arrival Rate Crodot Current Situation . . . 118
7.28 Box Plot Processing Time Minidots Blister 6x . . . 119
7.29 Box Plot Processing Time Crodots Current Situation Flowpack 2u . . . 120
7.30 Box Plot Processing Time Dots Current Situation Blister 4x . . . 121
7.31 Box Plot Arrival Rate Dots Current Situation . . . 122
7.32 Box Plot MTTR Current Situation . . . 123
7.33 Box Plot Utilization Current Situation . . . 123
7.34 Box Plot Arrival Crodots Normal Distribution Line 1 . . . 124
7.35 Box Plot Arrival Crodots Laplace Distribution Line 1 . . . 124
7.36 Box Plot Arrival Crodots Gumbel Distribution Line 1 . . . 124
7.37 Box Plot Arrival Crodots Empirical Distribution Line 1 . . . 124
7.38 Box Plot Arrival Crodots Logistic Distribution Line 1 . . . 125
7.39 Box Plot Arrival Dots Gumbel Distribution Line 1 . . . 125
7.40 Box Plot Arrival Dots Logistic Distribution Line 1 . . . 125
7.41 Box Plot Arrival Dots Empirical Distribution Line 1 . . . 126
7.42 Box Plot Arrival Minidots Cauchy Distribution Line 1 . . . 126
7.43 Box Plot Arrival Dots Gumbel Distribution Line 1 . . . 126
7.44 Box Plot Arrival Minidots Logistic Distribution Line 1 . . . 127
7.45 Box Plot Arrival Dots Laplace Distribution Line 1 . . . 127
7.46 Box Plot Arrival Minidots Empirical Distribution Line 1 . . . 127
7.47 Box Plot Processing Time Crodot Empirical Distribution Line 1 . . . 128
7.48 Box Plot Processing Time Crodot Lognorm Distribution Line 1 . . . 128
7.49 Box Plot Processing Time Dots Empirical Distribution Line 1 . . . 128
7.50 Box Plot Processing Time Dots Gamma Distribution Line 1 . . . 128
7.51 Box Plot Processing Time Dots Lognorm Distribution Line 1 . . . 129
7.52 Box Plot Processing Time Dots Beta Distribution Line 1 . . . 129
7.53 Box Plot Processing Time Minidots Empirical Distribution Line 1 . . . 129
7.54 Box Plot Processing Time Minidots Beta Distribution Line 1 . . . 129
7.55 Box Plot Processing Time Minidots Gamma Distribution Line 1 . . . 130
7.56 Box Plot Processing Time Minidots Lognorm Distribution Line 1 . . . 130
7.57 Box Plot Arrival Dots Empirical Distribution Line 3 . . . 131
7.58 Box Plot Arrival Dots Empirical Distribution Line 3 . . . 131
7.59 Box Plot MTTR Beta Distribution Line 3 . . . 131
7.60 Box Plot Capacity Beta Distribution Line 3 . . . 131
7.61 Box Plot MTTR Gamma Distribution Line 3 . . . 132
7.62 Box Plot Capacity Gamma Distribution Line 3 . . . 132
7.63 Box Plot MTTR Logistic Distribution Line 3 . . . 132
7.64 Box Plot Capacity Logistic Distribution Line 3 . . . 132
7.65 Box Plot MTTR Empirical Distribution Line 3 . . . 133
7.66 Box Plot Capacity Empirical Distribution Line 3 . . . 133
7.67 Black-box testing Line 1 . . . 134
7.68 Black-box testing Line 3 . . . 136

List of Tables

0.1 Overview donuts/packaging included in simulation model . . . II
0.2 Overview promising interventions packaging lines 1 and 3 . . . III
1.1 Market Categories . . . 2
2.1 Packaging lines . . . 6
2.2 Employees per line . . . 10
3.1 Lean techniques (Kumar et al., 2022) . . . 23
4.1 Summary input lines 1 & 3 . . . 32
4.2 Active states of the station within packaging line 1 . . . 42
4.3 Utilization current situation dots line 1 . . . 43
4.4 Utilization current situation crodots line 1 . . . 43
4.5 Utilization current situation minidots line 1 . . . 43
4.6 Active states of the station within packaging line 3 . . . 43
4.7 Utilization current situation line 3 . . . 43
4.8 Overview interventions line 1 . . . 44
4.9 Overview intervention 1: Vision system, line 1 . . . 46
4.10 Overview intervention 2: Buffers, line 1 . . . 47
4.11 Overview sub-interventions of interventions 3 . . . 48
4.12 Overview intervention 3.0: One Flowpackers, line 1 . . . 48
4.13 Overview intervention 3.1: Multiple Flowpackers, line 1 . . . 49
4.14 Overview intervention 3.2: Speed Flowpacker, line 1 . . . 50
4.15 Overview intervention 3.3: Different Flowpacker, line 1 . . . 50
4.16 Industrial robots vs Cobots (Buchert, 2021) . . . 50
4.17 Overview interventions line 1 . . . 51
4.18 Overview intervention 4.1: Only cobots, line 1 . . . 52
4.19 Overview intervention 4.2: Cobots + filter, line 1 . . . 53
4.20 Overview intervention 4.1: Cobots with two functions, line 1 . . . 53
4.21 Overview interventions line 3 . . . 53
4.22 Overview intervention 1: Vision system, line 3 . . . 54
4.23 Overview intervention 2: Buffers, line 3 . . . 55
4.24 Overview intervention 3.1: Multiple Flowpackers, line 3 . . . 55
4.25 Overview intervention 3.2: Speed Flowpacker, line 3 . . . 56
4.26 Overview intervention 3.3: Different Flowpacker, line 3 . . . 56
4.27 Combinations interventions line 1 . . . 56
4.28 Combinations interventions line 3 . . . 57
4.29 Overview interventions line 1 & 3 . . . 58
5.1 Utilization current situation dots lines 1 & 3 . . . 59
5.2 Results experiments intervention 1, line 1 minidot & crodot . . . 60
5.3 Results experiments intervention 2, line 1 crodots . . . 60
5.4 Results experiments intervention 2, line 1 dots . . . 61
5.5 Results experiments intervention 2, line 1 minidots . . . 61
5.6 Results experiments intervention 3.0, line 1 crodots . . . 62
5.7 Results experiments intervention 3.1, line 1 . . . 62
5.8 Results experiments intervention 3.2, line 1 . . . 62
5.9 Results experiments intervention 3.3, line 1 . . . 63
5.10 Results experiments intervention 4.1, line 1 minidots . . . 63
5.11 Results experiments intervention 4.1, line 1 dots . . . 63
5.12 Results experiments intervention 4.2, line 1 minidots . . . 64
5.13 Results experiments intervention 4.2, line 1 dots . . . 64
5.14 Results experiments intervention 4.3, line 1 minidots . . . 65
5.15 Results experiments intervention 4.3, line 1, dots . . . 65
5.16 Results experiments intervention 1 & 3.0, line 1 crodots . . . 65
5.17 Results experiments intervention 2 & 3.0, line 1 crodots . . . 66
5.18 Results experiments intervention 1 & 2 & 3.0, line 1 crodots . . . 66
5.19 Results experiments intervention 1 & 3.1, line 1 . . . 66
5.20 Results experiments intervention 1 & 3.2, line 1 . . . 67
5.21 Results experiments intervention 2 & 3.2, line 1 crodots . . . 67
5.22 Results experiments intervention 1 & 4.1, line 1 minidots . . . 67
5.23 Results experiments intervention 1 & 4.1, line 1 dots . . . 68
5.24 Results experiments intervention 1 & 4.2, line 1 minidots . . . 68
5.25 Results experiments intervention 1 & 4.2, line 1 dots . . . 68
5.26 Results experiments intervention 1 & 4.3, line 1 minidots . . . 69
5.27 Results experiments intervention 1 & 4.3, line 1, dots . . . 69
5.28 Overview payback periods interventions line 1 . . . 70
5.29 Overview interventions line 1 . . . 70
5.30 Overview results interventions line 1 - Flowpackaging . . . 71
5.31 Overview results interventions line 1 - Blister packaging . . . 72
5.32 Results experiments intervention 1, line 3 . . . 73
5.33 Results experiments intervention 2, line 3 . . . 74
5.34 Results experiments intervention 3.1, line 3 . . . 74
5.35 Results experiments intervention 3.2, line 3 . . . 75
5.36 Results experiments intervention 3.3, line 3 . . . 75
5.37 Results experiments intervention 1 &2, line 3 . . . 75
5.38 Results experiments intervention 1 & 3.1, line 3 . . . 76
5.39 Results experiments intervention 1 & 3.2, line 3 . . . 76
5.40 Results experiments intervention 2 & 3.2, line 3 . . . 76
5.41 Overview payback periods interventions line 3 . . . 77
5.42 Overview interventions line 1& 3 . . . 77
5.43 Overview results interventions line 3 . . . 77
6.1 Summary interventions . . . 84
6.2 Overview promising interventions lines 1 & 3 . . . 85
7.1 Capacity consumer packaging line 1 . . . 110
7.2 Capacity consumer packaging line 3 . . . 110
7.3 Arrival Rate MiniDots (sorted on P-value) . . . 116
7.4 Arrival Rate Dots (sorted on P-value) . . . 117
7.5 Arrival Rate CroDots (sorted on P-value) . . . 118

7.6 Processing Time Minidots Blister 6x (sorted on P-value) . . . 119
7.7 Processing Time Crodots Flowpack 2u (sorted on P-value) . . . 120
7.8 Processing Time Dots (sorted on P-value) . . . 121
7.9 Arrival Rate Dots (sorted on P-value) . . . 122
7.10 Down Time Flowpacker (sorted on P-value) . . . 123
7.11 Results Paired t-test Line 1 . . . 135
7.12 Results Paired t-test Line 3 . . . 136
7.13 Results Paired t-test Line 1 . . . 137
7.14 Results Paired t-test Line 1 . . . 137

Glossary

Abbreviation	Definition	Introduced in
Dots	Donuts, crodots, pop-dots, and Berliners	Section 1.1
EO	Europastry Oldenzaal	Section 1.1
SKU	Shop Keeping Unit	Section 1.1.2
CPP	Crictial Control Point	Section 2.5.1
CP	Control Point	Section 2.9
DES	Discrete Event Simulation	Section 3.1.1
OEE	Overall Equipment Effectiveness	Section 3.2
TOC	Theory Of Constraints	Section 3.2
DML	Dedicated Manufacturing Lines	Section 3.3.2
RMS	Reconfigurable Manufacturing Systems	Section 3.3.2
MMS	Matrix Manufacturing System	Section 3.3.2
SLP	Sytematic Layout Planning	Section 3.3.2
PM	Preventive Maintenance	Section 3.3.3
HACCP	Hazard Analysis Critical Control Point	Section 3.4
GMP	Good Manufacturing Practices	Section 3.4
QA	Quality Assurance	Section 3.4
MES	Manufacturing Executing System	Section 3.4
ERP	Enterprise Resource Planning	Section 3.4
KPI	Key Performance Indicators	Section 3.4
RAS	Robotics Autonomous System	Section 3.4
FIRM	Food Industry Robot Methodology	Section 3.4
MTTR	Mean Time To Repair	section 4
Cobots	Collaborative Robots	section 4.5

1 Introduction

In this chapter, multiple topics are discussed to get an idea about the company and the problem at hand. The introduction will start with a company background in Section 1.1, where the company, products and production lines are discussed. In Section 1.2, the problem statement and research motivation are described. The introduction continues with the research questions in Section 1.3 and ends with the scope (Section 1.4).

1.1 Company background

Europastry is a multinational company based in Barcelona, Spain, that specializes in the production and distribution of frozen bakery products. The company was founded in 1987 and has since grown to become one of the leading companies in the sector. Their main product categories include croissants and pastries, bread, cakes and desserts, pizza dough, and gluten-free bakery products. The company has a lot of factories and production plants worldwide and supplies its products to over 60 countries.

Figure 1.1: Products EO

Europastry Oldenzaal (EO) is located in the town of Oldenzaal in the Netherlands and serves as a production and distribution centre for Europastry's bakery products within the European market. EO produces a small part of all products sold by Europastry which include croissants, donuts and popdots. As will be described in more detail in section 1.4, the donuts (dots) are the focus of this thesis. The dots are manufactured, by creating the dough, leaving the dots to rise, and frying the dots. After frying, the products can be glazed, filled, or both before ending up in the freezer. The moment that the products are frozen (around 30 minutes), they go directly to the packaging lines where they are packaged into bulk packaging or consumer packaging. Bulk packaging is a box with 12-100 products per package, whereas consumer packaging is smaller packaging with 1-9 products per package. Finally, the dots are transported to the customers on pallets.

1.1.1 Packaging of EO

All bulk packaging is packaged in an American box or a tray with a top. The consumer packaging is a flow-pack (u-tray) or a blister. The flow-pack (u-tray) or blister ends up in an American box and continues to the pallets. The consumer and bulk packaging options are displayed in Appendix A. The packaging is stored in the raw material warehouse and the packaging that is needed during a shift is moved from the warehouse to the packaging line. In Section 2.3 a more detailed description of consumer and bulk packaging will be given. Of all SKUs of 2022, 9,79% was packaged in consumer packaging.

1.1.2 Customers of EO

EO sold products to 110 customers in 2022 and up until June 2023, there are 86 different customers. The customers of EO are in different categories and each customer category has different packaging preferences. There are three categories within EO: retail, food service, and others. An overview of the categories and their customers is displayed in Table 1.1. The division of the number of customers per customer category of 2022 is displayed in Figure 1.2. Food-service customers prefer bulk packaging since the dots are sold separately at their facilities. Retail customers mostly get bulk packaging at the moment, but their preference is changing towards approximately 50% consumer-packaged shop-keeping units (SKU). In 2022, the percentage of SKUs with consumer packaging is 9,04% for retail customers.

Table 1.1: Market Categories

Subfamily	**Customers**
Retail	Supermarkets & convenience stores
Foodservice	Restaurants & catering
Others	Distribution centres & others

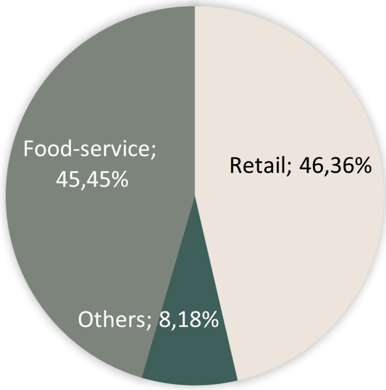

Figure 1.2: Percentage number of customers per customer category

1.2 Problem statement and research motivation

The core problem is that the capacity of the consumer packaging lines is not high enough. With capacity, the number of dots that get packaged per hour is mean. If the capacity increases at the consumer packaging line, more consumer-packaged SKUs can be produced and the scheduling department of EO is much less limited. Next to that, it will be less of a problem when more consumer-packaged SKUs will be sold in future. There are multiple causes for the core problem, they will be described below. In Figure 1.4, the problem cluster is displayed. The goal of this research is to analyze the packaging lines and increase the capacity of the consumer packaging lines at EO.

The first cause is a major movement within the food industry: pre-proofed, pre-baked, and pre-packaged. Pre-proofed is creating the dough of a pastry. Pre-baked is baking the pastry and finally pre-packaged means that the pastry is packaged separately. For all the dots, the movements pre-proofed and pre-backed are already implemented. Especially for the retail customers of EO, the movement of pre-packaged needs to be implemented at EO to keep up with the preferences of the customers for the products within the dots category (donuts, crodots, pop-dots, and berliners). Over time, EO has started to implement more consumer packaging, as can be seen in Figure 1.3. However, EO expects that customers will prefer even more consumer packaging in the upcoming years. The expectation is that around 30% of the shifts on the packaging lines 1 & 3 will package consumer packaging.

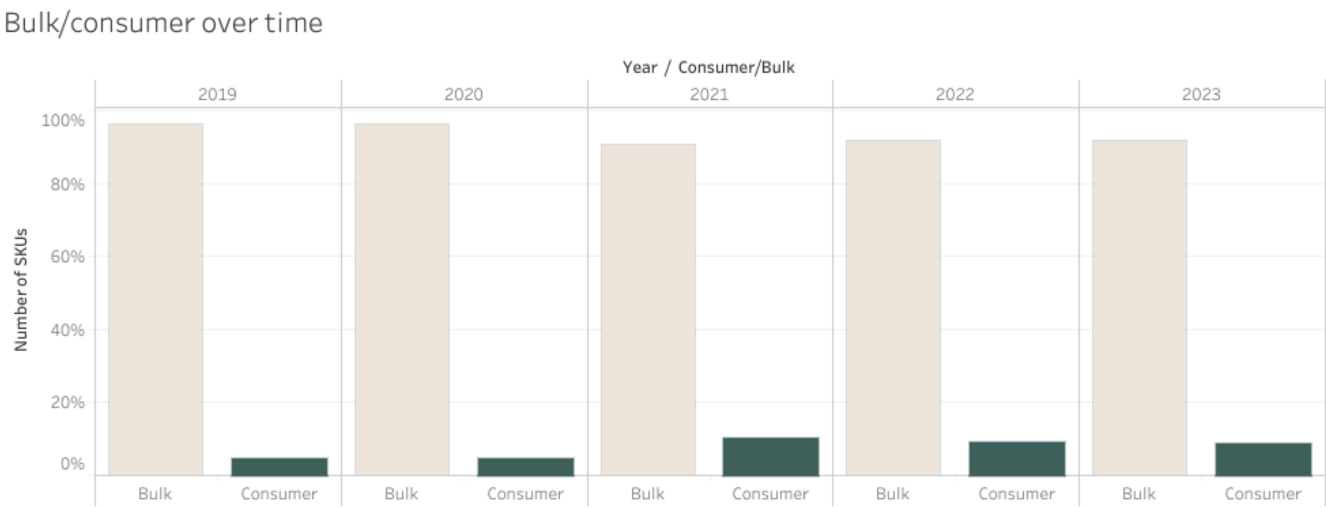

Figure 1.3: Percentage Bulk/Consumer per line over time

Furthermore, sustainability is becoming more important. The focus on how the packaging lines can become more sustainable is growing. From the sustainability point of view, it is important to improve the packaging line and create less waste and loss of capacity.
Finally, EO would like to go to (new) customers with several packaging concepts to ask which concept the customer would like. At the moment it happens the other way around, so EO asks the customer what packaging they prefer. This leads to a lot of different preferences and it is not possible to implement all preferences. In short, EO wants to change from a pull strategy to a push strategy with regard to the packaging of the dots.
All in all, packaging the SKUs in consumer packaging is becoming more important at EO. This leads to a need to efficiently package the dots in consumer packaging at the speed of the bakery or even higher to be ready for malfunctions on the line and for the future. The capacity is not high enough at the moment, so the packaging lines need to be redesigned to make sure that they are future-proof. That is why EO would like the packaging line to have a capacity of 120% of the bakery.

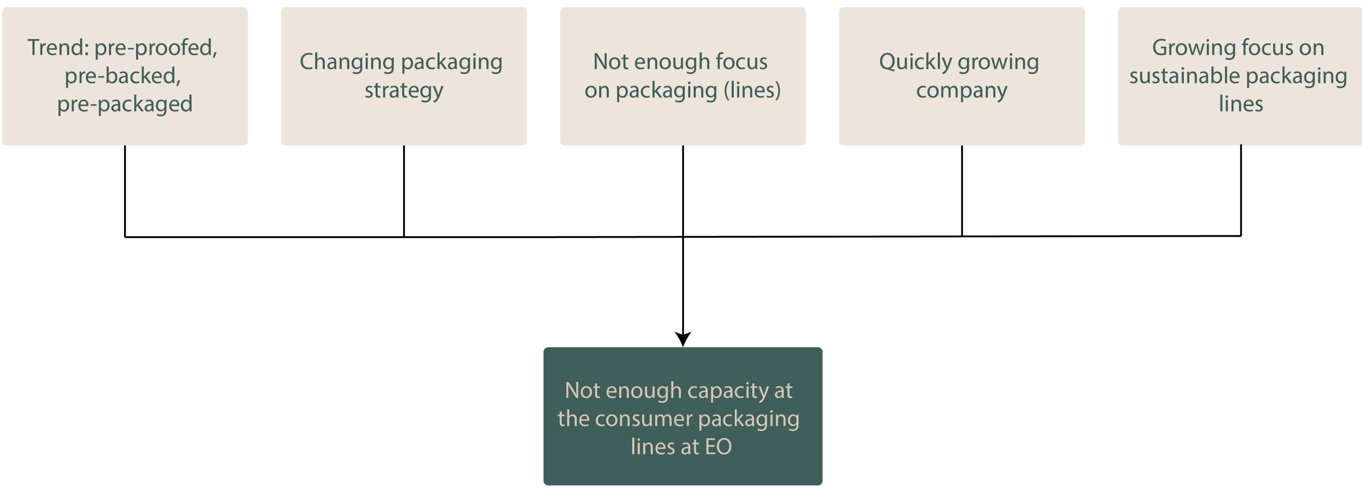

Figure 1.4: Problem cluster

The dots are produced in bulk and are directly packaged after production. To be able to package the dots in consumer packaging when necessary, there are two temporary solutions in place. The first solution is a lot of manual labour, which means that there are a lot of employees at the packaging lines to make sure that all the dots get packaged. The second temporary solution is that the dots get packaged in bulk and later when there is time and capacity, those dots get repacked into consumer packaging. If there is no time or capacity, the dots are repackaged by a third party. Both temporary solutions are not very efficient and more expensive than necessary. The motivation for this research is to replace temporary solutions with long-term solutions and to increase the capacity of the consumer packaging lines. At the moment, there is always a backup shift scheduled for bulk packaging in case the consumer packaging line has a malfunction, which results in more employees scheduled than might be necessary.

1.3 Research questions

To make this research quantifiable and to be able to increase the capacity of the consumer packaging lines for EO, a main scientific research question is formulated:

How can the utilization of the consumer packaging lines 1 & 3 be increased from 37,11% to 95,95% and 72,73% to 95,95%, respectively?

First of all, as discussed in Section 1.4, the consumer packaging lines 1 & 3 will be within the scope of this study. Next to that, by increasing the utilization of consumer packaging lines 1 & 3, the capacity (so the number of packaged dots per hour) will increase as well. The utilization (%) will be used as one of the performance measures, but more on that can be found in Chapter 4. Finally, the utilization for both lines has to increase to 95,95% instead of 100%, because other factors decrease the utilization to 95,95% which are out of the scope of this study.

1.3.1 Sub-questions

To be able to answer the main research question, the sub-questions that are displayed below are chosen. For each sub-question, a description is given of how this question will be answered.

1. *What is the current packaging process of the dots at lines 1 and 3 and what are the requirements and limitations of these packaging lines?*
   This question will be answered by analysing the current production and packaging lines in Chapter 2. The focus of this analysis will be the packaging lines. The database (Tableau) of the company is used to gather all the data shown in this chapter. Next to that, the question will ensure that the requirements and limitations are considered when generating the different interventions at a later stage. The analysis will be performed by doing walk-ins at the packaging lines, interviews with stakeholders and data analysis.
2. *What are the trends and best practices for increasing the capacity of packaging lines in literature?*
   This question will be answered in Chapter 3 by doing a literature review. Within this literature study, the focus will be on simulation models to be able to test possible interventions to improve the capacity, bottleneck analysis to determine where and why the capacity decreases and how to solve that, ways to improve the capacity of manufacturing lines and finally packaging lines in the food industry as this is a special part of manufacturing. The following sub-questions that will be discussed are as follows:
   (a) *What are important factors for simulating a packaging line?*
   (b) *What are the most effective methods for improving capacity on a consumer packaging line?*
   (c) *What are the most common methods to analyze and improve bottlenecks at packaging lines?*
   (d) *What is the most used approach in literature to design a packaging line layout in the food industry?*

3. *What interventions could potentially improve the current packaging line?*
   Based on the information collected in the previous questions, interventions can be generated on how the current situation can be improved. These generated interventions will be discussed in Chapter 4.5. These interventions will be tested by comparing the performance with the current situation using a simulation model.
4. *Which intervention is the most feasible for EO?*
   In Chapter 5 the results of the interventions are described and a recommendation will be given on the most interesting intervention(s).
5. *How could Europastry Oldenzaal implement the recommended intervention(s)?*
   The answer to this question is a description of the implementation of the recommended intervention(s), which will be described in Chapter 5.

1.4 Scope

In this section, the scope of this study will be described. First of all, the production of all dots is beyond the scope of this study. The study starts the moment the dots leave the freezer and reach the packaging lines. Next to that, the croissant line (line 2) will be out of scope. Most of the croissants are sold to customers who bake them in their own bakery and sell them separately and there is no need for consumer packaging. Furthermore, as can be seen in Figure 7.3 in Appendix B, there are no sales of consumer-packaged SKUs at line 4. This year, a small part is packaged for the consumer as a test, but it is not yet sold. Since there is already some consumer packaging possible and this packaging is still being tested and not sold yet, line 4 will be out of scope as well. EO just started using line 5 and there is no/limited data available. Next, the expectation is that the SKUs that will be produced at line 5 will be bulk-packaged. There might be some bulk-packaged SKUs that are now produced and packaged on line 1 or 3 that will be moved to line 5. This means that packaging lines 1 and 3 are the focus of this research. The deliverable to the company is an overview of promising interventions of adjusted packaging lines 1 and 3 with higher capacity with an implementation plan for those interventions. The first limitation is that not all the data might be available. If the data is available, it will be collected or measured. If not, assumptions might be made. Next to that, the limitations of EO and the packaging line have to be taken into account as described in Section 2.9.

2 Current situation

This chapter will describe the current situation, starting with the products of EO (Section 2.1). Afterwards in Section 2.2, an analysis of the demand and production will be given. For this section, the database (Tableau) of the company is used. Then, in Section 2.3, the packaging and the flow of packaging will be discussed. Furthermore, scheduling of the dots, the packaging lines, the employees and the factory layout will be described in Sections 2.4, 2.5, 2.6 and 2.7 respectively. Finally, in Section 2.9, the requirements, wishes and limitations are described. To get an overview of the topics discussed in this chapter, a summary is given in Table 2.1. In the column 'Products', the products of that line are displayed. The packaging options and the number of products per packaging are displayed in the column' Packaging options'. So, for example, Bulk - 36 means that the dots are packaged in bulk per 36 items. The column "Packaging' displays the options of bulk or consumer packaging. In the last column 'Utilization' the utilization of the packaging line is displayed. So, the bulk packaging line can package at 95,95% utilization for both lines 1 and 3, but for the consumer packaging lines, this percentage is lower. A complete overview of packaging lines 1 and 3 is displayed in Appendix C.

Table 2.1: Packaging lines

Line	Products	Packaging options	Packaging	Utilization
Line 1	Unfilled (mini)Donuts & Crodots	Bulk - 12/24/36/48/72/96	American box / Tray with top	95,95%
		Consumer - 2/4/6	Blisters / flow pack U-trays / flow-pack	37,11%
Line 3	Filled Donuts & Balldots	Bulk - 12/24/36/48/72/96	Tray with top	95,95%
		Consumer - 1/2/4/6	flow pack U-trays / flow-pack	72,73%

2.1 Products (SKUs)

EO manufactures croissants, dots, crodots, pop-dots, and Berliners. In total, there are around 246 SKUs sold in 2022 at lines 1 and 3. Line 1 packaged 111 SKUs and line 3 packaged 135 SKUs. Not all SKUs are produced continuously, some are specials that are produced on certain moments like Easter or Christmas. An overview of all SKUs per packaging line can be found in Appendix D. All SKUs have specific packaging, so several SKUs are the same product, but the products have different packaging or are produced for different customers. The SKUs all fall in the family 'dots'. Each SKU has a subfamily as well, an overview of the subfamilies and at which line they are packaged is displayed in Figure 2.1. As can be seen, the dots have the number of SKUs, which is followed by the decorated dots.

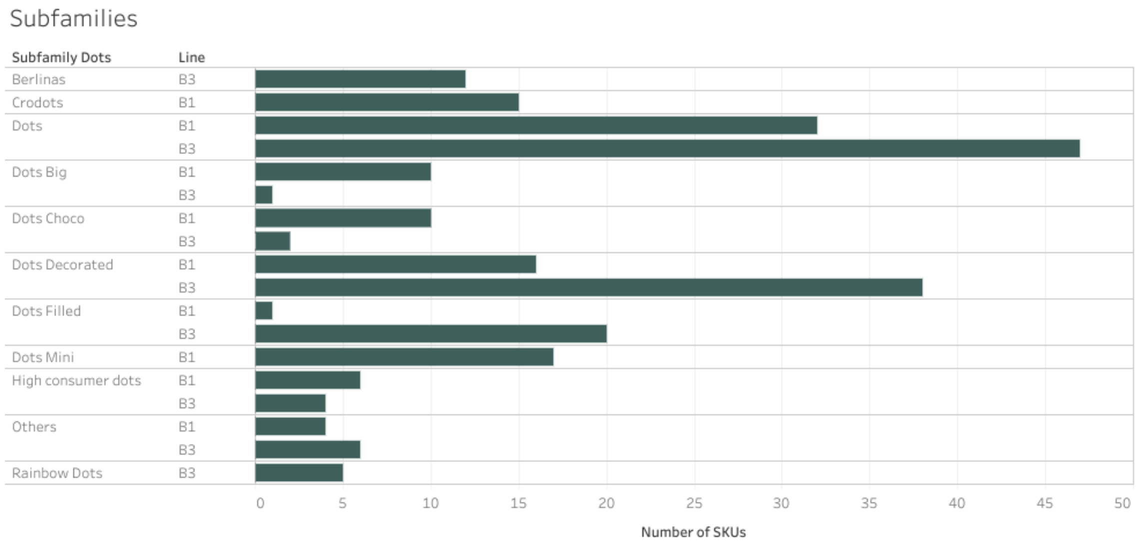

Figure 2.1: Number of SKUs per subfamily SKUs

2.2 Sales & production on lines

In this section, the sales of EO are discussed. First, in Figure 7.7 in Appendix B, the sales in units are displayed per customer category in 2019 - 2022 at lines 1 and 3. As can be seen in the figure, retail customers purchase most SKUs from EO and this is still growing. The catering/restaurant customers also grew over the years but at a slower pace. Next to that, in Figure 7.5 in Appendix B, the production in manufactured quantities (boxes) of lines 1 and 3 of 2022 is displayed. Line 3 produced the most boxes compared to line 1. A detailed overview of all SKUs sold per line can be found in Appendix E.

2.3 Packaging

In this section, a more detailed description of consumer and bulk packaging will be given. Consumer packaging is often referred to as a consumer unit. A consumer unit is a unit that the consumer purchases in a store (STAND, 2018). Often the consumer unit needs a bar code to scan the product. As mentioned in the introduction, consumer packaging will end up in the stores and it consists of 1 - 9 products per packaging. Bulk packaging has products that are not packaged by 1 or a few units but with 12 dots or more at once. These products are packaged in a tray with a top to close the box or an American box.

There are three kinds of packaging: primary packaging, secondary packaging and tertiary packaging. Primary packaging is designed to form a unit for the end user or consumer at the point of sale. Secondary packaging is intended to form a collection of several sales (primary) packages at the point of sale, regardless of whether they are sold as such to the end-user or consumer, or solely used to replenish the shelves at the point of sale. This packaging can be removed from the product without affecting its characteristics. Lastly, tertiary packaging is designed to facilitate the loading and transportation of several sales units or bulk packages.(ten Klooster et al, 2015). The packaging flow of EO is displayed in Figure 2.2. The secondary packaging for consumer packaging is the American box. When the bulk tray packaging has a top or the consumer packaging is in an American box, they get moved to the pallet, which, in this case, is the tertiary packaging.

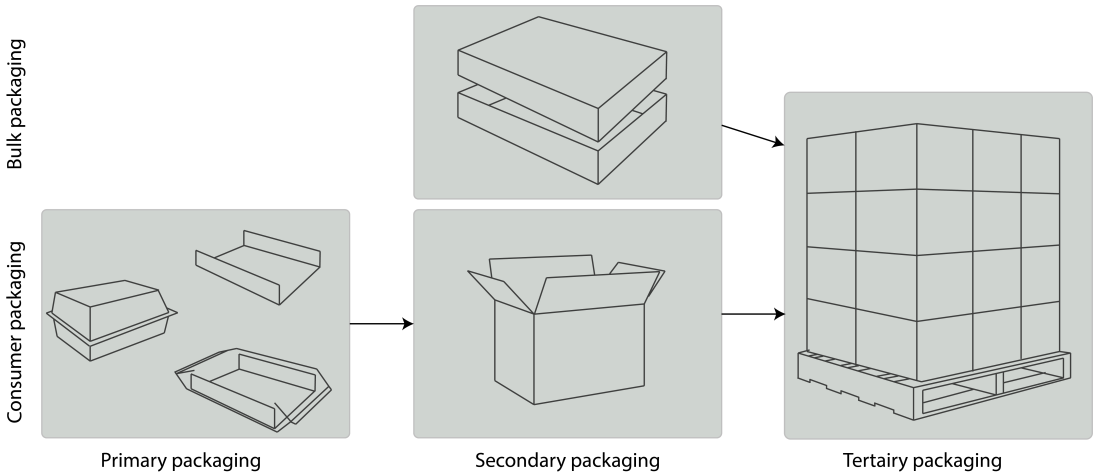

Figure 2.2: Packaging flow

2.3.1 Division Consumer vs. Bulk packaging

In Figure 2.3 an overview of the percentage bulk-consumer for the different SKUs for lines 1 and 3 is given for 2022. As can be seen, lines 1 and 3 have almost the same percentage of consumer packaging. Line 1 has a percentage of consumer-packaged SKUs of 9,17% and line 3 has a percentage of 10,66%. This means that line 3 has a slightly higher percentage.

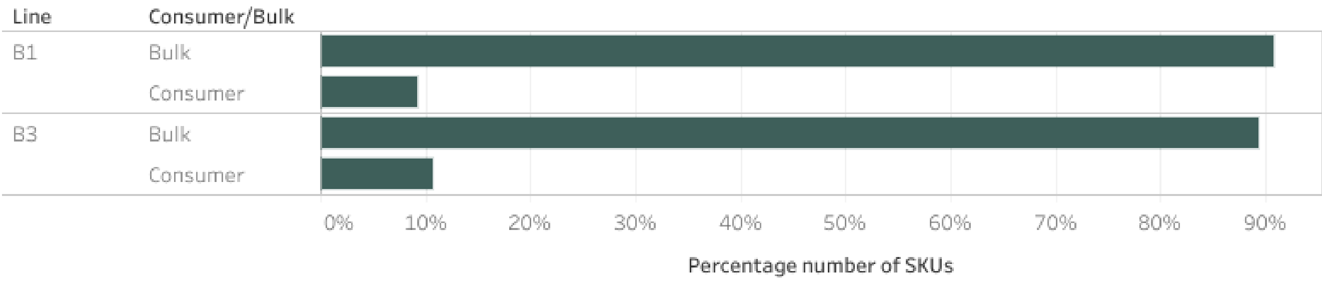

Figure 2.3: Percentage Consumer/Bulk packaging per line

2.4 Scheduling

Each packaging line manufactures 24/7 and is divided into 3 shifts of 8 hours per day. There are two cleaning shifts per week scheduled and some shifts are dedicated to maintenance. The packaging lines have to follow the production schedule since the dots that are made in the bakery are packaged immediately. This means that if the bakery switches the pastry production, the packaging line has to change immediately as well. In some cases, the bakery does not have any change over time, but the packaging lines do need to change between different packaging (settings). In this case, the bakery takes a small brake (around 15 - 30 minutes) to ensure the packaging lines are up and running. During a shift, the employees will have breaks, but the dots will keep coming. To keep packaging the dots, the employees have breaks in shifts. In each shift, one to three different SKUs are scheduled, this translates to 3 - 9 different SKUs every 24 hours. So, each day, the packaging line has to switch at least three times. An example schedule is displayed in Appendix F. The target (amount of boxes per shift) depends on the SKU and the specific packaging. Overall, the average target of all packaging lines is 5138 boxes per shift. This translates to an average of 28034 products per hour.

2.5 Current packaging lines

An overview of lines 1 and 3 is displayed in Table 2.1. In this section, more detailed information will be given regarding the packaging lines. The full workflow for both lines is displayed in Figure 2.4, and the flowchart of each packaging line is displayed in Appendix G. As can be seen in the flowchart, at the beginning of each packaging line, a control point is placed to check the dots for metal. Lines 1 and 3 are quite similar, but line 3 is fully automated for primary packaging with an automatic flowpacker. The primary packaged dots are manually placed in their secondary packaging, the American box. Line 1 has fully automated bulk packaging, but the consumer packaging is manual for the primary and secondary packaging.
Next to that, line 1 only packages unfilled and/or fully covered donuts and crodots, while line 3 packages the filled products. Both lines have multiple crossovers where the dots are sent to a sub-line for the correct packaging. When a consumer-packaged SKU is scheduled, the dots get divided at the crossovers so that some dots go to the consumer packaging line and others go to the bulk packaging line.

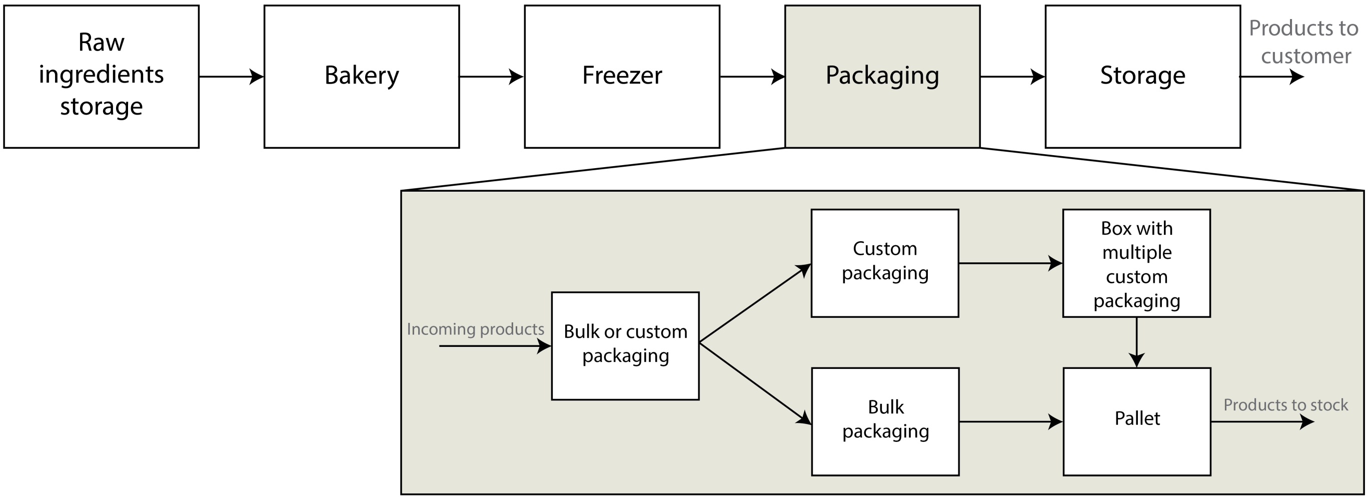

Figure 2.4: Workflow production and packaging Dots

2.5.1 Malfunctions

At the moment, the flowpacker machine at line 3 malfunctions sometimes. This machine is quite new (around two years old) and it is not yet used that often. The shift leaders or employees are therefore not yet fully used to working with the machine often, which leads to mistakes in using or setting up the machine. Next to that, there are multiple causes for these malfunctions. The first cause is the specifications of the dots. The dots are never the same size when they arrive at the packaging line, but the machines have specific ranges for the dots. A dot can have a diameter of 9.4 cm otherwise, it is too big for the packaging. When a dot is too big and it arrives at the packaging machines, there is a malfunction and the packaging machine stops which results in a lot of unnecessary waste. Another cause of the malfunctioning of the machine is that some dots are filled and sometimes the filling leaks from the dot during packaging. This results in a dirty conveyor belt or machine. The machine then has to be stopped to be cleaned. The machine itself does not cause this problem, but it causes downtime. Finally, some dots stick together while frying, so the dots cling together. When those dots arrive at the packaging machine, the machine stops which results in downtime.

These causes also have an influence when the dots are packaged by hand at line 1, but the employees can quickly discard these faulty dots and continue with the other dots or add a slightly bigger dot to several smaller dots so that they still fit in the packaging. This is a smaller disruption of the packaging process and therefore less of a problem.

Next to the flowpacker, there are other malfunctions at the line. The metal detector does not always function well. The metal detector is a critical control point (CPP) on the line. This results in waste when the metal detector is not functioning well, as the arriving dots cannot be processed and therefore cannot continue to the packaging lines. The metal detector malfunctions around 5% of the time. Finally, some other things cause downtime, like pushing the emergency button by accident or a sensor that is not functioning well. However, these things do not happen often and are mostly by accident.

2.5.2 Capacity of packaging lines

As shortly described above, the consumer packaging lines can not package at the capacity of the bakery. At line 1 the capacity per hour is displayed in Table 7.1 in Appendix H. The utilization could potentially increase to 95,95%, but EO has to schedule around 40 employees to make sure all dots get packaged. Next to that, the maintenance and malfunctions described in the sections above cause downtime, which decreases the capacity in some cases. When an SKU is scheduled with consumer packaging at line 1, a bulk-packaged version of that SKU has to be scheduled at the same time. When an SKU does not have a bulk packaged version of that SKU, part of the dots get packaged in bulk

anyway to be repacked later into consumer packaging.
At line 3 the SKUs are consumer-packaged by the automatic flowpacker. The flowpacker is designed to package all dots that arrive from the bakery, so if the flowpacker works well, it should be able to package all SKUs at 100% utilization. An exception is the flow pack with 1 dot. However, this is not always the case, as described in Section 2.5.1. In Table 7.2 in Appendix H an overview is given of the theoretical and practical capacity. To ensure the waste is as low as possible, the scheduling team always schedules another bulk packaging next to this consumer-packaged SKU, in case there is a malfunction or another reason why the flowpacker does not reach its full capacity. The practical utilization of all dots on both lines is lower, namely 54,52%.

2.5.3 Maintenance

As described above, the conveyor belts that transport the dots get cleaned two consecutive shifts a week. During the other shifts, the shift operators or employees clean the floor and the rest when/if there is time. Furthermore, the conveyor belts that transport the closed boxes get cleaned once a year. The flowpacker of line 3 is under maintenance for a week once a year. This maintenance is done by the company that installed the lines. Once a week, the flowpacker is checked on things like cooling water. Next to the processes on the first floor, the processes that are downstairs, like the folding of the packaging, have more maintenance tasks. There is minimal maintenance required for line 1 aside from cleaning the conveyor belts due to manual labour. The technical service employees mostly get called when a machine has a malfunction to set it up again. This is technically not in their job description, but the floor managers and employees are not always able to set up the machine themselves.

2.6 Employees

Both lines require manual labour, in Table 2.2 an overview can be seen of the number of employees on lines 1 and 3. The first row shows the total number of employees at the total line, so including both the bakery and the packaging. The second and third rows show the number of employees for the packaging section of the lines. For every line, there is one shift leader that supervises the line during a shift. This employee is responsible for the quality of the dots, the machines and the employees at the lines for that shift. Next to the shift leader, there are employees at the packaging lines on the ground floor (secondary packaging) and the first floor (primary packaging). For line 1, the capacity is influenced by the number of employees scheduled, since the packaging of the dots happens manually. For line 3, the capacity is not influenced by the number of scheduled employees.

Table 2.2: Employees per line

Employees	**Line 1**	**Line 3**
Average total line	21	20
Average packaging line - ground floor	3	3
Average packaging line - 1st floor	11	10

2.7 Current factory layout

An overview of the current factory layout is displayed in Figure 2.5. The total surface of the factory hall is around 200.000 square meters. The green part of the layout is dedicated to the packaging of the products. Appendix I, Figures 7.20 and 7.21 provide a more detailed overview of the layout of the packaging lines. The total surface of the packaging lines is around 5,000 square meters. At the moment the packaging lines are divided into two floors. The first floor is for the 'clean' packaging. The dots arrive here from the freezer and they get packaged in their primary packaging. From there, the packaged dots go down to the ground floor where they get placed in their secondary packaging if necessary and afterwards, they get placed on a pallet. On the ground floor, there is more use of cartons and wood (pallets) compared to the first floor. The reason for the current layout of the packaging lines is that on the first floor, everything has to stay clean and on the ground floor the dots are already packaged, so it is less important. The order of the packaging line is displayed in Figure 2.6.

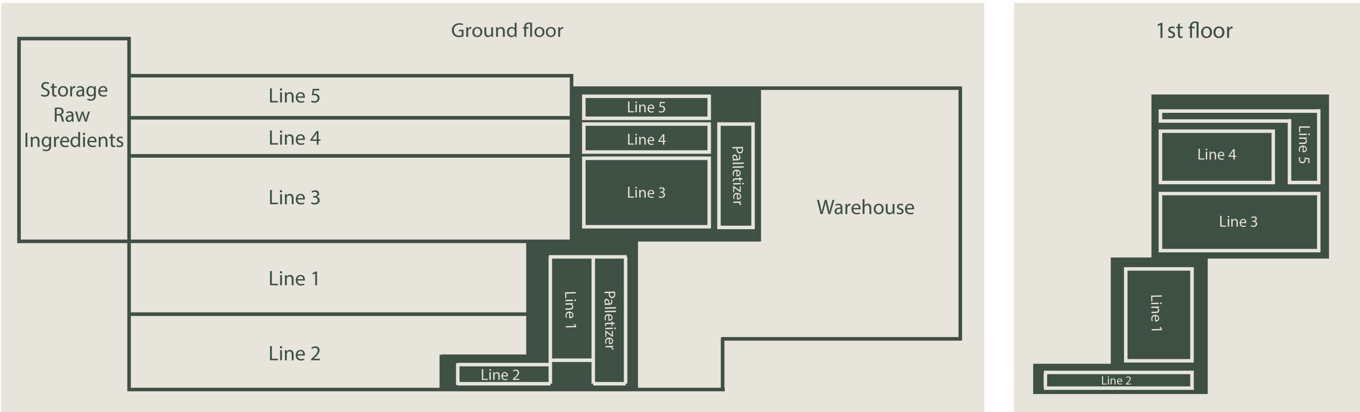

Figure 2.5: Current factory layout

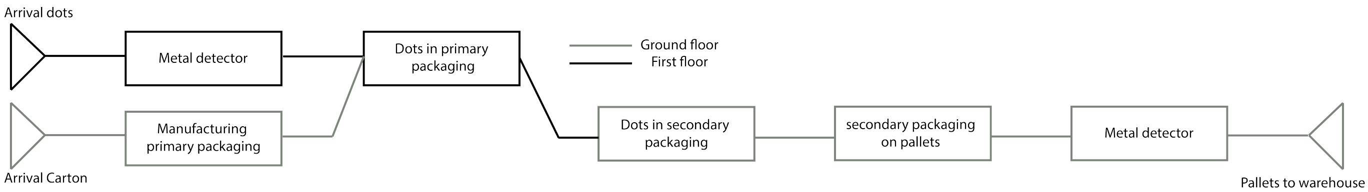

Figure 2.6: The order of the packaging line

2.8 Takeaways of the analysis regarding the capacity

From the analysis performed and described above, there are multiple takeaways regarding components of the packaging lines that influence the capacity or the other way around. First of all, the capacity influences the scheduling strategy of EO. For line 1, the division 60% bulk, and 40% consumer packaging always needs to be scheduled. For line 3, backup employees are always scheduled in case the flowpacker machine does not perform well. Next to that, the malfunctions of both lines influence the capacity, as it causes downtime. Downtime will lead to a lower capacity of that consumer packaging line. Furthermore, the maintenance causes downtime at the packaging lines, which results in less time to package all the dots, which then results in lower capacity. Another influence on the capacity of line 1 is the number of employees, as the dots get packaged manually. When there are fewer employees scheduled due to sickness or other reasons, the capacity decreases. Finally, the layout of the packaging lines might result in higher throughput time, as the dots have to go up and down multiple times. Higher throughput times of the dots might decrease the capacity.

2.9 Requirements, wishes and limitations

In this section, the requirements, wishes and limitations of EO regarding possible interventions are described.

Requirements:

- Packaging from Europastry Group has to stay in production. These packaging are used at every production plant of Europastry.
- The flow, as described in Section 2.5, has to stay the same.
- Control points (CP) and critical control points (CCP) like the metal detector have to be implemented in the new factory layout, to ensure the safety of the products.
- All dots have to be packaged at the packaging lines. Each dot can differ in size, which can differ quite a bit. The packaging line has to be able to process all dots as long as they are within the margins. Next to that, some dots can be sticky from sugar/caramel or another kind of topping/filling. The packaging line has to be able to handle those dots as well with minimal disruption.
- The proposed solution has to minimize manual labour. EO has a hard time getting enough employees for manual labour. Using a lot of manual labour increases the difficulty in managing the planning. The shift leaders are especially hard to find.
- For any adjustments at the packaging line, the safety of the employees needs to be ensured.

Wishes:

- EO would like to use the space that is currently used for the packaging lines. If this does not work out, another space could be advised.
- Another wish is to use the current machines in the new production layout.

Limitations:

- EO does not work with budgets, but with payback periods. Each possible investment is expressed in a payback period. Each year, EO has a budget to invest in the company. For this research, there is no payback period defined, but it has to be realistic.

3 Literature study

In this chapter, a literature study will be performed on several of the topics in this thesis. The chapter will start with information about simulating a production floor in Section 3.1. After that, bottleneck analysis and improvement will be discussed in Section 3.2. In Section 3.3 several ways to improve capacity that are in literature are described. Finally, the important factors regarding manufacturing lines in the food industry are discussed in Section 3.4.

3.1 Simulation

A system can be defined as a collection of entities that act and interact together toward the accomplishment of some logical end (Law, 2015). In Figure 3.1 an overview is displayed of the ways to study a system. Following this flowchart for this study, a simulation is the way to study this specific system. We cannot experiment with the actual system or with a physical model. Next to that, the study is too complex to solve with an analytical solution.

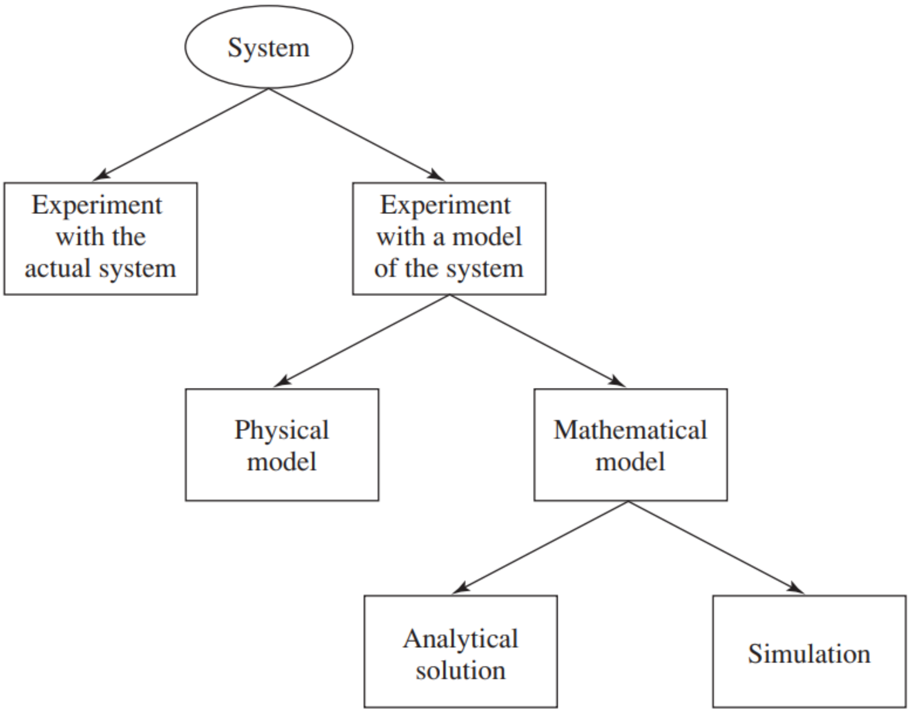

Figure 3.1: Flowchart of ways to study a system, from Law (2015, Chapter 1.2)

3.1.1 Discrete event simulation (DES)

Büth, Broderius, Herrmann, and Thiede (2017) describe the main methods for simulation modelling within the manufacturing industry. These are discrete event, agent-based, system dynamics and dynamic systems. Figure 3.2 shows an overview of the different simulation types and their usage within different management layers. Supply chain simulation is located at the middle abstraction layer (Borshchev & Filippov, 2004). According to Prajapat and Tawari (2017), DES is widely applied to analyse and optimize manufacturing systems and assembly lines. Next to that, it can answer key operational questions relating to throughput, capacity, resource allocation, utilisation, bottlenecks and supply and demand.

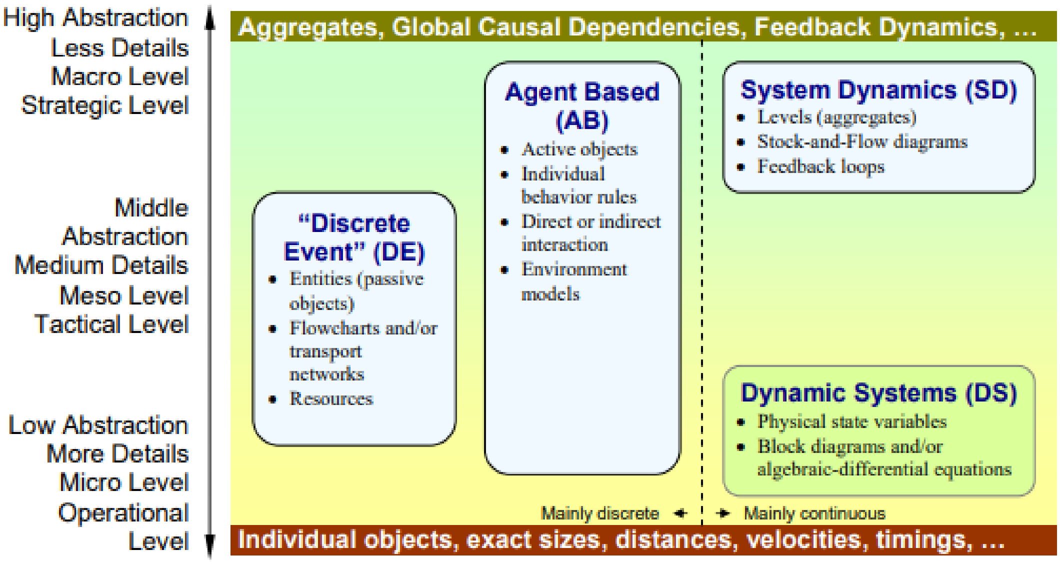

Figure 3.2: Overview of simulation types within different management layers, from Borshchev and Filippov (2004, page 3)

Discrete event simulation is a model that concerns itself with a system that evolves over time. The change of the state of a discrete system is triggered by events at separate points in time, rather than continuously over time (Law, 2015). A state can be described as a collection of variables necessary to describe a system at a particular time (Mes, 2022b). The number of products in a system can be seen as variables of a state that changes when production starts or stops. According to Negahban and Smith (2014), DES is one of the most commonly used simulation methods within manufacturing systems. For experiments within food production, DES can be successful as well (Abed, 2008). For this study, DES will be used to simulate the packaging lines of EO.

3.1.2 Simulation study design

In Figure 3.3, the steps of a simulation study can be found. This approach will be used as a basis for the simulation study. The steps will be described more in detail below:

- Step 1 concerns determining the problem, having kick-off meetings, determining the objective and determining the program that will be used. This step is done in Chapters 1 and 2.
- Step 2 will look into understanding the problem more thoroughly by collecting and analysing data. Next to that, it is important to list all assumptions. Translate the data and assumptions into workflows and determine the level of detail. This step is done in Chapters 2 and 4 by creating a conceptual model. More information about conceptual models can be found in Section 3.1.3.
- Step 3 is a step in the study that determines if all assumptions are valid and necessary to use. The assumptions used in this simulation study are described in 4.1.6 and are discussed with the interested parties.
- Step 4 concerns creating a programmed computer model and verifying/debugging the model. For this study, Siemens Technomatrix Plant Simulation is used. More about this step can be found in Chapter 4.
- Step 5 and step 6 ensure that the model that is created in step 4 is correct and validated before running any experiments. After the validation, the model can be used as a decision-support tool for this study. This step is described and executed in Section 4.2.1.
- Step 7 is used to determine experiments and the experimental settings. In this study, the experiments or interventions will be used to alter the packaging line (layout) to determine if this increases capacity. The

interventions and the experimental settings are discussed in Section 4.3.

- Step 8 and step 9 result in running the model and analyzing the output to determine if the performance of certain interventions could potentially increase the capacity of the packaging lines. The output of the simulation interventions is discussed in 5.
- Step 10 will make sure that all steps and results of the study are documented well so that they can be reviewed and may be used again for similar decisions.

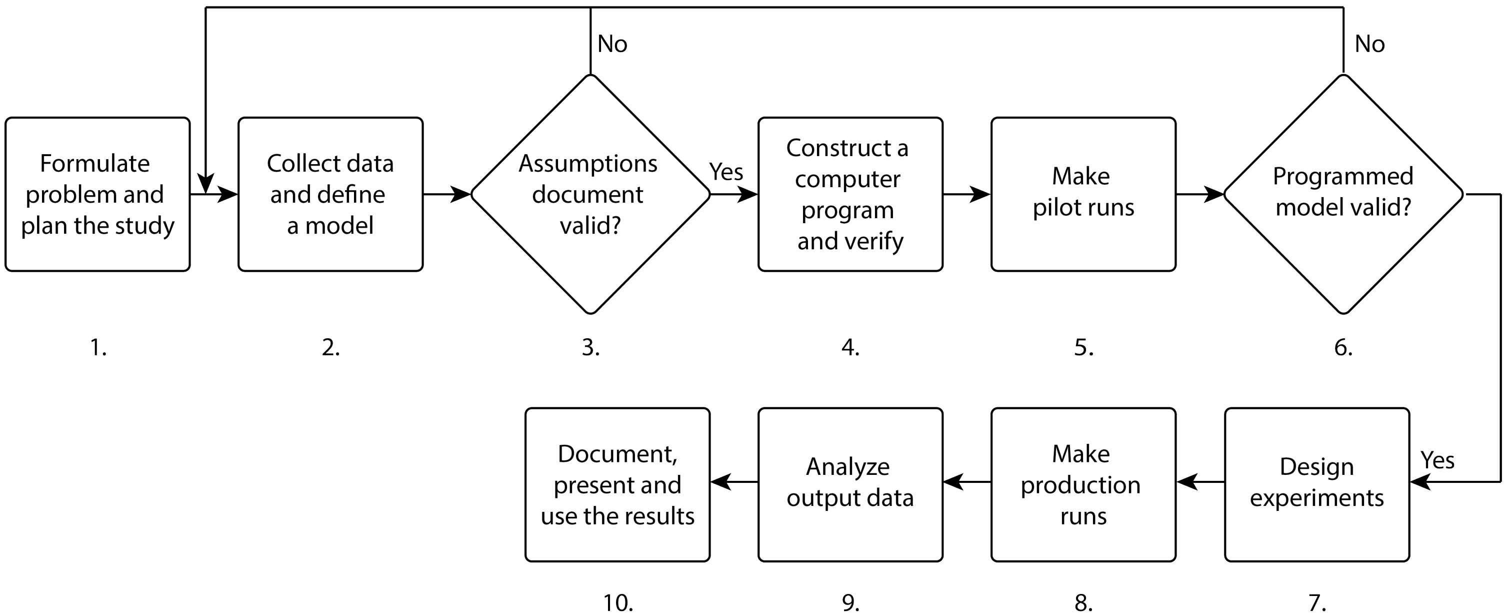

Figure 3.3: Steps in a simulation study, adapted from Law (2015, Chapter 1.7)

3.1.3 Conceptual Model

Robinson (2004) describes a conceptual model as *"The conceptual model is a non-software specific description of the simulation model that is to be developed, describing the objectives, inputs, outputs, content, assumptions and simplifications of the model."*. A framework for developing a conceptual model is displayed in Figure 3.4. This framework gives the user guidance over the iterative process of developing a conceptual model. A conceptual model should be as simple as possible. A conceptual model helps as a discussion framework and communication tool, as all stakeholders can understand it and everyone is on the same page (Robinson, Arbez, Birta, Tolk, & Wagner, 2015). Next to that, the benefits of a conceptual model are that it minimizes the likelihood of unclear or inconsistent requirements, it increases the credibility of the model, it is a starting point for the software model, it can act as verification or validation of the model and it helps with experimenting by documenting the inputs, outputs and content of the model (Robinson et al., 2015).

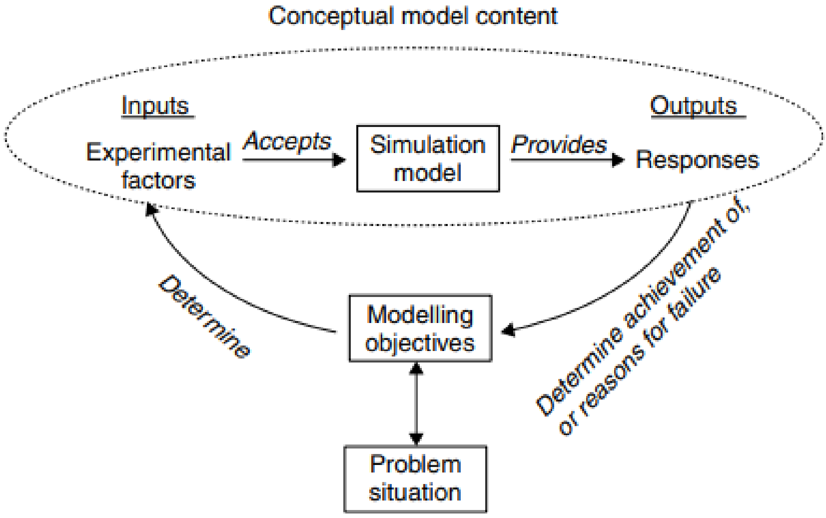

Figure 3.4: Framework for developing a conceptual model, from Robinson (2004, Chapter 6.2)

3.1.4 Experimental settings

There are different kinds of simulation output. First, there is a difference between transient and steady-state behaviour. For transient system behaviour, the performance depends on the initial conditions and is unbalanced whereas the steady-state behavior does not depend on the initial conditions. Secondly, there are terminating and non-terminating simulations. Terminating simulations have a natural event that specifies the end of a simulation run, for example, a store that closes at 18:00. A non-terminating simulation does not have a natural event, so this simulation type continues (Law, 2015). For this model, a non-terminating steady-state behaviour simulation type can be used, because the packaging lines do not stop and create steady-state cycles by all shifts.

Furthermore, to conduct successful experiments for a non-terminating steady-state simulation, a warm-up period, the number of replications per experiment and the run length have to be defined. The warm-up period needs to be taken into account before the simulation has usable output because the simulation starts with an empty system. For example, when a production shift starts, the first time period is not reliable, since the line might not be clogged yet or the employees have to start up which makes the production slower in the beginning. To determine the warm-up period, the Welch approach could be used (Law, 2015). Next to that, the number of replications has to be determined. This is done by using the sequential procedure. This procedure tests the number of replications until a confidence interval 1 - α for the mean is reached (Law, 2015). The recommendation is to choose $\alpha \leq 0,15$ and the number of replications bigger or equal to 10. The run length of the simulation and the number of replications are intertwined. If you make the run length longer, the number of replications decreases, so a trade-off needs to be made between the two. A guideline for choosing the run length is to at least take 10 times the warm-up period. The run length can be longer, but there need to be at least 5 replications per experiment (Mes, 2022a).

Finally, the validation and verification of the simulation (output) is very important for the validity of the study. First, verification is done by checking if the assumptions are correctly translated into the simulation program. Validation is concerned with determining if the simulation model is an accurate representation of the real world or system. Lastly, the model has credibility if the stakeholders of the system accept the model as correct (Law, 2015). In Figure 3.5 the timing of the verification, validation and credibility steps are displayed during the steps of a simulation study. Validation of a model that represents the real world can be done by comparing the model with the system. If the output of both of those are closely similar, the model can be seen as valid. Testing if the data is similar can be done by statistical tests (on independent data) or the inspection approach (Law, 2015). Another way to verify and validate the model is by black-and-white box testing, which will be discussed below.

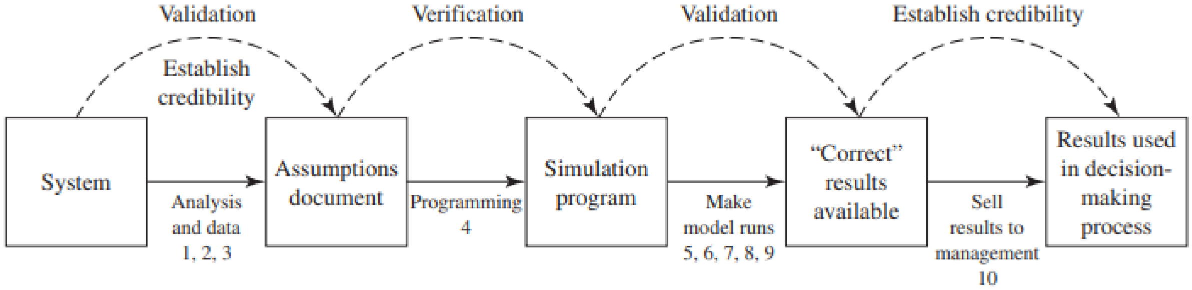

Figure 3.5: Verification, validation and credibility during the steps of the simulation study, from Law (2015, Chapter 5.1)

Black-and-white box testing

First of all white-box testing is often used as verification of the simulation model, which is often done by the modeller (Nidhra & Dondeti, 2012). White box validation is a check of the model to determine whether each part of the model represents the real world with enough accuracy to meet the objective of the simulation study (Robinson, 2004). Black-box validation does not concern itself with the coding and elements of the model but with the input and output of the model (Nidhra & Dondeti, 2012). Black-box testing asks the question: 'Does the model provide an accurate representation of the real world to meet the objectives of the study?' (Robinson, 2004). Black-box testing is done from the perspective of the end user. An overview of both the black-box and white-box testing techniques is displayed in Figure 3.6. Nidhra and Dondeti (2012) states that a system should be tested using both black-box and white-box testing. First, white-box testing consists of two techniques: static and structural. Static testing mostly means checking the code on the accuracy and correctness by debugging, visual checks and analysing the output data. Structural testing focuses more on the internal design of the code and the code structure. This could be done by one of the tests displayed in the figure, so control flow, basic path, loop or data flow testing. Black-box testing can be done in several ways, as displayed in Figure 3.6. All these options help determine the (lack of) similarity between the real world and the simulation model.

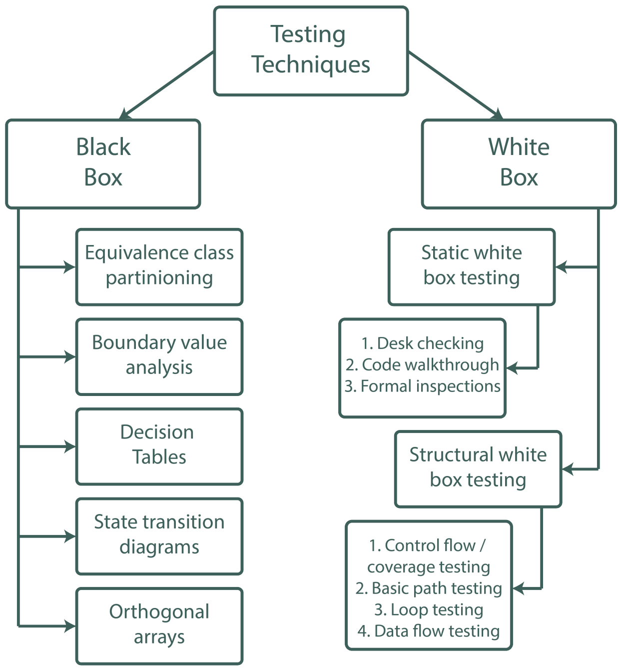

Figure 3.6: Black and white box validation, adapted from Nidhra and Dondeti (2012, section 3.2)

A way to combine black-and-white box testing to increase the testing coverage is grey-box testing. It considers both the internal and external of the software (Khan & Khan, 2012). Grey-box testing is more interpretable than black-box testing, less time-consuming and more computationally efficient than white-box testing (Li et al., 2021). Disadvantages of grey-box testing are that the source code is out of scope and therefore the tests are restricted, numerous systems stay untested and the experiments can be repetitive (Hussain & Singh, 2015). Hussain and Singh (2015) describe in their study that between, black-box, white-box and grey-box, white-box testing is the most reliable for detecting defects and analysing those.

3.1.5 Intervention design & analysis

An intervention can be described in different ways. The overall description of an intervention can be something like a hypothetical sequence of events or future for decision-making or dealing with uncertainty (Reilly & Willenbockel, 2021). The start of intervention analysis was in 1965 at Shell. Here it was used as a leadership tool, to react to already explored interventions and think about the future (van der Heijden, 2005). Intervention analysis is considered to be subjective, so there are not many approaches to use. However, Maack (2001), does describe steps for the intervention analysis process. These steps are displayed below:

1. *Define a focal issue or decision:* this step is there to determine a scope for the intervention analysis. Without it, the analysis might become too general.
2. *Identify driving forces:* identify the economic, environmental, political, social and technological factors that are important for the focal issue.
3. *Write intervention plots:* in this step the intervention plots are described that explain how the driving forces interact and how they affect the operation or strategic direction.
4. *Flesh out interventions:* design interventions that have a good understanding of the present with a clear focus on the wanted outcomes. The interventions should be based on the information gathered from previous steps and data analysis.
5. *Look at implications:* when the interventions are fully developed, the results of the interventions on the outcomes have to be discussed.
6. *Choose 'leading indicators':* the indicators will be the basis for the decision makers for choosing the intervention.
7. *Disseminate interventions:* the interventions should be written in easy-to-read language and distributed within the organization.
8. *Integrate intervention outcomes in daily procedures:* integrate the chosen intervention and monitor the progress.

Steps 1 - 4 are for understanding the system and developing interventions. Steps 5-8 are meant to make a decision and integrate the chosen intervention. Each step is iterative, as later steps can give new information which can be used in another newly developed intervention.

3.2 Bottleneck analysis and improvement

A bottleneck can be described as a resource whose isolated production rate is the smallest among those in the system or as the resource that has the largest impact on reducing the throughput of a system (Imseitif, Tang, & Smith, 2019). Simulation can be very useful for solving bottlenecks and bottleneck detection, especially for complex and dynamic production systems (Leporis & Králová, 2010; Velumani & Tang, 2017). When using simulation to detect bottlenecks, the method 'Criticality indicators-based method' can be used. This approach determines the criticality indicator (KR_i) per component of the production line. Components with a minimal KR_i are regarded as bottlenecks (Leporis & Králová, 2010). Another method to analyze bottlenecks in a manufacturing system is to determine the overall equipment effectiveness (OEE). Tang (2019) describes different methods to analyze and interpret the OEE of a manufacturing line to analyze bottlenecks. OEE can show how well a company uses its existing resources like equipment, labour and customer satisfaction (Sowmya & Chetan, 2016). OEE is calculated by three metrics: availability, performance and quality. The six big losses in OEE are displayed in Figure 3.7. The downtime losses are taken into consideration by the availability metric. The performance metric takes the speed losses into account and any quality losses are taken into account by the quality metric. A 100% OEE score is a perfect production that only manufactures good parts as fast as possible, with no downtime. An OEE of 85% can be seen as world-class. An OEE score of 60% is quite typical for manufacturers, but it does indicate that there is room for improvement (Sowmya & Chetan, 2016).

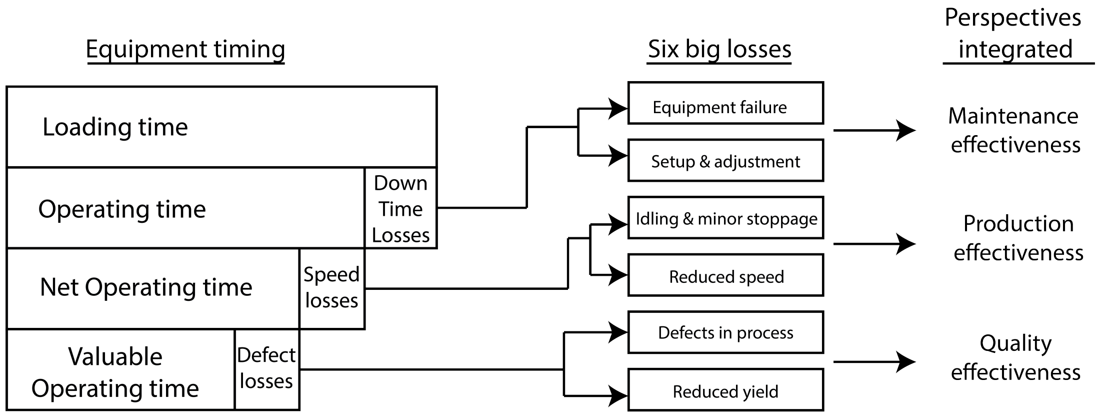

Figure 3.7: Six big losses in OEE, adapted from Sowmya and Chetan (2016, page 557)

Another methodology to analyse bottlenecks is the theory of constraints (TOC). This is a system improvement methodology that finds the constraints of a system, the weak links. The constraints determine the performance of the entire system and place a process control at that point (Jevgeni, Eduard, & Roman, 2015). The steps of TOC are displayed in Figure 3.8. The drum, buffer, and rope concept comes from the TOC. The weakest link or bottleneck is called the drum because it sets the 'beat' for the rest of the process that follows. The buffer is kept in front of it, to make sure that the process can always continue. The rope controls the prior activities so that those activities do not overproduce (Slack et al., 2010). This concept helps to determine where the process control should occur. In another paper, Velumani and Tang (2017) use DES combined with TOC to determine and solve bottlenecks in a manufacturing system.

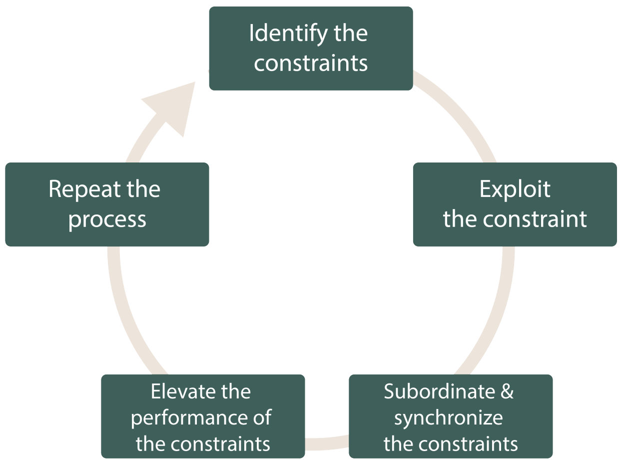

Figure 3.8: Steps of TOC, information from Slack et al. (2010, Chapter 15)

Another bottleneck detection technique that can be used within DES models is by giving each station within the simulation an active or inactive state. Inactive states could for example be being repaired, waiting or blocked. The duration of the periods of the active states of each station should be measured. The station with the longest average active period can be considered the bottleneck because this station is least likely to be interrupted by other machines and most likely to dictate the overall system throughput (Roser et al., 2001).

3.3 Capacity improvement

There are multiple ways to increase the capacity of a manufacturing line. This could, for example, be done by redesigning the layout of production machines or inventory or reducing the cycle time (Dias, Silva, Campilho, Ferreira, & Santos, 2019). Capacity could also be increased by better utilization of existing resources (Sowmya & Chetan, 2016). In the following sections (3.3.1, 3.3.2 & 3.3.3), different ways will be described in more detail.

3.3.1 Buffers

First of all, according to the TOC, placing buffers could improve the capacity. Colledani, Hotvath, and Angius (2015) describe how the system throughput and production lead time can increase by placing finite buffers. Placing buffers enhances the throughput of the production by reducing the reducing and starving time of workstations along the line (Ameen, Alkahtani, Mohammed, Abdulhameed, & El-Tamimi, 2018). When a machine along the line fails, buffers can also reduce the waste and disruption of the whole line (Shi & Gerswhin, 2009). The size of the buffer also influences the system performance (Pettersen & Segerstedt, 2008). There is a certain threshold and when that threshold is reached the system performance will improve, but at a certain buffer capacity, the system performance will remain stable, even though the buffer capacity might increase (Ameen et al., 2018; Kulkarni, 2020). However, buffers might increase cost and capital immobilization in the factory (Ouzineb, Mhada, & an I. El Hallauoi, 2018). So if buffers are used, it is important to take the cost into account and make a trade-off between system performance and costs. Imseitif et al. (2019) found that the location of the buffer is much more significant and effective than the capacity of the buffer. When a manufacturing line is not in balance (not every step has the same mean processing time), a system needs buffers to make sure the manufacturing line performs smoothly (Powell & Pyke, 1997). Several heuristics methods, allocation algorithms, dynamic programming approaches, search methods and queuing networks are developed to determine the number and location of buffers (Shi & Gerswhin, 2009).

3.3.2 Layout improvement

As described in Section 3.3, capacity can be improved by redesigning the layout of the manufacturing line. Figure 3.9 displays different layout options for different production varieties and quantities. If the layout is different than the one in the figure, higher costs and/or lower efficiencies might be faced (Groover, 2015). As the production quantity falls within mass production and there is not that much production variety within the packaging, the proposed process layout is the quantity or flow line production.

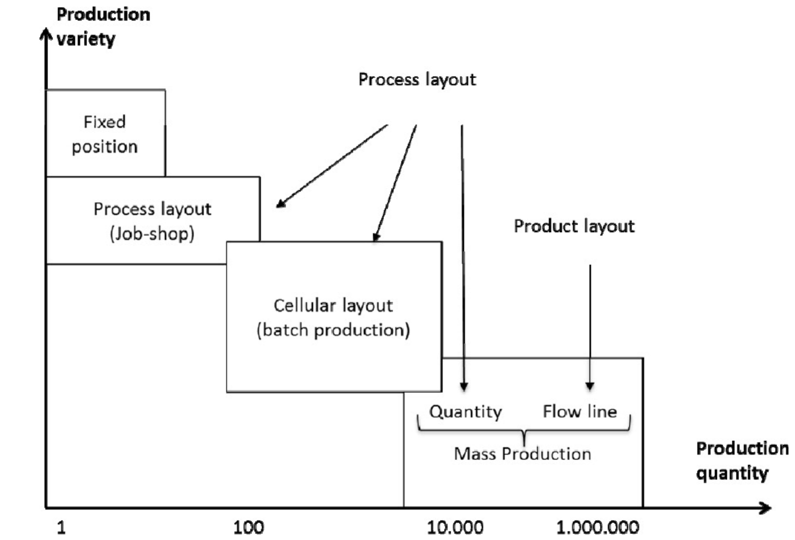

Figure 3.9: Possible layout for various quantity - variety combinations, from Groover (2015, Chapter 2.4)

Quantity production is the mass production of single parts on single pieces of equipment, often on standard machines dedicated to that specific part. Flow-line production is multiple workstations arranged in sequence and the part moves through the sequence to complete the product. This way of production is designed to maximize efficiency (Groover, 2015). There are two distinctions within flow-line production. First, there is the single-model production line. This is a line where there is no variation in the products on the line. When there is some variation in the products the flow-line is called a mixed-model production line. A flexible flow line can be defined as a production line where jobs pass through multiple stages with one or parallel machines at each stage and there is unlimited intermediate storage between any of the successive stages (C. Chen & Chen, 2009). An example of a flow-line production is displayed in Figure 3.10.

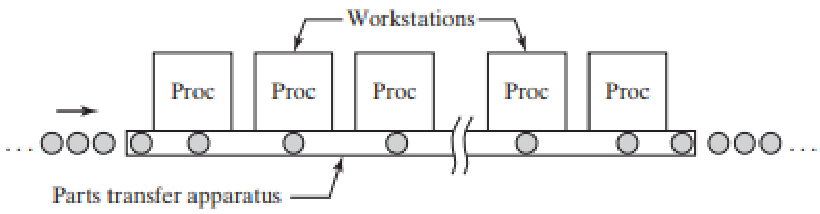

Figure 3.10: Example flow line production, Proc: process, from Groover (2015, Chapter 2.3)

There are three types of manufacturing systems: Dedicated Manufacturing lines (DML), Re-configurable Manufacturing Systems (RMS), and Matrix Manufacturing Systems (MMS) that are (mainly) suited to run at high capacity (Fries et al., 2021). DML is best suited to run at high capacity and has low operation costs and short lead time, but is not flexible as changes in the quantity of product might take a long time to modify. RMS has an adaptable and modular set-up to be able to change between volumes of products however, it is not a suitable system for high market volatility. RMS has several core characteristics that make it a valuable tool. These include scalability, convertibility, diagnosability, customization, modularity, and integrability (Koren, Gu, & Guo, 2018). Machines in an RMS should be adjustable quickly. Finally, MMS consists of flexibly linked, usually dedicated, process modules that allow products to have their own individual production path. Another way to increase capacity by changing the layout of the packaging line is by constructing parallel lines (Gökçen, Ağpak, & Benzer, 2006). Parallel lines might shorten the assembly line, but it might need more tools and equipment. Another advantage is that if one line breaks down, there is still one line that can continue running.

Systematic Layout Planning (SLP)

SLP is a layout design approach that is often used in the last decades (Yang et al., 2000). The procedure is displayed in 3.11. The first step is collecting the input data of the products (P), quantities (Q), routing (R), supporting (S), time (T) and activities. In step 2 the flow of materials is analysed in a from-to chart. Step 3 concerns creating an activity relationship chart among different departments. Steps 2 & 3 are combined into a relationship diagram in step 4. Steps 5 and 6 will take into account the space requirements and the available space, which will be incorporated in step 7 in a space relationship diagram. Together with the constraints (step 8) and limitations (step 9), layout alternatives can be developed. Step 11 will evaluate all layout alternatives and choose the final design. The application of SLP is focused on making the fastest material flow with the lowest cost and least amount of material handling (Suhardini, Septiani, & Fauziah1, 2017). Next to that, it can also be used for improved productivity and better layout planning (Buchari, Tarigan, & Ambarita, 2018).

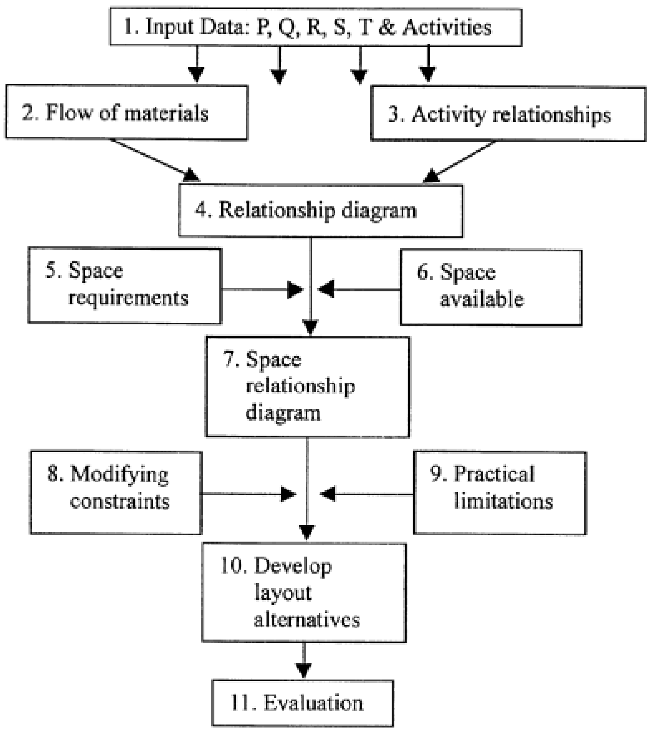

Figure 3.11: SLP procedure, from Yang et al. (2000, Chapter 2.3)

3.3.3 Maintenance

Maintenance is costly in both maintenance costs and downtime of the manufacturing line. Well-maintained hold tolerances better and raise consistency and quality of the product, but maintenance does affect cost and product lead time (Lee, 2007). According to McKone, Schroeder, and Cua (2007), the total productive maintenance and the manufacturing performance have a direct and indirect influence on each other. The production speed influences the deterioration of the machines in the production line. Lowering the production speed could have some influence on the speed of deterioration and therefore for maintenance planning (Koopmans & de Jonge, 2023). The production and maintenance functions influence each other. Production functions create demand for the maintenance functions and vice versa (Muchiri, Pintelon, Martin, & Chemweno, 2014). Preventive maintenance (PM) is an effective way to make sure that the production capacity of the manufacturing line stays on track, since PM decreases stochastic station failures (Zhou & Shi, 2019). Another way to increase the capacity is by load sharing. Multiple machines are processing the same product so that if one machine fails or has maintenance, the other machine can pick up the slack. For two-unit systems, the availability of the machines does not increase, but the cost decreases significantly. For three-unit systems, the availability reaches almost 100% (Koopmans & de Jonge, 2023).

3.3.4 Lean methodology

Incorporating the lean concepts in manufacturing systems can increase the capacity (Secola, n.d.). The lean methodology tries to decrease the waste and non-value-adding activities in a system (Karim & Zaman, 2018). Within waste, the lean methodology classifies overproduction, waiting, transportation, inappropriate production, excessive inventory waste, defects and unnecessary motions. There are five principles in the lean methodology (Kumar et al., 2022):

1. *Define value:* this step will make sure that the value is defined from the customer's point of view.
2. *Map the value stream:* map the material and information flows required to coordinate the operations conducted by manufacturers, suppliers, and distributors to deliver products to clients.
3. *Flow:* this step makes sure there are no interruptions in the process from start to delivery to the client
4. *Pull:* this principle states that nothing is done in the upstream process until there is a signal from the customer.
5. *Finding perfection:* this last step will try to find perfection, as this will separate a producer from the rest.

Several useful lean techniques can be implemented in a manufacturing system (Kumar et al., 2022). One of those, which is already used by EO, is the 5S system, a technique with 5S's: Sort, Set in order, Shine, Standardize and Sustain. Other techniques are displayed in Table 3.1.

Table 3.1: Lean techniques (Kumar et al., 2022)

Technique	Description
Bottleneck analysis	This technique involves the measurement of time in the whole production process. With this technique, the maximum needed time can be calculated and the bottlenecks can be identified.
Takt Time	Helps to determine the cycle of the production.
Cellular manufacturing	Produce in batches to ensure optimal use of machinery and it saves time.
SMED	Single minute exchange of die and this technique is used for reducing the set-up time
Total Productive Maintenance	Applied for maximum efficiency, consistency, and process capability.
Total quality management	This technique focuses on minimizing defects and improving quality.
Visual management	Uses immediate visual information so that the user can handle it accordingly.
Work standardization	Maintains homogeneity, it makes sure that there is not any variation within a task.
Flexible Manufacturing System	As described in Section 3.3.2
Production levelness	Reducing unevenness in the production system
Just-in-Time	Produce what is ordered when it is ordered. This technique reduces inventory costs and time.
Kanban	Use visuals to show the work to be done and the work in progress. This increases efficiency and decreases the work in progress.
Kaizen	Continuous improvement

3.4 Manufacturing lines in the food industry

In this section, the capacity and layout improvement within the food industry will be discussed, because packaging food takes other important factors with it, like preventing contamination and food hygiene. The main goal of food manufacturers is to produce something wholesome and safe.

Amit, Suhaak, Johari, and Kassim (2012) use SLP to design the facility layout for the production process of a snack food manufacturing company while looking at the capacity of workers and machines. The weaknesses found in that process were layout flexibility, productive area utilisation and closeness gap. The distances between workstations were changed to improve the material flow and a new machine was chosen to increase the capacity.

Within the food industry, it is important to include practices like hazard analysis and critical control points (HACCP) or good manufacturing practices (GMP) in the facility layout to try to ensure food safety. Both practices can be implemented to ensure a high level of hygiene. Quality assurance (QA) systems are implemented to improve quality and reduce cost. The layout should facilitate the prevention of cross-contamination of the products that are being produced Wanniarachchi et al. (2016). In Figure 3.12, the proposed framework for food processing industries is displayed. Step A addresses the capacity of the required machines. In step B the design parameters of the process are determined. Step C is concerned with generating the space requirements for the different sections. The layout alternatives are developed in step D and step E the most successful layout is chosen.

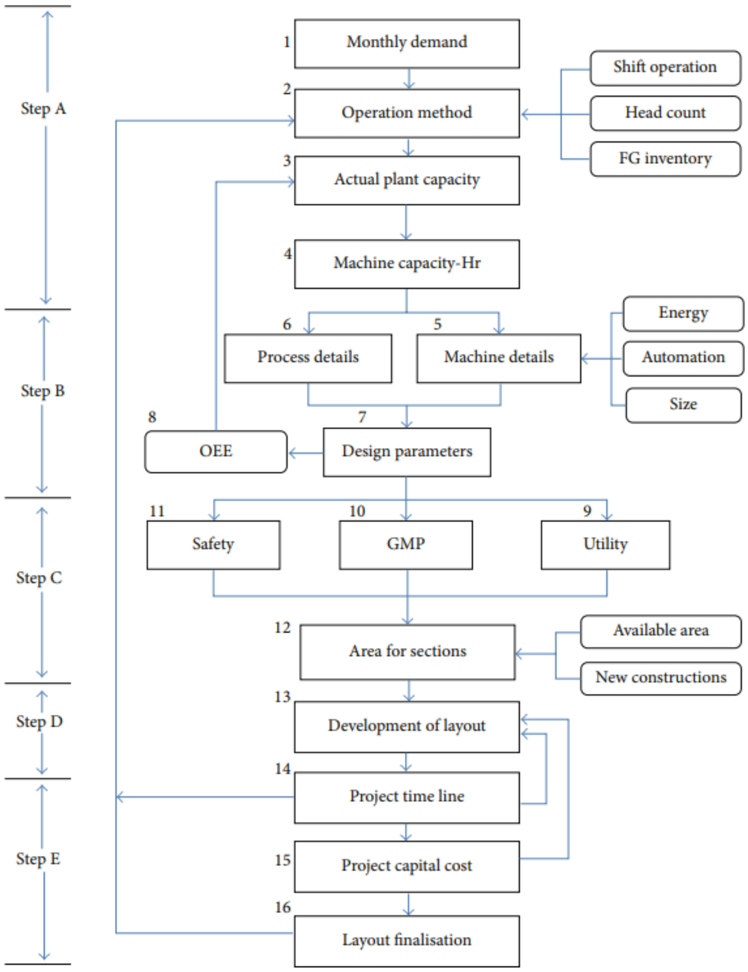

Figure 3.12: Proposed framework to develop a facility layout within the food production, from Wanniarachchi et al. (2016, page 3)

X. Chen, Nophut, and Voigt (2021) describe in their article the feasibility and practicality of a manufacturing execution system (MES) within the processing and packaging area within the food and beverage industry. MES is a process-oriented software system for managing and analyzing real-time information from the processes in the manufacturing line (X. Chen et al., 2021). It connects the enterprise resource planning (ERP) system with the manufacturing line and it gives information about key performance indicators (KPIs). MES enables the optimization of the complete manufacturing line by giving current and accurate data, which results in a fast response to changing conditions.

Over the past few years, there has been a noticeable increase in the use of robotics in the food industry. COVID-19 particularly had a big influence on the automation of food manufacturing lines and the use of robotics (Wang, Hirai, & Sa.Kawamura, 2021). Robots can be utilized for various tasks throughout the entire food production process, including quality control. Robotics is most often used within the packaging of the food. While the degree of improvement may differ depending on the food sector and process, productivity could increase by up to 25% (Iqbal, Khan, & Khalid, 2017). Next to that, a robot can help increase food safety and hygiene levels (Duong et al., 2020). (Duong et al., 2020) describe the use of robotics and autonomous systems (RAS) in the food industry. The development of RAS is encouraged due to its ability to operate in hazardous environments, cost-effectiveness, fatigue prevention, and support for co-working with employees/operators. (Bader & Rahimifard, 2020) describe the food industrial robot methodology (FIRM) to choose a suitable robot for the purpose. This methodology is displayed in Figure 3.13. Following the flow of this methodology might help to choose the correct robot. For this study, the start is choosing a foodstuff type, which is baked goods and confectionery. Following the steps, the next step is choosing the foodstuff condition, which is frozen. The foodstuff state is whole since does not have multiple parts. The next step is the classification of the foodstuff. The rigidity is semi-rigid. It is a frozen dot, so it can undergo some pressure, but with too much pressure the shape will be altered. The deformity of the dot is non-deformable. The third step is the specification of the operation type. According to the paper, primary packaging falls in the material handling category (Bader & Rahimifard, 2020). Finally, the identity step consists of the industrial robot's configuration and the end effector. For this study, an articulated or parallel configuration could be chosen and all grippers are an option as the end effector (Bader & Rahimifard, 2020).

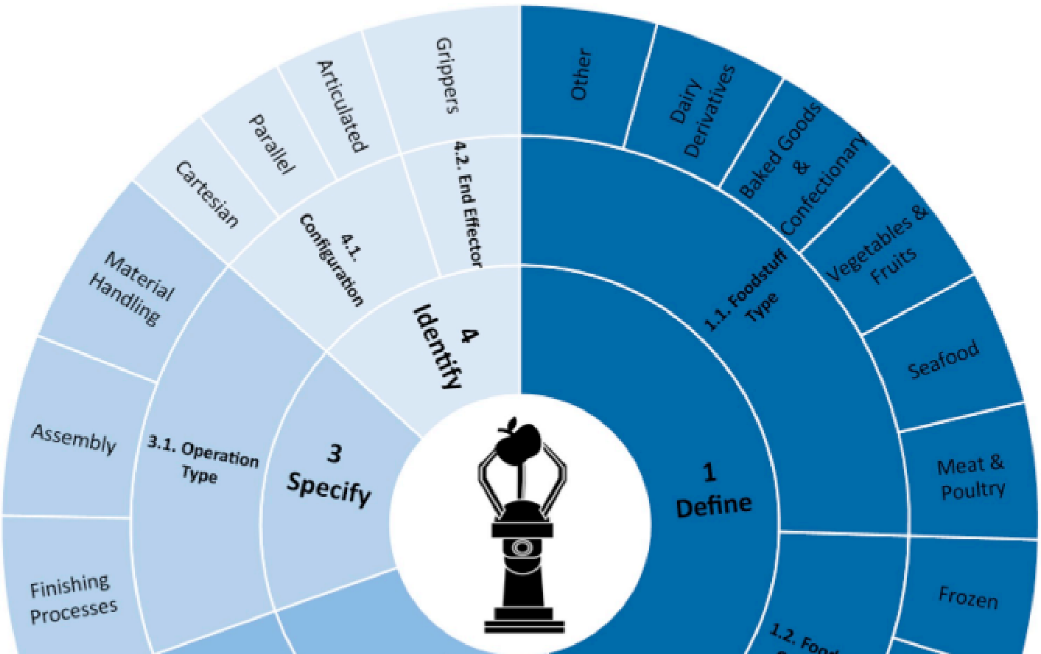

Figure 3.13: The food industrial robot methodology, from Bader and Rahimifard (2020, page 3)

3.5 Summary of Chapter 3

In this chapter, the second research question has been answered: *"What are the trends and best practices on increasing the capacity of packaging lines in literature?"*. This was done by looking into the simulation methods, bottleneck analysis, capacity improvement and looking into manufacturing line (improvement) in the food industry.

To summarize the literature study, an overview will be given of the methods that will be used in this thesis. First of all, from the literature study is concluded that a simulation study, especially DES is an effective tool for performing experiments regarding the improvement of the capacity of the packaging lines. Therefore, the steps of a simulation study will be followed as described in Section 3.1.2 as well as the experimental settings described in Section 3.1.4. Finally, the design and analysis as described in 3.1.5 will be used as a basis to design and analyse the interventions.

Next to that, the TOC will be used to identify the constraints in the system using DES as described in Section 3.2. In Section 3.3 multiple areas of improvement of the capacity of a manufacturing line are described. From these ways, the buffer, layout improvement and maintenance will be used as interventions in the simulation as a possible improvement. The information regarding manufacturing lines in the food industry in Section 3.4 will be used as inspiration and basis for the interventions. These interventions are described in Section 4.5.

4 Solution design

In this chapter, the solution design will be discussed. It will start with the conceptual model in Section 4.1. In this section, the objective, content, input, output, settings, simplifications, and assumptions of the conceptual model will be described. Section 4.2 continues with the simulation model, the experimental setup and the validation of this model. Next, the experimental design will be discussed in Section 4.3. Followed by the final section of this chapter, Section 4.5, which describes the potentially capacity-increasing interventions.

4.1 Conceptual Model

The conceptual model is used to gain a better understanding of the simulation model which is to be developed. The objective of this simulation model is to improve the capacity for packaging lines 1 and 3 as described in Chapters 1 and 2. The conceptual model created is in line with the framework explained in Section 3.1.3. The conceptual model has been implemented in a discrete event simulation model using Siemens Technomatrix Plant Simulation. In Figure 4.1, the conceptual model is displayed including the input, model content and output. In Sections 4.1.2, 4.1.3 and 4.1.4, the input, model content and output will be described, respectively. The simulation model will be developed in

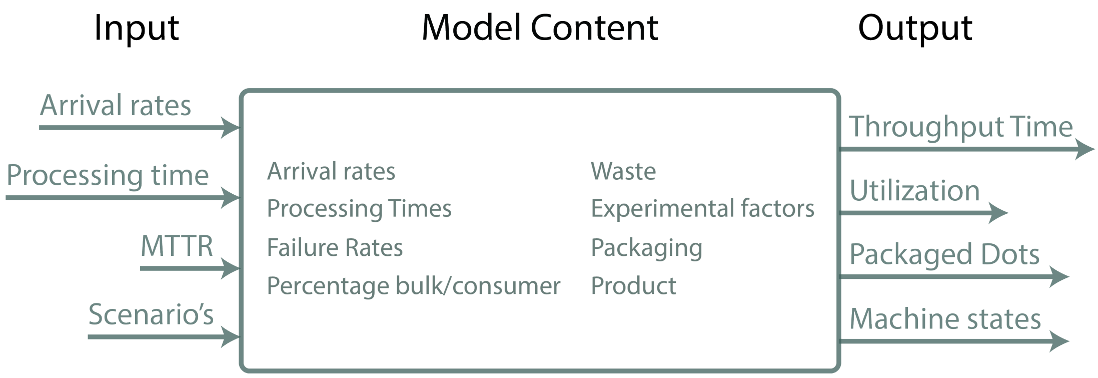

Figure 4.1: Conceptual Model

4.1.1 Data collection

To be able to build a simulation model of packaging lines 1 & 3, data for the inputs needs to be gathered. The output logs of 2022 and 2023 are used to determine the arrival rates and processing time. These logs are filled in by hand during and at the end of the shift. This means that the data could contain mistakes due to human error. Therefore the shifts in which there are more dots packaged than theoretically possible are left out of the data used for the simulation. Additionally, other input data needed is collected by measuring manually. According to the central limit theorem, 30 observations or more are needed for the sampling distribution to follow a normal distribution (Ross, 2021). Therefore, all measurements have at least 30 observations.

4.1.2 Inputs

In this section, all inputs, except the interventions, will be discussed. It will start with the arrival rates for both lines, followed by the processing time of line 1 and the downtime (MTTR) of line 3.

Arrival Rates

In this section, the distributions for the arrival rates of the dots will be determined for lines 1 and 3. To get a better understanding of how the sample data behaves, a histogram is created. Next, a Kolmogorov-Smirnov goodness-of-fit test with a confidence level of 95% is used to determine the distribution of the arrival rate. This is possible due to the data being of a continuous nature (Ross, 2021). To test a distribution, a null hypothesis and an alternative hypothesis are constructed as follows:

$$H_0\text{: The data follows the distribution}$$
$$H_a\text{: The data does not follow the distribution}$$

The p-value of this goodness-of-fit test for a specific distribution has to be bigger than 0,05 to not be able to reject the null hypothesis. However, this does not directly mean that the data does follow the distribution. To be able to conclude this, additional tests need to be performed. This is done by testing the possible distributions in the simulation model to evaluate the performance compared to the real world. To determine the p-value for a big selection of continuous distributions, a Python script is used. The Python script is displayed in Appendix K. Next to the p-value, the Python script determines the best parameters for these distributions as well. All distributions which are provided by Plant Simulation and which have a p-value higher than 0,05 are considered as possible distributions for the arrival rates of the dots (PlantSimulation, n.d.). The output of the Python script is displayed in Appendix L. Here, the 30 distributions with the highest p-value and the distributions which are provided by Plant Simulation (in bold) are displayed. The distributions that have a p-value greater than 0,05 and are provided by Plant Simulation are tested with 10 experiments with 3 replications each. Next to that, the continuous empirical distribution is tested for every input as well. These steps will be discussed in more detail in the paragraphs below for both packaging lines.

Line 1

At packaging line 1, three types of dots are packaged with consumer packaging: dots, minidots, and crodots. For each type of dot, a distribution is determined. The histograms can be seen in Figures 4.2, 4.3 and 4.4. On the y-axis, the count of the histogram is shown and on the x-axis, the bins are shown. However, due to confidentiality, the ranges of the bins are not shown. The number of data points is 75 for the crodots, 65 for the dots and 103 for the minidots. The box plots are displayed in Appendix L.

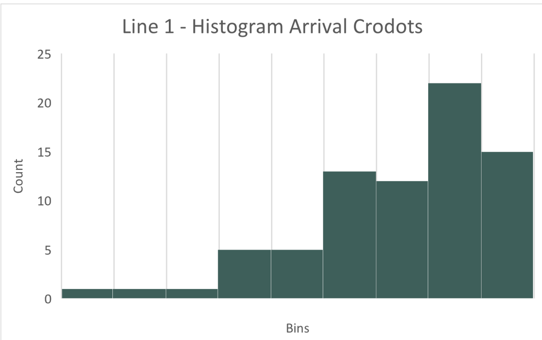

Figure 4.2: Histogram arrival crodots of line 1

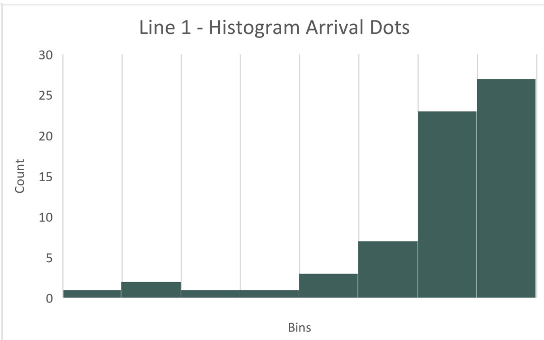

Figure 4.3: Histogram arrival dots of line 1

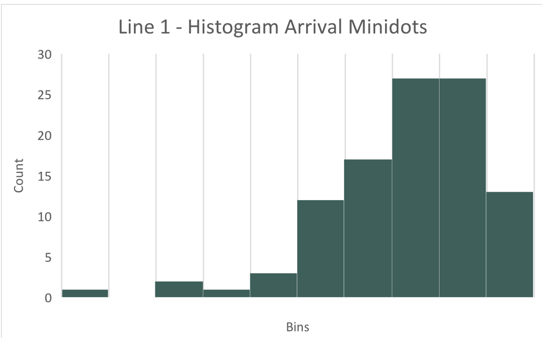

Figure 4.4: Histogram arrival mini dots of line 1

First, the distribution of the arrival rate of the crodots is determined. The Plant Simulation distributions with a p-value higher than 0,05 are a beta, Gumbel, logistic, Laplace and normal distribution. The parameter values of the beta distribution are not suitable for Plant simulation. The Gumbel, logistic, Laplace and normal distributions are tested in Plant simulation, as well as the continuous empirical distribution. The continuous empirical distribution is generated using real data as input to create random variables that follow the real data. The results of the tested distributions are displayed in Appendix M. As can be seen in the Appendix, the normal distribution, as well as the Laplace, Logistic, and Gumbel distributions, give unrealistic values which are much higher than the theoretical maximum value. The continuous empirical distribution is more realistic. Therefore, the continuous empirical distribution will be chosen as the arrival distribution of the crodots.

Secondly, the distribution of the arrival rate of the dots is determined. The possible distributions of the arrival rate of the dot are the beta, Logistic, and Gumbel distribution, as displayed in Appendix L. The box plots of the tested distributions are displayed in Appendix M. The beta distribution did not have any usable parameters, so it could not be used. Both the logistic and the Gumbel distributions gave unrealistically high values which means that these distributions are also not the right fit. The continuous empirical distribution was the most realistic in this case as well.

Finally, the distribution of the arrival rate of the minidots is determined. As can be seen in Appendix L, the Gumbel, logistic, Laplace, and Cauchy distributions have a p-value higher than 0,05 and are possible Plant Simulation distributions. These distributions are tested in the simulation model and the box plots are displayed in M. The logistic, Laplace and Gumbel distributions did not run for the full 10 experiments, because the arrival rate of the minidots was too high. This resulted in very long run times, and it was already clear that these distributions were not suitable for the arrival rate due to exceeding the theoretical maximum value. The Cauchy distribution also resulted in unrealistically high arrival rates. Therefore, the continuous empirical distribution will be used as the arrival rate distribution of the minidots.

Line 3

The distribution of the arrival of the dots of line 3 needs to be determined as well. As will be described in the assumptions and simplifications in Section 4.1.6, due to a lack of data, only the dots will be simulated on line 3. The histogram of the arrival of the dots can be seen in Figure 4.5. The number of data points is 111. The box plot and the Python script output are displayed in Appendix L. As can be seen in the Appendix, the Gumbel distribution is the only distribution provided by Plant Simulation that has a p-value higher than 0.05. However, as can be seen in the box plot displayed in Appendix M, the arrival rate values given by the Gumbel distribution are too high and, therefore, not realistic. The empirical distribution is tested in Plant simulation as well, and the box plot of the result is displayed in Appendix M. As can be seen in the Appendix, the arrival rate of the empirical distribution represents the current situation closely.

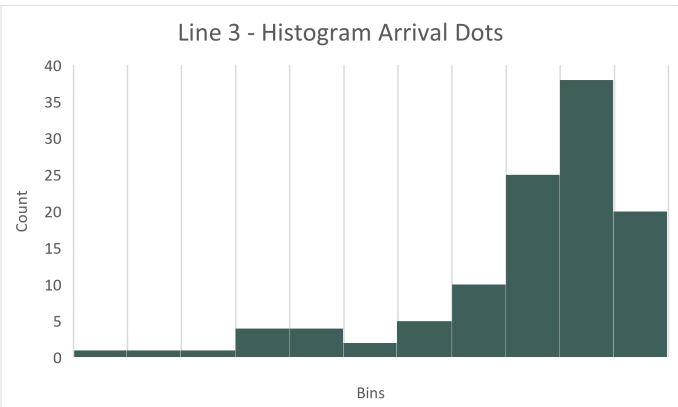

Figure 4.5: Histogram of the arrival of the dots of line 3

Processing Time line 1

Manual labour is used to package all dots at line 1. For every dot at line 1, the crodots, dots, and minidots, a packaging is chosen with the most available data points. All processing times already incorporated potential failures, because the available data does not allow these two factors to be separate. For each specific packaging type, there are not many data points. This results in a lot of distributions with a p-value higher than 0.05, because the data points can 'fit' in a lot of different distributions. Therefore, the most common distributions due to a lack of data and processing times have been chosen to be tested if they have a p-value ≥ 0.05. These distributions are the beta, empirical, gamma, log norm, triangle and uniform distribution (Baker & Trietsch, 2009; PlantSimulation, n.d.). Each dot category will be discussed below.

For the crodots, a flowpackaging with 2 units is chosen as packaging. There are 55 available data points and the box plot and the output of the Python script can be seen in Appendix L. The histogram is displayed in Figure 4.6. From the results of the Python script, the possible distributions from the ones described above are log norm and empirical. These are tested in plant simulation and their results are displayed in Appendix M. The log norm results do not show realistic values and the values are mostly too low. The empirical distribution shows more realistic values and will therefore be used for the processing time of the crodots.

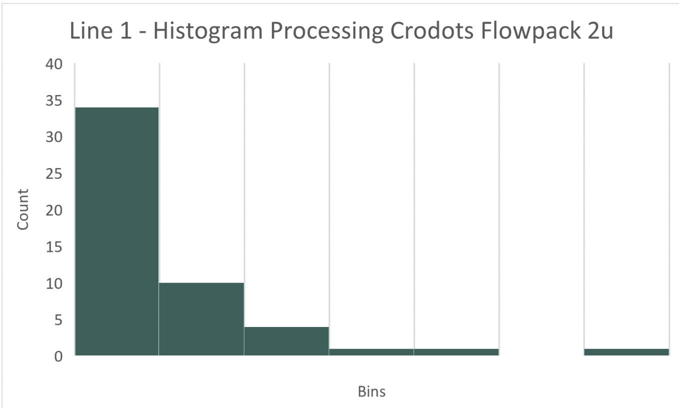

Figure 4.6: Histogram of the processing times Crodots Line 1 (flowpack 2u)

The blister with 4 dots is chosen for the dots on line 1. Unfortunately, only 19 data points are available for this package. The histogram can be seen in Figure 4.7. Four distributions for the processing time were tested: beta, empirical, gamma and log norm distributions, the box plots are displayed in Appendix M. All distributions except for the empirical distributions show unrealistic values, so the empirical distribution will be used for the processing times of the dots. The beta, gamma and log norm distributions mostly give unrealistically low values.

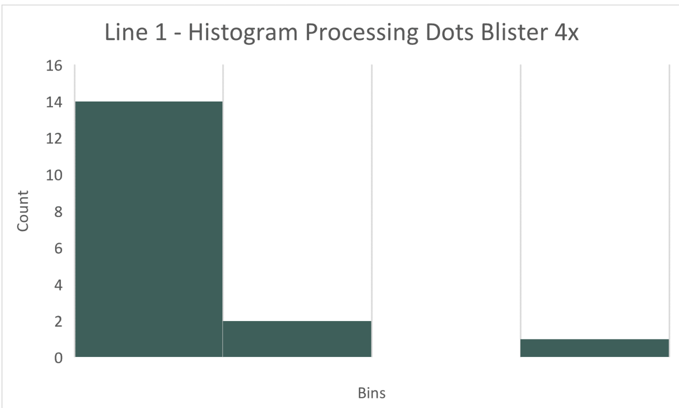

Figure 4.7: Histogram of the processing times Dots Line 1 (blister 4x)

Finally, for the minidots of line 1 a blister of 6 units is chosen. This packaging has 61 data points. The histogram is displayed in Figure 4.8. From the Python script displayed in Appendix L, the following distributions with a p-value higher than 0.05 are the beta, gamma, log norm and triangle distribution. Next to those distributions, the empirical distribution is tested as well. From these five distributions, the empirical distribution fits the processing time of the minidots best, because it gives to most realistic results.

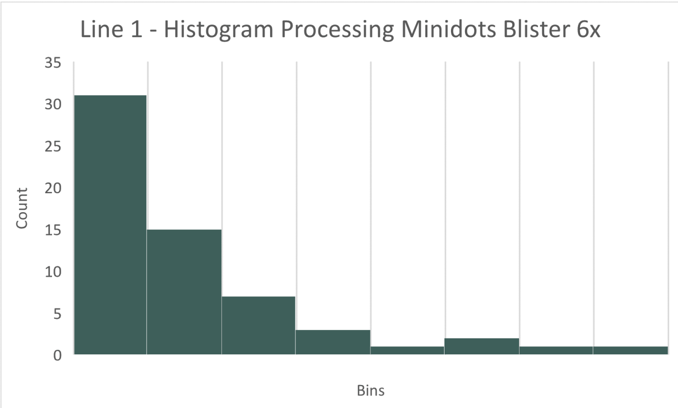

Figure 4.8: Histogram of the processing times Minidots Line 1 (blister 6x)

Downtime line 3

The flowpacker at line 3 runs at a constant speed for the flow pack with four dots. The only reason that the flowpacker does not reach that processing speed is downtime due to several factors, as described in Section 2.5.1. There are 32 data points available since the flowpacker has only been running since last May. For these data points, the downtime has been measured. The histogram of the downtime is displayed in 4.9. The box plot is displayed in Appendix L.

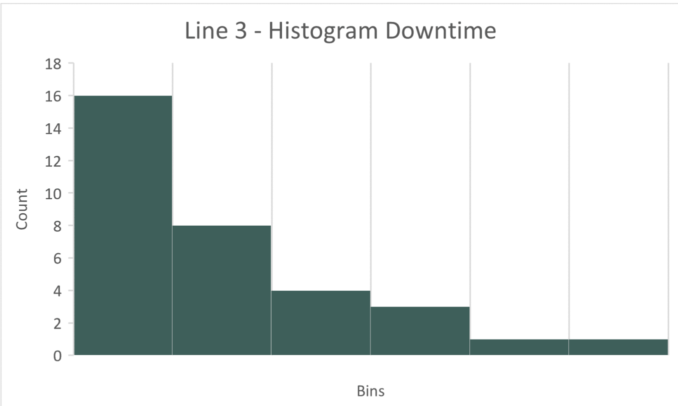

Figure 4.9: Histogram of the downtime of the flowpacker of line 3

This sample data is also tested in Python and the p-values of the test can be found in Appendix L. Since 32 data points are not that many, there are many possible distributions, the same as discussed for the processing time of line 1. Therefore the most common failure distributions have been chosen to be tested if they have a p-value ≥ 0.05. These distributions are beta, gamma, empirical, logistic, log normal, triangular and Weibull. The beta distribution resulted in an MTTR with very low values so that distribution is not suitable. The gamma distribution is more realistic, but the capacity has lower values than reality. The logistic distribution focused too much on the center values and therefore does not show outliers which results in a long MTTR or low capacity. Finally, the empirical distribution does have a slightly lower average capacity than reality but furthermore follows the current situation best compared to all the other possible distributions. Therefore, the empirical distribution will be used as the distribution for the MTTR of line 3. In Table 4.1, a summary is displayed of all input for both lines and their distributions used in the simulation model.

Table 4.1: Summary input lines 1 & 3

Line	Input	Dots	Distribution
1	Arrival rate	Crodots	Empirical
		Dots	Empirical
		Minidots	Empirical
1	Processing time	Crodots	Empirical
		Dots	Empirical
		Minidots	Empirical
3	Arrival Rate	Dots	Empirical
3	Downtime	Dots	Empirical

4.1.3 Contents

The content of the conceptual model is displayed in Figure 4.1. All these factors will help determine the output of the model. The flow of the model is described in the state transition diagrams in Appendix J. In these state transition diagrams, the steps and decisions made in the model are described. The factors that are displayed in the conceptual model are necessary to make those steps and decisions. Next to that, the experimental factors are also included in the model content, because these influence factors like processing time, failure rates and waste. Finally, the level of detail influences the model content. As Robinson (2004) describes; the level of detail should be such that the components of the model and the objective is reached, but not much more. This will be done for this study, so the settings and simplifications are discussed below in Sections 4.1.5 and 4.1.6.

4.1.4 Outputs

The output of the model is the throughput time, utilization, the number of packaged dots, and the machine states. All outputs, except for the utilization, will be used to explain and understand the model and interventions. The throughput time can help determine the warm-up period for the simulation. The packaged dots and machine states help to understand what happens in the simulations and give more information next to the utilization. The utilization will be used as a performance measure to be able to determine the best intervention. Next to utilization, the payback period will be the other performance measure. Increasing the capacity is the main goal of the study, so utilization will be the main performance measure. The utilization is measured by dividing the number of packaged dots by all the dots that arrive during that shift. The second performance measure will be the payback period, but this will not be an output of the model and will be determined separately for each intervention. As described in Section 2.9, EO works with payback periods. The payback period of the intervention has to be realistic. If the payback period is within a year, EO will implement it immediately. When the payback period is between one and five years, the intervention will need some more information before implementation. If the payback period is more than five years, the intervention needs to be future-proof to be implemented. To determine the best intervention, a trade-off needs to be made between the utilization improvement and the payback period of that intervention.

4.1.5 Settings

There are a few settings on which to base the model. These are displayed below:

- The working hours of EO are 24/7 from Monday to Sunday. Every 24 hours is divided into 3 shifts of around 8 hours each.
- Every week there are two consecutive cleaning shifts of in total 16 hours.
- The maximum arrival rate for the dots will be taken into account.
- The maximum throughput time for line 3 for the dots that are packaged in a flow pack (U-tray) per 4 dots will be taken into account.
- The simulation follows the flow described in Figure 2.6. The detailed state transition diagrams for the simulation can be found in Appendix J.

4.1.6 Assumptions and simplifications

To deal with uncertainties and the lack of sufficient data, the following assumptions and simplifications are made.

- To include all malfunctions on the lines stated in kilograms, the assumption has been made that a dot weighs 50 grams on average.
- The downtime of the flowpacker at line 3 is determined by calculating the time that the bulk packaging line was used during that shift. The bulk packaging line is only used when the flowpacker has a malfunction so that way, the downtime can be determined.
- The flowpacker at line 3 has been operational since week 20 of 2023. The only consumer packaging that is used on this machine is the U-tray with 4 dots. With the lack of data, only this u-tray with dots is simulated for line 3. The balldots that also get packaged on line 3 are not included in the simulation model.
- Due to data shortage, the dots and packaging that are included on line 1 are:
  - Dots - Blister 4 units
  - Minidots - Blister 6 units
  - Crodots - Flowpack 2 units
- For the bulk packaging, the current machines will be used. Since bulk packaging is not the focus of the study, it is not included in the simulation model.
- As the processes that are placed on the ground floor (folding of the packaging) are never a bottleneck or malfunction of the process, this process will not be changed and therefore not included in the simulation.
- The metal detector does not fail on line 1. However, it does fail on line 3. As there is more data available for the metal detector of line 3, that failure rate is taken for both line 1 and line 3.
- Processing times are based on the speed of the machines in packaging/minute.
- The packaging is always in stock and available since this is out of the scope of the study.

4.2 Simulation model

The simulation models are displayed in Figures 4.10 and 4.11, as lines 1 and 3 are modelled separately.

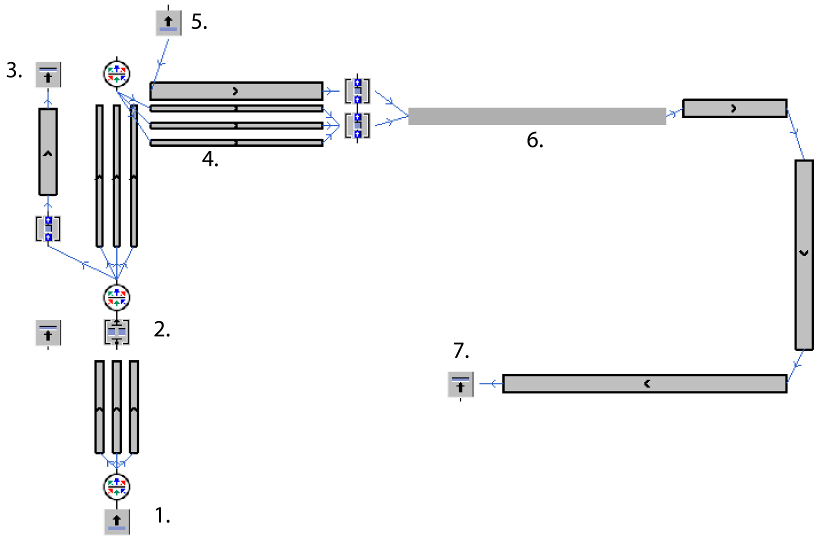

Figure 4.10: Simulation Line 1

As displayed, the lines are constructed quite similarly. The numbers displayed in the figures are as follows:

1. Arrival of the dots: Line 1 consists of the arrival of dots, crodots and minidots. At line 3 only the dots arrive.
2. Metal detector: As described throughout this thesis, each packaging line has a metal detector such as CCP to make sure that all dots are free of metal.
3. Bulk packaging line: Each packaging line consists of a consumer packaging line and a bulk packaging line. The bulk packaging line is incorporated in both models, but only as a drain for when the consumer packaging line is not able to package all the dots. It is not incorporated further, because it is out of the scope of this study.
4. Consumer packaging line: From this point onwards, the consumer packaging line is displayed.
5. Arrival Primary packaging: The primary packaging arrives at the consumer part of the packaging line at this point. The primary packaging of line 1 is manually placed at the line at the moment in the current situation. For line 3, they are placed in the flowpacker machine at the beginning of a shift. In the simulation model, it is represented like this, as it does not influence the performance of the model.
6. Packaging station / flowpacker machine: This is the point in the model where the dots and the primary packaging come together and the dots are packaged. For line 1 this is done by manual labour at the 'packaging station', and at line 3 the flowpacker is situated there.
7. Drain towards secondary packaging: Here the packaged dots go down to the secondary packaging. This is also the end of our simulation model.

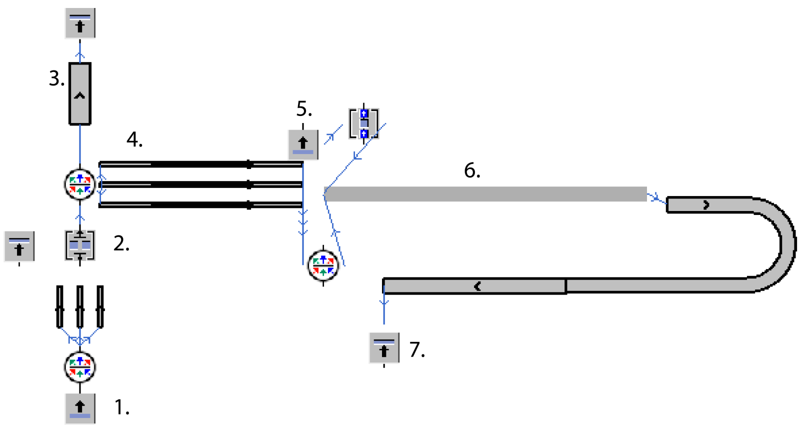

Figure 4.11: Simulation Line 3

In Figure 4.12 the statistics and the experiment settings that are implemented in the model are displayed. Note that the statistics and settings shown in Figure 4.12 are dependent on the experiment or interventions and could therefore change accordingly.

Performance Measures	Experimental Settings
nTotalDots=0	WarmUpPeriod=0.0000
nTotalDotsperHour=0	RunLength=0.0000
nPackagedDots=0	nExperiments=1
nPrimBoxes=0	nReplications=100
nSecondBoxes=0	CurrExperiment=1
nWasteDots=0	CurrRun=1
Utilisation=0	RunCounter=1
PackagingperMinute=0	ArrivalRate=0.1290
DotsCounter=0	ProcessingTime=1.7050
PackageCounter=0	
nTotalBulk=0	

Figure 4.12: Satistics Simulation Model Lines 1 & 3

4.2.1 Verification and Validation

As described in Section 3.1.4, a model needs to be verified and validated before performing experiments. First, the verification is done by checking if the relevant assumptions are correctly translated into the model. When looking at the list of assumptions that have been made, which can be found in Section 4.1.6, it can be concluded that every assumption has been taken into account during the development of the simulation model. The validation of a model is done by determining whether the model is an accurate representation of the real world. In this thesis, the validation of the model is done by black-box and white-box testing.

In black-box testing, the input and output of the model and the input and output of the real world are compared. To determine whether there is a significant difference between them, a paired t-test with a confidence level of 99% is performed. The result of the paired t-test is a confidence interval which can be used to determine whether the inputs/outputs differ significantly. In case the lower bound of the confidence interval is less than zero and the upper bound of the confidence interval is higher than zero, it can be concluded that the inputs/outputs do not differ significantly from each other (Mes, 2022a). When zero does not lie in the confidence interval, it can be concluded that the difference between the inputs/outputs is significant. Next to the paired t-test, state transition diagrams have been developed to determine the similarity between the simulation model and the real world when it comes to paths and transitions.

First, lines one and three are validated through black-box testing. In Appendix N the input and output of the different types of dots are displayed for both the real world and the simulation model. The results of the paired t-test show that the differences between the real world and the simulation model are not significant for the arrival rates, the processing times (line 1), the downtime (line 3) and the utilization due to the fact that zero lies within the confidence intervals. The state transition diagrams for the simulation model have been developed and are displayed in Appendix J. These are similar to the state transitions in the real world.

Secondly, lines one and three are validated through white-box testing. The code of both simulation models has been fully checked and debugged. Additionally, potential errors have been resolved by performing visual checks. Next to that, a control flow test has been performed which means that every statement for both models has been tested by verifying its potential outcomes (Nidhra & Dondeti, 2012).

Finally, to establish the credibility of the model, the model needs to be discussed with the management of EO. To make sure this was done properly, the model has been discussed on multiple occasions with the site director of EO. The results of these discussions were that the simulation model does resemble the real-world situation.

4.2.2 Experimental setup

As described in the literature study in Section 3.1.4 the experimental setup consists of determining the warm-up period, run length and number of replications. In this section, the experimental setup will be described to be able to conduct the experiments properly. First, the warm-up period will be discussed and, afterwards, the run length and number of replications will follow.

Warm-up period

For the warm-up period, the Welch approach is used. The Welch approach consists of plotting the moving average to determine the moment when the output data becomes 'stable'. The moving average is based on n replications with $n \geq 5$ and length m, where m is long (Law, 2015). To smooth out the bigger oscillations of the moving average, a window w is defined. The window w is determined as follows: $w \geq [n/4]$. The output data is considered 'stable' when it converges. To determine the warm-up period, the throughput time of each packaged dot is measured.

Line 1

For line 1, the different types of dots will be discussed separately, starting with the warm-up period of the minidots. The moving average of the throughput time of the minidots is displayed in Figure 4.17 for a run length of 8 hours. As can be seen in this figure, the moving average does not converge for a run length of 8 hours. This is also the case for a run length of 24 hours and a run length of 72 hours. The reason why this happens is quite logical and can be described in four different situations. These four different situations are visualized in Figure 4.13.

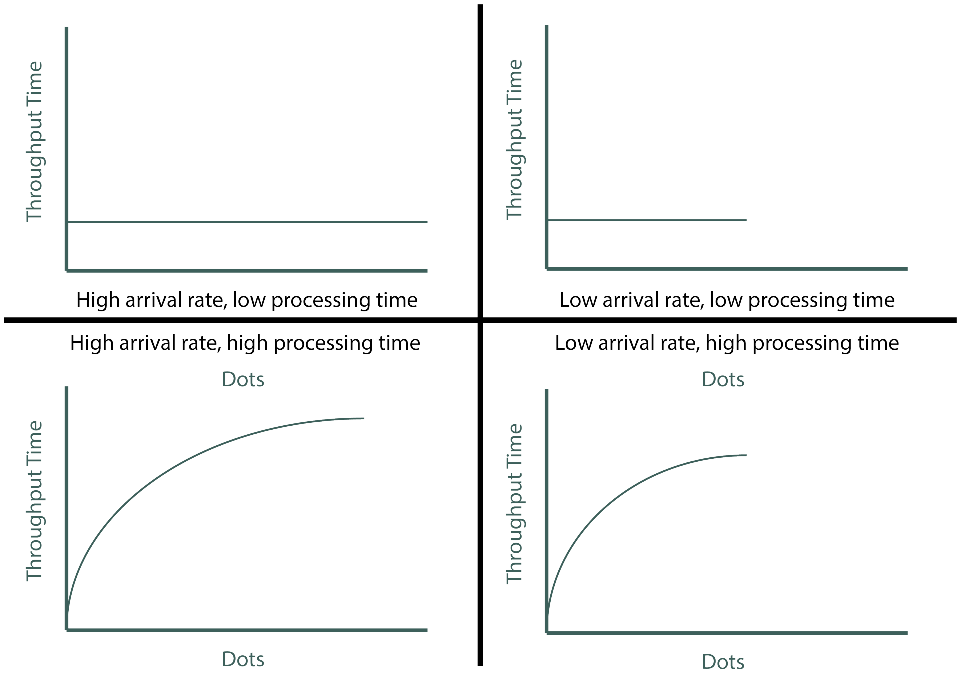

Figure 4.13: Warm up period situations line 1

Two variables influence the throughput time of each replication, namely the arrival rate and the processing time. For the upper two graphs in Figure 4.13, the processing time is low. This means that all the dots that arrive will get packaged quickly which results in a low constant throughput time. The difference between these two situations is simply the number of minidots that arrive at the packaging line, but the behaviour is similar. For the lower two graphs the processing time is high which means that the minidots will often have to wait until they get packaged, increasing the throughput time of the minidots. When the arrival rate is relatively high compared to the speed with which the minidots are packaged, the line will get clogged and no new minidots can arrive. In other words, the throughput time will increase up to a point where the whole line is full and every packaged minidot will be replaced by a newly arriving minidot. This could very possibly result in a part of the minidots not arriving at the packaging line in time during a shift. Taking these four possible situations into account, it is logical that the moving average of the minidots starts with an inclining slope which eventually starts stabilising. Next, the moving average starts to decrease drastically after a while due to a part of the minidots (which are a part of the situation with a high processing time) not arriving at the packaging line in time. This means that these minidots are not taken into account due to having no throughput time, leaving us with the minidots that arrived at the packaging line in time due to the lower processing time. Eventually, the moving average of the throughput time will consist of only the minidots that were packaged in the situation that had a high arrival rate and low processing time. So, the moving average of the minidots does not converge due to the waiting time of the minidots in specific replications where the processing time is high. In case the replications with waiting time are discarded, the moving average does converge. This is displayed in the graphs below (figures 4.14, 4.15 and 4.16. However, as the replications without waiting time only represent a small part of the data, these replications, on their own, cannot be used to determine the warm-up period.

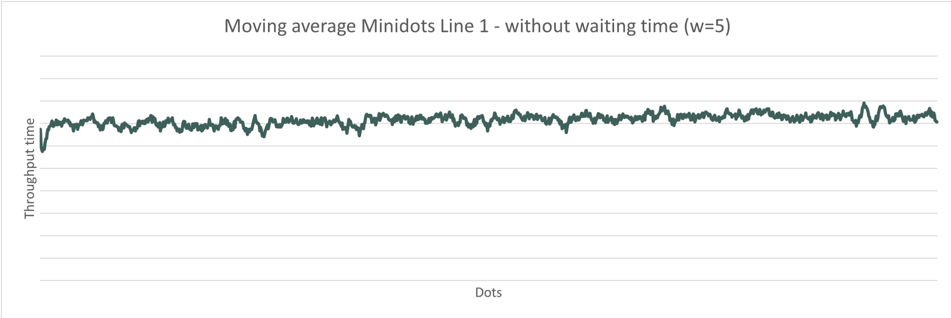

Figure 4.14: Warm up period without waiting time Minidots Line 1

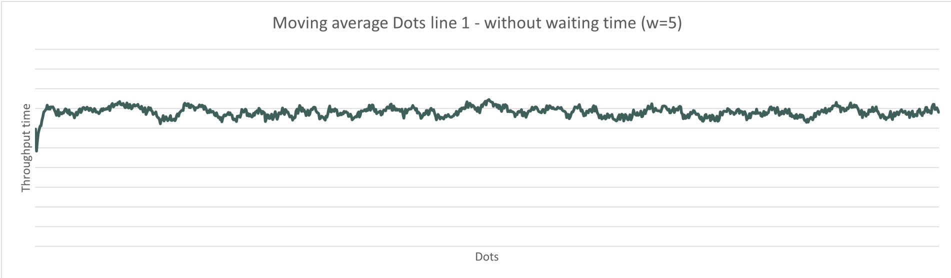

Figure 4.15: Warm up period without waiting time Dots Line 1

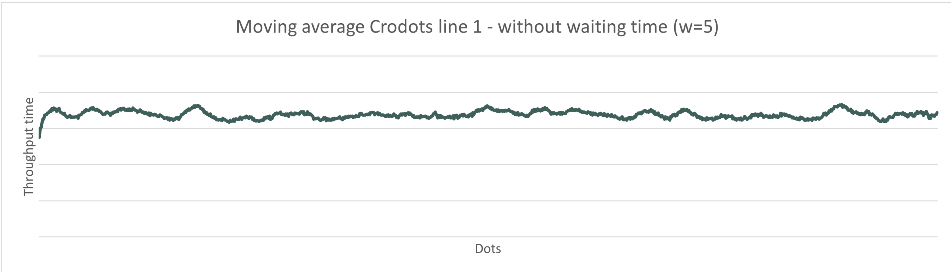

Figure 4.16: Warm up period without waiting time Crodots Line 1

The graph in Figure 4.17 is a moving average of 100 replications and follows the same behaviour as explained above. The behaviour of the moving average points never converges. However, the simulation does not fully terminate, as it does neither start nor end at 0, so the simulation is still non-terminating. A non-terminating simulation that does not converge can be treated as a terminating simulation (Mes, 2022a). That will be done for the simulation of the minidots at line 1, so that means that there will not be a warm-up period for the minidots.

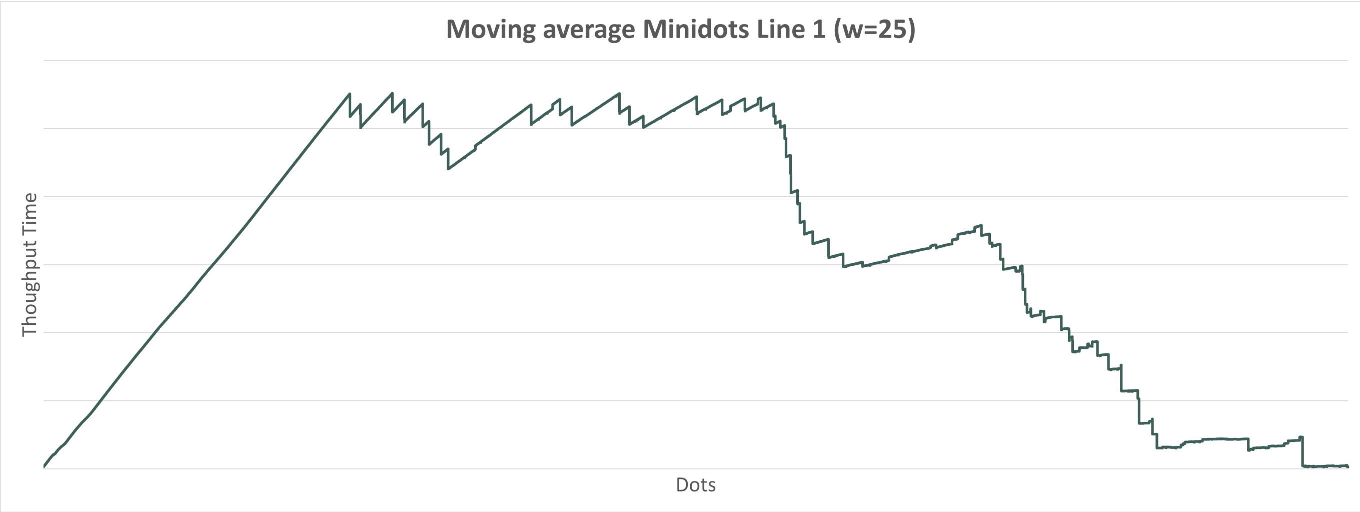

Figure 4.17: Warm up period Minidots Line 1

For the dots and crodots, the moving average is displayed in Figures 4.18 and 4.19 respectively. As can be seen, the behaviour is similar to that of the minidots. That is why the dots and crodots will also be treated as a terminating simulation and therefore won't have a warm-up period.

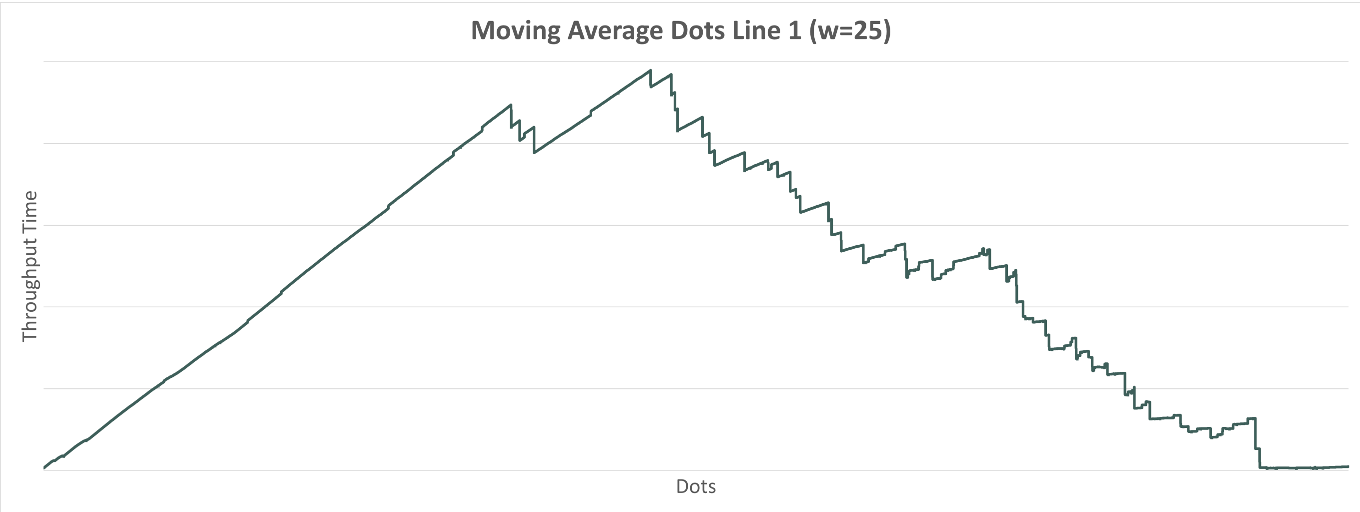

Figure 4.18: Warm up period Dots Line 1

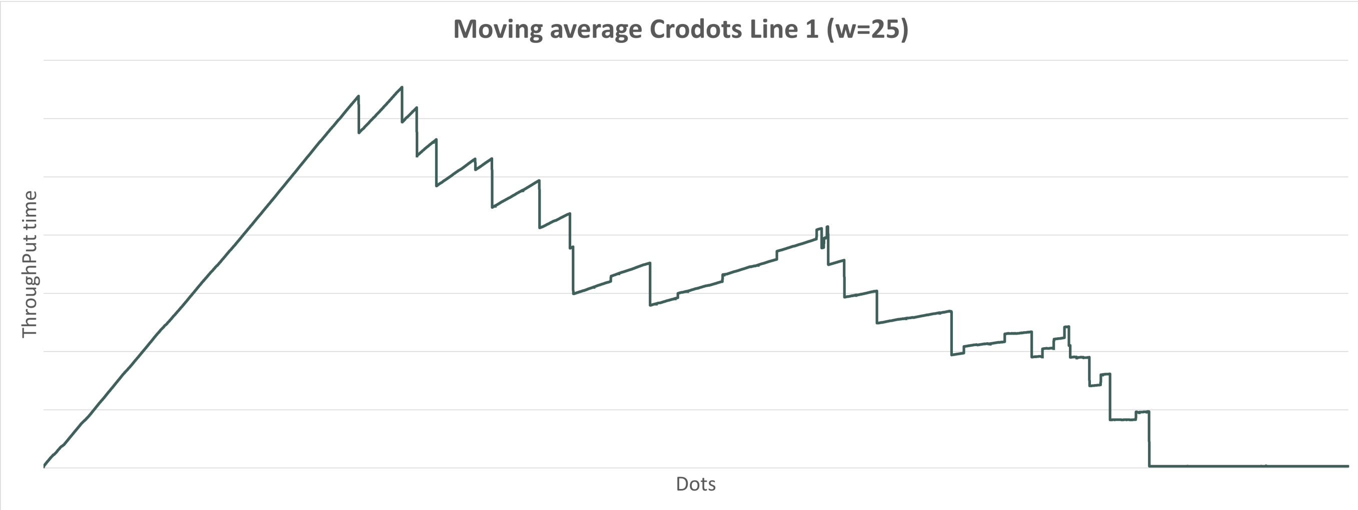

Figure 4.19: Warm up period Crodots Line 1

Line 3

In Figure 4.20 the moving average of the throughput time of the dots is displayed. The Welch approach is used with $n = 100$ replications with length $m = 8$ hours. ‘The window used is $w = 25$. As can be seen, the line converges at 11 dots, which translates to around 1,72 seconds. The warm-up period of line 3 is 1,72 seconds.

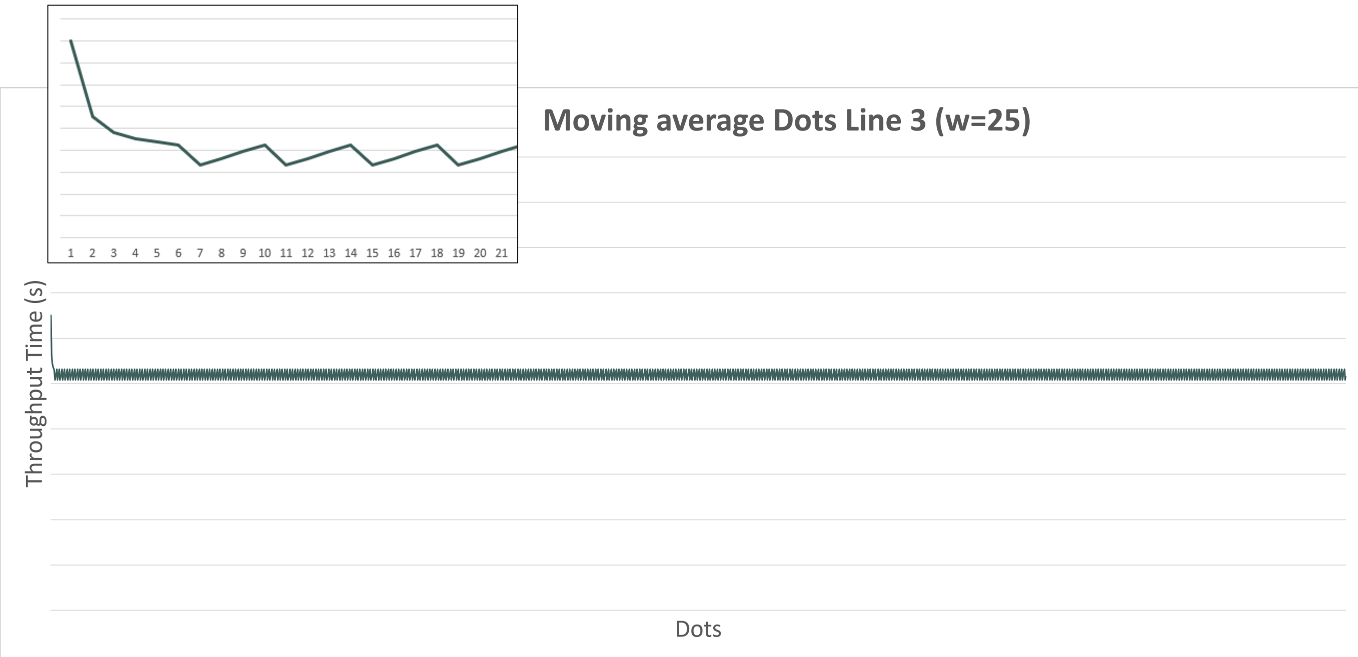

Figure 4.20: Warm up period line 3

Replications & Run length

Secondly, the number of replications has to be determined. The sequential procedure can be used to determine the number of replications using a confidence level of at least 85%. A guideline for choosing the run length is to at least take 10 times the warm-up period. The run length can be longer, but there need to be at least 5 replications per experiment (Mes, 2022a). As described in Section 3.1.4, the number of replications and the run length are intertwined.

Line 1

In this section, the dot categories will be discussed separately. To be able to perform the experiments properly, more about that in Section 4.5, the run length has to be long enough to see the results. Next to that, the computational time per experiment must be considered. Between the run length and the confidence level, similar to the computational time, a trade-off will have to be made. First of all, the simulation of the minidots will have a run length of 24 hours with 39 replications. With these experimental settings, the simulation has a confidence interval of 93% and an acceptable computational time. Second, the simulation of the dots will run for 24 hours and 37 replications with a confidence level of 94%. Finally, for a simulation of the crodots with a confidence level of 91%, a run length of 24 hours and 35 replications are needed.

Line 3

Similar to the run length of line 1, to be able to perform the experiments properly, the run length has to be long enough to see the results. Having in mind the trade-off between the run length and computational time, the decision has been made to set the run length to 24 hours. The experiment with a run length of 24 hours needs 30 replications to reach a confidence interval of 95%.

There is only an 'empty system' in the real world just after the cleaning shifts, which is once a week. Every start of a simulation run begins in an 'empty system'. However, a run length of 1 week for the simulation model results in a lot of computational time. Therefore, a run length of 24 hours was chosen to test the interventions for both lines 1 and 3. Nevertheless, it is important to make sure that the output of a run of 1 week is similar to the output of a run of 1 day. To determine whether there is a significant difference between the output of both run lengths, a paired t-test for both lines is performed with a confidence level of 99,9%. From the test, the conclusion can be made that the output of both run lengths does not differ significantly. The confidence intervals of this paired t-test are shown in Appendix O.

4.3 Experimental Configuration

In this section, the configuration of the experiments is described to be able to conduct those.

- First, the arrival rate of the dots will be an experimental factor. At the moment, the current situation is represented by the distributions described in Section 4.1.2, which is often not the theoretical 100% but somewhat lower due to malfunctions in the bakery. For the experiments, the interventions will be tested on the current arrival rate, 100% and 120% of the theoretical arrival rate. The packaging line and therefore the interventions should be able to package all dots with a 100% theoretical arrival rate, as that is how the packaging line is designed. After that, the intervention will be tested for 120%, because it is useful to be able to package the dots somewhat faster than the arrival rate, since then there is more buffer for potential malfunctions. So, there are three experimental factors regarding the arrival rate of the dots.
- For the experiments, the arrival of the packaging will not be changed, as that is not a bottleneck in the process. If the location of this part of the process is changed, the same order and area will be used.
- The same packaging as in the starting model will be used, because that way the experiments will be comparable to the current situation. Other packaging is also not validated in Section 4.2.1.
- Next to the packaging, the SKUs will stay the same as well. For line 1 these are the dots, crodots and minidots and for line 3 the dots. This is done for the same reason as using the same packaging.
- Finally, the interventions might also have experimental factors to be able to determine the best setup of that intervention. The intervention itself will discuss these experimental factors.

4.4 Current bottlenecks and utilization

In this section, the current bottlenecks and utilization are discussed to be able to compare them with the results of the interventions that are discussed at a later moment. These bottlenecks for both lines are determined by using the method described in the paper of Roser et al. (2001), so looking at the active and inactive states of the station in the simulation model. Additionally, during the analysis, the bottlenecks of the consumer packaging lines have been discussed with stakeholders and seen during walk-ins. From this bottleneck analysis, the bottlenecks of the system can be discovered. Interventions that will be described later in this chapter try to solve those bottlenecks in different ways.

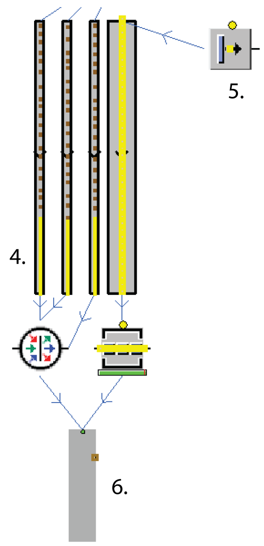

Figure 4.21: Bottleneck line 1 (yellow shows the overflow of dots)

First of all, the main bottleneck at line 1 is that the manual labour is often not quick enough for the arrival rate of the dots. The consumer packaging line already packages only 40% of the total dots, but this is still too much in some cases. This results in a situation as shown in Figure 4.21, where an overflow of dots (the yellow lines resemble an overflow) is displayed on the conveyor belt just before the packaging station. Next to that, when looking at the active states of all the stations of the simulation model in Table 4.2 it can be seen that the packaging station has by far the highest percentage of active state for both packaging types. For the blister packaging, the active states are determined by the average of both dot types (dots and minidots). This indicates that the packaging station is the main bottleneck of consumer packaging line 1. This is also found during the interviews with the stakeholders.

Table 4.2: Active states of the station within packaging line 1

Packaging	**Station**	**Active state (%)**
Flowpackaging	Conveyor belt before packaging station	0,04
	Packaging station	0,98
	Conveyor belt after packaging station	0,41
Blister packaging	Conveyor belt before packaging station	0,05
	Packaging station	0,98
	Conveyor belt after packaging station	0,35

To be able to compare the interventions that are discussed in Section 4.5 later and the current situation, the utilization of each dot category is shown in Tables 4.3, 4.4 and 4.5. For the interventions, all the arrival dots will go to the consumer packaging line. This is done because then the real improvement of utilization can be shown. To be able to compare the interventions with the current situation, the current situation is changed to sending all arriving dots to the consumer packaging line. As displayed in the Tables 4.3, 4.4 and 4.5 below, there are certain moments when the packaging line reaches higher than 40%, as the maximum of the experiments with a current arrival rate is higher, sometimes even the maximum utilization of the line. However, overall, the experiment capacities are at or below 40%.

Table 4.3: Utilization current situation dots line 1

Arrival Rate (dots/hour)	Min. Utilization (%)	Max. Utilization (%)	Avg. Utilization (%)
Current	19,30	95,94	40,66
100% theoretical	13,33	41,18	29,66
120% theoretical	11,10	34,31	24,71

Table 4.4: Utilization current situation crodots line 1

Arrival Rate (dots/hour)	Min. Utilization (%)	Max. Utilization (%)	Avg. Utilization (%)
Current	15,95	95,94	37,10
100% theoretical	10,77	46,77	25,63
120% theoretical	8,95	38,86	21.29

Table 4.5: Utilization current situation minidots line 1

Arrival Rate (dots/hour)	Min. Utilization (%)	Max. Utilization (%)	Avg. Utilization (%)
Current	11,91	65,65	33,58
100% theoretical	8,60	35,17	22,56
120% theoretical	7,17	29,31	18,80

line. For line 3, the same method is used to determine the bottlenecks. When looking at the active states of all the stations of the simulation model in Table 4.6, it can be seen that the flowpacker machine has the highest percentage of active states. This indicates that the flowpacker dictates the speed of the consumer packaging line. Next to that, the flowpacker has some malfunctions, as described in Section 2.5.1. This results in rerouting all dots that arrive during the downtime to the bulk packaging. For the interventions, it is therefore most interesting to look into improving the flowpacker machine or fixing the reasons for malfunctions of the flowpacker machine.

Table 4.6: Active states of the station within packaging line 3

Packaging	Station	Active state (%)
Flowpackaging	Conveyor belt before flowpacker machine	59,78
	Flowpacker machine	61,43
	Conveyor belt after flowpacker machine	20,07

Similar to line 1, the utilization of the current situation is shown in Table 4.7. As displayed, the utilization of the current arrival rate and the 100% arrival rate are similar. This might be the case because both arrival rates are at/below the designed packaging speed, so the flowpacker handles them similarly. However, the utilization decreases with a 120% arrival rate, which is logical, as the line was never designed for 120%. The maximum utilization of line 3 without failures is 95,95%.

Table 4.7: Utilization current situation line 3

Arrival Rate (dots/hour)	Min. Utilization (%)	Max. Utilization (%)	Avg. Utilization (%)
Current	43,00	84,46	72,73
100% theoretical	43,00	84,46	72,73
120% theoretical	37,05	72,34	62,46

4.5 Interventions

In this section, the interventions for lines 1 and 3 will be discussed. These interventions will be tested in the simulation model and afterwards compared with each other based on the performance measures. For each intervention, the cost and experiment configurations have been determined by the expert opinion of the employees of EO, existing information at EO or other references. The interventions potentially have instalment costs, so the assumption has been made that this costs around €50.000 for every intervention. For all interventions, a description of the intervention, the cost and the experiment configuration will be discussed.

4.5.1 Interventions line 1

This section will describe all interventions for line 1, which packages minidots, crodots and dots in flow packaging or blister packaging. Interventions 1 & 2 will be tested for all dot categories and all packaging options. Intervention 3 is to improve the capacity of the flow packaging and intervention 4 is meant to improve the capacity of the blister packaging. The packaging type is shown in the title of the intervention in parentheses. An overview of the intervention that will be discussed is displayed below in table 4.17.

Table 4.8: Overview interventions line 1

intervention	**Title**	**Packaging**
1.	Vision system	Both
2.	Buffer	Both
3.0	One flowpacker machines	flowpackaging
3.1	Two flowpacker machines	flowpackaging
3.2	Speed flowpacker machine	flowpackaging
3.3	Different flowpacker machine	flowpackaging
4.1	Only cobots	blister packaging
4.2	Cobots + filter	blister packaging
4.3	Cobots with two functions	blister packaging

Intervention 1: Vision system (flowpackaging & blisters)
The first intervention will implement a vision system at the beginning of the packaging line. This vision system will check for dots that are not within the specifications and remove them from the conveyor belt of the consumer packaging line. This could mean dots that stick together or dots that are too small or big. These dots do not fit in the packaging, which results in downtime and waste. These dots could be kept apart and packaged in bulk when suitable. When these dots do not meet the requirement, the dots should be discarded. This intervention might result in more waste, but on the other hand, the unfit dots are discarded anyway, so the waste might be the same. The only thing is that the vision system can count the unfit dots, so the exact number of dots that go to waste is known. This intervention could result in less downtime and fewer unsatisfied customers. In addition to the vision machine, robots are needed to ensure that all unfit dots are removed from the conveyor belt. These unfit dots need to be examined and if possible the dots will be bulk-packaged. Bulk packaging is less sensitive to the size of the dot compared to consumer packaging. So there will be one robot to remove all unfit dots and one robot to determine if the dots could still be bulk packaged and repack them. Furthermore, to make sure that the robots can handle the speed of the packaging line when the vision system detects more than 8 consecutive dots that are not within the margin, the packaging line stops to be able to determine if all dots are outside the margin. This intervention is illustrated in Figure 4.22.

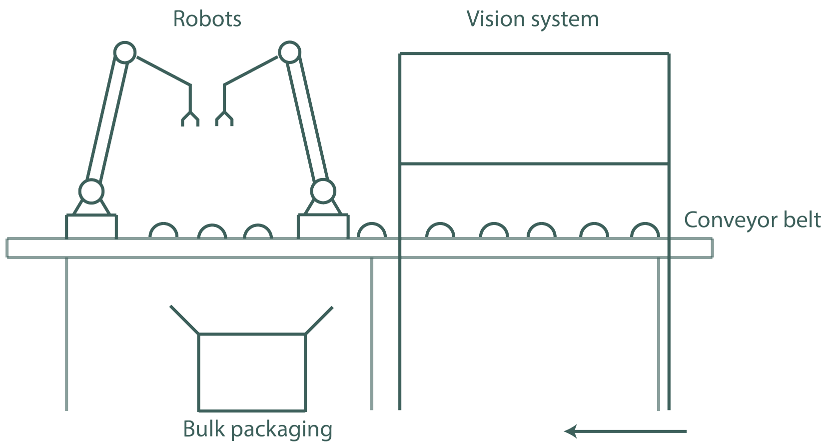

Figure 4.22: Illustration intervention 1: Vision system

A vision system with those functions would cost around €190.000. Next to that, two robots are needed to discard the unfit dots and possibly repack them, the average robot costs €27.000 (Thormundsson, 2019). Including the instalment costs, this intervention would cost around €294.000. In addition, the downtime cost will be reduced. This results in an investment of around €294.000 and somewhat more production costs due to electricity etc, but less downtime costs.
This intervention will be tested for both the flowpackaging and the blister packaging. The output files of each shift state if there was a failure, how much waste the failure generated, and the cause of the failure. To determine the failure and the MTTR with a vision system at the packaging lines, the shifts with a failure other than unfit dots will be taken as a guideline of how often a failure occurs and what the downtime would be. As mentioned before, it was not possible to split the data into downtime and processing time for the dots of line 1, so to determine the influence of the unfit dots, all shifts with unfit dots were discarded. With the shifts that were left, new processing times are determined for the minidots and crodots. For the dots that get packaged in a blister on line 1, the size of the dots was never a problem. Therefore, a vision system will not have any influence on the capacity of the blister with the dots and will not be included in this intervention.
Figure 4.23 shows how the intervention is implemented in the simulation model. Numbers 1,2 and 4 are similar to the ones in Section 4.2. Number 3 represents the vision system.

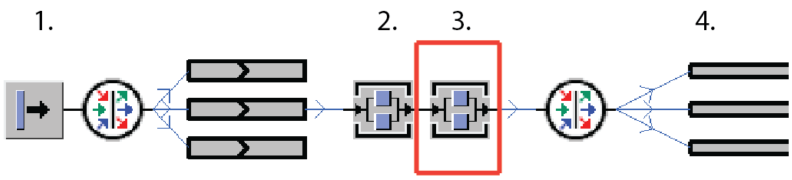

Figure 4.23: Simulation line 1, intervention 1: Vision system

In Table 4.9 an overview of the experimental configuration and the number of experiments of this intervention is displayed. The table explains the packaging type for this intervention in the column 'packaging'. This could be the flowpackaging, blister packaging or both. In the column 'experimental factors', the experimental factors are explained. In this case, the intervention will be tested with the current arrival rate, 100% theoretical arrival rate and 120% theoretical arrival rate. The next column 'Nr. of exp.' shows the number of experiments for this intervention, which is three in this case, one for each arrival rate. Finally, in the column 'costs' the costs for this intervention are shown.

Table 4.9: Overview intervention 1: Vision system, line 1

Intervention	Packaging	Experimental factors	Nr. of exp.	Costs
1. Vision system	Both	Arrival rate: Current, 100%, 120%	9	€294.000

Intervention 2: Buffers (flowpackaging & blisters)

At the moment, the conveyor belt before the packaging station is quite short. The moment that the packaging station has a malfunction or a capacity problem, the conveyor does not have space for many dots. When a buffer is installed, the flow of dots might be a bit slower and when there is downtime, the dots have more time before arriving at the packaging station. By then, the malfunction might already be resolved or it is easier to package all the dots. The buffer will be installed instead of the current conveyor line. Dots defrost in around 30 minutes, so this means that the buffer could take around 25 minutes since the dots need to stay frozen until they reach the warehouse. As described in Section 3.3.1, placing buffers in a manufacturing line could enhance the throughput and decrease the waste and disruption of the whole line. This intervention will be tested for both packaging types so for the crodots (flowpackaging), dots and minidots (blister).

For the addition of a buffer to a packaging line, there are costs for the buffer materials, the buffer space, and the added inventory cost in the buffer (Shi & Gerswhin, 2009). The buffer space is not a problem, as there is enough space for the packaging lines, so the added costs are the buffer materials and inventory. The buffer materials are fixed costs once, while the inventory cost adds to the production cost. On the other hand, the packaging line may have less waste because the throughput time increases and there is less disruption, which would save money. The investment cost for a buffer depends on the number of buffers and the size of the buffer. The inventory cost on the line would be the number of dots in the buffer multiplied by the cost price of that dot. So, the cost depends on the size of the buffer. As a buffer, spiral conveyors of 5 metres high will be used, these cost around €25.000 per piece and a dot takes around 4 minutes to reach the end of the spiral conveyor. The speed of the spiral conveyor needs to be as low as possible to be able to act as a buffer, but it needs to go quickly enough to make sure that the conveyor itself does not become a bottleneck.

The only necessary thing to include the buffer in the simulation is to implement the buffer. The location of the buffer will be before the packaging station, as that is the weakest link of the packaging line. The size and time of the buffer are included as an experimental factor, as the size could influence the performance of the packaging line. The maximum size of the buffer is the number of dots that arrive in 25 minutes to ensure that the dots remain frozen.

Figure 4.24 displays an illustration of intervention 2 and Figure 4.25 shows how the intervention is implemented in the simulation model. In Figure 4.25 the numbers 2,4 and 5 are the same as before. Number 3 now resembles the buffer, placed between the metal detector and the flowpacker. In Table 4.10 an overview is displayed of the experimental configuration and the number of experiments of this intervention.

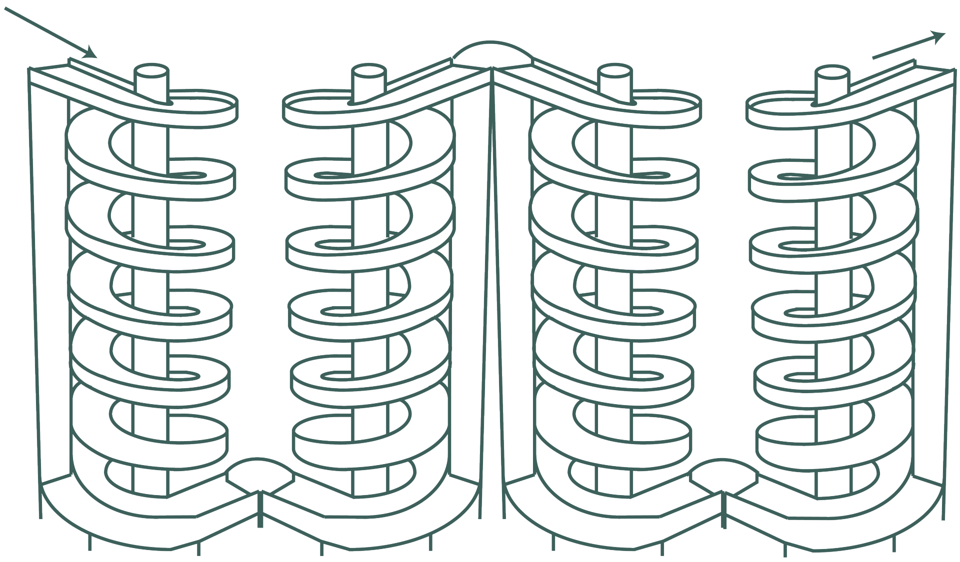

Figure 4.24: Illustration intervention 2: Buffers

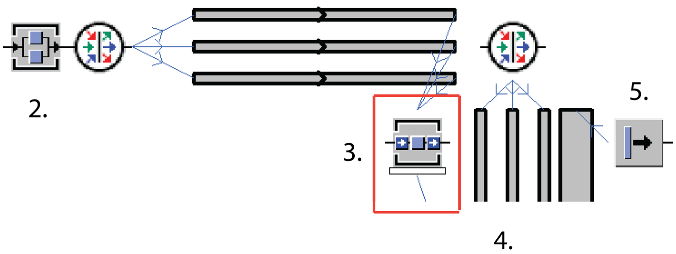

Figure 4.25: Simulation line 1, intervention 2: Buffers

Table 4.10: Overview intervention 2: Buffers, line 1

Intervention	Packaging	Experimental factors	Nr. of exp.	Costs
2. Buffer	Both	Arrival rate: Current, 100%, 120% Buffer capacity line 1 crodots: 2500, 5000, 7500 Buffer capacity line 1 dots: 5000, 9000, 12000 Buffer capacity line 1 minidots: 10000, 15000, 20000	27	€25.000 per buffer + €50.000 instalment costs

Intervention 3: Flowpacker machine (flowpackaging)

For intervention 3, four sub-interventions are created. All sub-interventions test whether one (or more) flowpacker machines would increase the capacity of line 1. The first intervention, intervention 3.0, includes a flowpacker machine at line 1. Intervention 3.1 tests how two flowpackers will perform on line 1. Intervention 3.2 adjusts the speed of the flowpacker machine, and intervention 3.3 uses a different flowpacker machine. For all sub-interventions for intervention 3, the assumption has been made that the flowpacker performs the same way on line 1 as it does on line 3 at the moment. An overview of the sub-interventions is shown in table 4.11.

Table 4.11: Overview sub-interventions of interventions 3

Intervention	Title	Packaging
3.0	One flowpacker machines	flowpackaging
3.1	Two flowpacker machines	flowpackaging
3.2	Speed flowpacker machine	flowpackaging
3.3	Different flowpacker machine	flowpackaging

Intervention 3.0: one flowpacker

Intervention 3.0 is the basis for interventions 3.1, 3.2 and 3.3 as it installs a flowpacker machine at line 1. Installing a single flowpacker costs around €350.000. Keeping in mind that next to the flowpacker, a conveyor line etc needs to be installed, a budget of €600.000 per flowpacker line is chosen. To simulate this sub-intervention, a flowpacker machine has been installed at the same place where the packaging station, of the flowpackaging is positioned now. Furthermore, as described above, the flowpacker machine performs the same way as it does on line 3, so these settings are used. Figure 4.26 shows how the intervention is implemented in the simulation. Numbers 4 and 5 are similar to before, only number 6 now represents the flowpacker instead of the packaging station. In Table 4.12 an overview is displayed of the experimental configuration and the number of experiments in this intervention.

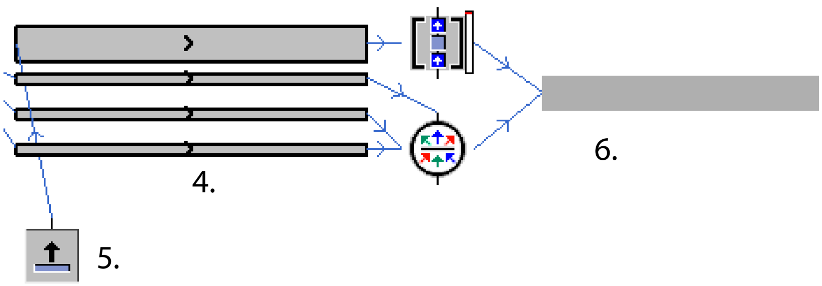

Figure 4.26: Simulation intervention 3.0: One Flowpacker

Table 4.12: Overview intervention 3.0: One Flowpackers, line 1

Intervention	Packaging	Experimental factors	Nr. of exp.	Costs
3.0. One flowpackers	Flowpackaging	Arrival rate: Current, 100%, 120%	3	€650.000

Intervention 3.1: two flowpackers

As described in the introduction of intervention 3, intervention 3.1 tests whether two flowpacker machines could increase capacity. If the first flowpacker is broken down, a second flowpacker can take its place, so the dots will always get packaged. Moreover, if EO wants to increase the dots/hour, the packaging line can package more dots/hour with both flowpackers. The cost for this intervention would be around €1,2 million since this intervention would install two flowpackers at line 1. To simulate this intervention, an additional flowpacker needs to be added to the simulation. Next to that, the ratio of dots for each machine needs to be determined. The second flowpacker could of course only be used when the first one is broken down, but the risk could be divided and run both flowpackers at 50% capacity or maybe an 80/20 ratio. This would be an experimental factor. The downtime of the current flowpacker will be used for the second flowpacker, for example when a 50% capacity is used, the downtime is divided over both flowpackers. In Figures 4.27 and 4.28 the intervention is shown and how it is implemented in the simulation model. Numbers 4,5 and 7 are the same as in Figure 4.11. Number 6 now resembles two flowpackers. In Table 4.13 an overview is displayed of the experimental configuration and the number of experiments of this intervention.

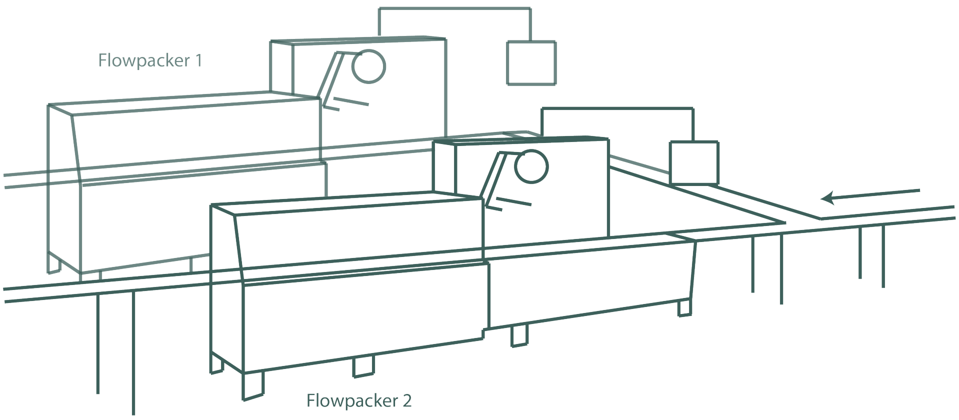

Figure 4.27: Illustration intervention 3.1: Multiple Flowpackers

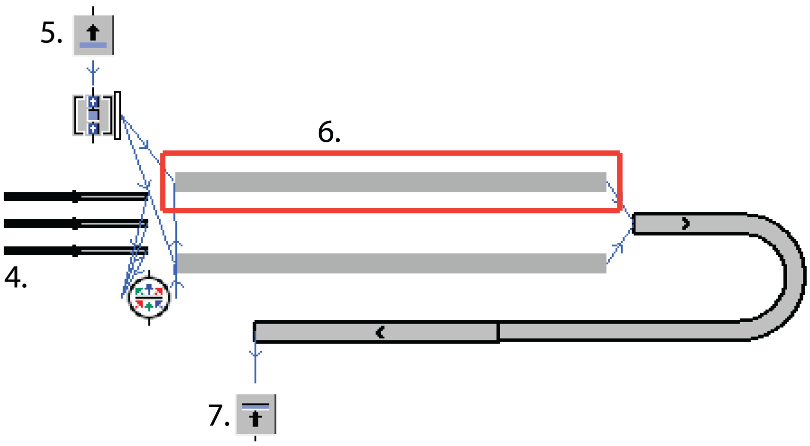

Figure 4.28: Simulation line 1, intervention 3.1: Multiple Flowpackers

Table 4.13: Overview intervention 3.1: Multiple Flowpackers, line 1

Intervention	**Packaging**	**Experimental factors**	**Nr. of exp.**	**Costs**
3.1. Multiple flowpackers	Flowpackaging	Arrival rate: Current, 100%, 120% Ratio of machines: 0/100%, 80/20%, 50/50%	9	€1.250.000

Intervention 3.2: speed flowpacker

If the packaging speed of the flowpacker increases, it is possible to package more dots per minute. If a breakdown has been resolved, it is easier to still package all the dots, as the machine works faster. The machine can increase, for a flow packaging of 2 dots, to 260 packages/minute. The cost of this experiment would be negligible since no new machines are needed and the production cost, such as electricity cost, do not differ much as well. To be able to run this experiment, the speed of the flowpacker is increased to 260 packages a minute for a flow packaging of 2 dots. In Table 4.14 an overview is displayed of the experimental configuration and the number of experiments of this intervention.

Table 4.14: Overview intervention 3.2: Speed Flowpacker, line 1

Intervention	Packaging	Experimental factors	Nr. of exp.	Costs
3.2. Speed flowpackers	Flowpackaging	Arrival rate: Current, 100%, 120%	3	€650.000

Intervention 3.3: different flowpacker

There are different flowpacker machines on the market, for example, continuous and intermittent flowpackers. Continuous flowpackers keep going and seal the flow packaging while the conveyor belt continues. Intermittent flowpackers seal the flow by stopping the conveyor belt and when the flow packaging is closed, the conveyor belt continues. Continuous flowpackers are more suitable for large-scale production compared to intermittent flowpackers. The current flowpacker at line 3 is a continuous flowpacker for medium-high-speed production. The flowpacker could be changed to a continuous flowpacker for high-speed production. If another version of the current flowpacker machine is chosen with high-speed options, the flowpacker could increase to 1000 packages/min. However, this speed is way too fast for the packaging lines, even if the arrival rate is increased to 120%. This would result in a lot of waiting time for the machine, which is not beneficial at all. For this intervention, the speed of the flowpacker will be incorporated as an experimental factor to see how much influence it has on the packaging line. For the flowpack with 2 units, the speed will be increased to 250, 275 and 300 per minute. The intervention will be implemented in the simulation models in the same way as intervention 3.0. The cost of this intervention would be installing new flowpacking machines. This would result in around €900.000. In Table 4.15 an overview is displayed of the experimental configuration and the number of experiments of this intervention.

Table 4.15: Overview intervention 3.3: Different Flowpacker, line 1

Intervention	Packaging	Experimental factors	Nr. of exp.	Costs
3.3. Different flowpacker	Flowpackaging	Arrival rate: Current, 100%, 120% Speed flowpacker line 1: 250, 275, 300	9	€950.000

Intervention 4: robots (blisters)

As described in Section 3.4, robots could be used to ensure higher productivity. Next to that, the wish of EO to reduce manual labour could also be fulfilled this way. As determined in Section 3.4, the most suitable robot for this situation would be an articulated or parallel configuration could be chosen and all grippers are an option as the end effector. Looking into the options of the grippers described by Bader and Rahimifard (2020), the pinching, enclosing or vacuum gripper might be most suitable to handle the dots. Next to robots, collaborative robots (cobots) can also be used for repetitive tasks like packaging Accorsia et al. (2019). The differences between robots and cobots are displayed in Table 4.16.

Table 4.16: Industrial robots vs Cobots (Buchert, 2021)

Aspect	Industrial Robots	Cobots
Better suited for mass production	x	
High variation in settings		x
Collaboration with employees		x
Easier programming		x
Cost per robot		x
Radius	x	
Heavier weights	x	
Require most technical skills	x	

As displayed in the table above, there are different advantages to both kinds of robots. First of all, EO produces and packages the dots in mass production, so the industrial robot is more interesting in that area. On the other hand, there are different dots and different packaging (sizes) that need to be packaged, so in that case, a cobot might be more interesting, since it has more variation in settings and flexibility. Cobots are also easier to program and need fewer technical skills. This is also a big advantage, as EO has a hard time finding the right technical employees at the lines. Next to that, cobots can be used next to employees. So EO could also choose a mix between employees and cobots. The speed of a cobot could be resolved by placing more cobots at the packaging line so that multiple cobots can package all the dots. Next to that, cobots are more suitable for more packaging options in the future. This is why cobots will be used in this intervention.

Most cobots that are in the market have a speed of 2 m/s, so that will be used as a guideline for the speed of the cobots in this intervention. The average cost of a cobot with a low payload and a speed of 2 m/s is €20.000. A higher payload would lead to a more expensive cobot, but since a primary packaging with dots would weigh less than 1 kilogram, that is not necessary. As the number of cobots still needs to be determined and any other extra adjustment to the layout of the packaging line, the price depends on the experimental factors described below. Next to that, the cobot would have some variable costs, like electricity and maintenance. However, the cost of manual labour will disappear when using cobots.

The cobots will be implemented in the simulation by adjusting the layout and speed of the process of the packaging station. The number of cobots will be an experimental factor for this intervention since there are different kinds of dots and they might need a different amount of cobots. Next to the number of cobots, the layout of the packaging line might also change. These will be sub-interventions for this intervention and will be discussed below in detail. An overview of the sub-interventions is given in table 4.11. As the unfit dots still arrive at the packaging lines in this intervention, this needs to be implemented in the model. For the minidots, 1 out of 6 shifts have unfit dots which results in downtime, which will be modelled. The dots do not have unfit dots regarding the blister packaging, so that won't be included. Next to that, the assumption has been made that the cobots have an availability of 95% with a corresponding downtime of 15 minutes on average.

Table 4.17: Overview interventions line 1

Intervention	**Title**	**Packaging**
4.1	Only cobots	blister packaging
4.2	Cobots + filter	blister packaging
4.3	Cobots with two functions	blister packaging

Intervention 4.1: only cobots

The first sub-intervention is that the current packaging station will stay the same regarding the systems and conveyors, only the employees will be replaced by cobots with an enclosing or gripping end effectors. An illustration of the intervention is displayed in Figure 4.29. As can be seen, the dots arrive at the conveyor belt, the cobots will package them and place the packaging with dots on the other conveyor belt. To be able to take one dot and put it in the packaging, the cobot needs to cover a distance of 1,1 to 1,5 meters, which takes 0,55 to 0,75 seconds. Taking into account that getting a packaging takes one second, the processing time for the blister with 4 dots is between 3,2 and 4 seconds and a blister with 6 minidots is between 4,3 and 5,5 seconds. The number of cobots for this experiment will be 8, 10 and 12.

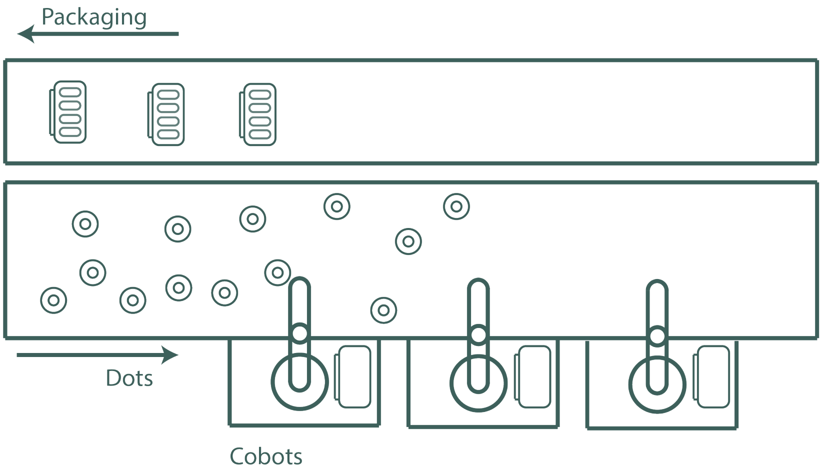

Figure 4.29: Illustration intervention 4.1: Cobots

Table 4.18: Overview intervention 4.1: Only cobots, line 1

Intervention	**Packaging**	**Experimental factors**	**Nr. of exp.**	**Costs**
4.1. only cobots	Blisters	Arrival rate: Current, 100%, 120% Number of cobots: 8, 10, 12	18	€20.000 / cobot + €50.000 instalment costs

Intervention 4.2: cobots + filter

The second sub-intervention is that the dots are forced into one row so that the cobot can get more dots at a time easily. The cobots have multiple vacuum grippers as end effector to be able to get the dots needed for one consumer packaging. For this intervention, the dots are forced in a row by a conveyor belt system that forces the dots in a row. For this option, the cobots are needed to take the number of dots required for the packaging at once and place them in the packaging. Taking the same distance as the previous sub-intervention, the cobot would need between 1,55 and 1,75 seconds per packaging. This could result in fewer cobots to complete the task. The number of cobots for this experiment will be 3, 5 and 7. Next to the cost of the cobots, the conveyor belt system costs around €300.000 and €50.000 of instalment costs. In Figure 4.30 the intervention is displayed. As displayed, the dots will be buffered so that they will get in one line. Afterwards, they are placed in the required pattern to be able to be picked up easily by the cobots. The cobots will take the amount needed for one packaging and package them. Finally, the cobot will place the packaged dots on the other conveyor belt.

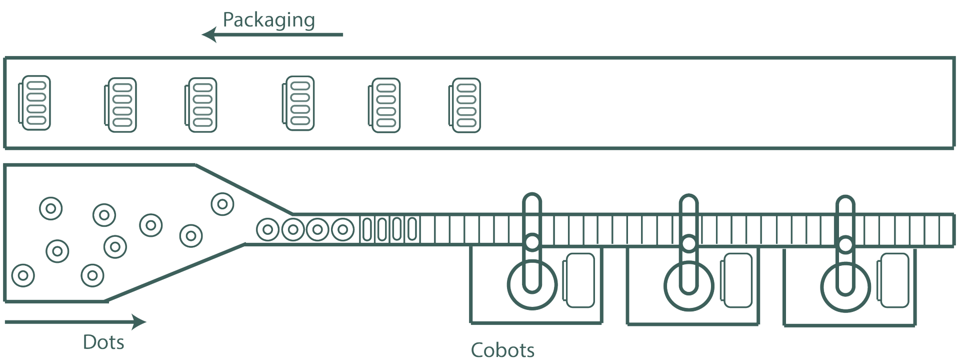

Figure 4.30: Illustration intervention 4.2: Cobots

Table 4.19: Overview intervention 4.2: Cobots + filter, line 1

Intervention	Packaging	Experimental factors	Nr. of exp.	Costs
4.2. Cobots + filter	Blisters	Arrival rate: Current, 100%, 120% Number of cobots: 3, 5, 7	18	€20.000 / cobot + €350.000

Intervention 4.3: cobots with two functions

The third sub-intervention follows the same principle as the previous sub-intervention, so the dots are forced in a certain pattern to enable faster packaging. For this sub-intervention, the dots are placed on another conveyor that enables the required pattern by cobots. This intervention is displayed in Figure 4.31. The same idea is used compared to Figure 4.30, but instead of the buffer, cobots are used to place the cobots correctly. These cobots need around 0.5 seconds to place all the dots in the conveyor. Furthermore, the intervention would be the same as the second sub-intervention. For this intervention, cobots are needed for the ordering of the dots and for packaging them, therefore the number of cobots in this experiment will be 3-9, 6-6, and 9-3. For example, the experimental factor of the cobots 3-9 means that 3 cobots will place the dots correctly on the conveyor belt and 9 cobots will package the cobots. The additional cost for the conveyor will be around €30.000 and €50.000 instalment costs.

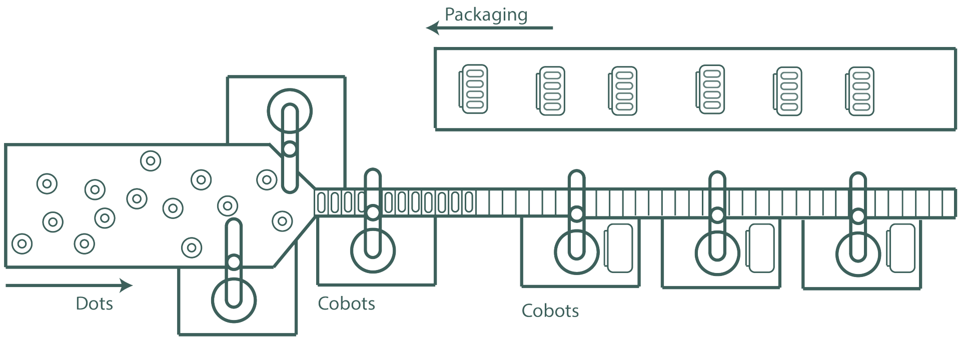

Figure 4.31: Illustration intervention 4.3: Cobots

Table 4.20: Overview intervention 4.1: Cobots with two functions, line 1

Intervention	Packaging	Experimental factors	Nr. of exp.	Costs
4.3. cobots with two functions	Blisters	Arrival rate: Current, 100%, 120% Number of cobots: 3-9, 6-6, 9-3	18	€20.000 / cobot + €80.000

4.5.2 Interventions line 3

For line 3, most interventions that influence the flowpackaging of line 1 are implemented for line 3 as well. The interventions are shown in table 4.21. As can be seen, intervention 3.0 is not in this table, because there already is one flowpacker at line 3. Therefore, this intervention is not relevant for line 3.

Table 4.21: Overview interventions line 3

Intervention	Title	Packaging
1.	Vision system	Both
2.	Buffer	Both
3.1	Two flowpacker machines	flowpackaging
3.2	Speed flowpacker machine	flowpackaging
3.3	Different flowpacker machine	flowpackaging

Intervention 1: Vision system

This intervention will be similar to intervention 1 of line 1, so a vision system that removes unfit dots from the packaging line. A vision system with robots for line 3 would cost around €244.000 as well. The same method has been used to determine failure and downtime with a vision system, which results in an availability of 95% and an MTTR of 1 minute. Next to that, the assumption has been made that the vision system or the robots do not catch all unfit dots and one dot per 500000 still goes through to the flowpacker, this results in around one unfit dot every 17 hours. Figure 4.32 shows how the intervention is implemented in the simulation model. The numbers 1 to 4 displayed in Figure 4.32 are the same as described in Section 4.2. Number 5 is the vision system, located after the metal detector. In Table 4.22 an overview is displayed of the experimental configuration and the number of experiments of this intervention.

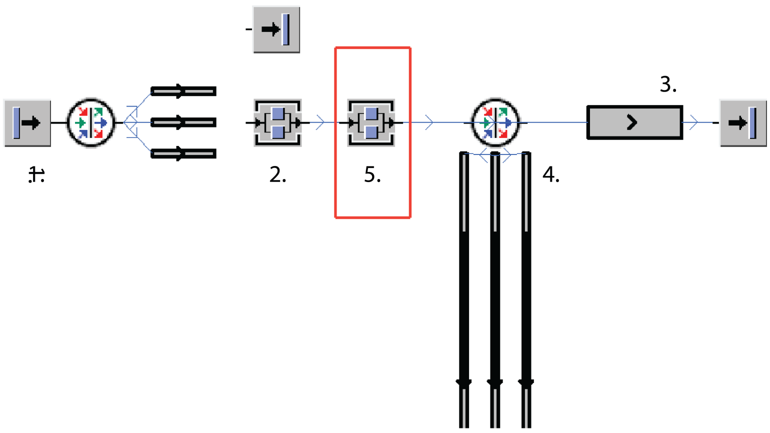

Figure 4.32: Simulation line 3, intervention 1: Vision system

Table 4.22: Overview intervention 1: Vision system, line 3

Intervention	Packaging	Experimental factors	Nr. of exp.	Costs
Vision system	Both	Arrival rate: Current, 100%, 120%	3	€294.000

Intervention 2: Buffers

For line 3, the buffers will be stationed next to the conveyor belt, so when the flowpacker machine malfunctions, the dots can be redirected to the buffers. The same spiral conveyors will be used and these cost around €25.000 a piece. For the simulation, the buffers will be located next to the conveyor belt and the size of the buffer will, again, be an experimental setting.

Figure 4.33 shows how the intervention is implemented in the simulation model. The numbers 2,4 and 5 are the same as in the simulation of the current situation. Number 3 now resembles the buffer. In Table 4.23 an overview of the experimental configuration and the number of experiments is displayed for this intervention.

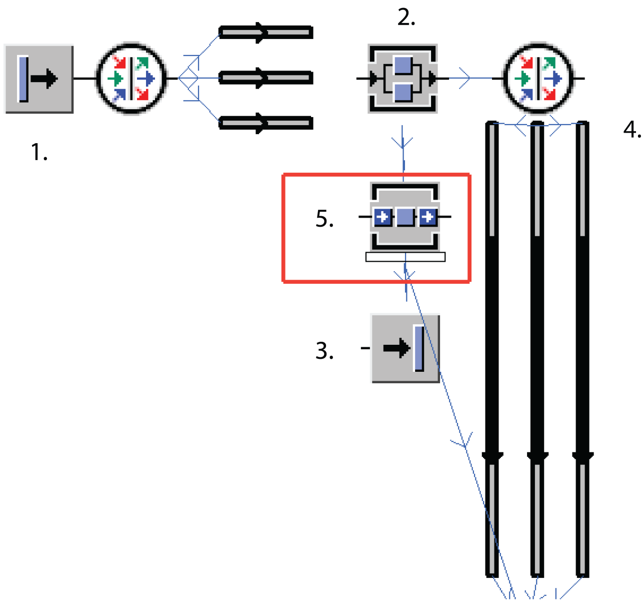

Figure 4.33: Simulation line 3, intervention 2: Buffers

Table 4.23: Overview intervention 2: Buffers, line 3

Intervention	Packaging	Experimental factors	Nr. of exp.	Costs
Buffer	Flowpackaging	Arrival rate: Current, 100%, 120% Buffer capacity line 3: 5000, 9000, 12000	9	€25.000 per buffer + €50.000 instalment costs

Intervention 3: Flowpacker

Three sub-interventions for intervention 3 are implemented at line 3. As line 3 already has a flowpacker machine, sub-intervention 3.0 is not included here.

Intervention 3.1: two flowpackers

Intervention 3.1 will be similar to intervention 3.1 of line 1. The cost of this intervention for line 3 would be around €600.000, as there already is one flowpacker machine. In Table 4.24 an overview is displayed of the experimental configuration and the number of experiments of this intervention.

Table 4.24: Overview intervention 3.1: Multiple Flowpackers, line 3

Intervention	Packaging	Experimental factors	Nr. of exp.	Costs
3.1 - Multiple flowpackers	Flowpackaging	Arrival rate: Current, 100%, 120% Ratio of machines: 0/100%, 80/20%, 50/50%	9	€650.000

Intervention 3.2: speed flowpacker

Intervention 3.2 will be similar to the one in line 1 as well. The only difference is that the dots get packaged per 4 at line 3 so that changes the maximum speed of the flowpacker machine to 130 packages/minute. Furthermore, the cost of this intervention and the method of including it in the simulation model are similar to the intervention described for line 1. In Table 4.25 an overview is displayed of the experimental configuration and the number of experiments of this intervention.

Table 4.25: Overview intervention 3.2: Speed Flowpacker, line 3

Intervention	Packaging	Experimental factors	Nr. of exp.	Costs
3.2. Speed flowpackers	Flowpackaging	Arrival rate: Current, 100%, 120%	3	-

Intervention 3.3: different flowpacker

Intervention 3.3 for line 3 is the same as line 1, except for the experimental factors. The speeds of another flowpacker machine for this intervention will be 150, 175 and 200 packages a minute. In Table 4.26 an overview is displayed of the experimental configuration and the number of experiments of this intervention.

Table 4.26: Overview intervention 3.3: Different Flowpacker, line 3

Intervention	Packaging	Experimental factors	Nr. of exp.	Costs
3.3. Different flowpacker	Flowpackaging	Arrival rate: Current, 100%, 120% Speed flowpacker line 1: 150, 175, 200	9	€950.000

4.5.3 Combination of interventions

A combination of interventions might lead to an even bigger improvement in the capacity of packaging lines 1 and 3. In addition, for line 1, the best flowpackaging intervention and the best blister packaging intervention will be combined, since both packaging are used at line 1. The experimental factors of each intervention will remain the same to determine the best combination possible. Therefore the following interventions are combined, as shown in Tables 4.27 and 4.28. Below, some intervention combinations will be discussed in more detail.

Table 4.27: Combinations interventions line 1

Combination	I1	I2	I3.0	I3.1	I3.2	I3.3	I4.1	I4.2	I4.3
Combination 1	x		x						
Combination 2		x	x						
Combination 3	x	x	x						
Combination 4	x			x					
Combination 5	x				x				
Combination 6		x			x				
Combination 7	x						x		
Combination 8	x							x	
Combination 9	x								x

First, the combinations of line 1 will be discussed. The first combination will be intervention 1 - vision system, and intervention 3.0 - one flowpacker. For this, the same assumptions and simulation settings will be used as used for intervention 1 at line 3. This means that the flowpacker (intervention 3.0) will have one unfit crodot every 26 hours due to the vision system (intervention 1). The second combination is a combination of intervention 2 - buffer and intervention 3.0 - one flowpacker. Similar to the first combination, the settings of the second intervention for line 3 will be used. Intervention 1 - vision system, intervention 2 - buffer and intervention 3.0 - one flowpacker will be combined for the third combination. For this combination, combination 1 and 2 will be combined in one simulation model to test the capacity improvement of line 1. Combinations 4 and 5 work similarly to combination 1, except for different settings/configurations of the flowpacker machine. Combination 6 will combine a buffer with a flowpacker machine at a higher speed. Combinations 7, 8 and 9 combine the cobot interventions with a vision system. These combinations will not influence the packaging of the dots, only the packaging of the minidots. At the moment, one in every sixth replication has an unfit dot. This frequency is chosen based on the output logs of the current packaging line. To determine the result of a vision system in this combination, the assumption has been made that a vision system reduces this frequency to one every 18 replications.

Table 4.28: Combinations interventions line 3

Combination	**I1**	**I2**	**I3.1**	**I3.2**	**I3.3**
Combination 1	x	x			
Combination 2	x		x		
Combination 3	x			x	
Combination 4		x		x	

Next, the combinations of line 3 will be discussed. These combinations are more straightforward, as the settings of both interventions can be combined more easily. So, for example, for the first combination of intervention 1 - vision system and intervention 2 - buffer, the packaging line will have a vision system and a buffer in case the flowpacker has a malfunction.

4.6 Summary Chapter 4

In this chapter, the conceptual model, the simulation model, the experimental design and the interventions are discussed. The objective of the conceptual model, and therefore the simulation model, is to increase the capacity of consumer packaging lines 1 & 3. Furthermore, all inputs, content and outputs of the conceptual model are described. The simulation model is displayed in figures 4.10, 4.11 and 4.12. Additionally, the simulation model is validated by black-and-white box testing. Next to the validation, the warm-up period, run length and number of replications are determined in section 4.3. Afterwards, the experimental configuration is discussed to be clear about which aspects of the simulation model and current situation will change during the experiments and which will not. The chapter continues with the current bottlenecks and capacity to be able to compare those with the results that will be discussed in Chapter 5. Finally, the interventions are discussed in section 4.5 and Table 4.29 gives an overview of all interventions that will be tested in this thesis.

Table 4.29: Overview interventions line 1 & 3

Line	Intervention	Packaging	Experimental factors	Nr. of Exp.	Cost
1	1. Vision	Both	Arrival rate: Current, 100%, 120%	3	€294.000
1	2. Buffer	Both	Arrival rate: Current, 100%, 120% Buffer capacity crodots: 2500, 5000, 7500 Buffer capacity dots: 5000, 9000, 12000 Buffer capacity minidots: 10000, 15000, 20000	27	€25.000 per buffer + €50.000 instalment costs
1	3.0 One flowpacker	Flowpackaging	Arrival rate: Current, 100%, 120%	3	€650.000
1	3.1 Two flowpackers	Flowpackaging	Arrival rate: Current, 100%, 120% Ratio: 0/100%, 80/20%, 50/50%	9	€1.250.000
1	3.2 Speed Flowpacker	Flowpackaging	Arrival rate: Current, 100%, 120%	3	€650.000
1	3.3 Different Flowpacker	Flowpackaging	Arrival rate: Current, 100%, 120% Speed flowpacker: 250, 275, 300	9	€950.000
1	4.1 only cobots	Blisters	Arrival rate: Current, 100%, 120% Number of cobots: 8, 10, 12	18	€20.000 per cobot + €50.000 instalment costs
1	4.2 cobots + filter	Blisters	Arrival rate: Current, 100%, 120% Number of cobots: 3, 5, 7	18	€20.000 per cobot + €350.000
1	4.3 cobots with two functions	Blisters	Arrival rate: Current, 100%, 120% Number of cobots: 3-9, 6-6, 9-3	18	€20.000 per cobot + €80.000
1	1 & 3.0	Flowpackaging	Arrival rate: Current, 100%, 120%	3	€894.000
1	2 & 3.0	Flowpackaging	Arrival rate: Current, 100%, 120% Buffer capacity: 2500, 5000, 7500	3	€650.000 + €25.000 per buffer
1	1, 2 & 3.0	Flowpackaging	Arrival rate: Current, 100%, 120% Buffer capacity: 2500, 5000, 7500	9	€894.000 + €25.000 per buffer
1	1 & 3.1	Flowpackaging	Arrival rate: Current, 100%, 120% Ratio: 0/100%, 80/20%, 50/50%	9	€1.250.000
1	1 & 3.2	Flowpackaging	Arrival rate: Current, 100%, 120%	3	€894.000
1	2 & 3.2	Flowpackaging	Arrival rate: Current, 100%, 120% Buffer capacity: 2500, 5000, 7500	9	€650.000 + €25.000 per buffer
1	1 & 4.1	Blisters	Arrival rate: Current, 100%, 120% Number of cobots: 8, 10, 12	18	€244.000 + €20.000 per cobot
1	1 & 4.2	Blisters	Arrival rate: Current, 100%, 120% Number of cobots: 3, 5, 7	18	€594.000 €20.000 per cobot
1	1 & 4.3	Blisters	Arrival rate: Current, 100%, 120% Number of cobots: 3-9, 6-6, 9-3	18	€324.000 €20.000 per cobot
3	1. Vision	Flowpackaging	Arrival rate: Current, 100%, 120%	3	€294.000
3	2. Buffer	Flowpackaging	Arrival rate: Current, 100%, 120% Buffer capacity: 5000, 9000, 12000	9	€25.000 per buffer + €50.000 instalment costs
3	3.1 Two flowpackers	Flowpackaging	Arrival rate: Current, 100%, 120% Ratio: 0/100%, 80/20%, 50/50%	9	€650.000
3	3.2 Speed Flowpacker	Flowpackaging	Arrival rate: Current, 100%, 120%	3	-
3	3.3 Different Flowpacker	Flowpackaging	Arrival rate: Current, 100%, 120% Speed flowpacker: 150, 175, 200	9	€950.000
3	1 & 2	Flowpackaging	Arrival rate: Current, 100%, 120% Buffer capacity: 5000, 9000, 12000	9	€294.000 + €25.000 per buffer
3	1 & 3.1	Flowpackaging	Arrival rate: Current, 100%, 120% Ratio: 0/100%, 80/20%, 50/50%	9	€650.000
3	1 & 3.2	Flowpackaging	Arrival rate: Current, 100%, 120%	3	€294.000
3	2 & 3.2	Flowpackaging	Arrival rate: Current, 100%, 120% Buffer capacity: 5000, 9000, 12000	9	€25.000 per buffer

5 Results

In this chapter the results of the interventions described in Section 4.5 will be discussed for both performance measures utilization and cost (payback period). The results of the interventions can be compared to the results of the current bottlenecks in Section 4.4, displayed below in Table 5.1. For all interventions, a table has been provided with all experiments of the intervention and the experimental settings. In the first column, the experiment number is shown, followed by the arrival rate of that experiment. The third column 'Min. Util. (%)' shows the lowest utilization of one of the replications within the experiment and the column 'Max. utilization (%)' shows the highest utilization of one of the replications within that experiment. The column 'Avg. Util. (%)' shows the average utilization of all replications of that experiment. Finally, the utilization improvement of the experiment compared to the utilization with the same arrival rate of the current system is displayed in the 'Improvement (%)' column. The improvement per experiment is determined by:

$$\textit{Improvement} = \textit{Average utilization of an experiment} - \textit{average utilization of the same arrival rate of the current situation.}$$

So for example the first experiment of table 5.2 (in the first row) uses an arrival rate of the current situation and the type of dot that is used is the minidot. The minimum utilization of one of the replications is 13,69% and the maximum utilization is 62,89%. Additionally, the average utilization of all replications of this experiment is 34,59%. Finally, the utilization improvement is 1,01%. The average utilization of the minidots for the current arrival rate is 33,58%. This is calculated by $\textit{Improvement} = 34{,}59 - 33{,}58 = 1{,}01$. The tables with the results of the interventions can be used as follows. The minimum and maximum utilization can be used to determine the variability of each experiment. Suppose an experiment has a minimum and maximum that are very close together (like 10% or so). In that case, it can be concluded that every replication performs quite similarly, which suggests a stable system. On the other hand, when there is a lot of difference between the minimum and maximum utilization, it suggests a very unstable system. Furthermore, the average utilization shows the average performance of that experiment. Finally, the improvement column shows the improvement compared to the current system. This can be used to determine if the intervention actually performs better and improves the utilization.

Table 5.1: Utilization current situation dots lines 1 & 3

Line	**Dot type**	**Arrival Rate (dots/hour)**	**Min. Util. (%)**	**Max. Util. (%)**	**Avg. Util. (%)**
1	Dots	Current	19,30	95,94	40,66
		100% theoretical	13,33	41,18	29,66
		120% theoretical	11,10	34,31	24,71
1	Crodots	Current	15,95	95,94	37,10
		100% theoretical	10,77	46,77	25,63
		120% theoretical	8,95	38,86	21.29
1	Minidots	Current	11,91	65,65	33,58
		100% theoretical	8,60	35,17	22,56
		120% theoretical	7,17	29,31	18,80
3	Dots	Current	43,00	84,46	72,73
		100% theoretical	43,00	84,46	72,73
		120% theoretical	37,05	72,34	62,46

5.1 Results interventions line 1

This section discusses the results of interventions 1 - 4.3 and the intervention combinations for line 1.

5.1.1 Intervention 1: Vision system

In Table 5.2, the result of the vision system for the crodots and minidots is displayed. As discussed earlier, the vision system does not have any influence on the dots of line 1 and is therefore not included in this intervention. For the minidots, the utilization increases somewhat, by around 1% for every experiment, so this might not be the best intervention on its own for the blister packaging. However, the minimum utilization for the minidots is higher compared to the current situation, so the variability per replication is somewhat lower. Same as for the minidot, the average utilization of the crodot also does not increase much.

Table 5.2: Results experiments intervention 1, line 1 minidot & crodot

Exp. nr.	Arrival Rate	Dot	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	Minidot	13,69	62,89	34,59	1,01
2	100% theoretical	Minidot	9,33	34,96	23,34	0,77
3	120% theoretical	Minidot	7,83	29,36	19,60	0,80
4	Current	Crodot	12,39	95,95	37,89	0,79
5	100% theoretical	Crodot	10,54	46,58	26,70	1,07
6	120% theoretical	Crodot	8,76	38,70	22,18	0,89

5.1.2 Intervention 2: Buffers

The results of each dot category are displayed in Tables 5.3, 5.4 and 5.5. The dot category will be discussed separately, starting with the results of the crodots. As can be seen in the table below, the utilization decreases for every experiment. The main idea of buffers across a manufacturing line is to give bottlenecks of the line time to process everything and therefore parts will move more fluently across the manufacturing line. However, the negative utilization improvements suggest that the buffer becomes a bottleneck itself and does not help guide the product more fluently across the packaging line. Even for the smallest buffer, which is a buffer of 8 minutes, the buffer becomes a bottleneck for the packaging line.

Table 5.3: Results experiments intervention 2, line 1 crodots

Exp. nr.	Arrival Rate	Buffer size	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	2500	12,27	77,93	32,66	-4,44
2	100% theoretical	2500	8,53	34,88	22,38	-3,25
3	120% theoretical	2500	7,11	29,06	18,65	-2,65
4	Current	5000	12,22	77,60	32,52	-4,57
5	100% theoretical	5000	8,50	34,73	22,28	-3,35
6	120% theoretical	5000	7,08	28,94	18,57	-2,73
7	Current	7500	12,16	77,22	32,36	-4,73
8	100% theoretical	7500	8,45	34,56	22,17	-3,46
9	120% theoretical	7500	7,05	28,80	18,48	-2,82

The table below, Table 5.4, shows the results of intervention 2 when packaging the dots in blisters of 4. Similar to the crodots, the buffer becomes a bottleneck for the packaging line.

Table 5.4: Results experiments intervention 2, line 1 dots

Exp. nr.	Arrival Rate	Buffer size	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	5000	9,23	95,85	36,73	-3,93
2	100% theoretical	5000	10,71	46,51	25,48	-4,18
3	120% theoretical	5000	8,90	38,64	21,18	-3,54
4	Current	9000	9,18	95,32	36,52	-4,14
5	100% theoretical	9000	10,65	46,25	25,34	-4,32
6	120% theoretical	9000	8,85	38,43	21,06	-3,65
7	Current	12000	9,13	94,83	36,34	-4,32
8	100% theoretical	12000	10,60	46,02	25,22	-4,45
9	120% theoretical	12000	8,80	38,24	20,95	-3,76

Finally, the results of intervention 2 for the minidots in a blister of six units are displayed in Table 5.5. The intervention does increase the utilization for the minidots, in contrast to the results of the crodots and dots. This might be explained by the fact that the combination of the arrival rate (which is higher for the minidots compared to the other dots) and their processing time result in a need for some buffer to be able to package all minidots. The utilization increases by 6,04% for the buffer size of 10000 and the current arrival rate. A buffer size of 10000 is also the preferred experimental setting, but it does not have a very big advantage over the other two buffer size settings. A buffer of 10000 would cost around €550.000.

Table 5.5: Results experiments intervention 2, line 1 minidots

Exp. nr.	Arrival Rate	Buffer size	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	10000	15,38	95,74	39,08	5,50
2	100% theoretical	10000	13,23	40,89	29,46	6,89
3	120% theoretical	10000	11,02	34,07	24,54	6,89
4	Current	15000	15,29	95,18	38,85	5,28
5	100% theoretical	15000	13,16	40,67	29,29	6,73
6	120% theoretical	15000	10,96	33,88	24,40	5,60
7	Current	20000	15,23	94,76	38,69	5,11
8	100% theoretical	20000	13,10	40,49	29,17	6,60
9	120% theoretical	20000	10,92	33,73	24,30	5,49

5.1.3 Intervention 3: Flowpacker

In this section, all results of the sub-interventions of intervention 3 will be described, which includes intervention 3.0 - one flowpacker, intervention 3.1 - two flowpackers, intervention 3.2 - speed flowpacker and intervention 3.3 - different flowpacker.

Intervention 3.0: one flowpacker

Table 5.6 shows the results when the crodots get packaged by a flowpacker machine. When comparing the two Tables (4.4 & 5.6), a big improvement in the utilization of at most 25% is created by placing a flowpacker machine at line 1 for the flowpacking of the crodots. On the other hand, the utilization decreases to 47% with a 100% arrival rate and decreases even more when using a 120% arrival rate. This might be explained that even though the flowpacker should be able to package all crodots with a 100% arrival rate, the malfunctions might cause disruptions which lower the utilization. If the arrival rate is increased to 120%, logically, the utilization drops even more. The variability per replication is lower than the current situation, as there is less difference between the minimum and maximum utilization. As described in the previous chapter, this intervention would cost around €650.000.

Table 5.6: Results experiments intervention 3.0, line 1 crodots

Exp. Nr.	Arrival Rate (%)	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	41,87	86,90	62,11	25,01
2	100% theoretical	34,87	55,27	47,17	21,54
3	120% theoretical	29,19	46,25	39,47	18,18

Intervention 3.1: two flowpackers

The results of intervention 3.1 for line 1 are shown below in Table 5.7. As expected, the addition of another flowpacker significantly increases the utilization to ± 95%. Note that the maximum utilization of these experiments is 95,95%, since other parts of the packaging line also have malfunctions, as discussed in Chapter 4. Thus this intervention would almost reach the maximum utilization for all experiments. Next to that, the mimimum utilization is also very high, which shows that all replications perform very well. This intervention performs really well for every arrival rate, so all average capacities of the experiments are very high. As can be seen in Table 5.1, the utilization decreases with the arrival rate, so when an intervention, such as this one, performs well for all arrival rates, the biggest improvement is made for the experiments with an arrival rate of 120%. This is just because the biggest improvement is made for this arrival rate, but it does not directly mean that the experiments with an arrival rate of 120% perform much better than the other two arrival rates. The ratio of the flowpackers does not make much difference since all experiments have almost similar results regarding utilization. However, there is a minimal preference for a 50/50 ratio. The total cost for this intervention for line 1 would be around €1.25 million.

Table 5.7: Results experiments intervention 3.1, line 1

Exp. nr.	Arrival Rate	Ratio FP (%)	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	100/0	93,81	95,79	94,92	57,82
2	100% theoretical	100/0	89,64	95,77	94,72	69,09
3	120% theoretical	100/0	89,61	95,76	94,73	73,44
4	Current	80/20	93,81	95,94	95,14	58,05
5	100% theoretical	80/20	89,64	95,95	95,17	69,54
6	120% theoretical	80/20	89,61	95,94	94,74	73,44
7	Current	50/50	93,81	95,94	95,38	58,28
8	100% theoretical	50/50	89,54	95,95	95,24	69,61
9	120% theoretical	50/50	93,83	95,94	95,32	74,03

Intervention 3.2: speed flowpacker

In Table 5.8 the results of intervention 3.2 for line 1 are displayed. For the packaging of the crodots, the speed of the flowpacker machine has quite a strong influence, as the utilization increases on average by 48.21%. The difference between the minimum and maximum utilization is closer together compared to intervention 3.0, so there is a somewhat more stable system. The utilization of each arrival rate is the same, which shows that the speed is high enough for all arrival rates to perform equally well. This intervention would cost EO around €650.000.

Table 5.8: Results experiments intervention 3.2, line 1

Exp. nr.	Arrival Rate	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	56,54	89,28	76,22	39,12
2	100% theoretical	56,53	89,28	76,22	50,59
3	120% theoretical	56,53	89,28	76,22	54,93

Intervention 3.3: different flowpacker

In Table 5.9 the results of intervention 3.3 are displayed. As can be seen, the utilization of intervention 3.2 (Table 5.8) and 3.3 (Table 5.9) are the same. This suggests that increasing the speed of the current flowpacker performs well enough and it is not necessary to change to another flowpacker. This intervention would cost EO an investment of around €950.000.

Table 5.9: Results experiments intervention 3.3, line 1

Exp. nr.	Arrival Rate	Speed FP (packages/min)	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	250	56,54	89,28	76,22	39,12
2	100% theoretical	250	56,53	89,28	76,22	50,59
3	120% theoretical	250	56,53	89,28	76,22	54,93
4	Current	275	56,54	89,28	76,22	39,12
5	100% theoretical	275	56,53	89,28	76,22	50,59
6	120% theoretical	275	56,53	89,28	76,22	54,93
7	Current	300	56,54	89,28	76,22	39,12
8	100% theoretical	300	56,53	89,28	76,22	50,59
9	120% theoretical	300	56,53	89,28	76,22	54,93

5.1.4 Intervention 4: robots

As described in Section 4.5, there are three sub-interventions to intervention 4: robots. The results of these sub-interventions are described below.

Intervention 4.1: only cobots

The results of intervention 4.1 are shown in Table 5.10 and 5.11, for the minidots and dots, respectively. As can be seen, the utilization increases quite a lot with this intervention compared to the current utilization of 50,23% on average. For the dots, the utilization is the same for 10 or 12 cobots, so 10 cobots would be enough for the dots. For the current arrival rate, the system is almost stable, as the minimum and maximum utilization only differ by 0,02%. For the minidots, the utilization is higher for 12 cobots. Therefore, the best experimental setting for this intervention is 12 cobots, which translates to a total cost of €290.000.

Table 5.10: Results experiments intervention 4.1, line 1 minidots

Exp. nr.	Arrival Rate	Number of cobots	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	8	68,48	89,84	86,95	53,27
2	100% theoretical	8	52,13	78,24	66,68	44,29
3	120% theoretical	8	43,44	65,20	55,72	36,91
4	Current	10	71,19	89,84	88,23	54,65
5	100% theoretical	10	43,44	65,21	55,72	33,16
6	120% theoretical	10	36,20	54,34	46,43	27,63
7	Current	12	71,19	89,84	88,30	54,72
8	100% theoretical	12	52,17	78,32	66,92	44,35
9	120% theoretical	12	43,48	65,27	55,77	36,96

Table 5.11: Results experiments intervention 4.1, line 1 dots

Exp. nr.	Arrival Rate	Number of cobots	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
10	Current	8	89,82	89,84	89,93	49,16
11	100% theoretical	8	89,82	89,82	89,92	60,15
12	120% theoretical	8	79,10	89,83	84,59	59,88
13	Current	10	89,82	89,84	89,83	49,16
14	100% theoretical	10	89,82	89,82	89,82	60,15
15	120% theoretical	10	89,83	89,83	89,83	65,12
16	Current	12	89,81	89,84	89,83	49,16
17	100% theoretical	12	89,82	89,82	89,82	60,16
18	120% theoretical	12	89,83	89,83	89,83	65,12

Intervention 4.2: cobots + filter

In Tables 5.12 and 5.13 the results of intervention 4.2 are displayed. The improvement of this intervention is around 50% for both dots and minidots. The number of cobots needed for the packaging of the minidots is 7, as this results in the highest utilization, mainly for the arrival rate of 100% and 120%. There are 5 cobots needed to package all dots, as the utilization does not increase when the number of cobots is increased to 7. Since the packaging of the minidots does need 7 cobots, the cost of this intervention would be €490.000. This cost consists of €140.000 for the cobots, €300.000 for the conveyor system and €50.000 for installing the intervention.

Table 5.12: Results experiments intervention 4.2, line 1 minidots

Exp. nr.	Arrival Rate	Number of cobots	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	3	56,25	88,27	85,13	51,56
2	100% theoretical	3	45,17	71,60	65,89	43,33
3	120% theoretical	3	37,64	59,67	54,91	36,11
4	Current	5	56,25	88,27	85,84	52,27
5	100% theoretical	5	50,18	79,56	73,22	50,66
6	120% theoretical	5	41,82	66,30	61,01	42,21
7	Current	7	56,25	88,27	85,85	52,27
8	100% theoretical	7	60,48	88,26	86,20	63,63
9	120% theoretical	7	56,29	88,84	81,90	63,09

Table 5.13: Results experiments intervention 4.2, line 1 dots

Exp. nr.	Arrival Rate	Number of cobots	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
10	Current	3	71,02	88,27	82,23	41,56
11	100% theoretical	3	70,56	77,88	73,27	43,60
12	120% theoretical	3	58,71	64,80	60,69	36,25
13	Current	5	88,26	88,27	88,26	47,60
14	100% theoretical	5	88,26	88,27	88,26	58,60
15	120% theoretical	5	88,26	88,27	88,26	63,55
16	Current	7	88,26	88,27	88,26	47,60
17	100% theoretical	7	88,26	88,27	88,26	58,60
18	120% theoretical	7	88,26	88,27	88,26	63,55

Intervention 4.3: cobots with two functions

The results of the last cobot sub-intervention are displayed in Tables 5.14 and 5.15. For the minidots, the best configuration of cobots is 6 ordering cobots and 6 packaging cobots. This results in an average utilization for the current arrival rate of 73,89%. For the dots, the best configuration of the cobots would be 3 ordering cobots and 9 packaging cobots. This might differ because the arrival rate of dots is lower than the arrival rate of the minidots. The cost of this intervention would be €320.000, €240.000 for the cobots, €30.000 for the conveyor adjustments and €50.000 for installing the intervention.

Table 5.14: Results experiments intervention 4.3, line 1 minidots

Exp. nr.	Arrival Rate	Number of cobots	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	3-9	41,65	89,32	59,27	25,69
2	100% theoretical	3-9	31,83	41,88	40,50	17,93
3	120% theoretical	3-9	26,53	34,90	33,75	14,94
4	Current	6-6	53,94	89,33	73,89	40,32
5	100% theoretical	6-6	40,56	55,20	52,17	29,60
6	120% theoretical	6-6	33,80	46,00	43,47	24,67
7	Current	9-3	39,51	89,32	55,92	22,34
8	100% theoretical	9-3	29,38	40,94	38,08	15,51
9	120% theoretical	9-3	24,49	34,12	31,73	12,93

Table 5.15: Results experiments intervention 4.3, line 1, dots

Exp. nr.	Arrival Rate	Number of cobots	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
10	Current	3-9	68,01	89,33	80,01	39,37
11	100% theoretical	3-9	87,44	89,33	89,21	59,55
12	120% theoretical	3-9	63,75	89,33	76,71	52,00
13	Current	6-6	67,53	69,59	68,31	27,65
14	100% theoretical	6-6	86,47	89,33	84,29	54,62
15	120% theoretical	6-6	62,62	68,23	64,70	39,99
16	Current	9-3	56,19	76,54	57,25	16,58
17	100% theoretical	9-3	72,16	76,54	73,81	44,14
18	120% theoretical	9-3	52,10	56,77	53,83	29,12

5.1.5 Intervention 1 & intervention 3.0

In Table 5.16 the results of the flowpackaging of the crodots are displayed. As can be seen, the utilization increases considerably, on average ± 60%. Compared to intervention 3.0, the utilization increases on average with ± 40%. Next to that, the minimum utilization of the combination is 79,03% or 79,04% compared to the 29,19-41,87% of intervention 3.0 on its own. The utilization is similar for all arrival rates, which might be caused by the fact that the flowpacker processes quickly enough when there are no/limited malfunctions.

Table 5.16: Results experiments intervention 1 & 3.0, line 1 crodots

Exp. Nr.	Arrival Rate (%)	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	79,04	93,90	88,84	51,74
2	100% theoretical	79,03	93,90	88,84	63,21
3	120% theoretical	79,03	93,90	88,84	67,54

5.1.6 Intervention 2 & intervention 3.0

The results of the combination of interventions 2 & 3.0 for line 1 are displayed in Table 5.18. This intervention was performed for the crodots in combination with a flowpacker. First of all, the utilization increases somewhat when using a bigger buffer. Next to that, the experiments with a 120% arrival rate (experiments 3,6 & 9) benefit from having a buffer. This intervention generally increases utilization between 20 and 40%, depending on the arrival rate. The minimum utilization increases as well for the combination compared to intervention 3.0 on its own. The best buffer size for this intervention is 7500, which results in 15 buffers, costing €350.000 in total. Since the buffer size has only a small influence, a smaller buffer could also do the job. A 2500-size buffer would cost €150.000 and a 5000-size buffer would cost €250.000.

Table 5.17: Results experiments intervention 2 & 3.0, line 1 crodots

Exp. nr.	Arrival Rate	Buffer size	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	2500	59,23	93,25	79,32	42,23
2	100% theoretical	2500	58,61	92,70	78,84	53,21
3	120% theoretical	2500	58,42	92,40	78,58	57,29
4	Current	5000	60,36	95,06	81,21	44,12
5	100% theoretical	5000	59,23	94,34	80,29	54,66
6	120% theoretical	5000	58,79	93,77	79,79	58,50
7	Current	7500	61,48	95,95	82,84	45,74
8	100% theoretical	7500	59,50	95,48	81,65	56,02
9	120% theoretical	7500	58,79	94,91	80,96	59,66

5.1.7 Intervention 1 & intervention 2 & intervention 3.0

In Table 5.18 the results from the experiments of intervention combination 1 & 2 & 3.0 are displayed. As can be seen, the maximum of almost all experiments have the maximum possible utilization, which shows that this intervention combination works well. Next to that, the average improvement is around 62%. The preferred buffer size for line 1 is 7500, but this is only a minimal preference. Cost-wise, the smallest buffer is most promising, since the buffers do not really perform that differently. With a buffer of 2500, the total buffer investment cost would be €150.000.

Table 5.18: Results experiments intervention 1 & 2 & 3.0, line 1 crodots

Exp. nr.	Arrival Rate	Buffer size	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	2500	78,59	95,95	91,10	54,01
2	100% theoretical	2500	72,42	95,95	89,74	64,11
3	120% theoretical	2500	72,42	95,87	88,45	67,16
4	Current	5000	73,35	95,95	89,97	52,87
5	100% theoretical	5000	72,42	95,95	90,33	64,70
6	120% theoretical	5000	72,42	95,94	90,49	69,20
7	Current	7500	80,85	95,95	92,87	55,77
8	100% theoretical	7500	72,42	95,95	89,16	63,53
9	120% theoretical	7500	78,69	95,94	92,04	70,75

5.1.8 Intervention 1 & intervention 3.1

Table 5.38 displays the results of the combination of interventions 1 and 3.1. These results are the same as for Intervention 3.1 alone, as the minimum, maximum and average utilization are similar. This shows that a vision system and two flowpackers together are not an interesting combination, as the two flowpackers perform well enough.

Table 5.19: Results experiments intervention 1 & 3.1, line 1

Exp. nr.	Arrival Rate	Ratio FP (%)	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	100/0	93,81	95,79	94,92	57,82
2	100% theoretical	100/0	89,63	95,77	94,72	69,09
3	120% theoretical	100/0	89,61	95,76	94,73	73,43
4	Current	80/20	93,81	95,94	95,14	58,05
5	100% theoretical	80/20	89,64	95,95	95,17	69,54
6	120% theoretical	80/20	89,61	95,94	94,74	73,44
7	Current	50/50	93,81	954	95,38	58,28
8	100% theoretical	50/50	89,54	95,95	95,24	69,61
9	120% theoretical	50/50	93,83	95,94	95,32	74,03

5.1.9 Intervention 1 & intervention 3.2

The results of combination interventions 1 & 3.2 displayed in Table 5.20 show that the combination is slightly better than intervention 3.2. For the current arrival rate and the 100% arrival rate, it increases the utilization slightly with 0,63%. However, the minimum utilization does increase with ±24%, which is a positive thing, because the experiments perform better overall.

Table 5.20: Results experiments intervention 1 & 3.2, line 1

Exp. nr.	Arrival Rate	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	80,74	93,55	88,66	51,56
2	100% theoretical	79,04	93,90	88,76	63,13
3	120% theoretical	79,03	93,90	89,19	67,89

5.1.10 Intervention 2 & intervention 3.2

A combination of the speed of the flowpacker and a buffer for malfunctions is a promising combination since this combination performs better than each intervention on its own. The results are displayed in Table 5.21. The buffer size does not have an influence, so a buffer with size 2500 would be sufficient, which would cost €150.000.

Table 5.21: Results experiments intervention 2 & 3.2, line 1 crodots

Exp. nr.	Arrival Rate	Buffer size	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	2500	60,42	95,95	92,13	55,03
2	100% theoretical	2500	59,59	95,92	90,47	64,84
3	120% theoretical	2500	58,77	95,20	86,66	65,37
4	Current	5000	60,42	95,95	92,13	55,03
5	100% theoretical	5000	59,59	95,93	90,48	64,85
6	120% theoretical	5000	58,87	95,95	86,78	65,48
7	Current	7500	60,42	95,95	92,13	55,04
8	100% theoretical	7500	59,59	95,95	90,52	64,90
9	120% theoretical	7500	58,87	95,50	86,99	65,69

5.1.11 Intervention 1 & intervention 4.1

The results of this intervention combination are displayed in Table 5.22 for the minidots and the dots in Table 5.23. First of all, since the vision system does not influence the utilization of the dots, the results for this intervention combination of the dots are similar to the ones of intervention 4.1 alone. For the minidots, the utilization has a minimum improvement compared to intervention 4.1 alone. To conclude, this combination might not be the most interesting, especially as the cobots perform quite well on their own.

Table 5.22: Results experiments intervention 1 & 4.1, line 1 minidots

Exp. nr.	Arrival Rate	Number of cobots	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	8	68,48	89,84	87,97	54,39
2	100% theoretical	8	52,13	78,24	67,78	45,21
3	120% theoretical	8	43,44	65,20	56,48	37,68
4	Current	10	72,99	89,84	89,25	55,67
5	100% theoretical	10	43,44	65,21	56,49	33,92
6	120% theoretical	10	36,20	54,34	47,07	28,27
7	Current	12	72,,98	89,84	89,32	55,75
8	100% theoretical	12	52,17	78,33	67,84	45,27
9	120% theoretical	12	43,48	65,27	56,53	37,73

Table 5.23: Results experiments intervention 1 & 4.1, line 1 dots

Exp. nr.	Arrival Rate	Number of cobots	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
10	Current	8	89,82	89,84	89,93	49,16
11	100% theoretical	8	89,82	89,82	89,92	60,15
12	120% theoretical	8	79,10	89,83	84,59	59,88
13	Current	10	89,82	89,84	89,83	49,16
14	100% theoretical	10	89,82	89,82	89,82	60,15
15	120% theoretical	10	89,83	89,83	89,83	65,12
16	Current	12	89,81	89,84	89,83	49,16
17	100% theoretical	12	89,82	89,82	89,82	60,16
18	120% theoretical	12	89,83	89,83	89,83	65,12

5.1.12 Intervention 1 & intervention 4.2

Similar to the previous intervention combination, the results displayed in Table 5.25 of the dots are exactly the same as the cobot intervention (intervention 4.2) alone. Additionally, in Table 5.24 the results for the minidots are displayed. This results in an improvement compared to intervention 4.2 on its own of $\pm 1\%$.

Table 5.24: Results experiments intervention 1 & 4.2, line 1 minidots

Exp. nr.	Arrival Rate	Number of cobots	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	3	67,20	88,27	87,04	53,47
2	100% theoretical	3	52,43	71,61	66,83	44,27
3	120% theoretical	3	43,69	59,67	55,69	36,89
4	Current	5	68,89	88,27	87,76	54,18
5	100% theoretical	5	58,25	79,57	74,26	51,69
6	120% theoretical	5	48,54	66,31	61,88	43,08
7	Current	7	68,69	88,27	87,46	54,19
8	100% theoretical	7	60,48	88,26	86,20	63,63
9	120% theoretical	7	56,29	88,84	81,90	63,09

Table 5.25: Results experiments intervention 1 & 4.2, line 1 dots

Exp. nr.	Arrival Rate	Number of cobots	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
10	Current	3	71,02	88,27	82,23	41,56
11	100% theoretical	3	70,56	77,88	73,27	43,60
12	120% theoretical	3	58,71	64,80	60,69	36,25
13	Current	5	88,26	88,27	88,26	47,60
14	100% theoretical	5	88,26	88,27	88,26	58,60
15	120% theoretical	5	88,26	88,27	88,26	63,55
16	Current	7	88,26	88,27	88,26	47,60
17	100% theoretical	7	88,26	88,27	88,26	58,60
18	120% theoretical	7	88,26	88,27	88,26	63,55

5.1.13 Intervention 1 & intervention 4.3

The last combination of interventions on line 1 is the combination of interventions 1 and 4.3. Again, the results of the dots did not change. For the minidots, the increase a little bit compared to intervention 4.3 on its own by 1,19%.

Table 5.26: Results experiments intervention 1 & 4.3, line 1 minidots

Exp. nr.	Arrival Rate	Number of cobots	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	3-9	48,64	89,33	60,85	27,27
2	100% theoretical	3-9	35,78	41,88	41,15	18,59
3	120% theoretical	3-9	29,81	34,90	34,29	15,49
4	Current	6-6	62,07	89,33	75.92	42,35
5	100% theoretical	6-6	45,43	55,20	53,01	30,44
6	120% theoretical	6-6	37,86	46,00	44,17	25,37
7	Current	9-3	44,88	89,33	57,39	23,82
8	100% theoretical	9-3	32,83	40,94	38,69	16,12
9	120% theoretical	9-3	27,36	34,12	32,24	13,44

Table 5.27: Results experiments intervention 1 & 4.3, line 1, dots

Exp. nr.	Arrival Rate	Number of cobots	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
10	Current	3-9	68,01	89,33	80,01	39,37
11	100% theoretical	3-9	87,44	89,33	89,21	59,55
12	120% theoretical	3-9	63,75	89,33	76,71	52,00
13	Current	6-6	67,53	69,59	68,31	27,65
14	100% theoretical	6-6	86,47	89,33	84,29	54,62
15	120% theoretical	6-6	62,62	68,23	64,70	39,99
16	Current	9-3	56,19	76,54	57,25	16,58
17	100% theoretical	9-3	72,16	76,54	73,81	44,14
18	120% theoretical	9-3	52,10	56,77	53,83	29,12

5.2 Payback period

The payback period per intervention is displayed in Table 5.28. These payback periods are determined as follows. There is a budget of €50.000 each year for investments such as these interventions. Next to that, the interventions improve the line so that certain costs do not have to be made anymore. For example, when installing the cobots intervention 4.1 at line 1, the salaries of the employees disappear, since they are not needed anymore. Next to that, a smaller percentage of the arrival dots have to be bulk packaged to be added to the inventory. Three cost-saving categories fit some of the interventions. These are the salary cost, the inventory cost of the bulk packaged dots and the repackaging of the dots. So, for each intervention the payback period is determined by the formula:

$$\textit{Payback period} = \textit{Investment cost} \div \textit{(investment budget + cost savings)}$$

So for example, intervention 3.1 has a payback period of 4,81 years. The investment cost for intervention 3.1 of line 1 is €1.250.000. The budget per year is, as mentioned above, €50.000. The costs that are saved by this intervention are the employee cost, the inventory cost of the part of the dots that have to get bulk packaged and the repack costs. First, on average there are 11 employees at line 1. The salary cost of those 11 employees is €1167,76 per shift. There is around 1 shift of consumer packaging each week, so that is 52 ∗ €1167,76 = €60.723,52 per year. The inventory of the bulk packaged dots is €2711,14 on average per shift, which results in €140.979,28 per year. Finally, no repackaging is needed, because all dots are already consumer-packaged. This saves €8.174,32 per year. Adding all these savings and the investment budget of €50.000 results in €259.887,12. So the payback period is 1.250.000 ÷ 259.887,12 = 4,81 years. However, the expectation is, as described in Chapters 1 & 2, that consumer packaging is becoming more important and the lines will have around 6 shifts each week that package dots into consumer packaging. When the lines have six consumer packaging shifts, more money is saved by the interventions and therefore the payback period is lower. So, both situations, the current (2 consumer packaging per week) and the expected (6 consumer packaging shifts per week), are displayed in the table below. When determining payback periods within EO, the operating costs are not taken into account, so that is also the case for determining these payback periods.

Table 5.28: Overview payback periods interventions line 1

Intervention	Payback period - current (years)	Payback period - expected (years)
1.	5,88	5,88
2.	11	11
3.0	4,84	2,15
3.1	4,81	1,91
3.2	3,37	1,36
3.3	4,92	1,98
1 & 3.0	3,55	1,36
2 & 3.0	5,01	1,99
1, 2 & 3.0	3,95	1,52
1 & 3.1	5,92	2,27
1 & 3.2	3,55	1,36
2 & 3.2	3,08	1,18
4.1	1,34	0,53
4.2	1,82	0,69
4.3	1,19	0,45
1 & 4.1	2,46	0,97
1 & 4.2	2,72	1,04
1 & 4.2	2,09	0,8

5.3 Comparison of all results Line 1

All interventions of line 1 discussed above are now compared with each other in this section. All interventions of line 1 are shown in Tables 5.30 and 5.31 with the best experimental configuration, the average utilization improvement (of all arrival rates), the average utilization (with the best experimental factor), the total cost and the payback period (current / expected situation). So, for example, the first row of Table 5.30 shows the results of the first intervention (vision system) for the crodots. There are no experimental factors that can be chosen and the average utilization of this intervention is 28,92%. The improvement compared to the current system of this intervention is 0,92%, the total cost is €294.000 and it has a payback period of 5,88 years for both the current and expected situation. All intervention titles and packaging types are shown in Table 5.29 to be able to connect the intervention number with the correct intervention.

Table 5.29: Overview interventions line 1

Line	Intervention	Title	Packaging Type
1	1	Vision system	Both
	2	Buffer	Both
	3.0	One flowpacker	Flowpackaging
	3.1	Two flowpackers	Flowpackaging
	3.2	Speed flowpacker	Flowpackaging
	3.3	Different flowpacker	Flowpackaging
	4.1	Only cobots	Blister packaging
	4.2	Cobots + filter	Blister packaging
	4.3	Cobots with two functions	Blister packaging

Table 5.30: Overview results interventions line 1 - Flowpackaging

Intervention	Dot	Exp. Config.	Average utilization (%)	Improvement (%)	Total Cost (€)	Payback period (years)
1.	Crodot	-	28,92	0,92	€294.000	5,88/5,88
2.	Crodot	Buffer size: 7500	24,34	-3,67	€425.000	11/11
3.0	Crodot	-	49,58	21,58	€650.000	4,84/2,15
3.1	Crodot	50/50	95,31	67,31	€1.250.000	4,81/1,91
3.2	Crodot	-	76,22	48,21	€650.000	3,37/1,36
3.3	Crodot	No preference	76,22	48,21	€950.000	4,92/1,98
1 & 3.0	Crodot	-	91,39	63,35	€894.000	3,55/1,36
2 & 3.0	Crodot	Buffer size: 7500	81,81	53,81	€1.025.000	5,01/1,99
1, 2 & 3.0	Crodot	Buffer size: 7500	91,36	63,35	€994.000	3,95/1,52
1 & 3.1	Crodot	50/50	95,31	67,31	€1.490.000	5,92/2,27
1 & 3.2	Crodot	-	88,87	60,86	€894.000	3,55/1,36
2 & 3.2	Crodot	Buffer size: 2500	89,75	60,07	€775.000	3,08/1,18

As displayed in Table 5.30, except for intervention 2 - buffer, all interventions for the flowpackaging of line 1 have a positive effect on the utilization of line 1. All interventions except for intervention 2 are shown in Figure 5.1. In this figure, the average utilization of the intervention is shown versus the payback period of the current situation. For example, intervention 1 has an average utilization of all arrival rates of around 28% and a payback period of almost 6 years. In this figure, the relation between the two performance measures can be seen, as choosing the best intervention utilization-wise, might also have a significantly higher payback period. Trying to find a promising intervention for both performance measures, the interventions in the upper right corner of the figure are most interesting, as those have a high average utilization and a lower payback period. Those promising interventions are displayed in the figure with orange dots. These interventions are chosen as promising, because they have a high average utilization, even though not fully 95,95%, and a payback period of lower than 5 years. For example, intervention 3.1 can reach the highest average utilization. However, when choosing intervention combination 1, 2 & 3.0, the payback period drops by 1-2 years while still achieving a high average utilization. Choosing the best intervention regarding the payback period, intervention combination 2 & 3.2 is most interesting, as it has the lowest payback period for the current situation of 3,08.

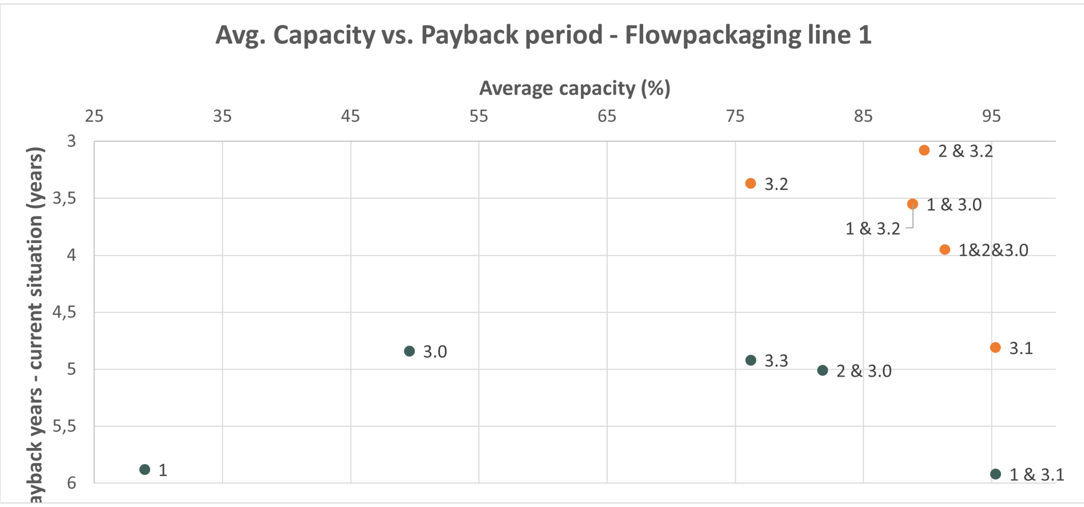

Figure 5.1: Avg. Utilization vs. Payback period (current situation) - flowpackaging line 1

Next, for the blister packaging, the complete overview of the results of each intervention (combination) can be seen in Table 5.31. Next to the table, the average utilization versus the payback period of the current situation is displayed in Figure 5.2 and 5.3. In figure 5.2 every intervention except intervention 1 is shown, as it does not improve the utilization. In Figure 5.3 every intervention is shown. Again, the most promising interventions are displayed in orange, which are interventions 4.1 and 4.2 for both dot types. These interventions are chosen because they perform best and have the lowest payback periods. As can be seen, interventions 4.1 and 4.2 perform better utilization-wise than intervention 4.3. Intervention 1 on its own or with a combination of one of the cobot interventions is not interesting for the blister packaging. Intervention 2 is not beneficial for the dots but has a small improvement for the minidots. From a utilization improvement point of view, it is more interesting to use the packaging line as it is and to use cobots instead of employees (Intervention 4.1) or to use a conveyor system that places the dots correctly (Intervention 4.2). Intervention 4.1 would be the cheaper option of the two and also has a slightly higher utilization, even though it differs only 1,57% on average. Intervention 4.1 has the highest utilization improvement and the second lowest payback period, so intervention 4.1 or 4.2 might be the best recommendation for the blister packaging of line 1.

Table 5.31: Overview results interventions line 1 - Blister packaging

Intervention	Dot	Exp. Config.	Average utilization (%)	Improvement (%)	Total Cost (€)	Payback period (years)
1.	Dot	-	-	-	€294.000	5,88/5,88
	Minidot	-	25,84	0,86		
2.	Dot	Buffer size: 5000	27,80	-3,88	€290.000	11/11
	Minidot	Buffer size: 10000	31,02	6,04	€550.000	
4.1	Dots	10 cobots	89,83	58,15	€290.000	1,34/0,53
	Minidots	12 cobots	70,33	45,35		
4.2	Dots	5	88,26	56,58	€490.000	1,82/0,69
	Minidots	7	83,65	57,67		
4.3	Dots	6-6	81,50	49,82	€320.000	1,19/0,45
	Minidots	6-6	56,51	31,53		
1 & 4.1	Dots	10 cobots	89,83	58,15	€534.000	2,46/0,97
	Minidots	12 cobots	71,23	46,25		
1 & 4.2	Dots	5 cobots	88,26	56,58	€734.000	2,72/1,04
	Minidots	7 cobots	86,08	61,10		
1 & 4.3	Dots	6-6	81,50	49,82	€564.000	2,09/0,8
	Minidots	12 cobots	57,70	32,72		

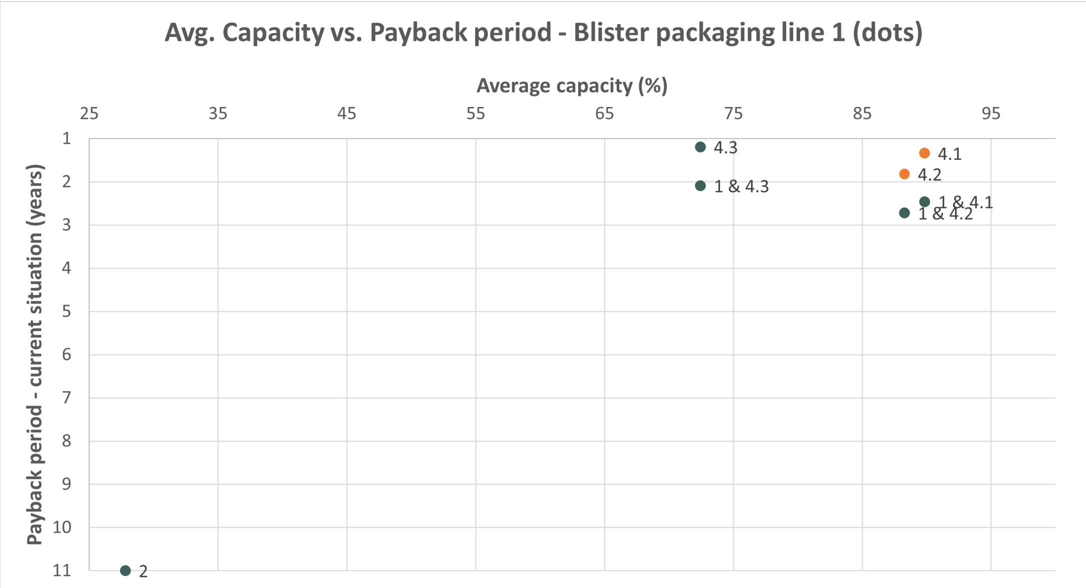

Figure 5.2: Avg. Utilization vs. Payback period (current situation) - blister packaging Dots line 1

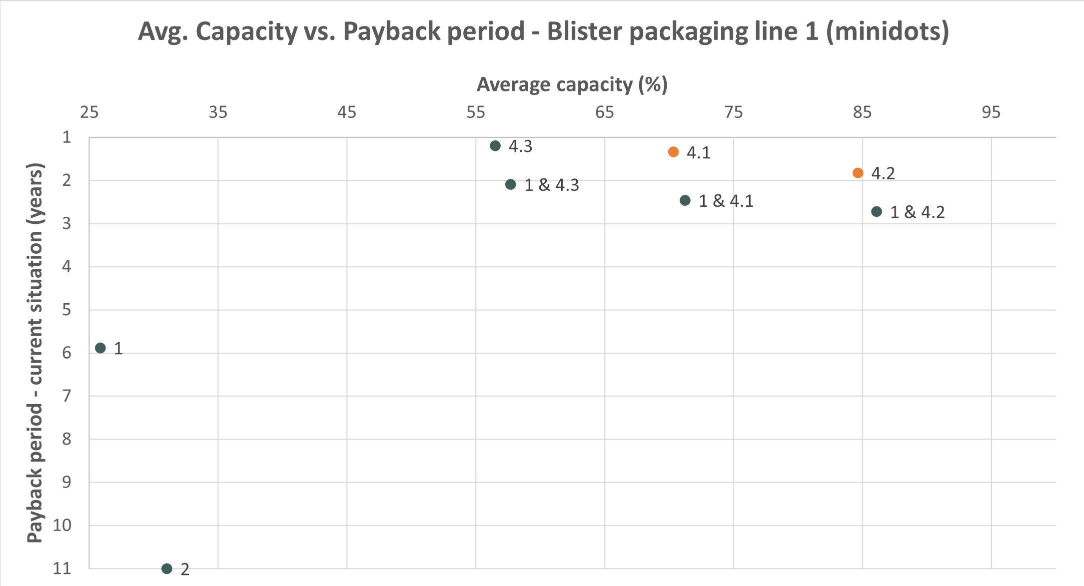

Figure 5.3: Avg. Utilization vs. Payback period (current situation) - blister packaging Minidots line 1

5.4 Results interventions line 3

Now that all the results of the interventions for line 1 have been discussed above, it is time for all results of line 3. These are described per intervention (combination) below.

5.4.1 Intervention 1: Vision system

For line 3, the results of the experiments of the vision system are displayed in Table 5.32. First, the average utilization increases from 62,46 - 72,73% (current situation) to 72,93 - 85,44% (intervention). Additionally, the difference between the minimum and maximum utilization is smaller, which suggests a more stable system. The utilization of the current situation and the 100% arrival rate are similar, this might be caused due to the fact that the packaging line performs similarly for both arrival rates with less disruption. The utilization decreases with a 120% arrival rate. This might be explained by the machine being designed for a 100% theoretical arrival rate without malfunctions. So, it is logical, if nothing is changed to the flowpacker itself, that the utilization decreases if the arrival rate is increased to 120% of the theoretical arrival rate. All in all, the vision system does increase the utilization of line 3 with ± 12%.

Table 5.32: Results experiments intervention 1, line 3

Exp. nr.	Arrival Rate	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	77,30	90,91	85,44	12,71
2	100% theoretical	77,30	90,91	85,44	12,71
3	120% theoretical	66,27	77,40	72,93	10,47

5.4.2 Intervention 2: Buffers

In Table 5.33 the results of the experiments of intervention 2 are displayed. Comparing the overall performance of this intervention with the current situation, the average utilization increases from 62,46 - 72,73% to 69,15 - 83,11%. Next to that, the minimum utilization increases as well, so all replications perform better. There is no clear preferable buffer size, as they all perform quite equally. Therefore it is most interesting to choose the cheapest option, a buffer with size 5000, which costs €250.000.

Table 5.33: Results experiments intervention 2, line 3

Exp. nr.	Arrival Rate	Buffer size	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	5000	69,23	90,91	81,80	9,07
2	100% theoretical	5000	64,68	89,91	77,95	5,22
3	120% theoretical	5000	56,72	89,02	70,98	8,52
4	Current	9000	69,92	91,83	82,64	9,91
5	100% theoretical	9000	65,57	87,57	78,29	5,56
6	120% theoretical	9000	54,81	85,44	69,15	6,69
7	Current	12000	70,22	92,34	83,11	10,38
8	100% theoretical	12000	65,79	88,93	78,23	5,5
9	120% theoretical	12000	54,81	74,08	65,17	2,71

5.4.3 Intervention 3: Flowpacker

In this section, all sub-interventions of intervention 3 will be described, which will be intervention 3.1 - two flowpackers, intervention 3.2 - speed flowpacker and intervention 3.3 - different flowpacker.

Intervention 3.1: two flowpackers

The results of this intervention are displayed in Table 5.34. This experiment performs very well since the maximal utilization for line 3 is 95,95% and this percentage is almost reached. There is a preference for a ratio of 80/20 or 50/50, as these both perform better than the 100/0 intervention. This might be explained by the fact that by using both flowpackers, the workload is divided, which results in easier packaging of the dots. Overall, the utilization when using this intervention could increase from 62,42 - 72,70% to 82,77 - 95,21%. The minimum utilization for the intervention is 77,57%, which shows that this intervention performs very well for all replications as well. As described earlier, this intervention would cost around €650.000 for line 3.

Table 5.34: Results experiments intervention 3.1, line 3

Exp. nr.	Arrival Rate	Ratio FP (%)	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	100/0	86,20	95,80	94,85	22,12
2	100% theoretical	100/0	89,90	95,73	94,82	22,09
3	120% theoretical	100/0	77,57	85,27	82,77	20,31
4	Current	80/20	86,20	95,80	94,95	22,22
5	100% theoretical	80/20	89,90	95,80	95,05	22,32
6	120% theoretical	80/20	89,90	95,80	94,70	32,24
7	Current	50/50	86,20	95,80	95,01	22,28
8	100% theoretical	50/50	91,91	95,80	95,24	22,51
9	120% theoretical	50/50	89,90	95,80	94,74	32,28

Intervention 3.2: speed flowpacker

The results of intervention 3.2 for line 3 are displayed below. The average utilization improvement for line 3 is 5,83%. As this intervention does not have any cost, any utilization improvement is welcome, but it does not have a very impressive result. The utilization for the current arrival rate and the 100% arrival rate are similar, which suggests that for those two arrival rates, the speed of the flowpacker is quick enough to perform equally. The experiment with an arrival rate of 120% especially performed well in this intervention.

Table 5.35: Results experiments intervention 3.2, line 3

Exp. nr.	Arrival Rate	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	64,74	86,85	76,61	3,88
2	100% theoretical	64,74	86,85	76,61	3,88
3	120% theoretical	60,88	82,09	72,20	9,74

Intervention 3.3: different flowpacker

The results of this intervention are displayed in Table 5.36. The average utilization increases with ± 7%, especially the utilization when using an arrival rate of 120% is really high for this intervention. The increase in the speed of the flowpacker does not influence the utilization, and therefore there is no preferred experimental factor. These results show that increasing the speed much more than the arrival rate has no influence, as is similar to the results of line 1.

Table 5.36: Results experiments intervention 3.3, line 3

Exp. nr.	Arrival Rate	Speed FP (packages/min)	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	150	64,74	86,85	76,61	3,88
2	100% theoretical	150	64,74	86,85	76,61	3,88
3	120% theoretical	150	64,74	86,85	76,61	14,15
4	Current	175	64,74	86,85	76,61	3,88
5	100% theoretical	175	64,74	86,85	76,61	3,88
6	120% theoretical	175	64,74	86,85	76,61	14,15
7	Current	200	64,74	86,85	76,61	3,88
8	100% theoretical	200	64,74	86,85	76,61	3,88
9	120% theoretical	200	64,74	86,85	76,61	14,15

5.4.4 Intervention 1 & intervention 2

As displayed in Table 5.37, the combination of interventions 1 and 2 elevate each other for the utilization performance of line 3. Although there is not much difference, the utilization for the combination is in all cases above 80%, whereas the separate interventions have experiments with a utilization below 80%. This results in an average improvement of 16,09% The best experimental factor is a buffer size of 12000, which results in the cost of the buffers of €650.000. Adding the vision system cost to the buffer cost, the total cost will be €894.000.

Table 5.37: Results experiments intervention 1 &2, line 3

Exp. nr.	Arrival Rate	Buffer size	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	5000	69,48	94,99	85,07	12,34
2	100% theoretical	5000	59,94	95,56	82,80	10,07
3	120% theoretical	5000	66,24	93,07	82,81	20,35
4	Current	9000	67,92	95,73	83,94	11,21
5	100% theoretical	9000	69,22	95,75	86,27	13,54
6	120% theoretical	9000	59,44	95,14	86,20	23,74
7	Current	12000	66,67	95,53	88,27	15,54
8	100% theoretical	12000	65,05	95,53	86,89	14,16
9	120% theoretical	12000	73,79	94,54	86,38	23,92

5.4.5 Intervention 1 & intervention 3.1

The results of the intervention combination are displayed in Table 5.38. Adding a vision system to two flowpackers does not increase the utilization much, which is logical, as the utilization already increased to almost its maximum with intervention 3.1 on its own. However, including a vision system raises the performance a little bit, and the added benefits of a vision system, like satisfied customers, might be useful as well.

Table 5.38: Results experiments intervention 1 & 3.1, line 3

Exp. nr.	Arrival Rate	Ratio FP (%)	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	100/0	95,39	95,80	95,65	22,92
2	100% theoretical	100/0	95,00	95,80	95,61	22,88
3	120% theoretical	100/0	82,71	82,71	81,99	19,53
4	Current	80/20	95,27	95,80	95,62	22,89
5	100% theoretical	80/20	95,00	95,80	95,64	22,91
6	120% theoretical	80/20	95,00	95,80	95,61	33,13
7	Current	50/50	95,26	95,80	95,61	22,88
8	100% theoretical	50/50	94,98	95,80	95,61	22,88
9	120% theoretical	50/50	94,98	95,80	95,63	33,17

5.4.6 Intervention 1 & intervention 3.2

In Table 5.39 the results are displayed for combination interventions 1 & 3.2. The utilization of the current and 100% arrival rate does not differ from the results of intervention 1. However, the utilization does improve for the 120% arrival rate. Overall, this is not the most useful combination.

Table 5.39: Results experiments intervention 1 & 3.2, line 3

Exp. nr.	Arrival Rate	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	77,30	90,92	85,44	12,71
2	100% theoretical	77,30	90,92	85,44	12,71
3	120% theoretical	73,28	85,59	80,65	18,19

5.4.7 Intervention 2 & intervention 3.2

In Table 5.40 the results are shown of the experiments with combination intervention 2 & 3.2. The biggest buffer size of 12000 performed best, which cost €650.000. The combination of the speed of the flowpacker and a buffer, similar to line 1, performs better than the separate interventions.

Table 5.40: Results experiments intervention 2 & 3.2, line 3

Exp. nr.	Arrival Rate	Buffer size	Min. Util. (%)	Max. Util. (%)	Avg. Util. (%)	Improvement (%)
1	Current	5000	68,81	91,92	81,56	8,83
2	100% theoretical	5000	68,90	91,91	81,52	8,79
3	120% theoretical	5000	60,57	81,87	72,02	9,56
4	Current	9000	69,88	92,71	82,54	9,81
5	100% theoretical	9000	69,79	92,65	82,41	9,68
6	120% theoretical	9000	60,57	81,87	72,02	9,56
7	Current	12000	70,08	93,01	83,10	10,37
8	100% theoretical	12000	70,05	92,98	83,02	10,29
9	120% theoretical	12000	60,57	81,87	72,02	9,56

5.5 Payback period interventions Line 3

In table 5.41 the payback periods per intervention are displayed. These payback periods are determined similarly to the ones of line 1, so:

$$\textit{Payback period} = \textit{Investment cost} \div \textit{(investment budget + cost savings)}$$

The cost savings for line 3 can be the employee salaries and/or the repackaging of the dots. The repackaging of the dots costs €12.739,20. There are 10 employees on average at line 3, so the salaries cost €1061,60 per shift for those 10 employees. So for example, intervention combination 1 & 3.1 has a payback period of 3,75 years for the current situation and 1,92 for the expected situation. The payback period of the current situation is determined by the reduction in salary costs and repack costs. The salaries would cost $52 * 2 * e1061,60 = 110.406,40$ per year. The repack costs are €12.739,20 and the budget each year is €50.000. So, the budget and cost savings add up to €173.145,60, which results in 650.000 ÷ 173.145,60 = 3,75 years. For the expected situation, the salary costs are not 2 times per week but 6 times per week, which results in more savings and therefore a shorter payback period. When determining payback periods within EO, the operating costs are not taken into account, so that is also the case for determining these payback periods.

Table 5.41: Overview payback periods interventions line 3

Intervention	Payback period - current (years)	Payback period - expected (years)
1.	5,88	5,88
2.	13	13
3.1	3,75	1,92
3.2	0	0
3.3	19	19
1 & 2	5,16	2,64
1 & 3.1	5,16	2,64
1 & 3.2	5,88	5,88
2 & 3.2	13	13

5.6 Comparison of all results Line 3

All interventions of line 3 are displayed in Table 5.43. The titles of the interventions are displayed in Table 5.42. All interventions have a positive effect on the utilization of the packaging line. The utilization improvement is lower compared to the previous tables of line 1, but the average capacities are almost similar for the same interventions. The utilization improvement of line 3 is lower because it already had a higher utilization than line 1.

Table 5.42: Overview interventions line 1& 3

Line	Intervention	Title	Packaging Type
3	1	Vision system	Flowpackaging
	2	Buffer	Flowpackaging
	3.1	Two flowpackers	Flowpackaging
	3.2	Speed Flowpacker	Flowpackaging
	3.3	Different Flowpacker	Flowpackaging

Table 5.43: Overview results interventions line 3

Intervention	Exp. Config.	Average utilization (%)	Improvement (%)	Total Cost (€)	Payback period (years)
1.	-	81,27	11,96	€294.000	5,88/5,88
2.	Buffer size: 12000	75,50	6,20	€650.000	13/13
3.1	50/50	95,00	25,69	€650.000	3,75/1,92
3.2	-	75,14	5,83	-	0/0
3.3	No preference	76,61	7,31	€950.000	19/19
1 & 2	Buffer size: 12000	87,18	17,87	€894.000	5,16/2,64
1 & 3.1	50/50	95,62	26,31	€894.000	5,16/2,64
1 & 3.2	-	83,84	14,53	€294.000	5,88/5,88
2 & 3.2	Buffer size: 12000	79,38	10,07	€650.000	13/13

Next to the table, the average utilization and the payback period of the current situation are plotted against each other in Figure 5.4. Similar to the figures for the interventions of line 1, the promising interventions are displayed in orange. From a utilization point of view, intervention combination 1 & 3.1 performs best. This combination of interventions raises the utilization to almost the maximum possible. Following intervention combination 1& 3.1 are intervention 3.1 and combination 1 & 2. From a payback period point of view, interventions 3.2 or 3.1 are most interesting, as those are the only ones with a payback period for the current situation of less than 5 years. Intervention 3.2, however, does not have a spectacular improvement. Intervention combinations 1 & 2 and 1 & 3.1 have a payback period of a little bit over 5 years, so that might still be promising enough to look into. So, combining both performance measures, intervention 3.1 would probably be the most interesting, since it has the second-highest improvement and is one of the cheaper options.

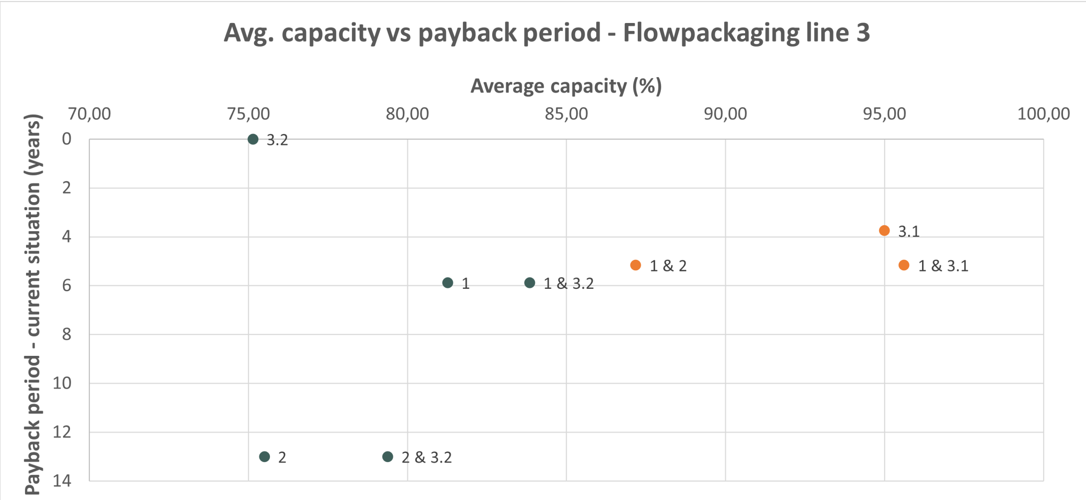

Figure 5.4: Avg. Utilization vs. Payback period (current situation) - flowpackaging line 3

5.7 Recommendation and implementation plan

In this section, the promising interventions for lines 1 & 3 will be discussed. Lines 1 and 3 will be divided into the sub-sections 5.7.1 and 5.7.2 respectively.

5.7.1 Line 1

For the flowpackaging of line 1, the interventions that are promising to look into further are shown below. These interventions are chosen because they perform best and they differ in price range. Within these promising interventions, a trade-off can be made between the utilization improvement and the payback period.

- Intervention 3.1 - two flowpackers
- Intervention 3.2 - Speed flowpacker
- Intervention combination 1 & 3.0 - vision system and a flowpacker
- Intervention combination 1& 2 & 3.0 - vision system, buffer and a flowpacker
- Intervention combination 1 & 3.2 - vision system and speed of the flowpacker
- Intervention 2 & 3.2 - buffer and speed of the flowpacker

For the blister packaging of line 1, the following interventions are promising and might be interesting to investigate further. These two interventions are chosen, because they have the highest utilization improvements.

- Intervention 4.1 - only cobots
- Intervention 4.2 - cobots + filter

First, for the flowpackaging of line 1, installing a flowpacker would be a start to improving the utilization. Adding a buffer or vision system would increase the utilization even more. Adding two flowpacker machines is the most successful intervention from a utilization point of view. For the blister packaging on line 1, it would be interesting to implement either intervention 4.1 or 4.2. The layout has to change according to the chosen intervention(s). The current layout and proposed layouts of all promising interventions are displayed in Figure 5.5. The orange parts of the proposed layouts are the parts that are added to enable the interventions. The numbers in the figure represent certain parts of the packaging line and the same numbers are used if possible as figure 4.10:

1. Arrival Dots
2. Metal detector
3. Bulk packaging line
4. Consumer packaging line
5. Arrival packaging (not in this figure)
6. Packaging station
7. Exit to secondary packaging
8. Blister packaging line
9. Cobots
10. Flowpackaging line
11. Flowpacker machine
12. Buffer
13. Vision system

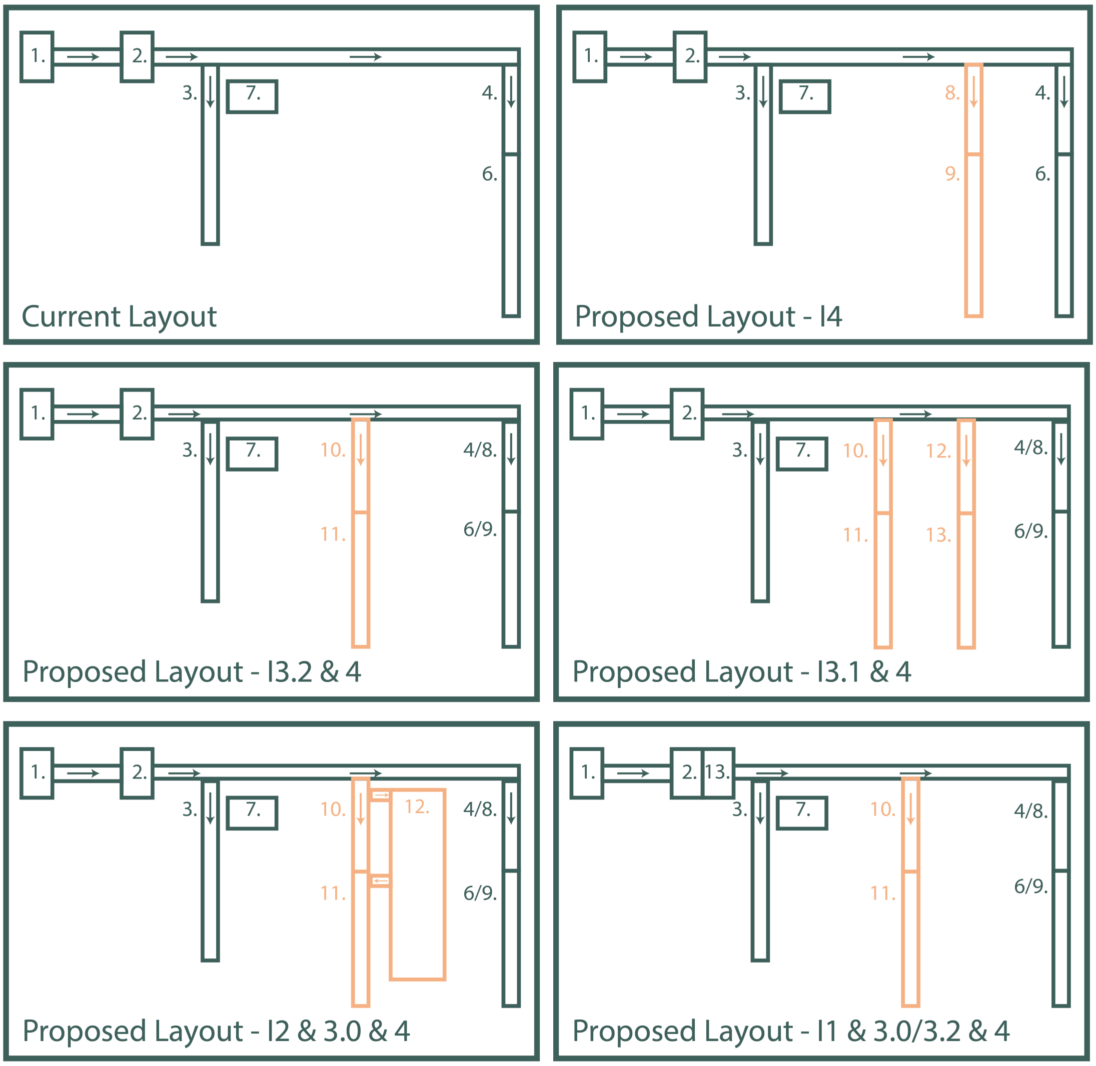

Figure 5.5: Proposed layouts line 1

As can be seen in some proposed layouts, the 4/8. and 6/9. represent the possibility of keeping the current packaging station for the blister packaging (numbers 4 & 6) or changing it around to one of the cobots interventions (numbers 8 & 9). Next to that, the sub-interventions of intervention 4 - cobots are not represented separately, as they would need around the same space and use almost the same layout. If for example, intervention 3.2 - speed flowpacker and 4.1 - only cobots would be chosen, the layout of packaging line 1 would have to be adjusted. The location of the arrival of the dots and the departure towards to secondary packaging are fixed. Additionally, the bulk packaging line needs space as well. Next to that, the floor has enough space to implement those two interventions by adding another exit on the line, so that there are three exits: bulk packaging, flowpackaging and blister packaging. The bulk packaging exit would be first on the line because then the bulk packaging line can stay in the same place as it is now. The flowpackaging exit would follow because the blister packaging exit would stay at the same place as it is now. By putting a flowpackaging exit on the line, the possibility of creating a sub-line is there and space to put the flowpacker machine.
To be able to implement the layout, it will not be possible to package the dots on line 1 for a time. It would be possible to do it in steps so that part of the packaging line stays operational. For example, when the blister packaging line is implemented, it could be possible to keep packaging the dots in bulk. If afterwards the flowpackaging line is installed, both the bulk packaging and/or the blister packaging line could still be used. When installing the vision system, the whole line is not operational as the vision system will be installed before the bulk, blister, or flowpackaging lines. Finally, the planning department of EO can schedule more consumer packaging (either blisters or flowpackaging) on

line 1. However, the utilization is not (yet) 100%, so with trial and error, they could adjust their planning strategy to the new line.

5.7.2 Line 3

For line 3, the promising interventions are:

- Intervention 3.1 - two flowpackers machines
- Intervention combination 1 & 2 - vision system and a buffer
- Intervention combination 1 & 3.1 - vision system and two flowpacker machines

These interventions are chosen, because they have the highest utilization improvements. Within these promising interventions, again, a trade-off can be made between utilization improvement and the payback period. For all options, space is needed to implement the interventions. The proposed layouts for the promising interventions can be seen in Figure 5.6. The numbering in the layout represents:

1. Arrival Dots
2. Metal detector
3. Bulk packaging line
4. Consumer packaging line
5. Arrival packaging (not in this figure)
6. Flowpacker machine
7. Second consumer packaging line
8. Second flowpacker machine
9. Buffer
10. Vision system

The implementation of either one of those interventions does cause downtime. However, to implement intervention 3.1 or combination 1 & 3.1 the current flowpacker machine or the bulk packaging line could still be used. For implementing intervention 1& 2 or intervention 1 & 3.1, a vision system must be installed. This will cause downtime for the complete packaging line. The buffer system needed for intervention 1&2 can be placed while either the consumer packaging line or the bulk packaging line is still operational. Connecting the buffer system to the conveyor line/flowpacker machine of the consumer packaging line will cause some downtime for the consumer packaging line, but this way it can be a limited amount of time. Similarly to line 1, the planning department has to adjust its planning strategy to the new utilization.

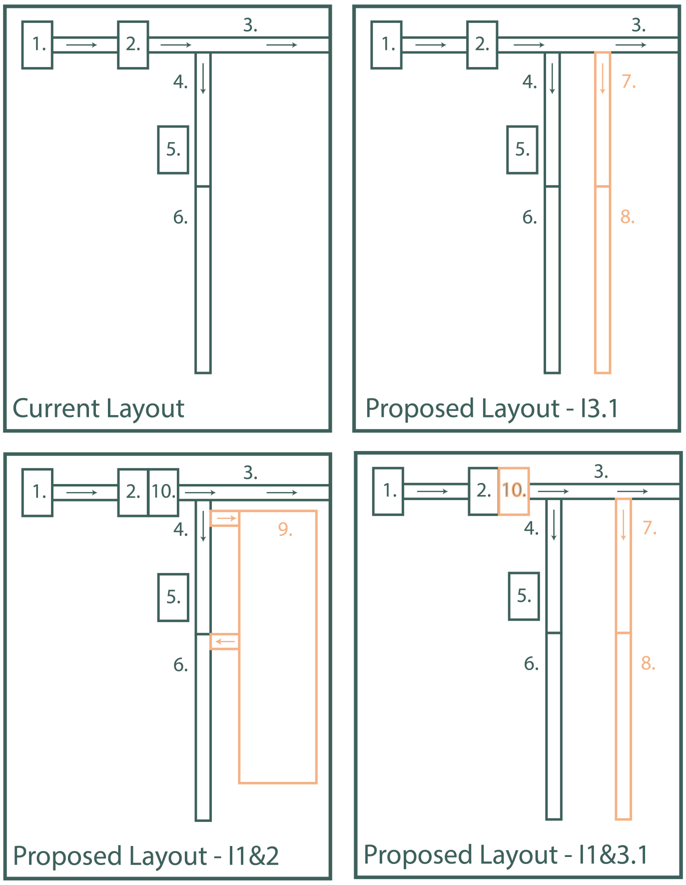

Figure 5.6: Proposed layouts line 3

6 Conclusion

In this chapter, this thesis will be concluded. It will start with the conclusion described in Section 6.1. It will be followed by the discussion in Section 6.2 and the recommendations in Section 6.3. Next, future research is described in Section 6.4. Finally, the theoretical and practical contributions will be discussed in Section 6.5.

6.1 Conclusion

The thesis will be concluded in this section. First of all, the goal of this study was to increase the capacity for the consumer packaging lines 1 & 3 of Europastry Oldenzaal. To be able to increase the capacity, the following research question is answered:

How can the utilization of the consumer packaging lines 1 & 3 be increased from 37,11% to 95,95% and 72,73% to 95,95%, respectively?

This research question is chosen because EO notes a shift towards consumer packaging for dots. This shift means that EO needs to be able to package more consumer packaging for dots when required. To answer this research question, five sub-questions were considered. These will be discussed below.

1. What is the current packaging process of the dots at lines 1 and 3 and what are the requirements and limitations of these packaging lines?

To answer this question, an analysis of packaging lines 1 and 3 has been performed to determine the problem at hand. Part of this analysis was an inspection of sales and production data. In addition, the output files of the shifts of 2023 have been analysed, and walk-ins on both lines have helped to analyse the current situation. Next to that, the malfunctions and hick-ups on the packaging lines have been analysed to determine why the capacity is insufficient. For line 1, the main conclusion is that more manual labour is needed to package all the dots. However, there are also unfit dots (too big, too sticky etc.) that cause malfunctions, limiting the line's capacity. For line 3, the flowpacker machine is theoretically able to package all of the arriving dots, but this is often not the case due to the amount of malfunctions. These malfunctions can be due to unfit dots, errors during machine setup or other causes.

Finally, the requirements of the packaging lines consist of:

- Packaging from Europastry Group has to stay in production.
- The flow has to stay the same.
- Control points (CP) and critical control points (CCP) have to be implemented in the new factory layout.
- All dots have to be packaged at the packaging lines.
- The proposed solution has to minimize manual labour.
- For any adjustments at the packaging line, the safety of the employees needs to be ensured.

The wishes of EO consist of:

- The space currently used is also used for the new solution.
- The machines currently used are used when possible.

2. What are the trends and best practices for increasing the capacity of packaging lines in literature?

In Chapter 3, the trends and best practices to increase the capacity of packaging lines have been explored. In this chapter, the focus was on bottleneck analysis and improvement, manufacturing lines in the food industry and how interventions could be tested to improve capacity. From this literature study, interventions could be created to test if these would increase the capacity.

3. What interventions could potentially improve the current packaging lines?

The full overview of the interventions that have been developed for this study is displayed in Table 4.29. There are 27 interventions in total for both lines. These 27 interventions consist of unique interventions and combinations of these unique interventions. A summary of all interventions is displayed in Table 6.1.These interventions are created based on the analysis of the current packaging lines and their bottlenecks. The bottlenecks were determined based on interviews with stakeholders and looking at each active/inactive state of each station of the packaging line in the simulation model. Each intervention tries to solve the bottleneck in separate ways.

Table 6.1: Summary interventions

Line	**Intervention**	**Description**	**Packaging**
1	1.	Vision system	Both
	2.	Buffer	Both
	3.0	One flowpacker	Flowpackaging
	3.1	Two flowpackers	Flowpackaging
	3.2	Adjusting the speed of the flowpacker	Flowpackaging
	3.3	Different flowpacker	Flowpackaging
	4.1	Only cobots	Blister packaging
	4.2	Cobots + filter	Blister packaging
	4.3	Cobots with two functions	Blister packaging
	1 & 3.0	Vision system and One flowpacker	Flowpackaging
	2. & 3.0	Buffer and One flowpacker	Flowpackaging
	1 & 2 & 3.0	Vision system, Buffer and One flowpacker	Flowpackaging
	1 & 3.1	Vision system and Two flowpackers	Flowpackaging
	1 & 3.2	Vision system and adjusting the speed of the flowpacker	Flowpackaging
	2 & 3.2	Buffer and adjusting the speed of the flowpacker	Flowpackaging
	1 & 4.1	Vision system and Only cobots	Blister packaging
	1 & 4.2	Vision system and Cobots + filter	Blister packaging
	1 & 4.3	Vision system and Cobots with two functions	Blister packaging
3	1.	Vision system	Flowpackaging
	2.	Buffer	Flowpackaging
	3.1	Two flowpackers	Flowpackaging
	3.2	Adjusting the speed of the flowpacker	Flowpackaging
	3.3	Different flowpacker	Flowpackaging
	1 & 2	Vision system & buffer	Flowpackaging
	1 & 3.1	Vision system and two flowpacker machines	Flowpackaging
	1 & 3.2	Vision system and adjusting the speed of the flowpacker	Flowpackaging
	2 & 3.2	Buffer and adjusting the speed of the flowpacker	Flowpackaging

4. Which intervention is the most feasible for EO?

The interventions were evaluated using two performance measures, namely the utilization improvement and the payback period. Based on these, promising interventions were selected as a recommendation to investigate further. The promising interventions are displayed in Table 6.2. In the table, the intervention and the type of dot are shown, followed by the average utilization (of all arrival rates) and the improvement of utilization compared to the current situation. Finally, the payback periods are displayed for both the current situation and the expected situation.

Table 6.2: Overview promising interventions lines 1 & 3

Line (packaging)	Intervention	Dots	Avg. utilization (%)	Improvement (%)	Payback period (years)
1 (flowpackaging)	3.1	Crodot	95,31	67,31	4,81/1,91
	3.2	Crodot	76,22	48,21	3,37/1,36
	1& 3.0	Crodot	91,39	63,35	3,55/1,36
	1& 2 & 3.0	Crodot	91,39	63,35	3,95/1,52
	1 & 3.2	Crodot	88,87	60,86	3,55/1,36
	2 & 3.2	Crodot	89,75	60,07	3,08/1,18
1 (blister)	4.1	Dot	89,83	58,15	1,34/0,53
		Minidot	70,33	45,35	
	4.2	Dot	88,26	56,58	1,82/0,69
		Minidot	83,65	57,67	
3 (flowpackaging)	3.1	Dot	95,00	25,69	3,75/1,92
	1& 2	Dot	87,18	17,87	5,16/2,64
	1 & 3.1	Dot	95,62	26,31	5,16/2,64

5. How could Europastry Oldenzaal implement the recommended intervention(s)?
In Section 5.7, the implementation of the different recommended intervention(s) is described. First, the adjusted layouts for the possible interventions are described for both lines. Followed by a description on how these adjusted layouts could be implemented over time. In short, this would mean for line 1 that an additional exit branch on the consumer packaging line is needed which separates the flowpackaging and the blister packaging, as they both get different packaging sub-lines. For line 3, there is enough space next to the current flowpacker machine to install either another flowpacker machine or a buffer system. For the relevant recommended interventions of both lines 1 and 3, the vision system would be placed after the metal detector. When one of these interventions is implemented, the planning department will have to change its strategy, since the packaging lines should be able to package more dots in a shift.

When taking into account the answers to the sub-questions, the main research question can be answered. There are multiple ways to potentially increase the capacity of the consumer packaging lines 1 & 3. For the flowpackaging on line 1, adding a flowpacker machine similar to the one already operational at line 3 and setting it up for maximum speed (intervention 3.2) would increase the utilization by 48,21%, ending up with an average utilization of 76,22%. Adding another flowpacker, buffer or vision system would increase the utilization for the flowpackaging by 15-20%. For the blister packaging on line 1, it is beneficial to install cobots. This would increase to utilization of the dots with 58,15% and the minidots with 45,35%, ending up with an average utilization of 89,83% and 70,33% respectively. Another possibility is installing cobots with a filter system (intervention 4.2), which would increase the utilization of the minidots by 57,67%. The average capacities by implementing intervention 4.2 would be 88,26% for the dots and 83,65% for the minidots. For line 3, the biggest utilization improvement of 26,31% could be realised with a second flowpacker machine, resulting in an average utilization of 95,00%. In conclusion, there are multiple ways to increase both consumer packaging lines 1 & 3. However, the interventions tested in this thesis did not completely succeed in improving the utilization to 95,95%.

6.2 Limitations

In this section, the limitations of this study will be discussed. In this study, a simulation model is used. A simulation model is a substitution of the real world which can be used to test different interventions. It makes use of assumptions and data to reflect the real world which means that it can be quite hard to make it follow reality perfectly. First, the assumptions made for this simulation study could influence the results of the interventions. An example of such an assumption that has been made is that the packaging is always available and never out of stock. This assumption is made because the availability of the packaging is out of the scope of this study. However, this assumption could influence the result of every intervention. For each intervention specifically, some assumptions have been made as well, for example, the processing time of cobots or the failure rate of a vision system. These assumptions do not apply to all interventions, but only to some of them. These assumptions could also influence the results of the interventions. Secondly, the data used for the simulation model is mostly gathered from the output logs of each shift of 2023 (until week 40). As discussed before in Chapter 4, the output logs are filled in manually by the line operators during/at the end of a shift. This might cause human errors and therefore incorrect data. Next to that, not every dot type or packaging type was represented in great amounts in the data. For example, only 19 data points were available for the dots that get packaged in a blister of 4, which means that there is a possibility that these 19 data points do not represent the dots in a blister of 4 well enough. It is better to have enough data points or to make use of other types of data, for example, real-time data generated by machines or other systems. If these types of data were available, the data used would contain more data points and would be less prone to error. Unfortunately, this was not possible in this study. Although the simulation model might not perfectly reflect the real world due to the assumptions made and lack of data, the simulation results can be still used to give a clear direction on which interventions could be beneficial to investigate further. Finally, the cost of each intervention only includes the investment cost and installation costs, but no potential extra cost of, for example, electricity or maintenance. This is done because Europastry does not include these when determining the payback periods, it only uses the cost of the initial investment of the intervention. The maintenance costs are also not included in the costs that are saved by the intervention for the payback period. Next to that, the maintenance cost are also hard to quantify beforehand, as it depends on multiple variables that are not known yet. However, not including these costs (like electricity and maintenance) might potentially influence the payback periods of the interventions and therefore the selection of the most promising interventions.

6.3 Recommendations

In section 5.7, a recommendation and implementation plan of the promising interventions is described. The promising interventions used in that section are also displayed in Table 6.2. Next to this recommendation, there are also other possible interventions that are not tested within this study due to time restrictions and unavailable data that could improve the capacity. Some of these untested interventions will be discussed in this section as a recommendation. The first intervention that will be discussed is the cleaning of the flowpacker machine at packaging line 3. This cleaning can be done in various ways and for different frequencies. At the moment, the flowpacker machine gets cleaned once a week, but when there is a breakdown that requires cleaning, it can be done more often. Currently, the weekly cleaning takes about 16 hours which results in quite some downtime for the flowpacker machine. This downtime could potentially be decreased if they cleaned the flowpacker machine more often than just once a week. Next to the frequency of cleaning, the cleaning can be done in multiple ways. One way to clean the flowpacker machine is, how it is currently done, with water and detergent. Another way could be to use dry ice. However, cleaning with dry ice has the risk of recontaminating the flowpacker with bacteria due to the fact that it does not inactivate the bacteria, it only removes them from the particular surface with force (Witte, David, Blättler, Schoder, & Rossmanith, 2017). So it can be used as a cleaning method, but not as a disinfectant. A completely different approach is to implement automated cleaning using an incorporated cleaning part on the packaging line which could be used between shifts to clean everything. The latter option would have the highest investment costs, but potentially lower downtime and processing costs compared to the other options where an employee performs the cleaning.

Another untested intervention that will be discussed as a recommendation is the adjustment of the layout in a way that both packaging lines are completely on one floor. At the moment, both lines are on the ground and first floor next to each other. It could be possible to use the complete ground floor for one packaging line and the complete first floor for the other packaging line. This way the throughput time will be reduced because the (packaged) dots do not have to travel between floors during the packaging process. Next to that, the visibility of the whole packaging process will be improved which could reduce chaos and improve productivity. It might also be easier to work together since there will be no separate 'islands' anymore.

6.4 Future research

Multiple topics could be explored for future research. First, as mentioned before, the data needed as simulation input was not always sufficient. Therefore, some packaging/dot categories were left out of this study. The first topic for future research would be to include all dot categories and packaging types in the simulation study. When data for these dot categories and packaging types is available, all interventions used in this study could be adjusted if needed and tested again. Besides that, more experiments or interventions could be added to see if these could increase the capacity even more. Another topic for future research would be to look into the cause of the dots being quite frequently too big or unfit to be packaged. By looking into the cause of this, the actual problem might be solved instead of trying to find ways to work around it. Additionally, from the output logs of the shifts, it turned out that quite some shifts did not perform as well as they could due to the packaging not being available or being out of stock. This could be another topic to research in the future since it could increase the overall capacity of the packaging lines as well. The packaging stock could perhaps be more structured or better located. This way, it is also easier to keep stock. Finally, portfolio management for EO packaging might be interesting to research in the future. EO's focus does not really lie on packaging and how it could help their clients. EO focuses more on the dots and views packaging as a secondary thing that needs to happen as well to be able to sell the dots. If there would be an increased focus on this area and EO uses a push strategy instead of a pull strategy, the packaging lines could be improved quite a lot due to the possibility of designing the packaging lines specifically for certain packaging. Additionally, the clients could become much happier due to being presented with several choices of packaging which makes choosing the right fit easier.

6.5 Theoretical and practical contribution

This thesis contributes to science by providing an up-to-date literature study of the possibilities in capacity improvement, bottlenecks detection and manufacturing lines in the food industry. Next to this, this thesis used the existing literature to explore the possibilities of increasing the capacity of the consumer packaging lines 1& 3 of EO. Additionally, the literature was used as input for a thoroughly tested simulation system and for the interventions described in Chapter 4. The contribution to practice for Europastry Oldenzaal is the thorough analysis of all (potentially capacity-improving) interventions for packaging lines 1 & 3 which has been used to identify a beneficial direction for further investigation. For all interventions, this included the creation of a validated simulation model and thorough testing of these interventions. Additionally, this thesis provides insights into the current real-world situation. This thesis can help EO take the right direction when improving the capacity of its packaging line.

References

Abed, S. (2008, September). A simulation study to increase the capacity of a rusk production line. *WSEAS TRANSACTIONS on INFORMATION SCIENCE APPLICATIONS, volume 5, 2008*. Retrieved from http://www.wseas.us/e-library/transactions/information/2008/28-316.pdf

Accorsia, R., Tufanoa, A., Galloa, A., Galiziab, F., Cocchia, G., Ronzonia, M., ... Manzinia, R. (2019). An application of collaborative robots in a food production facility. *Procedia Manufacturing*, *38*, 341–348. Retrieved from https://www.sciencedirect.com/science/article/pii/S2351978920300457 doi: 10.1016/j.promfg.2020.01.044

Ameen, W., Alkahtani, M., Mohammed, M., Abdulhameed, O., & El-Tamimi, A. (2018). Investigation of the effect of buffer storage capacity and repair rate on production line efficiency. *Journal of King Saud University – Engineering Sciences*, *30*, 243-249. Retrieved from https://www.sciencedirect.com/science/article/pii/S101836391830014X doi: https://doi.org/10.1016/j.jksues.2018.03.001

Amit, N., Suhaak, N., Johari, N., & Kassim, I. (2012). Using simulation to solve facility layout for food industry at xyz company. *IEEE Symposium on humanities, science and engineering research*, 647-652. Retrieved from https://ieeexplore.ieee.org/abstract/document/6268900?casa_token=3UNfcZaPBF8AAAAA:hVkmEisIaDS4NT8m3XY1VZ1Z4_tdCdh_M36_MmAw25EJBzrL-mWje7a6fP_UDBv4ijU2irt- doi: https://doi.org/10.1109/SHUSER.2012.6268900

Bader, F., & Rahimifard, S. (2020). A methodology for the selection of industrial robots in food handling. *Innovative food science emerging technologies*, *64*. Retrieved from https://www.sciencedirect.com/science/article/pii/S1466856420303258 doi: https://doi.org/10.1016/j.ifset.2020.102379

Baker, K., & Trietsch, D. (2009). *Principles of sequencing and scheduling.* John Wiley Sons, Inc.

Borshchev, A., & Filippov, A. (2004). From system dynamics and discrete event to practical agent based modeling: Reasons, techniques, tools. *The 22nd International Conference of the System Dynamics Society*. Retrieved from https://www2.econ.iastate.edu/tesfatsi/systemdyndiscreteeventabmcompared.borshchevfilippov04.pdf

Buchari, Tarigan, U., & Ambarita, M. (2018). Production layout improvement by using line balancing and systematic layout planning (slp) at pt. xyz. *IOP Conference Series: Materials Science and Engineering*, *309*. Retrieved from https://iopscience.iop.org/article/10.1088/1757-899X/309/1/012116/pdf doi: doi:10.1088/1757-899X/309/1/012116

Buchert, M. (2021). Cobot vs industrial robot: Differences and comparison. Retrieved from https://manplusmachines.com/differences-robots-cobots/#:~:text=While%20a%20robot%20performs%20a,or%20to%20work%20in%20tandem.

Büth, L., Broderius, N., Herrmann, C., & Thiede, S. (2017). Introducing agent-based simulation of manufacturing systems to industrial discrete-event simulation tools. , 1141-1146. doi: 10.1109/INDIN.2017.8104934

Chen, C., & Chen, C. (2009). Bottleneck-based heuristics to minimize total tardiness for the flexible flow line with unrelated parallel machines. *Computers Industrial Engineering*, *56*(4), 1393-1401. Retrieved from https://www.sciencedirect.com/science/article/pii/S0360835208001915 doi: https://doi.org/10.1016/j.cie.2008.08.016

Chen, X., Nophut, C., & Voigt, T. (2021). A model-driven approach for engineering customizable mes with the application to the food and beverage industry. *The International Journal of Advanced Manufacturing Technology*, *115*, 2607-2622. Retrieved from https://link.springer.com/article/10.1007/s00170-021-07317-7 doi: https://doi.org/10.1007/s00170-021-07317-7

Colledani, M., Hotvath, A., & Angius, A. (2015). Production quality performance in manufacturing systems processing deteriorating products. *CIRP Annals - Manufacturing Technology*, *64*, 431-434. Retrieved from https://www.researchgate.net/publication/277339005_Production_quality_performance_in_manufacturing_systems_processing_deteriorating_products doi: https://doi.org/10.1016/j.cirp.2015.04.122

Dias, P., Silva, F., Campilho, R., Ferreira, L., & Santos, T. (2019). Analysis and improvement of an assembly line in the automotive industry. *Procedia Manufacturing*, *38*, 1444-1452. Retrieved from https://www.sciencedirect.com/science/article/pii/S235197892030144X doi: https://doi.org/10.1016/j.promfg.2020.01.143

Duong, L. N., Al-Fadhli, M., Jagtap, S., Bader, F., Martindale, W., Swainson, M., & Paoli, A. (2020). A review of robotics and autonomous systems in the food industry: From the supply chains perspective. *Trends in Food Science Technology*, *106*, 355-364. Retrieved from https://www.sciencedirect.com/science/article/pii/S0924224420306518 doi: https://doi.org/10.1016/j.tifs.2020.10.028

Fries, C., Fechter, M., Ranke, D., Trierweiler, M., Assadi, A. A., Foith-Förster, P., ... Bauernhansl, T. (2021). Fluid manufacturing systems (flms) a novel approach for versatility in production. *Advances in Automotive Production Technology – Theory and Application*. Retrieved from https://link.springer.com/chapter/10.1007/978-3-662-62962-8_5

Groover, M. (2015). *Automation, production systems, and computer-integrated manufacturing* (4th ed.). Pearson Higher Education inc.

Gökçen, H., Ağpak, K., & Benzer, R. (2006). Balancing of parallel assembly lines. *International Journal of Production Economics*, *103*(2), 600-609. Retrieved from https://www.sciencedirect.com/science/article/pii/S0925527306000351 doi: https://doi.org/10.1016/j.ijpe.2005.12.001.

Hussain, T., & Singh, S. (2015). A comparative study of software testing techniques viz. white box testing black box testing and grey box testing. *International Journal of Allied Practice, Research and Review*, *2*(5). Retrieved from https://www.researchgate.net/profile/Tariq-Sheakh/publication/276028491_A_Comparative_Study_of_Software_Testing_Techniques_Viz_White_Box_Testing_Black_Box_Testing_and_Grey_Box_Testing/links/554f0bef08ae12808b3659f9/A-Comparative-Study-of-Software-Testing-Techniques-Viz-White-Box-Testing-Black-Box-Testing-and-Grey-Box-Testing.pdf

Imseitif, J., Tang, H., & Smith, M. (2019). Throughput analysis of manufacturing systems with buffers considering reliability and cycle time using des and doe. *Procedia Manufacturing*, *39*, 814-823. Retrieved from https://www.sciencedirect.com/science/article/pii/S2351978920304959?fr=RR-2&ref=pdf_download&rr=8090917a2a68b73a doi: https://doi.org/10.1016/j.promfg.2020.01.423

Iqbal, J., Khan, Z., & Khalid, A. (2017). Prospects of robotics in food industry. *Food Sci. Technol (Campinas)*, *37*(2). Retrieved from https://www.scielo.br/j/cta/a/g8Vvv8rW7D7rsfwctx9gmvc/?lang=en# doi: https://doi.org/10.1590/1678-457X.14616

Jevgeni, S., Eduard, S., & Roman, Z. (2015, February). Framework for continuous improvement of production processes and product throughput. *Procedia Engineering*, *10*, 511-519. Retrieved from https://www.sciencedirect.com/science/article/pii/S1877705815004257 doi: https://doi.org/10.1016/j.proeng.2015.01.398

Karim, A., & Zaman, K. (2018). A methodology for effective implementation of lean strategies and its performance evaluation in manufacturing organizations. *Business Process Management Journal*, *19*(1). Retrieved from https://www.emerald.com/insight/content/doi/10.1108/14637151311294912/full/html?fullSc=1 doi: https://doi.org/10.1007/s11465-018-0483-0

Khan, M., & Khan, F. (2012). A comparative study of white box, black box and grey box testing techniques. *International Journal of Advanced Computer Science and Applications,*, *3*(6), 12-15. Retrieved from https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=ab0ed151c010e03e2d34284ae5f89756372e7690#page=22

Koopmans, M., & de Jonge, B. (2023). Condition-based maintenance and production speed optimization under limited maintenance capacity. *Computers Industrial Engineering*, *179*. Retrieved from https://www.sciencedirect.com/science/article/pii/S0360835223001791 doi: https://doi.org/10.1016/j.cie.2023.109155

Koren, Y., Gu, X., & Guo, W. (2018). Reconfigurable manufacturing systems: Principles, design, and future trends. *Frontiers in Mechanical Engineering*, *13*, 121-136. Retrieved from https://link.springer.com/article/10.1007/s11465-018-0483-0#citeas doi: https://doi.org/10.1007/s11465-018-0483-0

Kulkarni, P. (2020). Analysis of throughput parameters in a flow line manufacturing system with varying the buffer limits. *International Journal of Engineering Research and Technology*, *9*(9). Retrieved from https://www.ijert.org/research/analysis-of-throughput-parameters-in-a-flow-line-manufacturing-system-with-varying-the-buffer-limits-IJERTV9IS090106.pdf

Kumar, N., S.Hasan, S., Srivastava, K., Akhtar, R., Yadav, R. K., & Choubey, V. (2022). Lean manufacturing techniques and its implementation: A review. *MaterialsToday:Proceedings*, *164*(3), 1188-1192. Retrieved from https://www.sciencedirect.com/science/article/pii/S2214785322018284 doi: https://doi.org/10.1016/j.matpr.2022.03.481

Law, A. M. (2015). *Simulation modeling and analysis),* (5th ed.). Mc Graw Hill Education.

Lee, J. (2007). Machine performance monitoring and proactive maintenance in computer-integrated manufacturing: review and perspective. *International Journal of Computer Integrated Manufacturing*, *8*(5), 370 - 380. Retrieved from https://www.tandfonline.com/doi/epdf/10.1080/09511929508944664?needAccess=true doi: https://doi.org/10.1080/09511929508944664

Leporis, M., & Králová, Z. (2010). A simulation approach to production line bottleneck analysis. *International Conference Cybernetics and Informatics*. Retrieved from https://www.researchgate.net/profile/Zdenka-Kralova/publication/354381258_A_SIMULATION_APPROACH_TO_PRODUCTION_LINE_BOTTLENECK_ANALYSIS/links/6135e5152b40ec7d8beadfd2/A-SIMULATION-APPROACH-TO-PRODUCTION-LINE-BOTTLENECK-ANALYSIS.pdf

Li, Y., O'Neil, Z., Zhang, L., Chen, L., Im, P., & Degraw, J. (2021). Renewable and sustainable energy reviews. *Renewable and Sustainable Energy Reviews*, *146*. Retrieved from https://www.sciencedirect.com/science/article/pii/S1364032121004639

Maack, J. (2001). . *Social Development Papers*, *36*, 62-87. Retrieved from https://d1wqtxts1xzle7.cloudfront.net/83322023/SDP-36-libre.pdf?1649252621=&response-content-disposition=inline%3B+filename%3DSocial_analysis_selected_tools_and_techn.pdf&Expires=1695913846&Signature=OM5~dW37PGpG61JDo3b0BMai9QJ9tkOhp1OI7Df5qt1TwgQQleAAdQt1e7GrMWUzEI-VhcLQSilHLLARIE-kuuKRe5wt5lTavjvmXuWvBfQYGCgD3J3m-d8H0i3BGSi7yaPPWbjRJNiOTB2LJgaCCnATEejzBwJ7uGGuCtW0Z7ezfxEt1P89~9tEJ865A7Y-iYoBoLpI73mexsUrY~6jI1CX4hVOlKG1xrT3o7kooTRP1SQ5K1r~MDMSasIdZxTstmVfPTsvnwi~ppN5B1h2DLl-7DnmVB42klPSQnF2P6Hrxec~idKmH1RUjRBx__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA#page=68

McKone, K. E., Schroeder, R., & Cua, K. O. (2007). The impact of total productive maintenance practices on manufacturing performance. *Journal of Operations Management*, *19*(1), 39-58. Retrieved from https://www.sciencedirect.com/science/article/pii/S0272696300000309?casa_token=RevLG_tnLWoAAAAA:MaV5sB-vsbPLV1YE3sZ0b8ro9QQrRn2xMmq2FLefW6DqaBHJGEskNBMXamnFe5rhO2dpwUWctg doi: https://doi.org/10.1080/09511929508944664

Mes, M. (2022a). *Data analysis [powerpoint slides]*. University of Twente.

Mes, M. (2022b). *Introduction basic principles [powerpoint slides]*. University of Twente.

Muchiri, P. N., Pintelon, L., Martin, H., & Chemweno, P. (2014). Modelling maintenance effects on manufacturing equipment performance: results from simulation analysis. *International Journal of Production Research*, *52*(1), 3287-3302. Retrieved from https://www.tandfonline.com/doi/full/10.1080/00207543.2013.870673?casa_token=wGKTZrYhe5AAAAAA%3AHZgKdlb7zLOqMEKNp2QdWFTwex-x2TiAMkx2BXud2ozec8gN7ko-6wet2u39afCKX4ofyJomBbGc doi: https://doi.org/10.1080/00207543.2013.870673

Negahban, A., & Smith, J. (2014). Simulation for manufacturing system design and operation: Literature review and analysis. *Journal of Manufacturing systems*, *33*, 241-261. Retrieved from http://www.sce.carleton.ca/faculty/wainer/papers/1-s2.0-S0278612513001301-main.pdf doi: https://doi.org/10.1016/j.jmsy.2013.12.007

Nidhra, S., & Dondeti, J. (2012). Black box and white box testing techniques –a literature review. *International Journal of Embedded Systems and Applications (IJESA)*, *2*(2), 29-50. doi: 10.5121/ijesa.2012.2204

Ouzineb, M., Mhada, F., & an I. El Hallauoi, R. P. (2018). Optimal planning of buffer sizes and inspection station positions. *Production Manufacturing Research*, *6*(1). Retrieved from https://www.tandfonline.com/doi/full/10.1080/21693277.2017.1422812?scroll=top&needAccess=true&role=tab doi: https://doi.org/10.1080/21693277.2017.1422812

Pettersen, J., & Segerstedt, A. (2008). Production performances vs machine down times and buffer sizes - a case study. *International working seminar on production economics*, *2*, 511-520. Retrieved from http://www.diva-portal.org/smash/get/diva2:1004149/FULLTEXT01.pdf

PlantSimulation, T. (n.d.). *Distribution functions.* Retrieved from https://docs.plm.automation.siemens.com/content/plant_sim_help/15/plant_sim_all_in_one_html/en_US/tecnomatix_plant_simulation_help/simtalk_reference/simtalk_reference_1/predefined_functions/mathematical_functions/distribution_functions/distribution_functions.html

Powell, S., & Pyke, D. (1997). Buffering unbalanced assembly lines. *IIE Transactions*, *30*(1), 55-65. Retrieved from https://www.researchgate.net/publication/227060598_Buffering_unbalanced_assembly_systems doi: https://doi.org/10.1023/A:1007493512502

Prajapat, N., & Tawari, A. (2017). A review of assembly optimisation applications using discrete event simulation. *International Journal of Computer Integrated Manufacturing*, *30*, 215-228. Retrieved from https://www.tandfonline.com/doi/epdf/10.1080/0951192X.2016.1145812?needAccess=true&role=button doi: http://dx.doi.org/10.1080/0951192X.2016.1145812

Reilly, M., & Willenbockel, D. (2021). Managing uncertainty: a review of food system scenario analysis and modelling. *Philosophical transaction of the royal society B*, *365*(1554). Retrieved from https://royalsocietypublishing.org/doi/full/10.1098/rstb.2010.0141 doi: https://doi.org/10.1098/rstb.2010.0141

Robinson, S. (2004). *Simulation: The practice of model development and use.* John Wiley Sons Ltd. Retrieved from https://lmsspada.kemdikbud.go.id/pluginfile.php/123916/mod_label/intro/simulation-the-practice-of-model-development-and-use.9780470847725.21800.pdf

Robinson, S., Arbez, G., Birta, L., Tolk, A., & Wagner, G. (2015). Conceptual modeling: Definition, purpose and benefits. *Winter Simulation Conference*, 2812 - 2826. Retrieved from https://www.informs-sim.org/wsc15papers/277.pdf

Roser, C., Nakano, M., & Tanaka, M. (2001). A practical bottleneck detection method. *Proceeding of the 2001 Winter Simulation Conference (Cat. No.01CH37304)*, *2*, 949-953 vol.2. doi: 10.1109/WSC.2001.977398

Ross, S. M. (2021). *Introduction to probability and statistics for engineers and scientists (sixth edition)* (6th ed.). Adademic Press.

Secola, L. (n.d.). Applicability of lean concepts in reducing change over time to increase production capacity. *Polytechnic University of Porto Rico.* Retrieved from https://prcrepository.org/bitstream/handle/20.500.12475/368/WI-11_Articulo%20Final_Lydianne%20Secola.pdf?sequence=1&isAllowed=y

Shi, C., & Gerswhin, S. (2009). An efficient buffer design algorithm for production line profit maximization. *International Journal of Production Economics*, *122*(2), 725-740. Retrieved from https://www.sciencedirect.com/science/article/pii/S0925527309002382 doi: https://doi.org/10.1016/j.ijpe.2009.06.040

Slack, N., Chambers, S., & Johnston, R. (2010). *Operations management* (6th ed.). Pitman Publishing.

Sowmya, K., & Chetan, N. (2016). A review on effective utilization of resources using overall equipment effectiveness by reducing six big losses. *International Journal of Scientific Research in Science, Engineering and Technology IJSRSET*, *2*(1), 556-562. Retrieved from https://www.academia.edu/25124754/A_Review_on_Effective_Utilization_of_Resources_Using_Overall_Equipment_Effectiveness_by_Reducing_Six_Big_Losses

STAND. (2018, August). 170 requirements for design of consumer unit (cu). Retrieved from https://stand.no/en/articles/170-requirements-for-design-of-consumer-unit-cu/#:~:text=Consumer%20Unit%20(CU)%20is%20the,a%20tray%20on%20the%20shelf

Suhardini, D., Septiani, W., & Fauziah1, S. (2017). Design and simulation plant layout using systematic layout planning. *IOP Conference Series: Materials Science and Engineering*, *277*. Retrieved from https://iopscience.iop.org/article/10.1088/1757-899X/277/1/012051/meta doi: https://doi.org/10.1088/1757-899X/277/1/012051

Tang, H. (2019, January). A new method of bottleneck analysis for manufacturing systems. *Manufacturing Letters*, *19*, 21-24. Retrieved from https://www.sciencedirect.com/science/article/pii/S2213846318301172 doi: https://doi.org/10.1016/j.mfglet.2019.01.003

ten Klooster et al, R. (2015). *Zakboek verpakkingen* (2nd ed.). Plato product consultants.

Thormundsson, B. (2019). Average cost of industrial robots in selected years from 2005 to 2017 with a forecast for 2025. Retrieved from https://www.statista.com/statistics/1120530/average-cost-of-industrial-robots/

van der Heijden, K. (2005). *Scenarios: The art of strategic conversation* (2nd ed.). Wiley.

Velumani, S., & Tang, H. (2017). Operations status and bottleneck analysis and improvement of a batch process manufacturing line using discrete event simulation. *Procedia Manufacturing*, *10*, 100-111. Retrieved from https://www.sciencedirect.com/science/article/pii/S2351978917302135 doi: https://doi.org/10.1016/j.promfg.2017.07.033

Wang, Z., Hirai, S., & Sa.Kawamura. (2021). Challenges and opportunities in robotic food handling: A review. *Front. Robot. AI*, *8*. Retrieved from https://www.frontiersin.org/articles/10.3389/frobt.2021.789107/full doi: https://doi.org/10.3389/frobt.2021.789107

Wanniarachchi, W. N. C., Gopura, R. A. R. C., , & Punchihewa, H. K. G. (2016). Development of a layout model suitable for the food processing industry. *Journal of Industrial Engineering*. Retrieved from https://downloads.hindawi.com/archive/2016/2796806.pdf doi: https://doi.org/10.1155/2016/2796806

Witte, A. K., David, M. B. R., Blättler, B., Schoder, D., & Rossmanith, P. (2017). Investigation of the potential of dry ice blasting for cleaning and disinfection in the food production environment. *LWT*, *75*, 735-741. Retrieved from https://www.sciencedirect.com/science/article/pii/S002364381630620X doi: https://doi.org/10.1016/j.lwt.2016.10.024

Yang, T., Su, C., & Hsu, Y. (2000). Systematic layout planning: a study on semiconductor wafer fabrication facilities. *International Journal of Operations Production Management*, *20*(11). Retrieved from https://www.emerald.com/insight/content/doi/10.1108/01443570010348299/full/html

Zhou, X., & Shi, K. (2019). Capacity failure rate based opportunistic maintenance modelling for series-parallel multi-station manufacturing systems. *Reliability Engineering System Safety*, *181*, 46-53. Retrieved from https://www.sciencedirect.com/science/article/pii/S0951832018306306?casa_token=i-qezLlVXTAAAAAA:LC9pYF6d9JXpfJZKDa9pif9criXdrSBdaItmwxiL1A63ZIkrS4x-tN-m7_GLfBs-D977nSIkVw doi: https://doi.org/10.1016/j.ress.2018.09.007