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A new production planning strategy for Ovimex

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Preface

Dear reader,

Before you lies my bachelor thesis called "A new production planning strategy for Ovimex". This thesis is part of the Industrial Engineering and Management program at the University of Twente. In this thesis, I conducted research at Ovimex regarding the way they currently schedule orders. I tried to optimize this by performing experiments in a simulation model. At Ovimex, I had contact with multiple people who all helped gathering the right information from the company. I want to thank Roland Wolters, production floor manager at Ovimex, in particular. He served as my supervisor at the company and was the main contact person for me. I want to thank him for our deliberations, brainstorm sessions and the feedback he provided. I enjoyed our collaboration and the experiences he shared.

I would also like to thank my first and second supervisor, Marco Schutten and Martijn Mes. Due to the coronavirus we were not able to plan personal face to face meetings. I want to thank them both for their efforts to make the online meetings useful. I want to thank my first supervisor, Marco Schutten, in particular for his valuable feedback, his input in certain parts and his critical reflection on my writing style.

Kind Regards,

Tim de Wolff
Enschede, July 2020

Management summary

Problem introduction

This research starts with a problem of the company Ovimex. Ovimex is a small printing company situated in Deventer. Ovimex counts around 50 employees. The experienced problem is that production planning goals are often not met. This results in overwork and backorders. Long waiting times are deduced as the main reason for this problem. Therefore, this research investigates the possibilities of reducing the waiting time per day with 10%.

Method

By the means of mapping of the current situation, a literature review and a model of the current situation, solutions are sought. These solutions consist of planning strategies to improve the throughput of orders through the company. In the model of the current situation, changes are made to observe how these affect the waiting time. The literature review shows that applying priority rules is one of the most convenient and effective ways. The experiments are centered around these priority rules to generate promising solutions to the problem. These rules prioritize jobs based on certain aspects. Table x provides the rules that are considered in this project.

Priority rule	**Abbreviation**
MinSlack	MS
Earliest Due Date	EDD
Most Operations Remaining	MOR
Least Operations Remaining	LOR
Shortest Queue Next Operation	SQNO
Shortest Processing Time	SPT
Similar Setup	SIMSET

Table x: Overview priority rules

Solutions

The solutions comprise of 5 different aspects in the production plan. Prioritizations at printers, laminators, cutters, and all other production steps, and having a print session or not. Ovimex currently uses a print session, meaning that all orders due on day 2 are printed at 18:00 at day 1. Thereby, Ovimex uses FIFO (<18:00) / SIMSET (>18:00) for printers, SIMSET for laminators, SQNO for cutters and SPT for the remaining stations. The following strategies improve the current situation on waiting time, throughput time and number of backorders:

1. *{Print session} {Printers LOR / SIMSET} {Laminator SPT} {Cutters SQNO} {Rest SPT}*
   The first solution is the solution that is focused on reducing waiting time at the production steps beside printing. Advantages are the 9% decrease in waiting time at production steps besides printing and 12% decrease in backorders. Disadvantages are that overall throughput and waiting times only improve 2% and 4%.

2. *{Print session} {Printers SIMSET + SPT} {Laminator SPT} {Cutters SQNO} {Rest SPT}*
   The second solution is focused on reducing overall waiting times and backorders. Advantages are the 74% decrease in backorders and 15% decrease in waiting time per day. Disadvantage is that the production steps time worsens by 5%.

3. *{No print session} {Printers SIMSET + SPT} {Laminator SPT} {Cutters EDD} {Rest SPT}*
   The third solution focusses on reducing the waiting time per day as much as possible. The advantages are the 74% waiting time decrease and 86% throughput time decrease. Disadvantage is that backorders are lowered by 77% which could be even more.

4. *{No print session} {Printers SIMSET + SPT} {Laminator EDD + SPT} {Cutters EDD} {Rest SPT}*
   The last solution focusses on reducing backorders. Biggest advantage is the 81% backorder decrease. The only disadvantage is that solution 3 lowers waiting times even more.

Recommendation for Ovimex is to investigate if print sessions could be omitted, and to implement priority rules in the production process. This report proves the advantages of the rules stated above.

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1. Introduction

This report contains research performed for the company Ovimex. Ovimex is a small printing company in Deventer. In this research, we aim towards helping Ovimex solve an encountered problem and create a better situation. Section 1 introduces the encountered problem of Ovimex. Afterwards, we discuss the derived core problem and research approach in Section 2 and 3. Lastly, in Section 4 we discuss the deliverables of this research. Goal of this chapter is to grasp the current situation at Ovimex and the problems that occur, distinguish a core problem, and design a realistic, clear approach to solve this core problem.

1.1. Problem Introduction

This project is aimed at the company Ovimex. Board members of the company explained that currently one of Ovimex' biggest issues lies with their inability to reach planning goals. To be more precise, their production planning goals. Ovimex produces printed products according to a production plan. Every morning, schedules are designed based on the production plan to determine when which product is produced. These schedules cannot always be followed due to multiple different reasons. Not reaching these goals results in stress and working late for production employees. Besides the presented problem, remarks were also given on the current lack of overview on the production floor as one of the potential causes. This includes not knowing where work-in-progress (WIP) is stored, unexpected work in the evening and no clear flow of products through the production process. Therefore, we attempt to create a better overview as well.

1.1.1. Company introduction

As explained, Ovimex is a small printing company situated in Deventer. Ovimex counts around 50 employees. These employees can be divided into production employees, sales employees, marketing employees, administration employees and the board. Ovimex calls itself a crossmedia-specialist as they produce all sorts of printed products. Examples of these products are business cards, flyers, instruction books and packaging boxes. These products are printed on one of their printers and often need the execution of a few other production steps to be considered a finished product. Ovimex is especially proud on their HP30.000 printer which they started using in 2017 (Figure 1). This printer has multiple printing options that their other printers do not have. Thereby, it is faster as well. They are currently the only Dutch company to have this printer.

The main selling point of Ovimex is that they can deliver on short notice. In the past, clients had to call or e-mail Ovimex to place an order. Nowadays, customers can design and order their own product using a tool called web2print. Orders are increasingly received via this tool. When Ovimex receives an order via this tool it can often be printed on the same day on either the HP30.000 or the HP12.000, which is another printer they possess. Finishing and shipping the product often happens on the day after. The orders can be of any size. Ovimex is very flexible in that matter. The production of orders is scheduled First In First Out (FIFO). Orders with longer production paths are sometimes moved forward to decrease the possibility of backorders. Thereby, on some machines, certain jobs are combined to reduce setup time.

Because of the earlier mentioned increasing receival of orders via the web2print tool and the ease to produce via this tool, Ovimex wants this tool to play an even bigger role in their company. This is the main reason that we only consider this order stream in this project.


Figure 1: HP30.000 printer at Ovimex

1.2. Problem identification

To be able to (partly) solve the presented problem, we discern a core problem. We do this by using a problem cluster and criteria core problems should satisfy (Heerkens & Van Winden, 2016). We briefly analyze the core problem to determine the current and desired state. Lastly, we derive a research question from the core problem to clarify the goal of this research.

1.2.1. Problem cluster

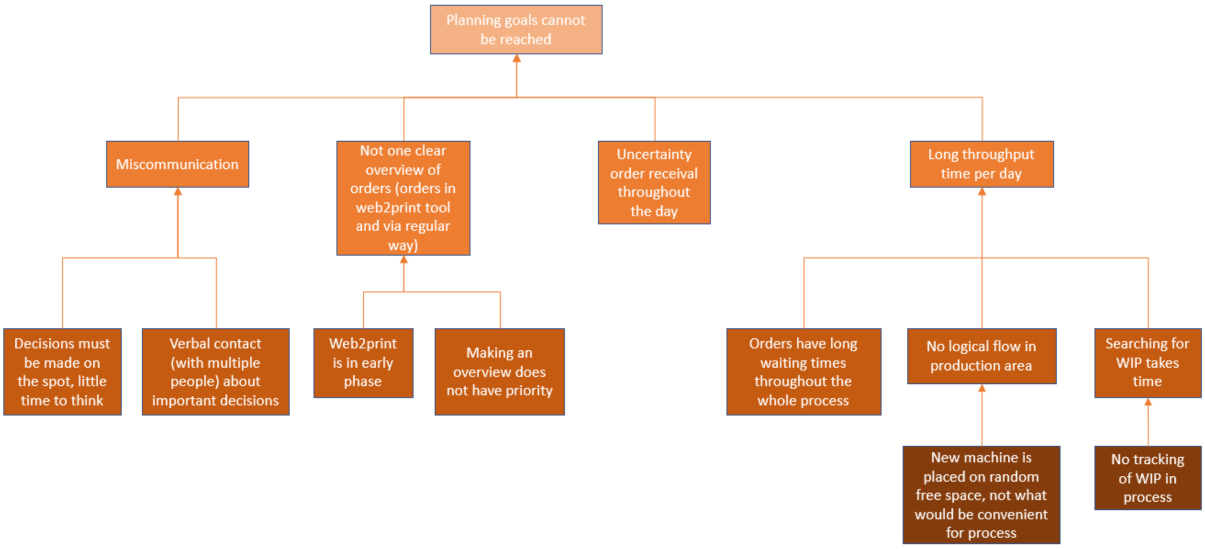

Figure 2: Problem cluster

The problem that Ovimex explained is formulated as ‘Planning goals cannot always be reached’. As this is the largest encountered problem, it is placed at the top of the problem cluster (Figure 2). Starting with this problem, we further discuss the problem cluster. This problem cluster describes the problems Ovimex faces, linked with the provided problem. A problem linked with a problem from a higher layer (lighter color in Figure 2) means that the problem from the lower layer (partly) causes the upper problem. Starting with the presented problem at the top, each problem is researched to find potential causes. This research includes interviews with several board members of Ovimex. Four problems cause the presented problem. These are ‘Miscommunication’, ‘Not one clear overview of orders’, ‘Uncertainty order receival throughout the day’ and ‘Long throughput time per day’ (Figure 2). Each of these problems were researched for causes as well, and so on. This procedure led to eight problems without causes. Such a problem with no causes (not linked with another problem downwards) is considered a possible core problem. Fixing such a problem contributes to fixing upper problems as well. The following eight problems remain (from left to right in Figure 2):

1. Decisions must be made one the spot, little time to think
2. Verbal contact (with multiple people) about important decisions
3. Web2print is in early phase
4. Making an overview does not have priority
5. Uncertainty order receival throughout the day
6. Orders have long waiting times throughout whole process
7. New machine is placed on random free space, not what would be convenient for process
8. No tracking of WIP in process

We reduce these 8 problems to one core problem. This project focusses on finding a solution for this problem. First, the chosen core problem should be influenceable by the problem solver (Heerkens & Van Winden, 2016). Problems 1, 2, 3, 4 and 5 are problems that cannot be influenced by the problem solver. Problems 1, 2 and 4 are influenced by the mindset and production style of Ovimex. Problems 3 and 5 on the other hand, are not in control of Ovimex. These five problems are therefore not chosen as core problem. This means that only three problems are left. Beside the influenceability, the core problem needs to be solvable in 10 weeks by the means of methods learned in the IEM program. Problem 8 does not appear achievable in 10 weeks and cannot be solved using methods learned during the IEM program. We do not choose this problem as core problem as well.

The two remaining problems, 6 and 7, both appear suited to serve as core problem. The choice between these two problems is made based on potential impact on Ovimex and achievability. To solve problem 7, Ovimex expectedly needs to move machines around and create an entirely new production floor plan. To solve problem 6, Ovimex needs to change the way they plan orders to create less waiting time. We can logically expect that Ovimex is sooner willing to integrate a solution to problem 6 rather than a solution to problem 7. This also emerged in a deliberation with a representative of the board of Ovimex about these two problems. Thereby, we expect that problem 6 has a bigger influence on the presented problem. This because the elimination of waiting time (problem 6) expectedly has a bigger influence on the total throughput time compared to a more logical flow in the production area (problem 7). This total throughput time has an influence on the presented problem. Therefore, the chosen core problem is: **‘Orders have long waiting times throughout the whole process’.**

1.2.2. Action problem

Now that we have distinguished the core problem, we derive an action problem. An action problem describes the current and desired state of a certain problem. Our core problem describes the long waiting times that Ovimex currently encounters. From the problem cluster (Figure 2) we derive that

Ovimex wants to lower these to reduce their overall throughput time per day to reach planning goals in the evening. Therefore, we focus on total waiting times per day. The action problem is stated as follows:
'The waiting time of all orders at Ovimex on one day is very long, this should be lowered by 10%.'

1.2.2.1. Reality
The reality of this action problem is the total waiting time all orders encounter on one day. The way that orders are currently scheduled partly causes this waiting time. At Ovimex, there is not enough data available to determine the reality. Therefore, measurements are needed. Section 2.2. provides these measurements. We determine the exact reality with the model (Section 5.2.).

1.2.2.2. Norm
The norm explains the desired situation. In the problem at hand, the norm represents the amount of waiting time Ovimex hopes to stay under. Ovimex explained that an improvement of any size would help them in (partly) solving their encountered problem. Based on the short length of the production process, the actions already taken to reduce the waiting time and the 10-week period of this project, we collectively decide to set a realistic time-decrease goal of 10%.

1.2.3. Research question and goal
From the previously introduced action problem, we derive a research question. This entire project aims to answer this question and solve the action problem. As explained, the solution for this problem lies with scheduling of orders (Section 1.2.1.). We expect that waiting time can be reduced when orders are scheduled differently. Finding an optimal procedure or strategy of doing so is the main challenge of this project. Therefore, the research question is formulated as follows:
'How can a production planning strategy be designed to decrease the waiting time at Ovimex?'

The obvious goal of this research is to answer this question. To be more specific, we design a production planning strategy that Ovimex can implement to decrease the waiting time of orders. The decrease of waiting time will have a positive impact on throughput time, working late of employees and unexpected work in the evenings. Goal is to provide multiple strategy options of which the advantages and disadvantages are laid out. Ovimex can choose for themselves if they decide to incorporate one (part) of the options.

1.3. Problem approach
In this section, we formulate a problem-solving approach using the defined problem and research question. This approach is designed by means of the MPSM and the 'Do, Discover, Decide' principle (Heerkens & Van Winden, 2016). The approach is centered around several phases. Each of these phases describe activities and sub-questions to answer. The answers to these sub-questions serve to answer the research question at the end of this project. Each phase represents one Chapter of this project.

1.3.1. Current situation
First, we discuss the current situation of Ovimex. To visualize and analyze the current situation we use a flowchart. A flowchart is a map that visualizes how processes are structured. The flowchart in this project visualizes the production process of Ovimex. The flowchart serves as an overview of the process and is of great value when attempting to improve the current situation. It shows the current process in a structural and precise manner. The flowchart is designed based on the floor plan, work descriptions and interviews with production floor managers and employees. Because of the remarks about the current lack of overview at Ovimex, we pay extra attention to the details of the flowchart. Because of this level of detail, Ovimex can use the flowchart for creating a better overview.

Afterwards, we discuss measurements regarding the reality. As mentioned, Ovimex currently has no data at hand regarding waiting time or throughput time (Section 1.2.2.1.) which causes that measurements are needed. Because of the coronavirus-outbreak, limitations to the measuring possibilities arose. Therefore, a representative of the management performed measurements regarding a few events related to the waiting time. These measurements are used to determine an exact reality in the model (Chapter 5.2.). The previously discussed flowchart (Figure 4) helps us determining the exact measurements that are needed. The following events are measured:

- Processing rates of machines.
- Changeover times. This involves the time a machine must be set up for a different type of product.
- Maintenance time of machines and the frequency of maintenance events.
- Calibration time of printers and the frequency of these events. This relates to the time a printer must calibrate. During a calibration, current settings are compared to standard settings and if needed aligned. This is needed to make sure that the printer works properly.

Chapter 2 focusses on the following questions to be able to understand the current situation:

- **'How is the production process of Ovimex structured?'**
    - 'What are the possible product types and their corresponding production steps?'
    - 'What other actions exist in the production process beside the materialistic operations?'
    - 'What are the durations and influences on durations for the events in the production process of Ovimex?'

1.3.2. Literature review

After we investigated the current situation, we discuss a literature review. During this review, previous research is investigated to find out how problems like our problem are handled and solved in the literature. Goal is to get an idea how the problem of Ovimex can be treated and resolved. Priority rules appear as a very good method of handling such problems (Section 3.1.). Therefore, a large part of Chapter 2 is focused on these rules. Section 3.1.2. explains how these rules work.

Chapter 3 focusses on answering the following questions:

- **'What methods are currently used to decrease waiting time at small production companies?'**
    - 'What difficulties arise when implementing such methods?'
    - 'How should priority rules for the experiments be selected?'

1.3.3. Model

As a third step of this project, we discuss a model which was designed based on the previously designed flowchart. The order arrivals are based on historic data. This model serves as a representation of the situation at Ovimex. First, the model mimics the current situation as accurate as possible. This to generate a status quo. This consists of values of chosen Key Performance Indicators. This status quo is shown to the board to test if it represents the current situation accurately. If this is the case, the model is finished and can be used to perform experiments. The waiting time per day of the approved status quo is considered as the reality of the action problem.

The choice of the type of model to use fell between a deterministic and simulation model. This mainly because Ovimex uses a make-to-order strategy. Make-to-order means that products are produced upon receival of orders. Both the deterministic and simulation model can handle such strategies. Because the current situation has a big influence on the type of model that is preferable, this choice is made during the project. We choose to use a simulation model because of the dependence of days and uncertainty of order arrival (Section 4.1.). Section 4.1. provides an extended explanation.

We answer the following questions in Chapter 4:

- **'How should a model be constructed to represent the production process in a valid way?'**
  - 'What order arrival distribution represents the current situation of Ovimex accurately?'
  - 'What are the relevant order characteristics and how should they be represented in the model?'
  - 'Which Key Performance Indicators should be chosen?'

1.3.4. Experiments

With the finished model, experiments are performed. We discuss these experiments to formulate solutions for the action problem. The solutions comprise of planning strategies. In the model, we mainly experiment with priority rules. Priority rules can be used to determine which order should be prioritized when multiple orders are waiting for a certain action from a machine or employee. We investigate if other changes need to be tested as well. Goal of the experiments is to decrease the waiting time. For each experiment, we compare the waiting time and some other Key Performance Indicators with the status quo to see if improvements are made. These changes can potentially be incorporated in one or multiple solutions.

During Chapter 5, we answer the following questions:

- **'Which scheduling changes lower the waiting time in the production process?'**
  - 'Which priority rules should be used in the experiments?'
  - 'What other changes besides priority rules are possible to implement?'

1.3.5. Conclusions and recommendations

With the model different solutions are generated. We construct a list with possibilities. This list explains the solution, together with the advantages and disadvantages. After the exposition of all possibilities, usually, a decision would follow. This report on the other hand, is meant to consult Ovimex. The final step therefore consists of giving a recommendation. We expand with reasoning. This recommendation and the previously mentioned advantages and disadvantages are all based on trade-offs between Key Performance Indicators.

1.4. Deliverables

The goal of this project is to formulate a new production planning strategy. This strategy should be able to schedule orders in a more sufficient way than is currently done. Thereby, this strategy should be able to handle the varying amount of orders Ovimex receives on different days. Experiments with a model test the efficiency of different strategies (Section 1.3.4.). Based on these efficiencies and trade-offs between different indicators, a recommendation to Ovimex is provided (Section 1.3.5.).

1.4.1. Flowchart

The first deliverable is the flowchart. As mentioned, this flowchart provides insight in the current production process and its procedures. Ovimex could potentially use this chart themselves to create more overview. A lack of overview was mentioned as one of the potential causes for the presented problem (Section 1.1.). This entire research uses the flowchart as a basis. This chart will therefore be validated by the company with a particular emphasis on details and accuracy of the described processes.

1.4.2. Model

The most important deliverable is the model. We use this model for the execution of experiments. It is important that this model represents the situation at Ovimex accurately to make sure that experiments are relevant for Ovimex. The model is considered as proof and explanation for the provided strategies and trade-offs. Ovimex could potentially use the model to conduct additional experiments as well.

1.4.3. Report

The last deliverable is this report. In this report every choice that is made is explained. This is of great importance as this provides readers with the needed knowledge to understand the project and the procedures within. The goal is to give a clear exposition of the overall process, the choices made, the outcomes this led to and the assumptions that are made.

2. Current situation

Chapter 2 provides the current situation of Ovimex. This current situation is what we endeavor to improve. First, we discuss the flowchart (Section 2.1.). Goal of this chart is to map the current situation in detail. This flowchart includes all relevant steps that an order follows to be transformed into an end product. As explained, the flowchart is one of the deliverables that is provided to Ovimex (Section 1.4.1.). Second, we discuss measurements of certain time lengths in the production process (Section 2.2.). Among these measurements are for example the production rates. We need these measurements in our model to ultimately determine the starting point for the model (Section 5.2.). Goal of this chapter is to get a thorough understanding of the current situation at Ovimex. We answer the following questions in this chapter:

- 'How is the production process of Ovimex structured?'
- 'What are the possible product types and their corresponding production steps?'
- 'What other actions exist in the production process beside the materialistic operations?'
- 'What are the durations and influences on durations for the events in the production process of Ovimex?'

2.1. Design of a flowchart

To understand the production process of Ovimex thoroughly, a flowchart is needed. This flowchart serves as a visualized representation of the production process and aids in the design of the model as well. First a detailed version is discussed to get familiar with the process entirely. This version is subsequently simplified. Result is a detailed flowchart which we use as a basis for the model (Chapter 4.). In this second more detailed version, the irrelevant steps are left out and the chart is focused on the core of the process. The steps that are left out are parts that are not included in the model. This to make sure that the flowchart can function as a basis for the model. Information needed for the flowchart was retrieved via interviews and research of internal documents.

2.1.1. Product types

For both flowcharts, insight is needed in the different product types that Ovimex distinguishes. This gives an impression of the variety of products Ovimex produces. These are not linked to production steps yet as products from the same type do not necessarily have the same production steps. The production steps possible for the different product types are explained in Section 4.3.

HP30.000	
Category	*Description*
A1	Commercial print
A4	Synthetics
A6	Carton

Table 1: Product categories HP30.000

HP12.000	
Category	*Description*
B1	Folders
B2	Flyers (2 pagers)
B3	Brochures stitched
B4	Brochures PUR
B5	Brochures sewed
B6	Books PUR
B7	Books sewed
B8	Loose paged sets
B9	Press sheets
C0	Business cards
C1	Postal paper
C2	Pads
C3	Periodic
C4	Other

Table 2: Product categories HP12.000

As explained, web2print orders are always printed on either the HP12.000 or the HP30.000 (Section 1.1.1.). This because the conversions of web2print files to digital print files can be made in seconds. The HP12.000 can print one- or two-sided on paper with a maximum thickness of 0.4 millimeters. The HP30.000 can print one-sided with or without sealing on paper with a maximum thickness of 0.6 millimeters. Therefore, most orders can only be printed on one of the two printers. Thus, orders are categorized first on the printer that will perform the printing job. These two order groups can be categorized further on size, number of pages, usage, and production steps.

The production steps that are used to categorize are explained in the next part (Section 2.1.2.). Each order is placed in one of the 17 categories (Tables 1 and 2). Each of these categories represents a specific product group. Production employees only need one glance at the category to get an idea which sort of production steps to expect and how much pages a product will approximately have. This helps in creating a better overview and eliminates mistakes.

2.1.2. Production steps

Besides a category, each order has a predetermined series of production steps to go through. When the order is received, both the production steps and the sequence of these steps are automatically generated. As mentioned, production steps do not fully depend on the category (Section 2.1.1.). Each of the production steps is performed by a machine or employee. The following production steps are distinguished by Ovimex:

- **Stapling:** Binding of multi-paged orders using staples.
- **Die cutting:** Contour cutting (predefined shape).
- **Wire-o:** Binding of multi-paged orders using a ring binder.
- **Drilling:** Shaping one or multiple holes of a predefined size and form.
- **Creasing:** Applying folding lines.
- **Perforating:** Applying tear lines.
- **Folding:** Folding products (often small boxes).
- **Laminating:** Adding a lamination layer on the product.
- **Stitching:** Binding multi-paged orders using stitches.
- **Perfect binding / PUR:** Binding multi-paged orders using glue.
- **Cutting:** Cutting away the unnecessary parts of the sheet.

Most of these production steps are fairly straightforward. Though, a few remarks are needed. First, die cutting is seen as one production step. This step is performed on either a normal die cutting machine or a digital one (Table 3). These machines are very different in speed and the type of jobs they usually perform. The step is described as one because the action is similar. The machine on which this step is executed depends on the difficulty of the job and the number of products. Second, the lamination layer that is added on a product can differ. At Ovimex five different types of lamination are distinguished. These are: scratch-resistant, linen, gloss, soft-touch, and matt. Third, all production steps are optional except cutting. 99.9% of products needs cutting. This is assumed to be 100% (Section 4.4.).

2.1.3. Remaining actions in production process

Beside the previously explained production steps, several other actions are needed to produce a product. We need to understand these actions as some need to be added to the flowchart. We only consider activities directly related to the production process as these have an impact on the core of this project. Indirectly related activities are out the scope. The following activities are left out:

- Marketing
- Sales
- Purchasing
- Financing
- Administration

During deliberations, information was gathered regarding the actions that were to be included. A list was constituted with all the needed activities to enable the actual production process. As mentioned, these are the activities that are integrated in the flowchart as well. Each action is listed together with a short explanation:

- **Information check:** When an order is received, the delivered information (due date, order size etc.) is checked to see if all required information is received by the department Prepress DTP. It is also made sure that the product file is converted correctly to a printing file.
- **Customer contact:** If orders cannot be delivered on time or certain information is missing, customers are contacted to deliberate about next steps or to ask for the needed information.
- **Printing orderbag:** An orderbag is a one-paged document with all relevant information about the order (due date, order size, production steps, order number). This document is printed and kept with the order to keep track of the progress.
- **Monitoring:** To make sure production steps are executed right and the schedule is followed, the production floor managers monitor the employees on the production floor.
- **Storage:** WIP's and end products can often not directly move to the next production step or customer. Until this is possible, they are stored. At Ovimex WIP or end products that need to be stored for a short period of time are placed at predetermined places on the production floor (beside specific machines). For WIP or end products that need longer storage, a small warehouse is connected to the production floor.
- **Transportation:** When WIP can enter its next production step or an end product can be packaged, transportation is needed. To do this, forklifts are used.
- **Changeovers:** When a new order arrives at a machine with different settings than the previous order, the settings need to be adjusted.
- **Filling:** Certain machines (printers, laminators etc.) need materials. These need to be filled when levels are too low.
- **Grouping:** At some machines orders with the same settings are grouped to save setup time. This task is performed by production employees.
- **Packaging:** End products are packaged in carton boxes.

2.1.4. Description process

Now that all product types, production steps and other activities are known, a description of the production process can be discussed. We discuss this briefly as the flowchart visualizes the process clearly. This description is based on several interviews and conversations with production floor managers and other employees of Ovimex. The description follows an order in its path through the company. Reasoning is that the flowchart is constructed the same. We discuss some extra information as well.

The start of the production of an order is dependent on the time on which an order is placed and the due date. Normally, production starts at 18:00 on the day before the due date. At that time, Ovimex prints all received orders that are due on the next day in one large shift. When these jobs are finished, the WIP is stored for the night. On the following day, the day on which the order is due, all remaining production steps are performed between 06:00 and 22:00. When all production steps are performed, the order is moved to the Expeditie department. This department packages all products and makes sure that the order gets administrated correctly. At 22:00 DHL comes to the company and ships the products to the customer.

Besides this usual production flow, orders can arrive with a due date on that same day. Thereby, orders can arrive after 18:00 with a due date on the next day. In both these situations, it is not possible to print the product on the day before the due date at 18:00. These orders are therefore printed as soon as possible. For orders arriving after 18:00 due on the next day, this means on the next morning. The unfinished print jobs of the previous night are printed on the next morning as well. Orders that arrive due on the same day, get printed minutes after arrival.

Customers that order via the web2print tool can choose a due date ranging from the present day to 3 days later. Most clients choose a due date one day later than the current day. Note that the due date does not mean that the customer receives the order on that day. It means that the order is shipped from Ovimex at 22:00 on that day. To prevent overwork, Ovimex has set product-dependent time borders. A due date for the same day can only be chosen before such a time border. The following borders have been set:

- 14:00, Products with two or more production steps.
- 16:00, Products that need creasing and cutting.
- 18:00, Products that only need cutting.

Every day, in the morning at 06:00, a schedule is made with all known jobs for the day by the production floor manager. This schedule consists of the remaining production steps needed for the orders printed in the evening on the day before and all production steps for the orders received after 18:00 on the day before. The schedule is mainly designed First In First Out (FIFO). Though, roughly, all jobs that have more than one remaining production step, are prioritized over jobs with only one step left. The changes made are solely based on personal experience from the production floor manager. Orders received during the day are planned in immediately in the same manner. Grouping certain jobs at the printers or laminator to reduce setup time belongs to the responsibilities of the machine operators. The schedule for the print session at 18:00 is made around 17:30 based on grouping of jobs with the same settings.

2.1.5. Detailed flow chart

All the previously gathered information is used for the flowchart. As mentioned, first, a detailed version is discussed. This helps us create a thorough understanding of the production process. The detailed flowchart is designed as a swimlane diagram. This adds clarity and accountability to the chart. In other words, it visualizes clearly who is responsible for what task. In this type of diagram every actor in the process has its own lane. Activities that are performed by a particular actor are placed in the corresponding lane. Ovimex in its entirety is represented as a pool. The different lanes representing a department or employee are placed inside this pool. External parties have a separate pool or lane.

Beside the pool and lane symbols, a lot of other symbols are used as well. For this flowchart the pool, lane, event, activity, gateway, sequence flow, message flow, association, and data object symbols are used (Figure 3). Most of the symbols and their meaning is quite straightforward. Events represent occurrences that start or stop the process, an activity describes an action, a gateway splits the flow in multiple possibilities, the connecting objects connect the previously mentioned objects, and the data object is used to visualize that data is stored or used.

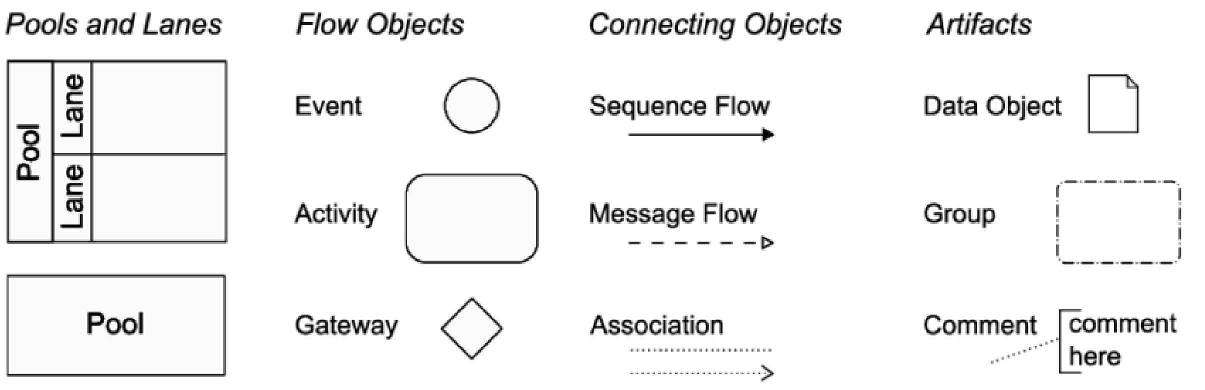

Figure 3: Bizagi symbols (Müller & Rogge-Solti, 2011)

In this chart the process starts by the customer placing an order via the web2print tool (Appendix 8.1.). When the customer places the order, the department Prepress DTP automatically receives the needed order and customer information. When all needed information is present, an orderbag (Section 2.1.3.) is printed. As soon as Prepress DTP approves the order, the corresponding order file is automatically sent to the right printer. As explained, the time on which an order is printed depends on the due date and time of receival (Section 2.1.4.). After the product is printed and coupled to its orderbag, the remaining part of the production process is carried out. This part consists of one or several production steps following a schedule made by the production floor manager. In the flow chart this is represented by a message that is sent to the production floor manager as soon as an order is printed. The production carries on as soon as the production steps are planned. In the chart, the execution of production steps is visualized by a gateway that checks if all production steps are finished. If false, the WIP is stored until it can be transported to next production step. If true it is transported to the Expeditie department where the end product is packaged. DHL picks up all finished orders at 22:00 and delivers them to the customer. The delivery at the customer is seen as the end event.

2.1.6. Simplified flow chart

To be able to use the flow chart as the basis for the model, the detailed flowchart had to be simplified. The activities that are not used in the model are excluded from this second simpler version of the flowchart. In this chart the same symbols are used as in the detailed flowchart (Figure 4). In this flowchart, pools and lanes are not used anymore. For the model it is not relevant which employee performs what specific task. It only matters which activities need to be performed in what order. Thus, all activities are placed in a correct order without specifying which employee or external party performs a certain task.

This flowchart starts with the receival of an order and ends with the transportation of the end product to the Expeditie department. The customer placing the order, packaging the end product and delivering the order are not incorporated in the model. The activities and gateways of the detailed flow chart and simplified flow chart are very alike. The main difference is that some irrelevant parts are left out. The flow of the product through the company stayed the same.

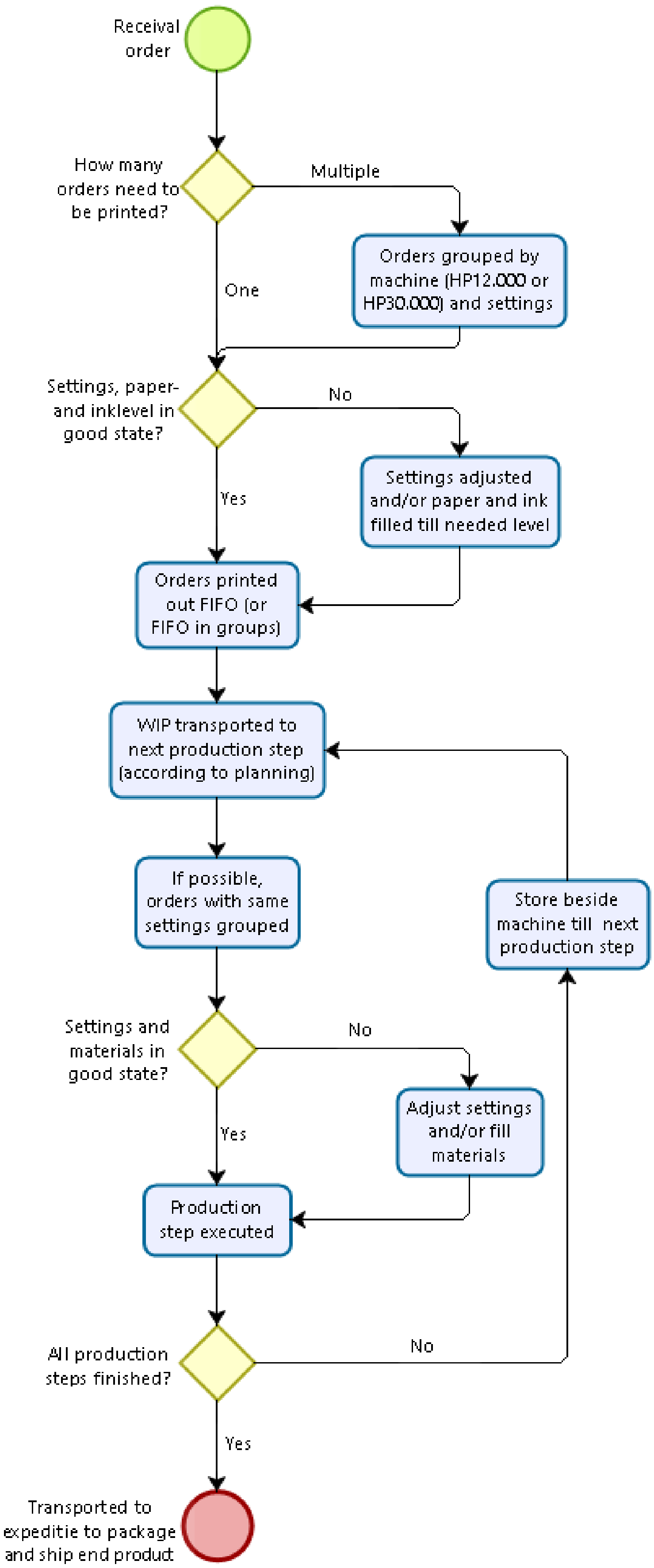

Figure 4: Simplified flow chart

2.2. Measurements reality

To further familiarize ourselves with the current situation, we discuss several measurements of events in the production process. We need these measurements to determine the reality with the use of the model (Section 5.2.). The flowchart we discussed (Section 2.1.) helps us determine which measurements are needed. The measurements are divided into four components which we explore separately.

2.2.1. Measured times production steps

The measurements are performed by one of the production floor managers. The daily job of a production floor manager consists of scheduling all orders (Section 2.1.4.), managing the production floor employees, and making sure the planning goals are met. Because of these responsibilities, we can reasonably expect that he has a good understanding of the overall process and the measurements that are needed.

In collaboration with this production floor manager we decide that four types of measurements are needed. Only the steps that can be influenced or that have a large impact on the overall throughput are measured. We for example leave out transportation time. The factory is small to an extent that walking from one side of the factory to another does not take that much time. Therefore, the influence of transportation on the overall throughput is minimal. The following measurements are needed:

- Processing rates of machines.
- Changeover times.
- Maintenance time of machines and the frequency of maintenance events.
- Calibration time of printers and the frequency of these events (Section 1.3.1.).

The processing rate represents how many orders can be processed by a certain machine in a specified time unit. This is measured in products per hour. The difficulty of the jobs is approximately similar. Changeover time represents the duration of a changeover measured in a time unit. The production floor manager explained that durations of changeovers only differ per machine. Changeovers from the same machine are of an approximate equal time length. We therefore use one changeover time per machine. Thereby, we establish which properties of orders induce changeovers. Maintenance time contains the duration of a maintenance activity on a certain machine. This includes both preventive and corrective maintenance. Because these vary a lot and no data is available for these events, we determine an average per machine. In the model, we add variability (Section 4.4.). The frequencies are estimated. For the printers, we determine the maintenance time with an alternative procedure as relevant data is available (Section 2.2.2.). Calibration time includes the time a machine must calibrate. As mentioned, at Ovimex, only the printers need calibration activities (Section 1.3.1.). These calibrations are, as was the case for the changeovers, of an approximate equal length. Thereby, no relevant data is available. Therefore, we again determine an average duration as well as an average frequency.

We explored all production steps in Section 2.1.2. This section provides all steps and a short explanation. Except the production step stapling, which is carried out by hand, all production steps are performed by a machine operated by employees. For each of these steps, eight pieces of information are needed (Table 3). Abbreviations in the table are explained in the legend below Table 3. The following information is measured or noted for each production step:

- Number of machines
- Processing rate
- Changeover time
- Property for which a changeover is needed
- Maintenance time

- Frequency of maintenance event
- Calibration time
- Frequency of calibration event

This information is needed to represent the situation at Ovimex accurately. A few aspects of the data-table are noteworthy. First, as explained, calibration time only occurs for the digital printers. The other machines do not need calibrations. Second, there are two similar drilling and cutting machines. Furthermore, there are two die cutting machines as well. These are separated as these machines are very different in speed and the type of jobs they receive. Third, most of the processing times are mentioned in products per hour (Table 3). For some it is stated differently. For drilling this is stated in drills per hour. One drill means that one hole is drilled in a pile of products. This pile can consist of a maximum of 100 products (Section 4.4.). This means that the production step drilling is dependent on both the number of products ordered and the number of holes needed per product. For printers this is stated in sheets per hour (Table 3). The printers at Ovimex print products on sheets of 750x530 mm (Section 4.3.2.). Often multiple products can be placed on one sheet depending on the size of the product. Therefore, the term products per hour could not be used. The number of products that fit on one sheet is considered for each order in the model (Section 4.3.). For cutting the processing rate is stated in minutes per order. The production floor manager explained that it is not possible to determine a certain rate of products per hour for cutting. He explained that it always takes approximately four minutes. We therefore assume that every order needs 4 minutes for the production step cutting (Section 4.4.). Fourth, most changeovers are needed between every order. For laminating and printing this is only needed between different laminate and paper types. This automatically means that for these steps, orders can be scheduled strategically to reduce changeover time. Fifth, question marks are placed at the maintenance times and frequencies of the printers. Section 2.2.2. provides an explanation of how this information is calculated and determined. This is not added to Table 3 as multiple separate maintenances are distinguished for the printers.

Prod. step	**Nr.**	**Proc.**	**Change O. (min)**	**Between**	**Maint. (min)**	**Freq.**	**Cal. (min)**	**Freq.**
Printer:								
HP30.000	1	3400 sh/h	5	Paper type	?	?	15	4/day
HP12.000	1	1750 sh/h	5	Paper type	?	?	15	4/day
Other:								
Stapling	1	200 p/h	10	Order	10	1/day	-	-
Die cutting	1	300 p/h	20	Order	10	1/day	-	-
Digital die cutting	1	20 p/h	5	Order	5	1/day	-	-
Wire-o	1	100 p/h	10	Order	15	1/day	-	-
Drilling	2	75 d/h	10	Order	10	1/day	-	-
Creasing	1	500 p/h	5	Order	10	1/day	-	-
Perforating	1	400 p/h	15	Order	10	1/day	-	-
Folding	1	3000 p/h	15	Order	10	1/day	-	-
Laminating	1	500 p/h	5	Laminate type	10	1/day	-	-
Stitching	1	500 p/h	15	Order	10	1/day	-	-
Perfect binding	1	200 p/h	15	Order	10	1/day	-	-
Cutting	2	4 min/o	1	Order	10	1/day	-	-

Table 3: Measurements current situation

Legend:

- Prod. Step = Production step
- Nr. = Number of machines
- Proc. = Processing time
- Change O. = Changeover time
- Maint. = Maintenance time
- Freq. = Frequency
- Cal. = Calibration time
- sh/h = Sheets per hour
- p/h = Products per hour
- d/h = Drills per hour
- min/o = Minutes per order

2.2.2. Determining the maintenance time of the printers

In contrast to the other production steps, there is data available for the maintenance times for printers. The web2print orders are always printed on digital printers because of the fast conversions (Section 2.1.1.) This saves time and makes faster production possible. Faster production is preferred as the web2print orders often have a close due date. Ovimex has two digital printers, the HP12.000 and the HP30.000 (Section 1.1.1.).

To retrieve the needed data from the two printers, we use the PrintOS tool. This is a tool designed by HP, the manufacturer of the machines, and gives insight in the performance of printers. In the PrintOS tool, maintenance is divided into three subcategories: failure recovery, jam recovery and restarts. Jams occur when paper is blocked somewhere in the printer. Failures are all other types of errors that can occur. One of the operators explained that these failures are often caused by errors from a motor or ink. Restarts are preventive maintenance. For each of these subcategories a calculation in Excel is made to determine the average duration and the average frequency of such an event (Appendix 8.2.). Because of the form of the data, the variability could not be determined. However, we do add variability to the model (Section 4.4.). The procedure proceeds as follows:

- **General:** For this calculation, data from 29-01-2020 until 29-04-2020 is used (the past three months when performing the calculations). This period includes 66 working days. On each of these days, the printers are switched on for a certain amount of time. This time is called uptime. The average uptime of the HP12.000 was 16 hours per day (24 hours) and for the HP30.000 10 hours per day. These averages are based on the estimation of the production floor manager because these times differ slightly on different days. Though, it is safe to assume that these estimations are accurate.
- **Failure/jam recovery:** From the PrintOS tool, we retrieve the total number of failures/jams in the appointed period and the percentage of failure/jam recovery time. The total number of failures/jams is converted into failures/jams per day. The total failure/jam recovery time per day was determined by the taking the corresponding percentage of the average uptime per day. The average duration of a failure/jam is calculated by dividing the failure/jam recovery time per day by the average number of failures/jams per day (both calculated previously). The time between starts of failures/jams was calculated by taking the uptime and dividing it by the average number of failures/jams per day. This could subsequently be used to calculate the time until a next failure/jam. This is done by subtracting the average duration of a failure/jam recovery from the time between starts of these events. Tables 4 and 5 provide the outcomes.
- **Restarts:** For the calculation of restarts, the number of restarts and their separate lengths are retrieved from the PrintOS tool. The average length of a restart was determined by using the Excel function 'average'. The number of restarts per day and time between restarts are

calculated using the previously explained method. Table 6 provides the corresponding results.

	#failures per day	Average time of failure (min)	Time until failure (min)
HP12.000	8.2	11.7	105
HP30.000	4.4	17.8	118.8

Table 4: Failure calculation outcomes

	#jams per day	Average time of jam (min)	Time until jam (min)
HP12.000	11.7	7.4	74
HP30.000	2.5	14.1	221.6

Table 5: Jam calculation outcomes

	#restarts per day	Average time of restart (min)	Time until restart (min)
HP12.000	0.5	6.2	1753.8
HP30.000	0.6	4	1066.3

Table 6: Restart calculation outcomes

2.3. Conclusion

In this chapter we discussed the current situation of Ovimex. Goal was to get a thorough understanding of the production process and the duration of certain events within. The chapter was centered around the following question:

- 'How is the production process of Ovimex structured?'

First, we discussed two versions of the flowchart (Section 2.1.). These flowcharts were based on the information retrieved while answering the main question: 'How is the production process of Ovimex structured?'. Interviews were held, and internal documents were investigated to find out which product types are available, what production steps are possible and what other actions are needed in the production process. Seventeen types of products are produced by Ovimex using printers and 11 remaining production steps. Important steps in the process beside the actual production steps are scheduling orders, grouping orders, setting up machines, storing orders and transporting orders. Important aspects of the production process are the close due dates, the different production step sequences, and the print session at 18:00 every day. The second version of the chart serves as basis for the model (Chapter 4.). This version was constructed as a simplified version of the detailed flowchart we discussed in Section 2.1.5. The second version only consists of the key activities in the production process of Ovimex that we plan to incorporate in our model (Figure 4). Both charts were checked at Ovimex to validate that the production process is understood correctly.

Second, the durations of certain events were measured or calculated. The respective measurements were processing rate, changeover time, maintenance time and calibration time for all production steps (Table 3). These measurements and calculations gave an idea of the length of this process and are needed for our model (Chapter 4.). The information for example showed that setup time can be saved at the laminating and printing step, by grouping certain jobs.

3. Literature review

In this chapter, we review literature. This chapter is divided in two separate parts. First, we review research regarding the problem at hand (Section 3.1.). This regards how solutions are found to similar problems as our problem. This also includes potential strategies. Second, priority rules are explained (Section 3.2.). This includes how these rules should be chosen for experiments, the rules that are reasonable to consider, and the way experiments should be performed. This chapter focusses on answering the following questions:

- 'What methods are currently used to decrease waiting time at small production companies?'
- 'What difficulties arise when implementing such methods?'
- 'How should priority rules for the experiments be selected?'

3.1. Research

The first part of this literature review focusses on research focusing on likewise problems. The goal is to determine what techniques and strategies are used to decrease waiting time. The focus lies on companies or situations that are comparable to the current situation of Ovimex. As mentioned, Ovimex schedules orders FIFO and combines orders at certain machines to save setup time (Section 1.1.1.).

3.1.1. Reactive scheduling

The most relevant parts of Ovimex' current situation are their production strategy, the arrival of orders and the complexity of their production process. We have already discussed that products are only produced when orders have arrived (Section 1.1.1.). This production strategy is called make-to-order (Gawronski, 2012). The order arrival at Ovimex is diverse. Orders can arrive that are due in three days, but orders can also arrive that have to be produced and shipped on the same day. This means that the information regarding the jobs to produce, constantly changes. Ovimex has a wide variety of products that all have a different sequence and number of production steps. Thereby, processing times per station differ per product. Such a system is called a dynamic or complex job shop (Wisniewski et al., 2012) (Eguchi et al., 1999). For such constantly changing environments, reactive scheduling is a good solution (Xanthopoulosa, Koulouriotisa et al., 2016). This type of scheduling can react to unexpected events and takes the new production information that is continuously arriving into account (Branke et al., 2016) (Xanthopoulosa et al., 2016). Ovimex currently uses reactive scheduling as well. The challenge of this project is to find a better way of doing so.

3.1.2. Priority rules in reactive scheduling

One way of reactive scheduling that has proven to work in many situations is the use of priority rules, or in other words, dispatching rules (Branke et al., 2016) (Xanthopoulosa et al., 2016) (Eguchi et al., 1999). When multiple jobs can be chosen for a certain activity, these rules attach priorities to the jobs, to determine which job should be processed first. Prioritizing the jobs takes place at the last possible moment. Namely, when the machine or employee is ready to receive a new job (Xanthopoulosa et al., 2016). To clarify, there is no predetermined schedule. Because of the rapidly changing environment, it is hard to determine if a certain rule or combination of rules is optimal. Therefore, research is often aimed towards finding a rule that works very good instead of a rule that is known to be the best possible (Eguchi et al., 1999). An advantage of priority rules is their ability to handle complex systems. Because of the high variety of situations that occur and the rapid changing environment in the production process of Ovimex, priority rules can be used conveniently. Implementation of these priority rules can often be done relatively easily. No huge changes in the production process are needed.

Which priority rule or set of rules generates the best results is highly system dependent (Branke et al., 2016). Theory suggests distinguishing the attributes or goals that are most relevant for the system and design a custom priority rule or use an existing one (Branke et al., 2016). Examples of attributes are processing times, setup times, waiting times, due dates etc. To test whether certain rules work, models are used to apply the rules to. The outcomes can be compared to the outcomes of other experiments (Gawronski, 2012) (Eguchi et al., 1999). Simulation models are a good way of testing these priority rules (Wisniewski et al., 2012), but there are other possibilities of testing these rules as well. The focus during this project lies on priority rules. We do perform some other experiments as well. Chapter 5. provides an explanation of these experiments.

3.2. Priority rules

In this second part of the literature review we focus on the priority rules to experiment with in the model. This includes what aspects to consider when experimenting with such rules, and which rules to consider suitable. The focus lies on how to match priority rules to the specific environment that is dealt with. This Section provides an explanation of the priority rules we use in our experiments and reasoning why. Chapter 5 explains the exact experiments as these are dependent on the structure of the simulation model.

3.2.1. Method

As mentioned earlier, Ovimex currently schedules the production of orders FIFO (Section 1.1.1.). Ovimex also combines some jobs to save setup time at several stations. This can be summarized as using a priority rule called SIMSET (Gawronski, 2012). It is shown that a lot of (combinations of) priority rules improve a situation that uses FIFO (Richter & Winkler, 2017) (Koruca & Aydemir, 2014) (Gawronski, 2012) (Wisniewski et al., 2012). These priority rules do not only improve the throughput time and reduce the waiting time. They often have a positive impact on the number of backorders and the production capacity as well. To determine which priority rules to test, it is important to know which goals are important for Ovimex (Section 3.1.2.). This project is dedicated to decrease waiting time and throughput time. Time related priority rules must therefore be considered. Ovimex' orders also have a due date on which the production process should be finished.

Our experiments are performed to generate information regarding the performance of certain rules. We use the information to further optimize the overall strategy. This way of learning from and doing experiments is based on hyper-heuristics. These heuristics generate optimal priority rules for a specific problem by using performance measurements of certain rules to learn (Branke et al., 2016). This way of learning is called unsupervised learning. Heuristics can also learn supervised. During supervised learning cycles, the heuristic receives 'good' schedules from relatable problems to learn from (Branke et al., 2016). As the problem of Ovimex is very specific, this type of learning is irrelevant. We do not use a hyper-heuristic but, perform experiments and learn from the results in the same manner as hyper-heuristics do when learning in an unsupervised way. After a rule is tested, the results are used to determine if the rule is promising or not.

3.2.2. Time and due date related rules

One single priority rule for an entire system often has poor performance (Richter & Winkler, 2017). Combinations of multiple priority rules (Gawronski, 2012) or different priority rules at different workstations (Wisniewski et al., 2012) generate better results. We discuss a few existing priority rules that have been proven to work in several other comparable situations.

Min Slack (MS) is a priority rule that is proven to be very efficient in decreasing waiting and throughput times in dynamic environments (Richter & Winkler, 2017) (Xanthopoulosa et al., 2016). The rule also takes the due date into account. Slack is calculated by subtracting the remaining processing time from the time until the due date. The job with the lowest slack is prioritized. The slack depends on the time at which the priority is calculated. Because these values constantly change, this is called a dynamic priority rule (Pinedo, 2009). Another way to deal with due dates is using the Earliest Due Date rule (EDD). Possibly in combination with other rules (Richter & Winkler, 2017) (Koruca & Aydemir, 2014) (Gawronski, 2012) (Wisniewski et al., 2012) (Xanthopoulosa et al., 2016). Because the due date stays the same during the entire process, this value is not time dependent. We call such rules static priority rules (Pinedo, 2009). Other rules that take the time until the due date into account are the Most Operations Remaining (MOR) and the opposite Least Operations Remaining (LOR) (Wisniewski et al., 2012). These rules prioritize jobs on the number of steps that remain in an order's process. A priority rule that does not look at the number of remaining operations but the queue at the workstation of the next operation is the Shortest Queue Next Operation (SQNO). This rule prioritizes the job of which the next operation has the shortest queue at its workstation. This to divide the load over the other machines and to create a better throughput (Pinedo, 2009). A rule that has a proven positive impact on the waiting time is Shortest Processing Time (SPT) (Koruca & Aydemir, 2014) (Gawronski, 2012). This rule prioritizes jobs that have the shortest processing time. The waiting time of these jobs decrease which lowers the overall waiting time as well. We do not use the Weighted Shortest Processing Time (WSPT) (Pinedo, 2009) as Ovimex explained that they do not value certain orders or clients higher than others. Thereby, the due date is not used to attach weights as the EDD, and MS rules are used for the due date aspect. This is also the reason we do not use Apparent Tardiness Costs (ATC). We do not attach weights to certain orders or clients and we already use MS, SPT, EDD and combinations of these rules. The last rule that we do use is the Similar Setup (SIMSET) rule. Ovimex has already integrated this rule in a part of their company. The rule also has good results in combination with several of the previously mentioned rules (Gawronski, 2012).

The discussed existing priority rules all improve a certain situation in which only FIFO was used. Thereby, these rules are related to at least one of the three goals that are the most important to Ovimex. These are respectively reducing waiting time, reducing throughput time, and delivering on the due date. For now, we consider all these 7 priority rules as possibilities for the experiments. Table 7 provides an overview of all the priority rules we use in this project and their abbreviations. Chapter 5 provides the exact structure of the experiments.

Priority rule	**Abbreviation**
MinSlack	MS
Earliest Due Date	EDD
Most Operations Remaining	MOR
Least Operations Remaining	LOR
Shortest Queue Next Operation	SQNO
Shortest Processing Time	SPT
Similar Setup	SIMSET

Table 7: Priority rules

4. Model

In this chapter, the model is discussed. The model is based on the flowchart (Figure 4) and previously gained knowledge about products, production steps and planning procedures. First, the choice between a deterministic and simulation model is made and argued (Section 4.1.). Afterwards, an arrival distribution is determined (Section 4.2.). Lastly, we discuss how all aspects of the production process of Ovimex are represented in the model (Section 4.5.). This explanation is expanded with a list of assumptions (Section 4.4.). To make sure that the model is a valid display of the reality, the list of assumptions and the values of the Key Performance Indicators (KPIs) are checked with Ovimex. The KPIs are based on the variables that the board of Ovimex value. If they confirm that these are reasonably similar to the reality, the model is seen as a valid and reliable representation. This chapter is focused on the following questions:

- 'How should a model be constructed to represent the production process in a valid way?'
- 'What order arrival distribution represents the current situation of Ovimex accurately?' 'What are the relevant order characteristics and how should they be represented in the model?'
- 'Which Key Performance Indicators should be chosen?'

4.1. Deterministic vs. Simulation

The choice of the type of model to use fell between a deterministic and simulation model. Section 1.3.3. already briefly explained that the simulation model is the chosen option. This section expands this explanation with some more reasoning. This is based on the findings in the previous paragraphs.

The simulation model and deterministic model were considered the most because of the make-to-order tactic Ovimex uses in their production process (Section 1.3.3.). Both the simulation model and deterministic model can handle such strategies well. Other methods and models were considered briefly but turned out less desirable.

During the design of the flowchart, the interviews, and the conversations with the production floor managers, a simulation model appeared to be the best option. This choice is based on a couple of factors. First, a deterministic model works the most convenient if days can be considered as separate independent units. The model could be designed with the goal to determine the best strategy for several of these units. Each of these units would represent a certain day. Strategies that work best in one or multiple units could be included in the recommendation. In one of the interviews with a production floor manager, he explained that days cannot be presumed as independent. Production steps of orders are often moved to different days based on their due date (Section 2.1.4.). Thereby, most orders are produced on multiple days. Second, the uncertainty of order arrivals can be represented very convenient in the simulation model based on historic order arrival data. Third, because the days could not be assumed as separate independent units, the only good alternative deterministic model seemed to be a model that determines which orders to move to another day. To clarify, this model could determine which orders to produce on the same day as arrival and which to move to a subsequent day. A simulation model is expected to find a better solution as only a small portion of orders are entirely moved to a next day.

The simulation model is made in Tecnomatrix Plant Simulation. This program is developed by Siemens and was taught in the second year of the IEM bachelor. The reason for the choice of this program is the gathered experience during the bachelor, the available tutorial at the University website and the free license via the University of Twente.

4.2. Arrival distribution orders

In this section, data of real order arrivals are translated into an arrival distribution. The goal is to represent the real situation at Ovimex as accurate as possible and to answer the sub-question: 'What order arrival distribution represents the current situation of Ovimex accurately?' In the arrival distribution no difference is made between separate categories. This because no relation is found between category type and timing of an order arrival. Section 4.3. explains how categories are assigned to arriving orders.

As explained, we derive the arrival distribution from historic data. The data holds the arrived orders from January and February 2020. Of all days on which orders are received, 40 are considered 'normal' working days. Weekends are excluded because almost every Saturday and Sunday, zero orders are received. We exclude January 1st, 2nd, and 3rd as well as there are considerably less orders received on these days compared to the other working days. This can be explained by the celebration of New Year's Eve. To be able to represent the real situation accurately in the simulation model, the data is compared to different distributions.

We compare the order arrivals per day because Ovimex plans the production per day and we expect to see a trend in arriving orders per day. Thereby, order arrivals per day is a stochastic variable that can be compared to a distribution. How arrival differences between hours are made is explained afterwards (Section 4.2.1.). The procedure of comparing this data to distributions is as follows. First, we divide the data set into subgroups. The number of orders received on a certain day is considered as a data point. These data points get divided into the subgroups based on their value. In this comparison the groups are 0-10, 10-20 etc. We form groups of size 10 as we do not have a huge amount of data points. Thereby, the data points are diverse enough to fall into different groups. Second, distribution-frequencies are determined using Excel functions. Third, the real frequencies are compared with the distribution-frequencies and we investigate if significant differences are visible. A difference is nearly always visible. If the difference is too large, the distribution cannot be used to represent the dataset.

As mentioned, the data is divided into subgroups of size 10 (Table 8). To judge if the similarity is satisfactory, a chi squared test is done. This test gives a numerical value to the difference between the real data and the distribution, based on the following formula:

$$\mathrm{X}^2 = \frac{(real - distr)^2}{distr}$$

The sum of all X^2 values are compared to a critical value based on the probability of error, in this case taken as 0.05, and degrees of freedom. Degrees of freedom is calculated by taking the number of subgroups and subtracting 1, gives 13.

Because of the higher concentration of data points at and around the 170-180 group, the data is compared to the normal distribution first. This distribution has high frequencies around the mean that flatten as the numbers get farther away. The second comparison is made with the gamma distribution because the form of the graph does not follow a normal distribution completely (Figure 5).

Subgroup	Frequency
130-140	1
140-150	2
150-160	5
160-170	4
170-180	8
180-190	3
190-200	5
200-210	3
210-220	2
220-230	2
230-240	2
240-250	1
250-260	1
260-270	1

Table 8: Observed frequencies

The comparison with the normal distribution (Figure 5) gives X^2= 10.3 and a critical value of 22.4. The X^2 value is below the critical value. This means that, based on this data, there is not enough evidence to reject that the data set follows a normal distribution. The lack of evidence is partly caused by the small data set. Unfortunately, Ovimex does not have a larger data set at hand.

For the second comparison, we compare the data set with the gamma distribution (Figure 6). This comparison returned X^2= 7.5 with the same critical value of 22.4. This means that there is even less evidence to reject that the data follows a gamma distribution. This second test proves that it is more likely that the data follows a gamma distribution instead of a normal distribution. The number of arrived orders per day therefore follow the gamma distribution in the simulation model.

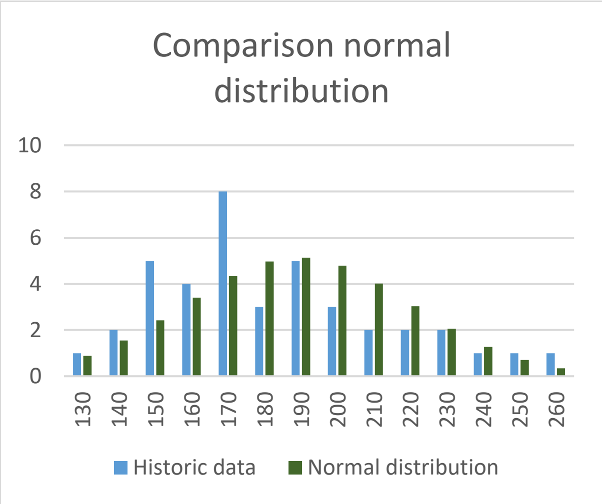

Figure 5: Comparison normal distribution

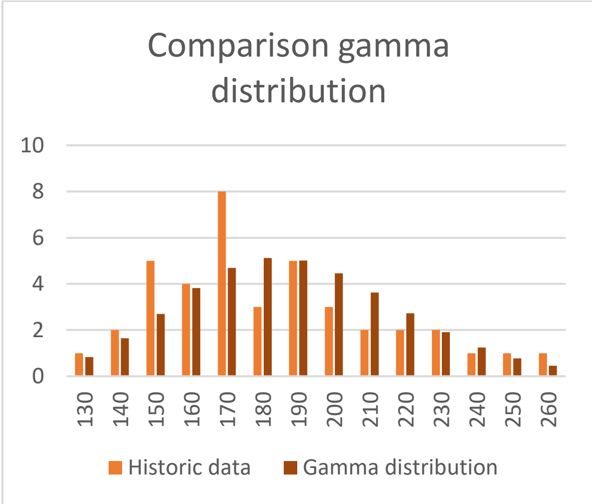

Figure 6: Comparison gamma distribution

4.2.1 Hourly order arrival

As the order arrival per day is acquired, we can investigate the variety on the day itself. To determine this variety, the same data set is used. First, all orders in the data set were divided into groups based on their hour of arrival (Figure 7). It stands out that more orders are received in the middle of the day compared to the early morning and late evening. This seems logical as most people's daily routine starts in the morning and ends in the afternoon.

To mimic the higher frequency of order arrivals in the middle of the day, the percentages of order arrivals during the respective hours are used. If for example 20% of all orders arrive between 14:00 and 15:00 in the investigated data (Figure 7), 20% of the arrived orders per day, determined by the gamma distribution, arrive between 14:00 and 15:00 in the simulation model as well. Because the number of arriving orders per day varies due to the gamma distribution, receivals per hour vary as well.

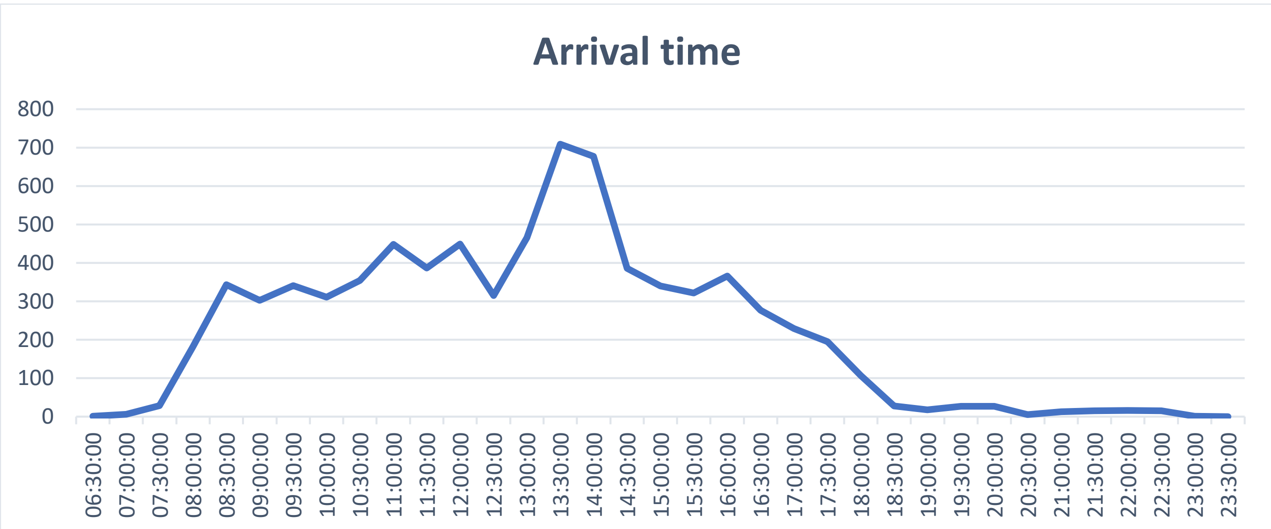

Figure 7: Arrival times of received orders

4.3. Order characteristics

In the Section 4.2. we discussed the arrival distribution representing the arrival of orders of Ovimex. In this section, we discuss the characteristics orders have, and how these should be represented in the model. We cover the order characteristics that are distinguished and how to represent these in the model. We use the same data set as we did for the determination of the arrival distribution (Section 4.2.). In this data set all arrived orders are shown together with their unique order information. The following information is used:

- Order category
- Number of products ordered
- Number of pages per product
- Paper type
- Production steps that are needed
- Dimensions of one product (length x width)

4.3.1. Order category

At Ovimex, 17 different order types are designed to group orders. Ovimex mainly does this to give employees of the company an idea of the production steps and size to expect (Section 2.1.1.). Due to the small size of certain groups, similarity of production steps of different groups and the inconvenience of having many groups, seven groups are deduced from the original seventeen (Table 9). Types B3, B4 and B5 are combined because they are all brochures. These types are similar in their plurality of pages. Types B1 and B2 are combined since they often need similar production steps. All types that are combined as 'other' are types that are relatively small (Table 9) and have little similarity to other categories. Type A6 was not added to category 'other' because these products must always be printed on the HP30.000 in contrast to the other types in category 'other'. Type C1 was not added because the products in this category always need the exact same production steps and have the exact same size. Not all categories Ovimex uses are represented in these 7 categories because some categories, as for example books PUR (B6), are never ordered via the web2print tool. The tool does not support these types of products yet.

For each category, the percentage of total orders that has that particular category is calculated (Table 9). These percentages are used in the model to give each order a category. For example, approximately 17% of all arrived orders in the model will have the category 'commercial print'.

Category	**Original type**	**Percentage (%)**
Brochures	B3, B4 & B5	6.7
Business cards	C0	36.6
Carton	A6	1.3
Commercial print	A1	17.0
Flyers	B1 & B2	29.0
Writing paper	C1	0.6
Other	B8, B9, C2 & C4	8.9

Table 9: Order categories

4.3.2. Method other characteristics

Beside the category, an order has five characteristics that are considered during this project. These characteristics have an influence on processing times, the path an order follows through the company and the overall throughput time. These characteristics are determined using the information from the data set (Section 4.3.). We consider the following characteristics:

- Amount
- Paper type

- Size
- Production steps
- Up

Amount represents the number of products that is ordered. Paper type typifies the type of paper a product is made off. Size constitutes of the number of pages per product. We assume that each of these pages have the same dimensions (length * width) and imprint (Section 4.4.) because the extra printing time needed when such differences occur is negligible. Thereby, it is assumed that all pages are printed on the same paper type as the request to print on different paper types barely ever happens. Production steps include all production steps needed to finish a product excluding printing and packaging. As mentioned, it is assumed that all products need cutting (Section 2.1.2.). This production step is therefore not mentioned in this part. Up states how often one page of a product can fit on one sheet. Printers print sheets (Section 2.2.1.). The processing rate is therefore dependent on how often a product fits on one sheet. Each paper type has a specific sheet size. Because these are almost all 750x530 mm and all others differ only slightly, 750x530 mm is considered as the only sheet size (Section 4.4.).

In the model, every order receives a value for each of these properties. These values are based on historic data in the same way we discussed in Section 4.3.1. For each of these properties, we calculate percentages for the different possible values (Table 9). These percentages are derived from the data set. Because orders can be very different, we analyze data within the distinguished categories. Within these groups, we should see little variety which results in more accurate results. For example, a product cannot consist of one page and need the production step stitching. Because we analyze data within the categories, such mistakes are filtered out.

For up, only the standard dimensions big, A3, A4, A5, A6, A7 and small have been distinguished with respective up numbers of 1, 2, 4, 8, 16, 32 and 50. Clients are able to design a custom length and width of the product. Due to the data form and difficulty of calculations we do not consider these dimensions (Section 4.4.). Thereby, most orders request one of the standard dimensions.

4.3.2.1. Due date

Beside the characteristics discussed in this section, orders also receive a due date. We do not discuss this due date in detail as there is no data available regarding this characteristic. The due date can range from the day on which the order arrives till 3 days later. Giving this due date is based on interviews with the production floor manager. He explained that approximately 81% of the arrived orders is due one day after its arrival, 2% 2 or 3 days after arrival, and 17% is due on the same day of its arrival. Being due on the same day is only possible if the order is ordered before the corresponding specified deadline (Section 2.1.4.). We use these percentages to give due dates in the same manner as the other characteristics are given. Percentages change when order deadlines for that day have passed.

4.3.3. Outliers

Because of the large amount of data, we can expect that outliers are present. Outliers are data points that differ a lot from the other data points in the set. Not excluding these data points might give an incorrect view on the reality. Therefore, outliers should be detected and adjusted or deleted.

Most methods available to detect outliers are designed for numeric data. The properties paper type and production steps consist of text which eliminates these possibilities. There are a few methods available to detect outliers for non-numeric or categorical data, but most of these methods are dependent on context. Because, for an outlier to exist, there must be a measure of distance (Haslbeck, 2018). In the context of these two properties there is no measure of distance. There is no paper type 'in between' two other paper types. Other methods use numeric values to describe categorical data. This could for example be done by weighing the count of certain parts of the categorical data point. For example, every time a data point includes the letter 'z', 10 is added to the total weight. This would be used to attach a numeric score to the data point (Rokhman et al., 2017). This is also not preferable in this context as this would get a very lengthy process. Thereby, these methods are often used for a set of unique data points. In our case there are a lot of similar data points. Because no sufficient method has been found, we eliminate data points that occur less than 1% in the data set of order arrivals in January and February. We apply this value because it does not influence the variety of possibilities but eliminates all unlikely events that only occur one or a few times.

Next to categorical data, there are also three characteristics that hold numeric data. As mentioned, these are amount, size and up (Section 4.3.2.). Due to time considerations and sample size, which is 7713 orders, lengthy methods as Grubbs' test (Grubbs, 1969) of outliers and z-scores (Frost, 2019) are not used. The simple but effective method boxplot (Frost, 2019) seemed like a good solution.

4.3.3.1. Boxplot method

We try out the boxplot method on the amount of business cards. A total of 2822 orders are placed with different amounts ordered. To design the boxplot, a so-called five number summary is needed consisting of the minimum, first quartile, median, third quartile and maximum. By the means of Excel functions these are found relatively easy (Table 11). A lower and upper limit, numbers outside these limits are considered outliers, were calculated using the IQR rule (Frost, 2019). Result of this calculation was that 1336 data points of the total 2822 data points are considered outliers. This number is far too high. Table 10 shows that peaks are positioned at rounded numbers. For example, 507 orders of 50 business cards are placed. With the current calculation of the lower limit (Table 11), these are all considered as outliers.

To be able to consider all the important data points we use the same rule for the numeric data as we do for the categorical data. Reasons are the before mentioned elimination of unlikely events and the convenience of using the same rule for all characteristics. To clarify, all data points that occur less than 1% are eliminated.

Amount	count	percentage
25	22	0,8
50	507	18
100	1440	51
150	22	0,8
200	99	3,5
250	144	5,1
300	39	1,4
400	19	0,7
500	218	7,7
600	13	0,5
750	16	0,6
1000	95	3,4
1500	12	0,4
2000	19	0,7
Other	157	5,6

Table 10: Business cards, amount

box plot products ordered	
min	1
Q1	100
median	100
Q3	125
max	55750
IQR*1,5	37,5
lower	62,5
upper	162,5

Table 11: box plot

4.3.4. Characteristics brochures

The first group of orders, as explained, consists of the three original groups B3, B4 and B5 (Section 4.3.1.). These original categories all consisted of a separate group of brochure orders with different binding production steps. However, these products are often similar in size, up and paper type. Notable is that almost all products need a production step that ties different pages together. These are stitching, stapling and PUR (Figure 8). The small amount of orders that does not need such a step, is for example tied by the customer self.

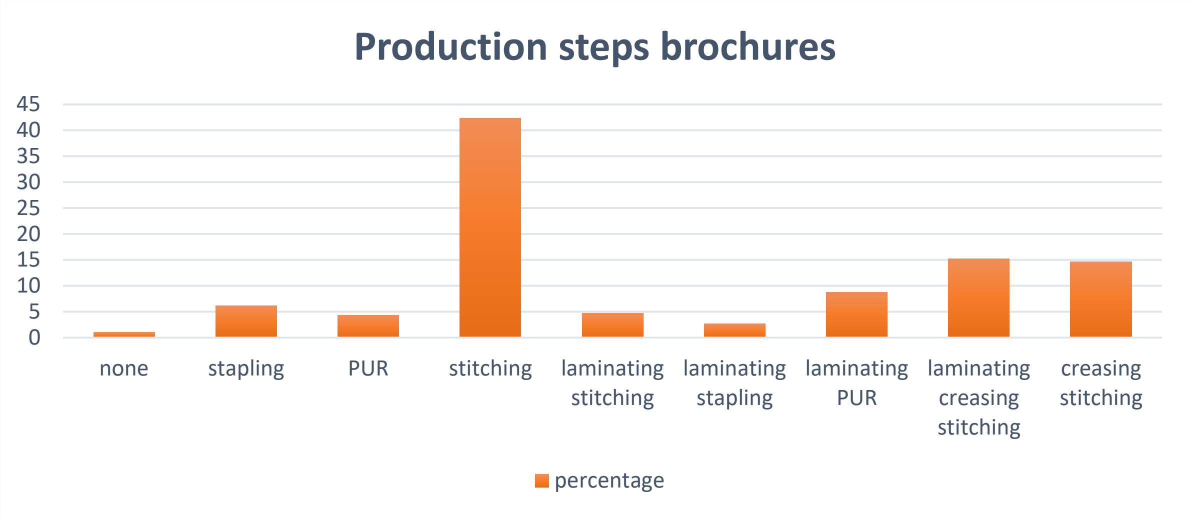

Figure 8: Brochures, production steps

For the paper types of brochures, it stands out that there are a few popular types. Mc silk, Maxi offset and Mc gloss are used very often while other paper types barely get chosen (Figure 9). The size of brochures is, as expected, always multiple pages long. Figure 10 shows that a wide variety of sizes is chosen.

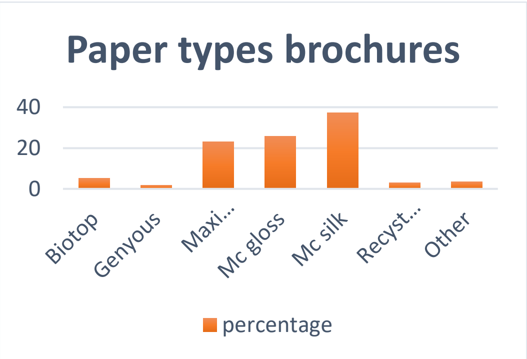

Figure 9: Brochures, paper types

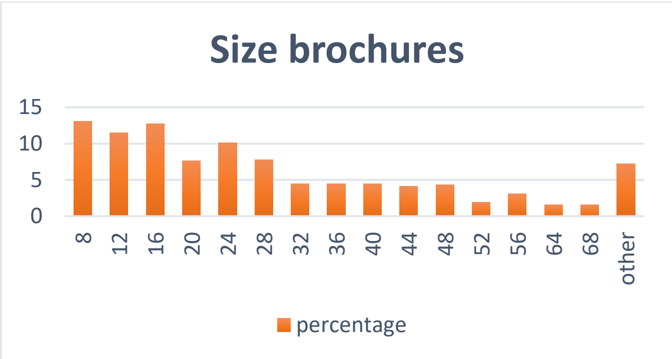

Figure 10: Brochures, size

Most often small brochures are made of A4, A5 or A6 (Figure 11). The production floor managers explained that multi paged orders often have smaller dimensions. The amount peaks on round numbers like 50 and 100 (Figure 12). It stands out that brochures are ordered in relatively small amounts. Section 4.5.2. explains how these percentages are used in the model.

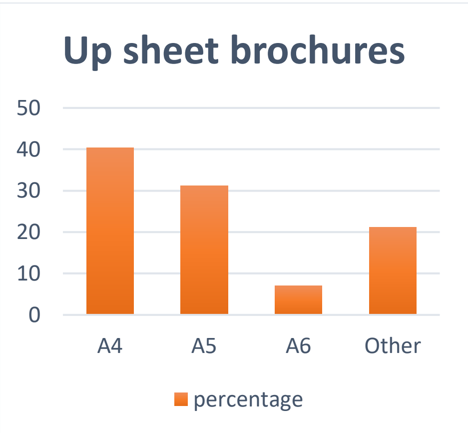

Figure 11: Brochures, up

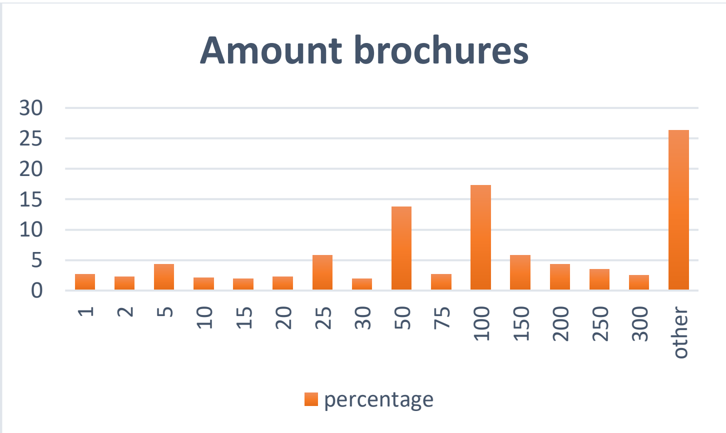

Figure 12: Brochures, amount

4.3.5. Characteristics other

Because the method of finding the percentages for each category is very alike, not every category is discussed. Appendix 8.3. provides small discussions and graphs of the categories that are not discussed in this chapter. The category that we do discuss in the detail is the category other. This category is a combination of the remaining categories that were either not big enough or did not have enough in common regarding the characteristics to become a separate category. We therefore expect a lot of diversity. For the characteristics paper type and size this is indeed the case. Because this was expected, and no additional remarks are needed we do not discuss these graphs.

What we do discuss, are relations between differences in size and the other properties. In all categories almost all products consisted of multiple pages or overwhelmingly consisted of one page. This made a relation between size and other properties obsolete. The 'other' category is the only category with a high variety in sizes of products. Brochures also have a lot of variety in size, but these are all books of multiple pages. The effect that is investigated is the difference between size 1, size 2 and size >2. Figure 13 and 14 show that no binding production steps (PUR, wire-o, stapling and stitching) are needed for 1- or 2-pagers. Though, the difference in production steps between size 1 and 2 is higher than we might expect. For products with a size larger than 2 the previously mentioned binding production steps do occur (Figure 15). The percentages of products that need these steps are quite low. We can explain this by the occurrence of original type B8, loose paged sets (Table 6), in category other. As the name already reveals, these sets do not require binding.

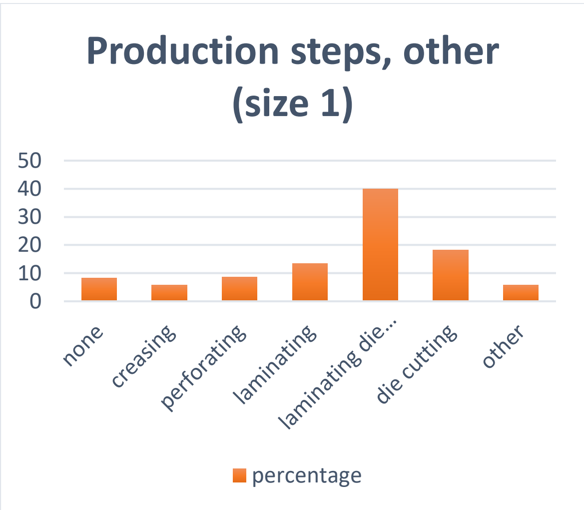

Figure 13: Other, production steps (size 1)

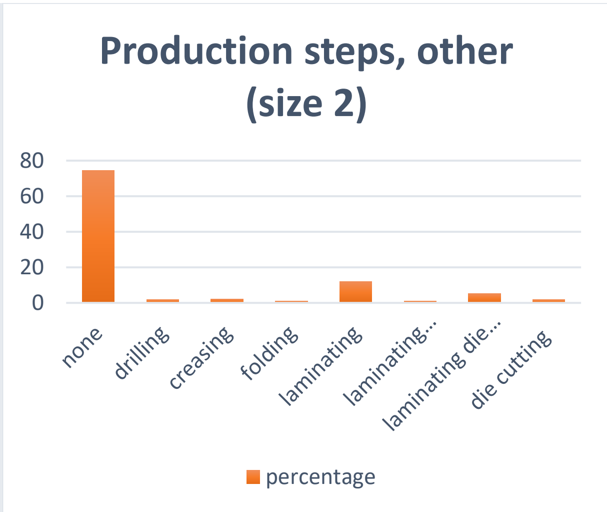

Figure 14: Other, production steps (size 2)

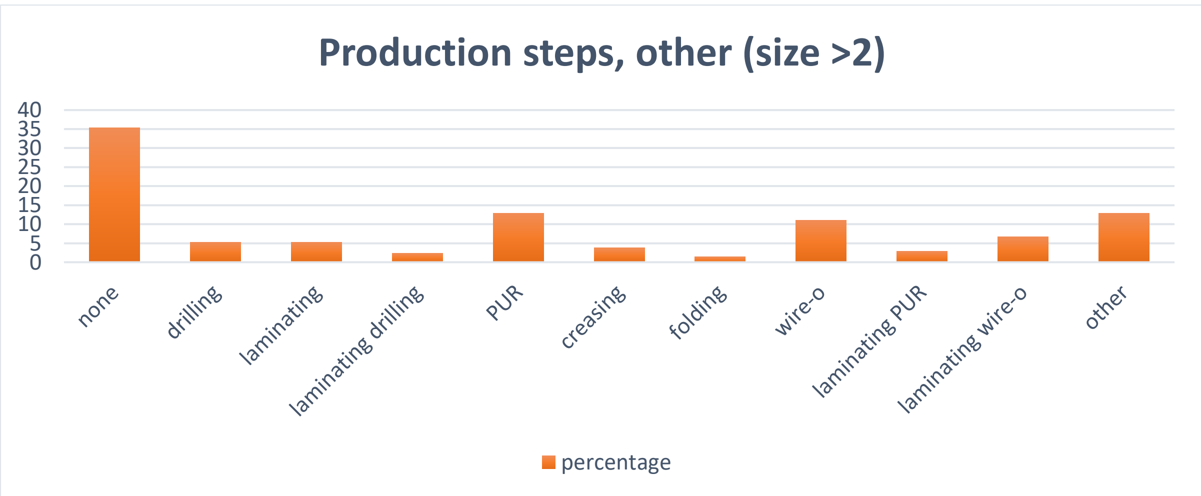

Figure 15: Other, production steps (size >2)

Next to the relationship with the additional production steps, a link is also present between the size and up. The difference occurred when testing size 1 and size >1. Products with size 1 are overwhelmingly large products (Figure 16). Products with size >1 are on the other hand almost never this large (Figure 17). An explanation of this phenomenon is that multi-paged products are more often holding detailed information (often in text form). Examples are books, menu's, instruction manuals and so on. The big products of size 1 often comprise of posters or advertisements.

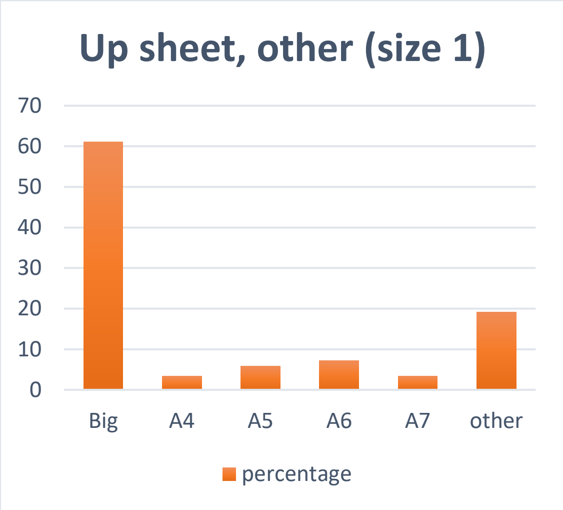

Figure 16: Other, up (size 1)

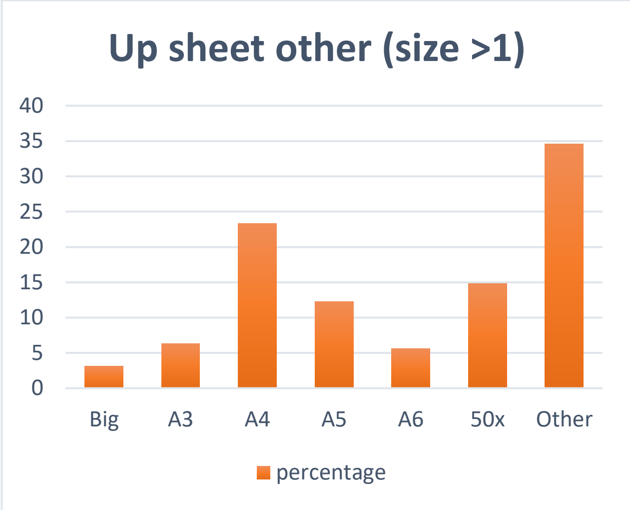

Figure 17: Other, up (size >1)

The last relation that we discuss, is the relation between amount and size. It sounds logical that for example one paged posters are ordered in larger impressions. When the amounts of size 1 and 2 were tested, the two graphs appeared very similar. Therefore, we only distinguish between size 1 or 2 and size >2. As expected, in size 1 or 2, the amounts are often of a higher quantity (Figure 18). Products that have a higher number of pages than 2 are often ordered in considerably lower amounts (Figure 19).

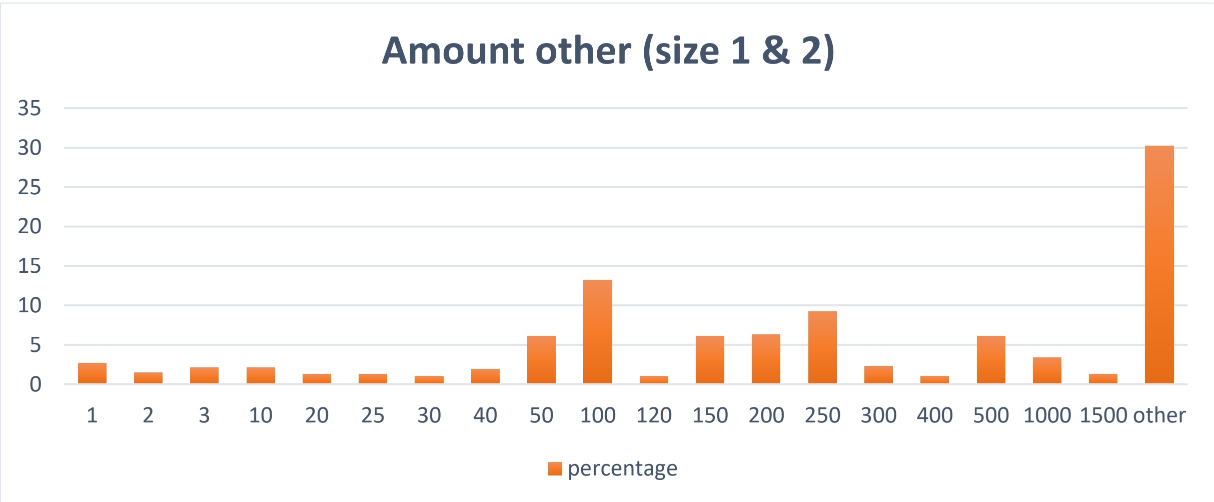

Figure 18: Other, amount (size 1 or 2)

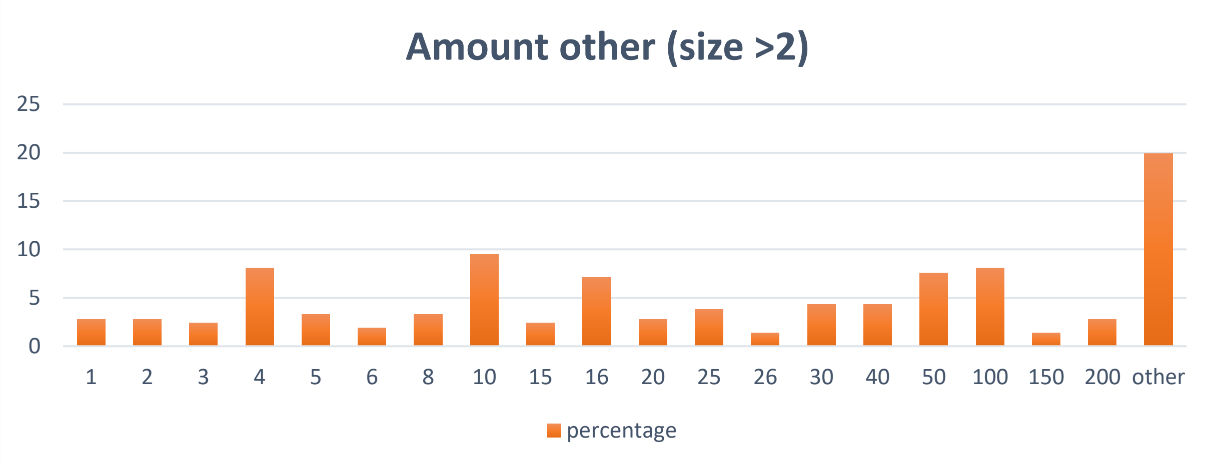

Figure 19: Other, amount (size >2)

4.4. Assumptions

During the design process, certain assumptions had to be made to lower the code complexity. These assumptions are verified with a representative of the management of Ovimex to confirm that they agree with these modelling choices. The assumptions are designed in a way that their influence on the validity of the model is minimal. The list of assumptions is stated below.

List of assumptions

- All products need the production step 'cutting'.
- Cutting jobs all take 4 minutes.
- All pages of a product are the same (paper type, dimensions, and imprint).
- All sheets are 750 x 530 mm.
- Different sized drill holes in one product are not possible.
- The possible number of drill holes in one product ranges from 1 to 6.
- The drilling machine can drill one hole in 100 products at the same time. This counts as one drilling activity.
- Die cutting jobs with an amount < 25 are processed on the digital die cutter. Jobs over 25 are processed on the regular die cutter.
- Production steps other than printing are finished in the evening, even if they are not finished at 22:00.
- Printing jobs that are still waiting to be printed at 00:30 are moved to the storage and are printed the next day at 06:00.
- All paper types that are chosen under 1% in each of the categories do not appear.
- All orders have one of the 7 standard dimensions (related to up size).
- All failures and maintenance activities have a variance of ¼ of the mean.

4.5. Design simulation model

Now that the order arrivals and their characteristics are known. We have all needed input for the simulation model. The flowchart presents a good visualization of the current situation (Figure 4). How to represent the order arrivals (Section 4.2.) and their characteristics (Section 4.3.) is determined previously. In this section, we discuss the simulation model. The flowchart serves as a basis. The assumptions that are made (Chapter 4.4.) are incorporated in this model. We use the finished model for the experiments afterwards. Chapter 5 provides these experiments.

4.5.1. General

First, we quickly walk through the basics of the model. We discuss how the model is constructed and where certain aspects can be found. Goal of this model is to represent the situation of Ovimex in an accurate and clear way. Figure 20 provides a screenshot of the model.

We start this overview with explaining the different building blocks of the model. The model consists of 15 separte blocks of 9 different colors (Figure 20). These colors visualize the type of items the block contains. There are three light green blocks called 'arrival', 'printers' and 'production steps'. The orders flow through these three blocks while being transformed into an end product. These end products leave the system at the light yellow block called 'exit'. During the process there are two storage possibilities. WIP can be stored before it is being printed or after it has been printed. These two storages are located in the red box at the top (Figure 20). The 5 blue blocks contain all code that is needed to support the rest of the model. The bright green block, called 'sorting', contains code that is meant to be altered. This code is changed during the experiments. The purple block called 'statistics' contains order statistics grouped per order and per day. These statistics are used to draw conclusions and give reccomendations. The white block in the top left corner contains all general information for this model. This block controls the day count, the time the production stops and the overall working of the model. The orange block on the right side called 'experiments' is the block that controls the experiments (Section 5.3.). The last part is the grey block on the right side of the model (Figure 20). This block contains all global variables. These variables can be divided into 'input', 'counters' and 'indicators'. We use the indicators during the experiments. Counters are used to keep track of certain aspects that are needed in the code. The input variables are the specified times that we use in this model. Processing starts at 06:00 in the morning. All products due on the current day that are not finished at 22:00 are considered backorders. Processing stops at 00:30 when, if present, jobs are sent to storage (Section 4.5.3.).

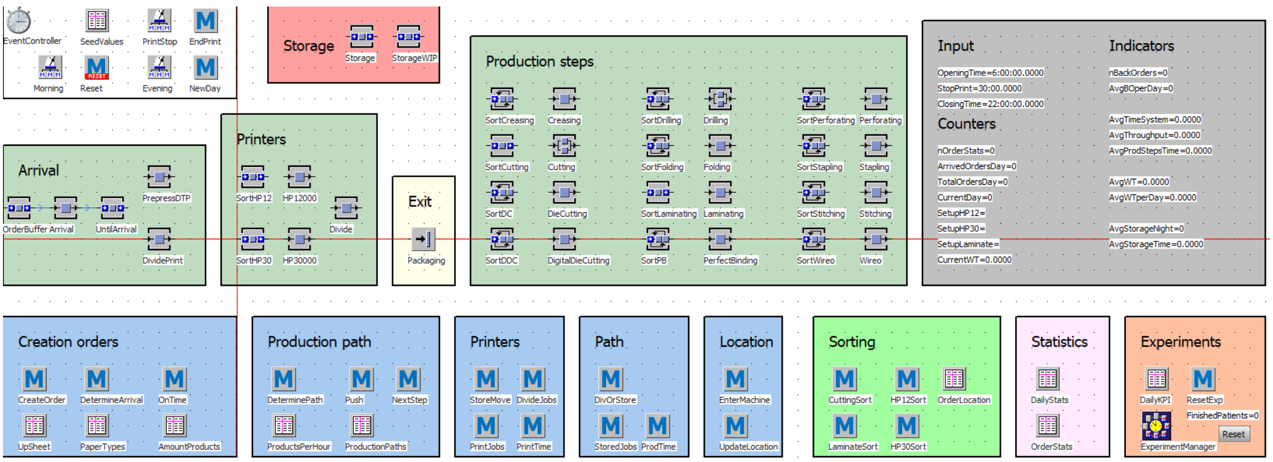

Figure 20: Simulation model

4.5.2. Arrival orders

In this simulation model, orders are represented as moving units (MUs). In the morning at 06:00, the model creates a certain amount of orders based on the gamma distribution (Section 4.2.). Each of these orders are sent to the arrival block. In this block orders receive an hour of arrival. The hour of arrival is based on percentages (Section 4.2.). The exact minute of arrival within this hour is given randomly. After the exact time of arrival is determined, the order stays in the arrival block. To clarify, at this moment the order is not yet actually arrived. The order is moved to Prepress at its exact arrival time, which counts as the real arrival. This arrival is managed by a methCall. Beside the arrival time, orders also receive their characteristics during this arrival sequence. These characteristics are all given based on the percentages determined in Section 4.3.

With the due date, the next destination of the order is determined. If an order is due today, Prepress sends the order to the printers immediately. If it is due tomorrow or even later, the order is stored. Section 4.5.3. explains when stored orders are printed.

4.5.3. Printing

As explained, orders that arrive are either sent to one of the printers or the storage based upon their due date (Section 4.5.2.). We can divide the arriving orders in three groups:

1. Orders that are due on the same day as their arrival day
2. Orders that arrive after 18:00 due on the next day
3. Orders that arrive before 18:00 that are due on the next day or orders that are due 2 or 3 days after their arrival.

Group 1 is the group of orders that gets sent to one of the printers directly. Orders that belong to group 2 are too late to get printed at 18:00 on the day of arrival. Therefore, these orders are stored and subsequently printed on the next morning at 06:00. Orders of group 3 are the orders that can get printed at 18:00. Each order of this group is moved to one of the printers at 18:00 on the day before its due date. Note that the storage of these orders does not take up actual storage space. These orders are not printed yet. These are therefore placed in a separate buffer (Figure 20).

The printer that an order is sent to is dependent on the category the order belongs to. The orders of categories Commercial print and Carton are printed on the HP30.000. All other orders are printed on the HP12.000. Orders ready to be printed are sent to the buffer before the printer. Placing the orders in these buffers first gives us the opportunity to sort the orders. At Ovimex, orders that arrive during the day are printed FIFO. In the evening they group the orders by paper type to save setup time. In the model, all print jobs that arrive at 18:00 at one of the printers are therefore printed in a sequence that is dependent on the paper type. All jobs that are still waiting at 00:30 to be printed, are stored for the night. They return to the buffer the next morning at 06:00.

The processing time of an order is dependent on the size, up and amount properties of the orders. Before the order enters the buffer, the processing time is calculated using the processing rates of the printers of Ovimex (Table 3). The following formula illustrates how these processing times are calculated (in seconds):

$$Processing\ time = \frac{\frac{Amount * Size}{Up}}{rate\ (sheets\ per\ hour)} * 3600$$

Besides the processing and setting up state, printers can also be in failure state. In this state, printers are not able to process an order or to set up for another order. We use this failure state to add the calibrations (Table 3) and the failures, jams, and restarts (Section 2.2.2.) to the printers. To add variability, we assume that each of these events has a variability of 25% of the mean (Section 4.4.). The maintenances and variabilities of all other machines are added similarly.

After an order is printed it can either be stored or moved to its next production steps. The orders that are finished after 18:00 are stored for the night. They are moved to their next production step the next morning at 06:00. Orders finished before 18:00 are moved to their next production step directly.

4.5.4. Remaining production steps

When an order is printed it can be moved to the first step of the remaining production steps. As explained, the order is moved to its next step directly, or on the next morning (Section 4.5.3.). Moving to a next production step is arranged by two attributes every order has. The production path and the step. The path is received at the arrival by means of the percentages (Section 4.5.2.). Step is a counter we use to keep track of the progress of the order. When an order exits the printer the step changes to 1. In a table, all production paths are listed. With the help of the known path and step, the next step is determined. The order is sent to the corresponding buffer or sorter of this production step (Figure 21). The order waits for its turn and gets processed. The processing time is dependent on the processing rate (Table 3) and the amount. When an order exits a machine, the step is updated by adding 1. The order is subsequently sent to the following production step. If an order is finished the next production step turns out to be packaging. The order gets sent to packaging and leaves the system (Figure 20).

When orders arrive at a buffer or sorter, the order looks if it can directly move to the machine. This is possible if the sorter or buffer is empty and the machine is not occupied. If this is not the case, the order waits. As soon as a job leaves the machine, a new job is pulled to the machine. In the current situation, the cutting machine pulls new jobs based on the length of their path. All jobs with more than one step left are prioritized over all jobs that only need cutting (Section 2.1.4.). At the laminating machine this is based on the laminate type to save setup time (Section 2.1.4.). At all other machines, jobs are retrieved FIFO. These machines therefore have sorters instead of buffers. Prioritizing is done by the methods and table in the sorting block (Figure 20). These are the methods that are meant to be altered during the experiments (Chapter 5.).

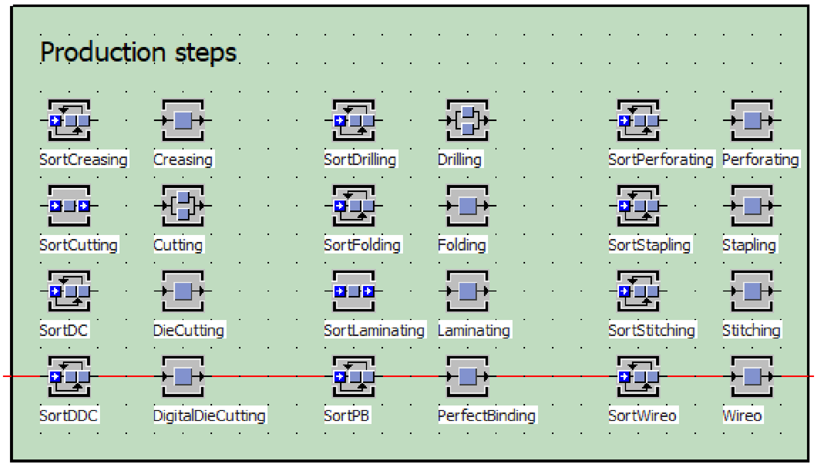

Figure 21: Production steps block

4.5.5. Key Performance Indicators

We have a working model that moves orders through their respective production processes. Thereby, the orders are sorted in the same way that Ovimex does. To be able to determine the reality and to be able to compare experiments, we need to add key performance indicators (KPI). These indicators keep track of certain values. If we add a priority rule, we can compare the KPI values of this experiment to the values of other experiments to conclude if improvements are made. In deliberation with a representative of the board of Ovimex, we came to 4 different measurements we want to keep track of. All these measurements are divided in multiple indicators to save calculations afterwards. The following KPIs are chosen:

- Waiting time, the time an order is waiting in a buffer before a machine.
    - Average waiting time per order
    - Average waiting time per day
- Throughput time, the time between arrival and leaving of the system.
    - Average time in system (arrival until exit)
    - Average throughput time (printer until exit)
    - Average production time (first production step until exit)
- Backorders, orders that are not finished at 22:00 on their due date.
    - Number of backorders
    - Backorders per day

- Storage, WIP or order documents stored.
    - Average stored WIP per night
    - Average storage time per order

The solid bullets explain the KPI. The open bullets list the variables that are measured in the model. Waiting time is the most important KPI. We attempt to decrease this waiting time by 10% during this project. Waiting time is typified as the time an order is waiting in a buffer before a machine. Storages are not added as these are intended which would create a lopsided image. A positive and logical side effect of lowering the waiting time would be to decrease the throughput time. Therefore, the throughput time is tracked. Backorders are important as well. In the current situation, backorders are kept low. These should not increase to hefty as this would dissatisfy customers. Storages are mainly kept for the trade-offs. Ovimex does not seek to lower the storages per night or the overall storage time. But they do not want storages per night to increase too much due to the available capacity. Storage time per order shows how long an order is present in the process whilst not waiting or processing. This can be used to draw conclusions regarding waiting time. We do not track storage time of WIP as WIP is always stored during the night. This means that only the number of WIP stored per night is relevant. Statistics of these different values are kept in the two tables in the purple statistics block (Figure 20).

4.5.6. Validation

To conclude that our model is an accurate representation of the reality, the model needs to be validated. The first step of the validation was to verify all assumptions with the board of Ovimex. They agreed with the made assumptions (Section 4.4.). All assumptions were agreed upon during deliberations with Ovimex. There was not much discussion as most assumptions rule out situations that almost never occur. The other assumptions had to be made due to a lack of data. The second step was to run the model and verify if the values of the KPIs are similar to the real situation. To do this, the model ran for 100 days and measured all KPIs. The observed values were shared with Ovimex. Ovimex verified internally, with some production employees, that the observed values are sufficiently similar to the real world. Section 5.2. provides more insight in the values of the KPIs at the current situation. To conclude, our model's assumptions are agreed upon and the outcomes are approved. Our model can therefore be considered as valid and is ready to do experiments with.

4.6. Conclusion

This chapter focused on the model and how it is designed. Goal was to design a model to accurately represent the current situation of Ovimex. The chapter centered around the following question:

- 'How should a model be constructed to represent the production process in a valid way?'

First, we discussed reasons why simulation was preferred over a deterministic model (Section 4.1.). Simulation appeared the better option as it can handle variance in order arrivals and moving the production of orders to other days in a better manner. Second, we discussed the arrival distribution (Section 4.2.). The order arrivals per day were fitted to a gamma distribution to be able to represent the order arrivals in the model. By fitting such a distribution to the historic data, we prove that we represent the data in a valid way. We afterwards concluded that hourly arrivals could only be handled by an experimental distribution based on the historic data.

After we determined the arrival distribution, we discussed all order characteristics in depth (Section 4.3.). The respective characteristics are remaining production steps, up, size, amount, and paper type. This discussion was divided per category to make sure that we do not end up with order characteristic combinations that are not possible. We concluded that these characteristics, just like the order category, due date, and hour of arrival should be represented using the percentages at which they occur.

Lastly, we discussed the finalized model in depth (Section 4.5.). We followed an order in its path through the model. Some additional information was given about how certain parts were structured and why certain choices were made. The values resulting from this model, as well as the assumptions made, were verified at Ovimex to validate the model. With their agreement, we concluded that the model is valid and reliable and that the model is ready for the experiments.

5. Experiments

With the finished model, experiments can be performed. In this chapter, we discuss these experiments as well as their outcomes. The outcomes are used to provide recommendations afterwards (Chapter 6.). In these experiments, we test different strategies. The outcomes give an idea how these strategies will perform at Ovimex. First, we discuss how to set up certain experiments (Section 5.1.). This regards what run time to use, if a warmup period is needed and, how much replications are needed. Second, we decide which initial experiments to perform (Section 5.3.). Third, based on the outcomes of these experiments, follow up experiments are designed and discussed (Section 5.4.). The following questions are answered:

- 'Which scheduling changes lower the waiting time in the production process?'
- 'Which priority rules should be used in the experiments?'
- 'What other changes besides priority rules are possible to implement?'

5.1. Model Settings

Before we can start with the experiments, the settings of the model need to be determined. Our simulation model has multiple properties that influence the measurements in preciseness. These respective settings are warmup period, run length and number of replications. The determination of these settings is discussed in Appendix 8.4. because these methods do not directly influence the outcomes. The warmup period and number of replications are calculated using statistical methods while the run length is determined without calculations. The outcomes are slightly overestimated to add a margin of safety and to make sure that the experiments are valid. We use the following settings in the model:

- Warmup period: 5 days
- Run length: 50 days
- Number of replications: 5 replications

5.2. Reality

In the beginning of this report we concluded that we did not have enough information at hand to determine the reality of this problem. With the model, we have all needed input to determine the reality. With the model settings (Section 5.1.) we can determine an exact reality. We use this reality to compare with the experiments to see if improvements are made. All experiments are managed by an experiment manager which is added to the model (Figure 20). This unit runs the model with the settings determined above (Section 5.1.). The reality contains a value of all KPIs (Section 4.5.5.). In the upcoming experiments, we try to improve these values.

The current situation can be divided in five key aspects. First, print sessions start at 18:00 until 00:30 at latest for all orders due on the next day. Second, print jobs are scheduled FIFO before 18:00 and SIMSET (Table 7) after 18:00. Third, cut jobs are prioritized on the number of processing steps left. All jobs with multiple steps are prioritized over jobs with one single step. This is stated in Table 12 as #Steps. Fourth, laminate jobs are scheduled SIMSET. Fifth all other jobs are scheduled FIFO. With these five key components the reality is determined (Table 12). A legend of the table is stated under Table 12.

Current situation		**Results**			
Print session	Yes	AvgWTperDay (h)	1182.88	nBackOrders	172.44
Print jobs	FIFO / SIMSET	AvgWT (h)	6.26	AvgBOperDay	3.45
Cut jobs	#Steps	AvgTimeSystem (h)	19.24	AvgStorageN	129.68
Laminate jobs	SIMSET	AvgThroughput (h)	14.14	AvgStorageTime	12.68
Rest	FIFO	AvgProdStepsTime (h)	3.27		

Table 12: Starting point experiments

Legend:

1. AvgWTperDay = Average waiting time per day
2. AvgWT = Average waiting time per order
3. AvgTimeSystem = Average time in system per order (arrival – exit)
4. AvgThroughput = Average throughput time per order (start print – exit)
5. AvgProdStepsTime = Average production time per order (production step 1 – exit)
6. nBackOrders = Number of backorders in total
7. AvgBOperDay = Average number of backorders per day
8. AvgStorageN = Average number of stored WIP per night
9. AvgStorageTime = Average time in storage per order

Table 12 lists the values of the KPIs during the current situation. First, we notice that the number of backorders is quite low. This is the case at Ovimex as well. This is mainly caused by the order deadlines (Section 2.1.4.). We need to make sure that this value does not increase too hefty during the implementation of another strategy. Second, the average stored WIP per night is stated at 129.68. Ovimex confirmed that this is very similar to their stored WIP per night. Third, the waiting time per order is stated at 6.26 hours. The combined waiting time of all orders per day comes to a total of 2946.88 hours. This is almost 50 days of waiting time. This value is the value that we mostly focus on during the next experiments. These values come close to the waiting times Ovimex experiences. Fourth, an order spends, on average, 19.24 hours in the system (Table 12). When looking at the waiting time, we can conclude that orders experience a waiting time of about one third of their overall time in the system. This is extremely high as storage time is not incorporated in this waiting time. Ovimex confirmed that the 19.24 hours resulting from the model accurately approaches the real throughput time. Most orders are received one day before their due date which also fits this result. On the left side of Table 12 the scheduling strategies of the experiment are listed as the schedule strategy. In following experiments, we alter parts of this current strategy.

5.3. Initial experiments

With the determined reality, we now continue with the discussion of the actual experiments. The outcomes of these experiments are compared to the values of the reality to evaluate the performance. During each of the initial experiments, only one of the five components of the current situation (Table 12) is changed. Because of this procedure, experiments are easily comparable as no other settings are changed (Wisniewski et al., 2012). We repeat this for all 5 components. In these experiments we use the priority rules from Table 7. MinSlack (MS), Shortest Queue Next Operation (SQNO), Shortest Processing Time (SPT), Most Operations Remaining (MOR), Least Operations Remaining (LOR), Earliest Due Date (EDD) and Similar Setup (SIMSET). These rules are related to the goals of Ovimex and are applicable in our situation (Section 3.2.2.). We first discuss which experiments are performed and why (Section 5.3.1.). Afterwards, we discuss interesting outcomes of these experiments (Section 5.3.2.). After the initial experiments, follow up experiments are designed that combine certain aspects of the initial experiments based on their outcomes (Section 5.4.).

5.3.1. Choice initial experiments

Table 13 provides an overview of all the initial experiments. In this section, we discuss the first two columns of this table. As already explained, we change one of the 5 components of the reality (Section 5.2.) in each of these experiments. Column 1 states the component at which a change is made. Column 2 specifies the priority rule that is used at this station. 'SIMSET + SPT' means that we first prioritize on setup and afterwards on processing time. 'MS / SIMSET' means that MS is used before 18:00 and SIMSET after 18:00. 'No, FIFO' means that the print session is eliminated, and FIFO is used during the entire day.

The first group of initial experiments are the laminating experiments. Laminating is always the first step in production path after printing. Therefore, multiple priority rules could make a difference as the remaining process often contains multiple steps. With the 7 possible priority rules 3 experiments are performed MS, SPT and SIMSET + SPT (Table 13). MOR and LOR experiments are not performed because these are based on similar aspects as MS. In their case, the number of production steps left. Thereby, the MS experiment generated bad results (Section 5.3.2.). The EDD rule is not used because of the similar due dates. The SQNO rule is not used as the next operation for all laminating jobs is cutting. Therefore, all jobs would receive the same priority by both these rules.

The second group contains the experiments regarding the prioritization of print jobs. In the current situation, Ovimex uses SIMSET for the jobs during the print session, and FIFO for the other jobs. We discuss 6 experiments. Three that use one or two rules for the entire day, and three that use different rules during the day and in the evening. SIMSET, SPT and SIMSET + SPT are the rules that we use for an entire day. Using SQNO for the print jobs does not make sense as the only two possible next steps are laminating and cutting. Using LOR, MOR or MS during the print sessions in the evening would not make sense as well because all the finished jobs are stored afterwards. We therefore add three experiments that use LOR, MOR or MS during the day and SIMSET in the evening.

The third group contains the experiments regarding cut jobs. Currently all jobs with multiple production steps left, are prioritized over the jobs with cutting as their last production step. Because the processing time of cut jobs is assumed to always be 4 minutes, the rule SPT cannot be used. Thereby, with the use of a print session, all cut jobs that arrive at the cutting machine are due on that same day. Therefore, EDD is not used as well. SIMSET is not used as setups are needed between every order. The remaining priority rules are tested in four experiments. MOR, LOR, MS and SQNO.

The fourth group of experiments regard the other working stations. These working stations are used considerably less than the printing, cutting and laminate station. Because of the lower use, testing different priority rules for every working station is not worth the effort. Thereby, the overwhelming number of products that needs one of these production steps, only needs one of them as their last step. This expectedly causes that the same priority rule generates the best results for each station. Because these working stations are often the last step, no next queue is present. Therefore, SQNO is not used. Because of the results in the laminate MS experiment (Section 5.3.2.), MS, MOR and LOR are not considered. Thereby, again, all orders arriving at the stations have similar due dates which rules out EDD. SIMSET is also not used as there are changeovers needed between every order. One experiment with SPT is performed (Table 13).

In all previous experiments, we only use priority rules. The last experiments entail the current situation without a print session. Experiments with a print session on another time were also considered. Print sessions at 18:00 often last until 00:30 without all jobs being finished which causes that jobs must be moved to the next morning regularly. Moving the print session to a moment after 18:00 would only cause more overwork. Moving the print session to an earlier moment would endanger the throughput of the orders that arrive due on the same day. Therefore, we only experiment without the print session entirely. All orders are sent directly to their printer regardless of their due date. When the print job is finished it is dependent on the time if they are sent to their next production step or not. Finished print jobs after 22:00 are stored first to prevent that the model lets machines work during the night. These orders move to their remaining production steps at 06:00 on the next morning. Because it does not make sense to have different priority rules at different times, we discuss four experiments with one priority rule or combination for the entire day. FIFO, SIMSET, SIMSET + SPT and SPT. MOR, LOR, EDD and MS experiments are discussed in the follow up experiments. As mentioned, SQNO does not make sense for printers.

Station	Exp	KPI 1	KPI 2	KPI 3	KPI 4	KPI 5	KPI 6	KPI 7	KPI 8	KPI 9
-	-	*1182.88*	*6.26*	*19.24*	*14.14*	*3.27*	*172.40*	*3.45*	*129.68*	*12.68*
Laminating	MS	1217.05	6.44	19.42	14.32	3.45	220.40	4.41	129.68	12.68
	SPT	1148.67	6.08	19.06	13.96	3.09	140.80	2.82	129.68	12.68
	SIMSET + SPT	1168.71	6.18	19.16	14.06	3.19	157.50	3.15	129.68	12.68
Printing	SIMSET	1141.05	6.04	19.00	13.90	3.64	86.00	1.72	133.79	12.70
	SPT	1308.67	6.95	20.26	15.16	2.77	204.80	4.10	113	12.35
	SIMSET + SPT	1059.45	5.60	18.99	13.88	3.73	79.20	1.58	138.15	13.11
	MS / SIMSET	1198.57	6.34	19.36	14.26	3.27	184.00	3.68	129.87	12.71
	MOR / SIMSET	1200.16	6.35	19.35	14.25	3.30	172.20	3.44	129.68	12.68
	LOR / SIMSET	1182.80	6.26	19.23	14.13	3.24	186.50	3.73	129.68	12.64
Cutting	SQNO	1155.80	6.11	19.10	14.00	3.12	174.80	3.50	129.68	12.68
	MS	1186.34	6.28	19.26	14.16	3.28	172.20	3.44	129.68	12.68
	MOR	1186.44	6.28	19.26	14.16	3.29	172.40	3.45	129.68	12.68
	LOR	1190.62	6.30	19.29	14.18	3.31	193.20	3.86	129.68	12.68
Other	SPT	1164.60	6.16	19.15	14.04	3.17	172.20	3.44	129.68	12.68
Print session	No, FIFO	6852.50	36.83	48.05	48.05	0.53	5207.9	104.12	14.96	10.95
	No, SIMSET	407.74	2.13	2.58	2.58	0.86	46.50	0.93	3.34	0.19
	No, SIMSET + SPT	339.17	1.77	2.18	2.18	0.82	41.00	0.82	2.95	0.14
	No, SPT	853.68	4.47	5.81	5.81	0.52	307.20	6.14	7.73	1.09

Table 13: Results initial experiments

5.3.2. Outcomes initial experiments

Beside the structure of the experiments, Table 13 also provides the outcomes of all the initial experiments. We stated the current situation as the first row to make differences easily visible. Due to the size of the table, the KPI names did not fit as column headers. Therefore, the numbers from the legend of Table 12 are used. All time related KPIs (1 till 5 and 9) are stated in hours. We discuss the outcomes of all these experiments in this section.

When we compare the results of the MS laminate experiment with the current situation, we conclude that all results, except storages, aggravated. Main change is the number of backorders. This value increased by almost 50. These bad results are explicable. All waiting orders have the same due date (Section 2.1.4.) and have a relatively short amount of time to go in their process (small values of KPI 5). This causes that slack values are relatively close to each other. This means that orders that are prioritized because of their slightly lower slack value would also be finished on time if they were not prioritized. The added value of MS, which is often to reduce the number of backorders and reduce the overall throughput, is therefore minimized. In this case saving setup time, which is used in the current situation, saves more time, and still delivers the orders in time. On top of that, even more orders are delivered in time because of the saved setup time. The laminate SIMSET + SPT and SPT experiment do improve the KPIs. Less backorders are recorded. And all waiting time and throughput time related KPIs decreased (Table 13). The SPT experiment performs better on every KPI compared to the SIMSET + SPT experiment. From these outcomes we conclude that the waiting time saved by using SPT is larger than the setup time saved when using SIMSET. SPT also generates improvements in the other workstations experiment. These improvements are explicable by the waiting time that is saved in the stations itself. These savings lower the backorders, throughput times and overall waiting times. The average waiting time per day is for example lowered by over 18 hours.

The print SIMSET and SIMSET + SPT experiments clearly generate better results than the current situation and print SPT experiment. The results from the SPT experiment are worse than the current situation. The SIMSET and SIMSET + SPT rules show small improvements in most time related KPIs. The biggest change is visible in the number of backorders which more than halved in both experiments. Two interesting, slightly strange results are visible. First, the average production steps time of the SPT experiment is lower than the current situation while its total time in the system is longer. For the SIMSET and SIMSET + SPT experiment, this is exactly the other way around. This shows that the flow through the remaining production steps (all steps beside printing) is faster when more waiting time is experienced at the printing station. Using SPT causes waiting time at the print station which causes the time between orders' departure from the printer, and therefore also between arrivals at their following production steps, to be larger. The opposite happens when using SIMSET or SIMSET + SPT. Orders arrive closer to each other due to the saved setup time. This causes their production steps time to be larger. Second, storages per night and overall storage times are lower in the SPT experiment compared to the current situation and the other two experiments. The lower storage numbers are caused by the longer waiting times at the printer. Because of these longer waiting times, less jobs are finished at the end of the print session causing less WIP stored. This also causes the lower storage time. Because less jobs are finished in the printing sessions, jobs are stored later than usual causing the storage time to be lower. From the three print experiments that use different rules during the day and evening, the LOR experiment generated the best results regarding the time related KPIs (Table 13). Most promising result is the improved production steps time (KPI 5). Although the backorders of this experiment were slightly higher than the other two experiment, all time related KPIs improved. The higher number of backorders is caused by the prioritization of jobs with a relative short path to go. Jobs with longer paths are performed later on the day which causes them to become backorders.

From the cutting experiments, only the SQNO rule generated promising results. All time related KPIs slightly improve from the current situation. Waiting times dropped which caused the throughput times to drop as well. This drop is caused by the better flow that is created through the remaining production steps. Because the change is made after the printers, logically, the storage KPIs have not changed. The backorders did increase slightly. This can be explained by how the current situation is constructed. In the current situation, jobs with multiple steps left are prioritized which gives these orders a higher chance of being finished on time.

The outcomes of the experiments without print sessions are divergent. The results of the FIFO experiment are terrible (Table 13). 5208 of all orders are backorders which comes down to about half of all orders. Thereby, throughput times and waiting times increased immense. We observe this to a lesser extent with the SPT experiment. Although waiting and throughput times decrease, over 300 backorders are generated. These outcomes are caused by the large amount of setup time. The outcomes of the experiments with SIMSET and SIMSET + SPT with no print session show enormous improvements (Table 13). We only discuss the SIMSET + SPT experiment as these results are better for every KPI. All categories show huge improvements compared to the current situation. First, more than 4 times less backorders are created. Second, throughputs decreased tremendously. Current throughput time is a little over 14 hours, in this experiment a little over 2. Third, waiting times are also more than 3 times lower than before. Fourth, very few products need to be stored. The average storage time therefore gives a lopsided portrayal. The products that do have to be stored, are still stored for the whole night. Because so few products are stored, the average drops a lot. The improvements are mainly caused by the flow through the company. In the current situation, orders are stored during the day and night. All these orders are sent to only a few machines at the same time (to printers at 18:00 or 06:00 and to cutting or laminating at 06:00). Because of these choices, huge waiting lines develop before these machines, causing a lot of waiting time. Advantages of using no print session is that orders can flow through the company much easier as the waiting lines are shorter. Thereby, orders are immediately processed instead of on the due date causing less backorders to occur.

5.4. Follow up experiments

With the results from the initial experiments (Section 5.3.) follow up experiments are designed. Because of the enormous differences between the outcomes when using a print session and when not using a print session, we split these follow up experiments. First, we discuss experiments that do use a print session at 18:00 (Section 5.4.1.). Because a lot of initial experiments were performed with a print session as well, only a few are needed. These experiments are performed to show if the priority rules that seem optimal at the different stations, do not counteract each other. Second, we discuss experiments without a print session (Section 5.4.2.). This section requires more experiments.

5.4.1. Follow up experiments with a print session

As mentioned, we first discuss the follow up experiments without a print session. Table 14 provides the outcomes of all these experiments and the reality as the first row. The column headers represent the same KPIs as in Table 13. Because multiple stations are changed in these experiments, the experiments are labelled A till E. The rules that are applied in these experiments are stated below Table 14.

Exp	KPI 1	KPI 2	KPI 3	KPI 4	KPI 5	KPI 6	KPI 7	KPI 8	KPI 9
-	*1182.88*	*6.26*	*19.24*	*14.14*	*3.27*	*172.40*	*3.45*	*129.68*	*12.68*
A	1002.28	5.30	18.68	13.58	3.43	45.40	0.91	138.15	13.11
B	1081.69	5.72	18.69	13.58	3.32	45.80	0.92	133.86	12.70
C	1131.21	5.99	18.97	13.87	2.98	152.20	3.04	129.34	12.65
D	1038.01	5.49	18.87	13.77	3.62	77.80	1.56	138.15	13.11
E	1165.64	6.17	19.14	14.04	3.15	185.5	3.72	133.79	12.65

Table 14: Follow up experiments with a print session

A = {Laminate SPT} {Printing SIMSET + SPT} {Cutting SQNO} {Rest SPT}
B = {Laminate SPT} {Printing SIMSET} {Cutting SQNO} {Rest SPT}
C = {Laminate SPT} {Printing LOR / SIMSET} {Cutting SQNO} {Rest SPT}
D = {Laminate SIMSET} {Printing SIMSET + SPT} {Cutting SQNO} {Rest SPT}
E = {Laminate SIMSET} {Printing LOR / SIMSET} {Cutting SQNO} {Rest SPT}

We discuss 5 experiments. Each of these 5 experiments are centered around the priority rules that seemed optimal in the initial experiments. To clarify, these are the rules that resulted in the lowest waiting times. For the print jobs, using the SIMSET + SPT rule for the entire day generated the best results (Section 5.3.2.). For the cut jobs this was the SQNO rule and for both the laminate and other jobs this turned out to be the SPT rule. Experiment A therefore combines all these rules in one experiment (Table 14). When we compare these results to the reality (Table 12), we see the same phenomenon happening as before (Section 5.3.2.). Production steps time and storages increase. Beside these slight increases, all other values decreased even more. The average waiting time per day, which is the core of this project, decreased by almost 200 hours which is a very good result. Thereby, almost 75% of all backorders disappeared which is a huge improvement. Based on these results, we conclude that the rules do not counteract each other. Experiment B is not discussed as it again shows that SIMSET performs worse than SIMSET + SPT (Section 5.3.2.).

As mentioned, using other rules than SQNO for cut jobs and SPT for other production steps, does not make sense (Section 5.3.2.). We investigate if SIMSET for laminate jobs performs better in combination with other rules. For the print jobs we saw that the LOR/SIMSET rule did lower the production steps time and the overall waiting and throughput times (Section 5.3.2.). We test these two rules separately and combined (experiments C, D and E in Table 14) to see if slightly altering the optimal situation gives different results. The two experiments using SIMSET for the laminate jobs (D and E in Table 14) clearly prove that SIMSET is worse than SPT. The results of every KPI are better when we use SPT instead of SIMSET. This is visible if we compare experiment C with E and A with D, which are experiments where only the laminate priority rule is altered. When we compare the LOR/SIMSET experiment (C) to experiment A, we notice that the overall waiting times, overall throughput times and backorders are aggravated. On the other hand, the average production steps time is decreased by over 14% (0.45 hours). This means that, on average, an order saves about half an hour in the production steps time which fully consists of eliminated waiting time. Thereby, overall waiting times, overall throughput times and backorders are considerably better than they were in the current situation (Table 14).

5.4.1.1. Conclusion experiments with print session

As all experiments with a print session are discussed, we draw conclusions. There are several understandable reasons that can cause that Ovimex does want to keep using a print session. First, stock levels of finished products will increase as a lot of orders will be finished before their due date. Second, Ovimex may not want to change their entire process as this structure has worked for years. Third, having a print session gives employees more time to group orders by paper type in advance. Fourth, production floor managers have more time to plan for most arriving orders. Only the orders that are due on the same day, need to be planned right away. If Ovimex indeed wants to keep the print session, they could however make some improvements by adding priority rules to the stations. The solution that causes the biggest decrease of waiting time is the solution that comprises of using SIMSET + SPT for the printers, SQNO for the cutters and SPT for all other machines. Backorders decrease by almost 130 which is a decrease of 74% (Table 15). Thereby, the overall waiting time per day decreased almost 200 hours which is a 15% decrease. This practically means that every order, on average, receives almost one hour less waiting time. The waiting time that is saved in this solution is mostly saved at the printers. If Ovimex rather wants to save more time in the remaining production steps part of the company, using LOR during the day and SIMSET in the evening for both printers would be better. This solution lowers the average production steps time by 9%. This decrease completely consists of waiting time. Thereby, the other KPI values of this solution also improve when comparing their KPIs to the current situation (Table 15). To conclude, both options improve the current situation significantly. It is up to Ovimex, if they want to incorporate one of these, where they would like to see the biggest change.

	Current	**Print SIMSET + SPT**	**Print LOR / SIMSET**
AvgWTperDay (h)	1182.88	1002.28	1131.21
AvgWT (h)	6.26	5.30	5.99
AvgThroughput (h)	14.14	13.58	13.87
AvgProdStepsTime (h)	3.27	3.43	2.98
nBackOrders	172.40	45.40	152.20

Table 15: Overview important KPIs solutions with print session

5.4.2. Follow up experiments without a print session

The second group of follow up experiments we discuss, are the experiments without a print session. In Table 13 we saw the immense decrease of all measured KPIs when eliminating the print session and using SIMSET or SIMSET + SPT at the print station. These follow up experiments continue on these experiments. We draw separate conclusions on these experiments as the outcomes are not comparable to the situation with a print session. Due to the size of Table 16, experiments are added below with a corresponding letter in the same manner as Table 14

Exp	KPI 1	KPI 2	KPI 3	KPI 4	KPI 5	KPI 6	KPI 7	KPI 8	KPI 9
-	*1182.88*	*6.26*	*19.24*	*14.14*	*3.27*	*172.40*	*3.45*	*129.68*	*12.68*
A	382.79	1.99	2.45	2.45	0.73	34.80	0.70	3.11	0.19
B	374.66	1.95	2.41	2.41	0.69	44.80	0.90	3.11	0.19
C	419.37	2.19	2.64	2.64	0.92	36.60	0.72	3.11	0.19
D	419.34	2.19	2.64	2.64	0.92	35.60	0.71	3.11	0.19
E	307.07	1.60	2.01	2.01	0.65	40.60	0.81	2.95	0.14
F	4857.98	26.61	34.79	34.79	0.52	4406.60	88.11	15.87	7.92
G	314.91	1.64	2.05	2.05	0.69	35.00	0.70	2.95	0.14
H	306.97	1.60	2.01	2.01	0.65	39.60	0.79	2.95	0.14
I	312.17	1.63	2.04	2.04	0.68	40.80	0.79	2.95	0.14
J	314.82	1.64	2.05	2.05	0.69	33.40	0.67	2.95	0.14

Table 16: Follow up experiments without a print session

A = {Laminate EDD + SPT}	{Printing SIMSET}	{Cutting SQNO}	{Rest SPT}
B = {Laminate SPT}	{Printing SIMSET}	{Cutting SQNO}	{Rest SPT}
C = {Laminate MS}	{Printing SIMSET}	{Cutting SQNO}	{Rest SPT}
D = {Laminate EDD}	{Printing SIMSET}	{Cutting SQNO}	{Rest SPT}
E = {Laminate SPT}	{Printing SIMSET + SPT}	{Cutting SQNO}	{Rest SPT}
F = {Laminate SPT}	{Printing EDD + SPT}	{Cutting SQNO}	{Rest SPT}
G = {Laminate EDD + SPT}	{Printing SIMSET + SPT}	{Cutting SQNO}	{Rest SPT}
H = {Laminate SPT}	{Printing SIMSET + SPT}	{Cutting EDD}	{Rest SPT}
I = {Laminate SPT}	{Printing SIMSET + SPT}	{Cutting SQNO}	{Rest EDD + SPT}
J = {Laminate EDD + SPT}	{Printing SIMSET + SPT}	{Cutting EDD}	{Rest SPT}

5.4.2.1. Due date related experiments at the laminate station

In these experiments, orders that arrive at the machines from the remaining production steps do have different due dates. This was not the case in the experiments where a print session is used. Therefore, the rules MS and EDD become relevant. EDD can be used separately or in combination with another rule. In our case, SPT could be combined with EDD. This gives us three priority rule (pairs) related to the due date. To see which of these three due date dependent priority rules work the best, three experiments are discussed at the laminating station. EDD + SPT, MS and EDD (experiment A, C and D). The laminating station is chosen as jobs that are finished are never stored afterwards and different processing times occur. If either of these aspects were different, this would affect the outcomes. For comparing purposes, we add a fourth experiment that only uses SPT at the laminating station (experiment B). For the other stations, one priority rule is used during each experiment. SIMSET for print jobs, SQNO for cut jobs and SPT for the remaining stations.

If we compare MS, EDD and EDD+SPT, EDD+SPT clearly has the best results (Table 16). This experiment scores better on every KPI (experiment A in Table 16). The differences are not large, but clearly visible. Therefore, the MS and EDD experiment are not discussed in detail and not considered in the remaining experiments. Because MS did not perform better than EDD + SPT, MOR and LOR experiments are not executed. MOR and LOR are based on similar aspects as MS (Section 5.3.1.). The experiment that uses SPT instead of EDD+SPT for the laminate jobs shows even bigger improvements on the time related KPIs. The improvements are very small but visible in each of these KPIs (Table 16). However, backorders are higher as this rule does not take the due date of orders into account.

5.4.2.2. EDD+SPT experiments

Section 5.4.2.1. shows that EDD+SPT is the best in taking the due date into account. In this section, we discuss 5 experiments which test the EDD+SPT combination for other stations. As cut jobs always have the same processing time, we use EDD at this station. To be able to compare the results, the rule is implemented at each station separately (experiment F till I). For the other stations we use the optimal state from the initial experiments (Section 5.3.). These are SIMSET+SPT for printers, SQNO for cutters and SPT for all other stations. For comparing purposes, we also discuss an experiment with each station in its optimal condition (experiment E).

For the printers (experiment F) and remaining production steps (experiment I), this rule turns out unsuccessful. When applying the rule to the printers, all values increase a lot (Table 16) which is obviously unwanted. We already concluded earlier that saving setup time should be the main concern at the printers (Section 5.3.2.). When applying this rule to the remaining production steps, all values slightly increase (Table 16). This shows us that SPT saves so much waiting time that it even creates less backorders than when orders are prioritized on their due date. Using EDD at the cutters does create a very slight improvement (Experiment H). The number of backorders slightly decrease, which could be expected, but all other KPIs stay constant as well (Table 16). Therefore, we conclude that using EDD for the cutters in a situation without a print session, is preferred. Experiment G, which applies EDD+SPT to the laminator, shows some interesting results. Backorders are lowered, which is obviously due to the prioritization on due date, but all time related KPIs slightly worsened. Because of the main prioritization on due date, less waiting can be saved by the SPT part of the combination.

5.4.2.3. Final experiment

Before we can draw conclusions, we discuss one final experiment. For the printers, cutters and remaining stations, the optimal rule is clear. These are respectively, SIMSET+SPT for printers, EDD for cutters and SPT for the remaining stations. Alternatives for these rules generate worse or equal results for each KPI (Table 16). The laminating station does present two good alternatives. SPT and EDD+SPT. The final two experiments therefore consist of the 3 optimal values and one of the two laminate possibilities. The experiment with SPT as alternative is already discussed (experiment H in Table 16). Experiment J in Table 16 provides the optimal values combined with the EDD+SPT rule at the laminator. In the results we see, as expected, that all time related KPIs slightly worsened (Section 5.4.2.2.). The waiting time per day increases by 8 hours in total compared to experiment H (Table 13). This occurs as less waiting time can be saved because orders are prioritized on their due date. On the other hand, backorders are lowered by 6.

5.4.2.4. Conclusion experiments without print session

Now that we have discussed all experiments without print sessions, conclusions can be drawn. In these experiments we saw that all throughput and waiting times can be lowered drastically by eliminating the print sessions. Waiting times from orders can be lowered by 74% to under 2 hours (Table 17). The overall throughput time can even be lowered by 86% as a lot of storage time is eliminated as well. According to these results, if Ovimex were to stop using print sessions, two interesting options arise. Either using SPT or EDD+SPT for the laminating station. As mentioned, printers, cutters and remaining production steps have clear optimal rules (Section 5.4.2.3.). The option that should be chosen depends on the goal of Ovimex. If they value waiting time higher than due dates such that 6 extra backorders do not matter, SPT is the most optimal. If due dates should be kept low as well, EDD+SPT is more optimal as this rule lowers the backorders by 81% instead of 77% (Table 17).

	Current	Laminating EDD + SPT	Laminating SPT
AvgWTperDay (h)	1182.88	314.82	306.97
AvgWT (h)	6.26	1.64	1.60
AvgThroughput (h)	14.14	2.05	2.01
AvgProdStepsTime (h)	3.27	0.69	0.65
nBackOrders	172.40	33.40	39.60

Table 17: Overview important KPIs solutions without print session

5.5. Conclusion

This chapters focus lied on the experiments with the model. The goal was to find one or multiple priority rules or combinations of priority rules that improve the KPIs we set in Section 4.5.5. This chapter centered around the following question:

- 'Which scheduling changes lower the waiting time in the production process?'

After briefly discussing the model settings warmup period, run length and number of replications, we discussed the reality of our action problem. Our action problem focusses on lowering the waiting time per day (Section 1.2.2.). We discussed the reality values of all KPIs (Section 5.2.). Most important values were the 6.26 hours of waiting time per order, almost 1200 hours of waiting time per day, 172 backorders and throughput time of over 14 hours (Table 12).

With this reality in mind, we discussed initial experiments (Section 5.3.). Each of these experiments only changed one of the 5 predetermined aspects of the current production strategy. These 5 aspects are the print session and the prioritization at the printers, cutters, laminator, and other stations. From these initial experiments we concluded that applying certain priority rules can improve the current situation significantly. SPT for the laminator, SQNO for the cutters, SPT for the other stations and SIMSET, LOR / SIMSET or SIMSET + SPT for the printers improved the current situation the most. In the experiments without print sessions we even saw that results were improved drastically. Because of these results, we separated the follow up experiments in two groups. A group of experiments that do use a print session and a group that does not.

Because most initial experiments did use a print session, only 5 follow experiments were needed with a print session (Section 5.4.1.). From these experiments we concluded that SQNO and SPT are optimal for the cutters and laminator and other stations, respectively. For the printers this depends on the goal of Ovimex. If their focus lies on lowering the overall waiting time and decreasing backorders, SIMSET + SPT is optimal. This solution lowers the backorders by 74% and the waiting time by 15%. If they rather lower the waiting time for production steps besides printing and do not mind only slightly less backorders, LOR / SIMSET is optimal. This solution lowers the backorders by 12% and lowers the waiting time for productions steps by 9%.

In Section 5.4.2. we discussed 10 follow up experiments regarding a situation without a print session. Because the due date is a factor in these experiments, due date related experiments were relevant for multiple stations. SIMSET + SPT and SPT still turned out optimal for the printers and remaining stations. KPIs slightly improved when applying EDD instead of SQNO to the cutters. For the laminate station EDD+SPT and SPT produced almost identical results. The rule that is optimal depends on the focus of Ovimex. Do they rather eliminate some extra waiting time, or do they rather eliminate some extra backorders? Most significant results were the possibilities of an 86% throughput time decrease, 74% waiting time decrease and 81% backorder decrease.

6. Conclusions and recommendations

In this last chapter we review the steps taken to be able to draw conclusions. We discuss the sub questions we answered and answer the main research question (Section 6.1.). The answer to this question is expanded with some extra conclusions we draw from the experiments (Chapter 5.). These conclusions are based on tradeoffs between the KPIs. After the conclusions we give a recommendation to Ovimex regarding these strategies. The aim of this recommendation is to properly formulate how to possibly incorporate parts of the provided solutions and how to further investigate these possibilities.

6.1. Conclusion

We started this project by investigating the current situation of Ovimex. Main goal was to get a thorough understanding of this current situation. We answered the following question: 'How is the production process of Ovimex structured?'. We discussed order types, production steps, scheduling strategies and all other relevant aspects of the production process of Ovimex. Seventeen types of products are produced by Ovimex using printers and 11 remaining production steps. Important aspects of the production process are the close due dates, the different production step sequences, and the print session at 18:00 every day. Result of this chapter was the flowchart from Figure 4 which visualizes this entire process.

After investigating the current situation, we continued by discussing methods that are currently used to decrease waiting time (Chapter 3.). For these methods, we mainly investigated situations like the current situation of Ovimex. Such a situation is often referred to as a complex or dynamic job shop. We focused on answering: 'What methods are currently used to decrease waiting time at small production companies?'. We saw that complex job shops are often handled using reactive scheduling. This type of scheduling reacts to the continuously arriving order information (Section 3.1.1.). We decided to focus on priority rules. These rules prioritize jobs based on a certain aspect when an operation is free to receive a new job. Keeping the goals of Ovimex in mind, which are decreasing waiting and throughput time and reducing backorders, 7 priority rules were selected: MinSlack (MS), Shortest Queue Next Operation (SQNO), Shortest Processing Time (SPT), Most Operations Remaining (MOR), Least Operations Remaining (LOR), Earliest Due Date (EDD) and Similar Setup (SIMSET). These rules are related to the goals of Ovimex and are applicable in our situation (Section 3.2.2.).

Chapter 4 provided the discussion about the entire model. We focused on the question: 'How should a model be constructed to represent the production process in a valid way?'. Before we discussed the model in detail, we first chose the model type (Section 4.1.), discussed the arrival distribution which represents the order arrival (Section 4.2.) and discussed all order characteristics (Section 4.3.). We concluded that the arriving orders per day could be represented best by the gamma distribution. Hourly order arrivals are handled by an experimental distribution. Section 4.5. provided a discussion about all the important aspects of the model. We followed an order in its path through the model. Important aspects were the creation of orders, the determination of the path and the prioritizations at the different stations. The finished model was validated by verifying the outcomes and assumptions (Section 4.4.) with Ovimex.

The last step, besides drawing conclusions, was to discuss the experiments. Main goal of these experiments was to lower the waiting time. The following question was answered: 'Which scheduling changes lower the waiting time in the production process?'. We discussed one group of initial experiments and two groups of follow up experiments. In the initial experiments we only changed one of the 5 predetermined aspects of the current production strategy. These 5 aspects are the print session and the prioritization at the printers, cutters, laminator, and other stations. SPT for the laminator, SQNO for the cutters, SPT for the other stations and SIMSET, LOR / SIMSET or SIMSET

+ SPT for the printers are the rules that generated the best results. In the first group of follow up experiments, which is the group with a print session, we saw that SQNO and SPT are optimal for the cutters and laminator and other stations, respectively. For the printers this depends on the goal of Ovimex. In the second group, without a print session, SIMSET + SPT and SPT still turned out optimal for the printers and remaining stations. EDD was more optimal for the cutters instead of SQNO. For the laminate station EDD+SPT and SPT produced similar results. The rule that is optimal, again, depends on the focus of Ovimex.

6.1.1. How can a production planning strategy be designed to decrease the waiting time at Ovimex?

All the previously discussed information serves to answer the main research question. In this project we noticed that the way Ovimex currently schedules order is not optimal. Mainly in Chapter 5., we saw that multiple priority rules and combinations of these rules resulted in improved values of the KPIs. We distinguish four solutions as the most promising strategies.

1. *{Print session} {Printers LOR / SIMSET} {Laminator SPT} {Cutters SQNO} {Rest SPT}*
   The first solution is the solution that is focused on reducing waiting time at the production steps beside printing. This solution does use a print session and prioritizes LOR at printers during the day and SIMSET in the evening. Advantages are the 9% decrease in production steps time and 12% decrease in backorders (Table 15). Disadvantages are that overall throughput and waiting times only improve 2% and 4%.

2. *{Print session} {Printers SIMSET + SPT} {Laminator SPT} {Cutters SQNO} {Rest SPT}*
   The second solution uses a print session as well but prioritizes SIMSET + SPT at printers the entire day. This solution is focused on reducing overall waiting times and backorders. Advantages are the 74% decrease in backorders and 15% decrease in waiting time per day. Disadvantage is that the production steps time worsened by 5% (Table 15).

3. *{No print session} {Printers SIMSET + SPT} {Laminator SPT} {Cutters EDD} {Rest SPT}*
   The third solution focusses on reducing the waiting time per day as much as possible. This solution does not have a print session and prioritizes laminate jobs SPT. The advantages are the 74% waiting time decrease and 86% throughput time decrease (Table 17). Disadvantage is that backorders are lowered by 77% which could be even more.

4. *{No print session} {Printers SIMSET + SPT} {Laminator EDD + SPT} {Cutters EDD} {Rest SPT}*
   The last solution focusses on reducing backorders as much as possible. This solution also has no print session but prioritizes laminate jobs EDD + SPT. Biggest advantage is the 81% backorder decrease. The only disadvantage is that solution 3 lowers waiting times even more (Table 17).

From these solutions we conclude that multiple priority rules can decrease the waiting time per day at Ovimex. The strategy that is optimal depends on the goals that Ovimex values the highest and if they want to keep a print session or not. At the start of this project we formulated the following action problem: 'The waiting time of all orders at Ovimex on one day is very long, this should be lowered by 10%.' (Section 1.2.2.). In solutions 2, 3 and 4 we reach this 10% decrease of waiting time per day easily.

6.2. Recommendation

Main aim of this research is to provide a recommendation to Ovimex regarding how they should alter their production planning strategy to decrease waiting time. Waiting time appeared as one of the main causes of their experienced problem of not reaching planning goals. Section 6.1.1. provides the main findings of this report. This section lists the four most promising results that Ovimex could incorporate. Section 6.1.1. explains all advantages and disadvantages of these solutions.

Because some assumptions are made and Ovimex has another order stream as well, we recommend the following to Ovimex. First, Ovimex should investigate if they want to stop using the print session. The results in this report prove that not using this session improves the current situation on multiple levels. Ovimex should investigate the effect of this change to other parts of the company. How does this change affect the storage levels of finished products? Do we need to hire more production employees? Can we offer closer due dates? Can we expand our production capacity? Does eliminating this print session work for the other order stream as well? All these types of questions need to be answered before such a change can be made. Second, Ovimex should investigate applying priority rules at all stations in their company. This report proves the added value certain rules can bring. Further investigation is needed to prove that these rules work for the other order stream Ovimex receives as well. Using one of the solutions provided in Section 6.1.1. is our recommendation. Third, Ovimex should think about how they can most conveniently implement these priority rules. It should be convenient and easy to use for the machine operators and the production floor managers. An idea could be to integrate this in the web2print tool. Screens could be placed at the different workstations coupled to the web2print system currently used by the production floor managers. These screens could show the next job to produce, making it very easy to use. Fourth, if Ovimex decides to implement priority rules or stops using the printing session, new calculations should be made regarding capacity. With the improved flow of orders through the company, they might be able to expand the capacity. This should be investigated.

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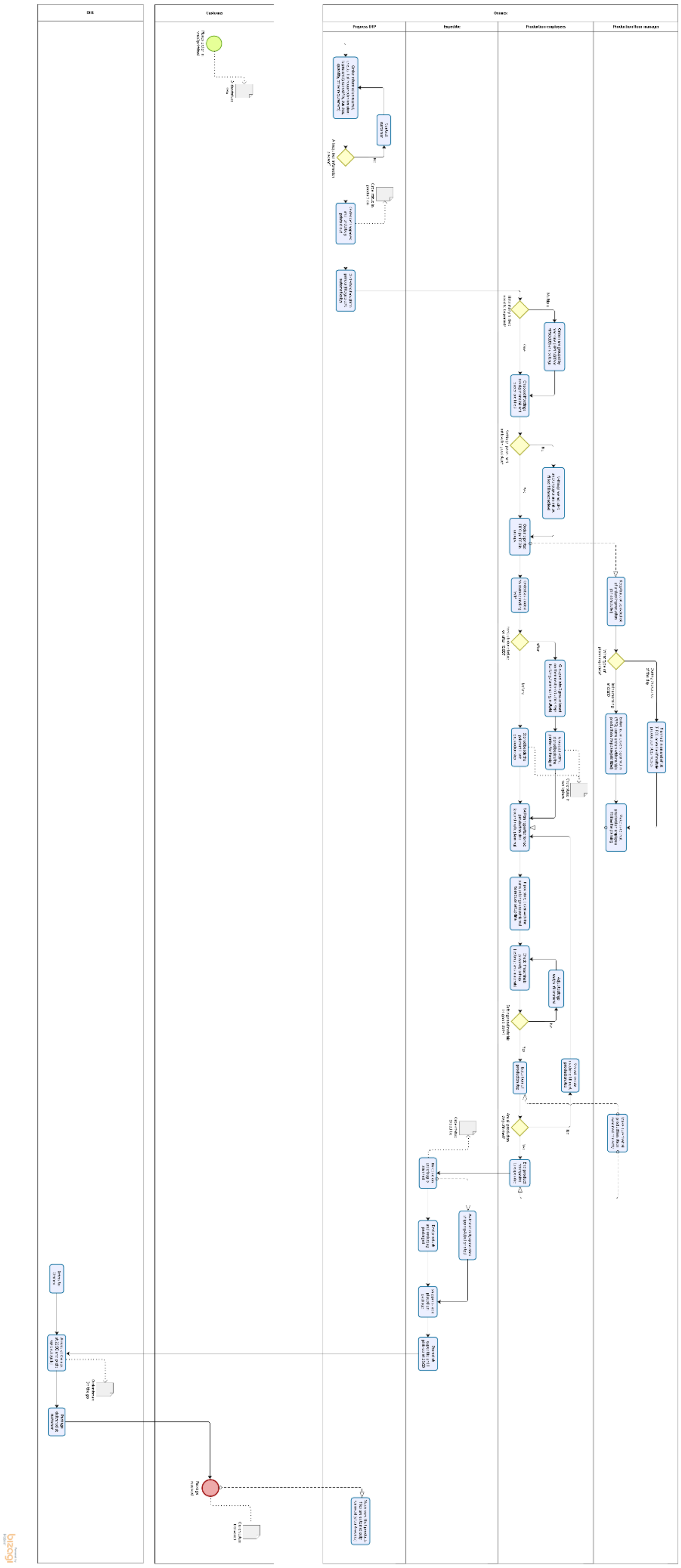
8. Appendix

8.1. Appendix detailed flow chart



8.2. Calculation maintenance time printers

Calculation average duration and frequency of jams and failures for HP12.000 and HP30.000

#working days		66	66
		HP12.000	**HP30.000**
Average up-time (h)		16	10
# failures		543	290
failure recovery (%)		10	13
# jams		769	168
jam recovery (%)		9	6
# restarts		36	37
calculation failures			
	# failures per day	8,227273	4,393939
	failure recovery time per day (h)	1,6	1,3
	Average duration failure (h)	0,194475	0,295862
	Average duration failure (min)	11,66851	17,75172
	frequency, time between (h)	1,750276	1,98
calculation jams			
	# jams per day	11,65152	2,545455
	jam recovery time per day (h)	1,44	0,6
	average duration jam (h)	0,123589	0,235714
	average duration jam (min)	7,415345	14,14286
	frequency, time between (h)	1,249623	3,692857
calculation restarts			
	# restarts per day	0,545455	0,560606
	average duration restart (min)	6,194444	4
	average duration restart (h)	0,103241	0,066667
	frequency, time between (h)	29,23009	17,77117

8.3. Appendix detailed flow chart

Characteristics business cards

Products that fall within the category business cards are very alike. Business cards always go up 50 times on one sheet. Therefore, graph is created for up. Thereby, the size of a business card is always 1. In the properties production steps, amount, and paper type, it is also visible that business cards are very alike. Often there are no production steps at all or only laminating needed (Figure A1), the amount ordered is more than half of the times 100 (Figure A2) and the paper type Mc silk is by far the most popular (Figure A3).

Figure A1: Business cards, production steps

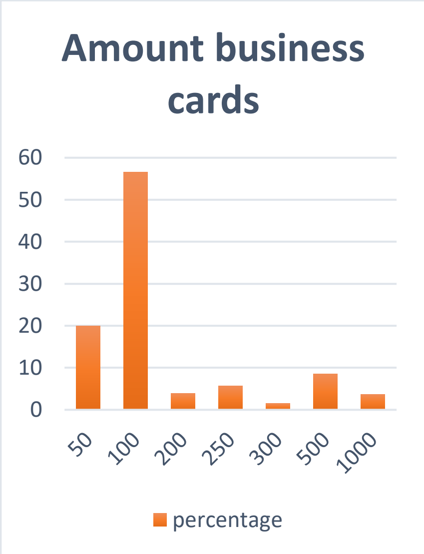


Figure A2: Business cards, amount

Figure A3: Business cards, paper type

Characteristics commercial print

The commercial print category is, beside the carton category, the only category that is printed on the HP30.000. Commercial print orders have clear standard properties. First, production steps are almost in all cases nonexistent (Figure A4). Only some products need creasing, laminating, or both. Second, Yupo Blue YPI 400 is by far the most popular paper type. This is chosen in almost 80% of all cases (figure A5). Third, in most cases, commercial print products are ordered with A4 dimensions.

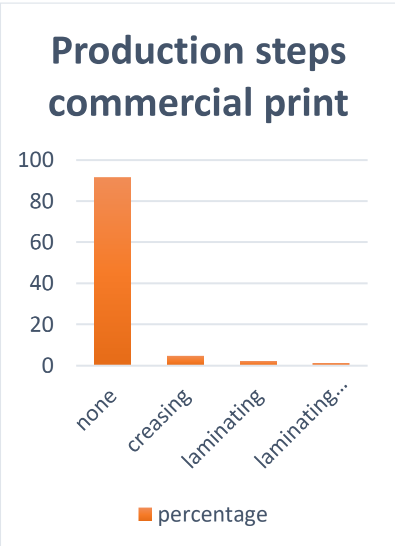


Figure A4: Comercial print, production steps

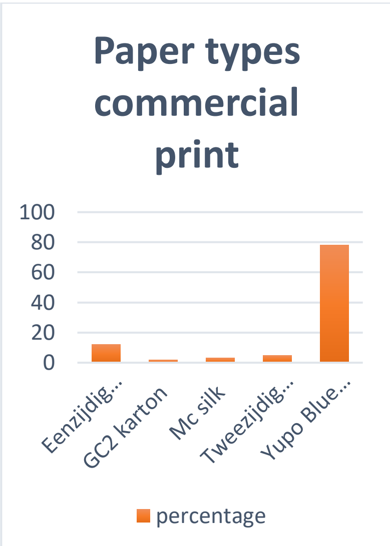


Figure A5: Commercial print, paper types

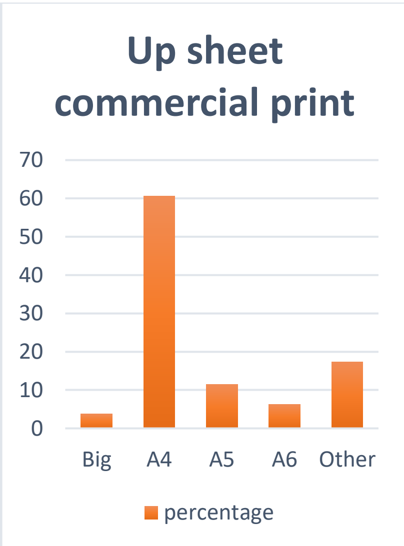


Figure A6: Commercial print, up

In the amount characteristic, more diversity is visible. A lot of different amounts are chosen and there are no clear favorites. Even the most popular amounts of 30 and 50 barely get chosen more than 10% (Figure A7). As diverse as the amount topic, as unilateral is the size of these products. 1293 of the 1308 data points are of size 1. No other possibility has over 1% of the orders. These other data points are therefore, as explained, considered outliers (Chapter 4.3.3.).

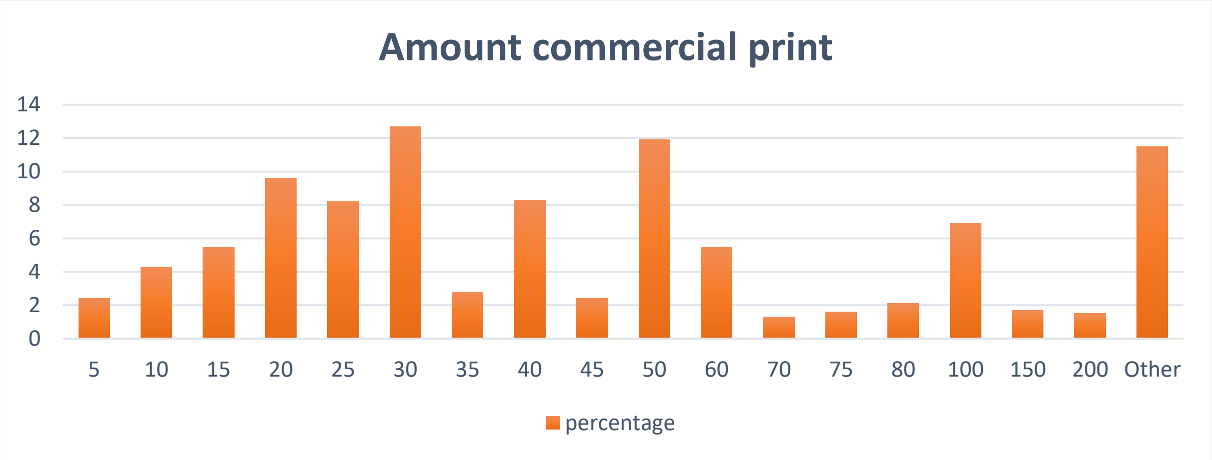


Figure A7: Commercial print, amount

Characteristics flyers

The flyers category can be viewed as the most diverse category due to the high presence of a lot of the different possibilities. The only characteristic that is similar in most cases is size. In almost all cases flyers are 1 or 2 pagers (Figure A9). The production steps on the other hand are already more diverse. About half of the flyers needs no additional production steps, but the other half has a various array of needed production steps (Figure A8).

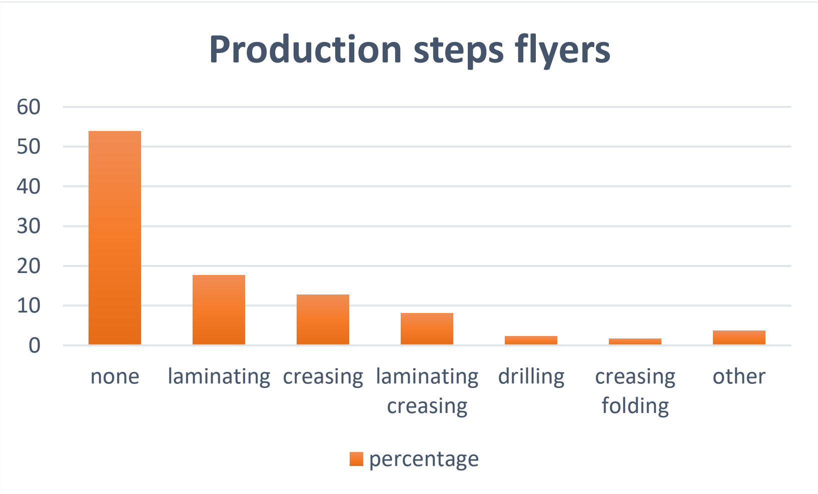


Figure A8: Flyers, production steps

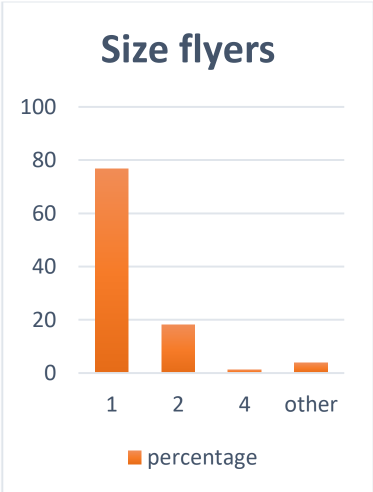


Figure A9: Flyers, size

The other characteristics are even more diverse than the afore mentioned production steps. In Figure A10 it is visualized that all dimensions are present. Thereby, there is a big chunk of data points that has custom dimensions. There is also not a clear favorite paper type for customers. Mc silk is popular as was the case in the previously discussed categories. Difference is that a lot of other paper types are chosen regularly as well (Figure A11). Amount peaks at rounded numbers. Most chosen amounts are 100 and 50 (Figure A12). But the difference is again that other amounts are chosen regularly as well. The big percentage of 'other' visualizes this clearly (Figure A12).

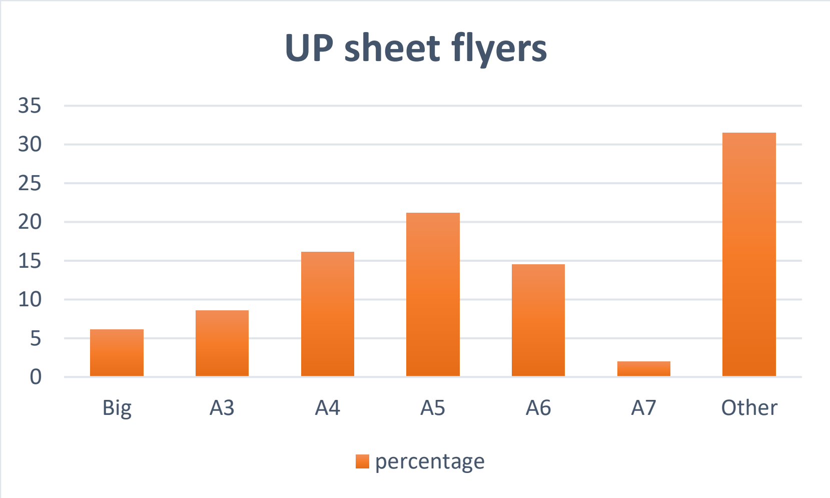


Figure A10: Flyers, up

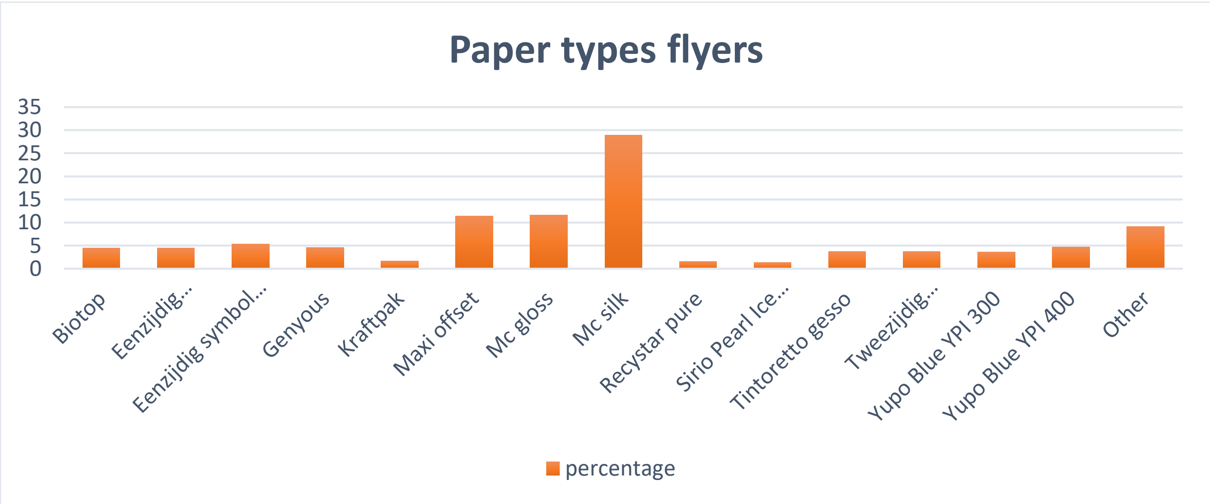


Figure A11: Flyers, paper types

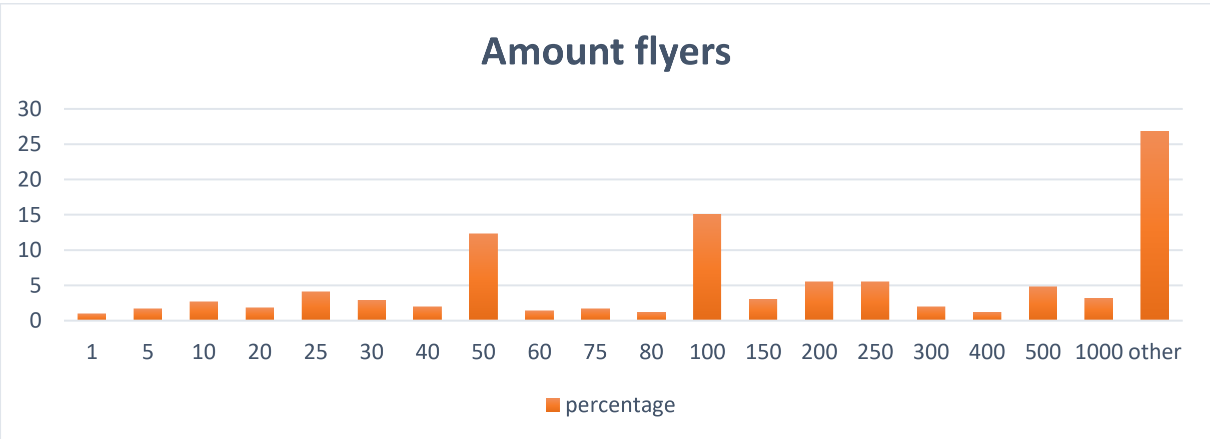


Figure A12: Flyers, amount

Characteristics carton and writing paper

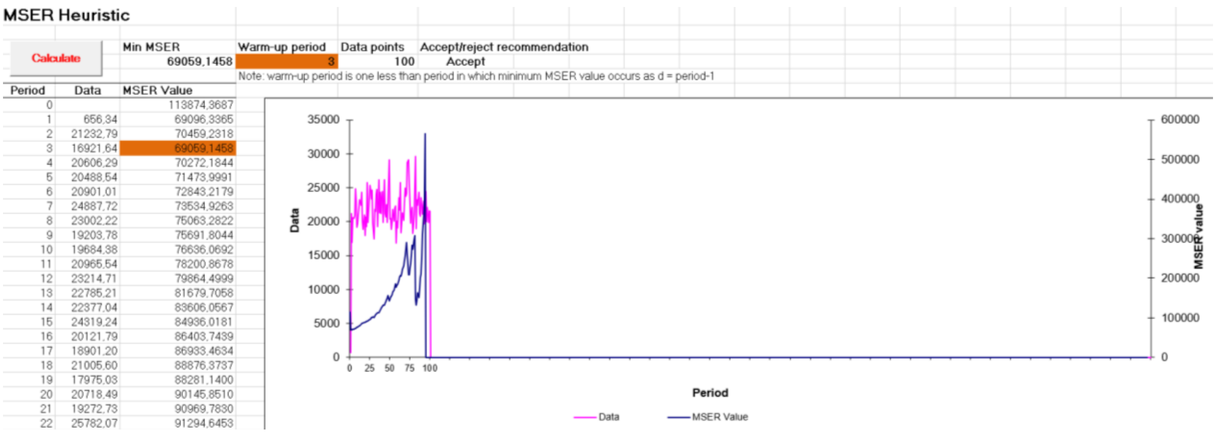
The two smallest categories, carton and writing paper, mainly consist because of the uniqueness of their products. Carton products are always printed on GC1 carton. These products are often small boxes. This causes that the production steps die cutting and creasing are always needed. The size of the products is always 1 and because the boxes are very small, 50 products fit on one sheet. The products are almost never needed in large numbers, in 93% of the cases, only one product is ordered. Because no other values of each of the categories exceed 1% of the total, the mentioned values are assumed to always occur.

Writing paper is the smallest category that is distinguished. Writing papers are always of size A4 and consist of only 1 page. The product is 90% of the time printed on Genyous paper. The other 10% of the orders, Biotop or Conqueror is used (either 5%). Because the product does not need additional production steps. The only characteristic that does have variety is amount. As is the case in all previously discussed categories, peaks can be found on rounded numbers. Because there are no patterns found in the behavior of this characteristic, no graph is discussed.

8.4. Appendix model settings

Warmup period

For the determination of the warmup period, the Marginal Standard Error Rule (MSER) method is used. With this method, a warmup period can be calculated based on a KPI. As explained, the KPI for this project is waiting time. To be able to calculate a warmup period in days, the KPI average waiting time per order per day. Using the data of five replications, which is randomly chosen, a warmup period of 3 day is returned. This warmup period is quite low, but this can be explained. Ovimex' products have a relatively quick throughput. Orders arrive, and often, they are shipped the day after. This results in a low amount of WIP in storage. In normal situations, only the WIP that is printed is stored for the night to be finished on the next day (Section 2.1.4.). Because these storage levels are so low, the model enters a steady state quite quickly.



Period	Data	MSER Value
0		113874,3687
1	656,34	69096,3365
2	21232,79	70459,2318
3	16921,64	69059,1458
4	20606,29	70272,1844
5	20488,54	71473,9991
6	20901,01	72843,2179
7	24887,72	73534,9263
8	23002,22	75063,2822
9	19203,78	75691,8044
10	19684,38	76636,0692
11	20965,54	78200,8678
12	23214,71	79864,4999
13	22785,21	81679,7058
14	22377,04	83606,0567
15	24319,24	84936,0181
16	20121,79	86403,7439
17	18901,20	86933,4634
18	21005,60	88876,3737
19	17975,03	88281,1400
20	20718,49	90145,8510
21	19272,73	90969,7830
22	25782,07	91294,6453

Figure A13: MSER graph warmup period

In actuality, the warmup period should be determined for every KPI and experiment separately. Since this takes a huge amount of time, the warmup period is only determined based on the standard model and the most important KPI (waiting time). To add a margin of safety, we slightly overestimate the warmup period. Therefore, a warmup period of 5 days is used in the experiments.

Run length

The second input value that needs to be specified is the run length. The run length represents the amount of time the model simulates during an experiment. In general, the longer the run length, the more accurate the measurements. A disadvantage of long run lengths is that it will take longer to execute the experiments.

While determining the run length of the model, no statistical method is used. This length should though be reasonably higher than the warmup period. For our experiments, we use a run length 10 times higher than the warmup period, so 50 days. Mainly because it is a rounded number that is easy to use during calculations after the experiments. Thereby, this value should generate more than enough data points to end up with accurate measurements. The value also causes that the experiments do not take up too much time.

Number of replications

The last value is the number of replications. Each experiment is performed several times to validate the outcomes. To calculate this number, the confidence interval method is used. We use the same data that is used for the determination of the warmup period. The average waiting times per order per day for 100 days for 5 replications. The value for the allowed relative error (d) is chosen to be 0.05. Goal of the method is to perform replications until the width of the confidence interval is sufficiently small relative to the average. In Excel relative errors are calculated using the following formula:

$$\frac{t_{n-1,1-\alpha/2}\sqrt{S^2/n}}{\left|\bar{X}\right|} < d$$

For the average waiting time per order per day, the relative error turned out smaller than the chosen allowed relative error as soon as 2 replications. We again add a margin of safety to make sure that all the measurements are valid and because we only calculated the number of replications for the base model. Therefore, during the experiments, 5 replications are used.