MASTER THESIS

Model of a flow-shop with order dependent sequencing to experiment with capacity and priority rule changes

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MANAGEMENT SUMMARY

Ovimex is a printing company from Deventer. The factory consists of 3 industrial printers (HP30000, HP12000 and HP T240) and multiple finishing operations. The product portfolio includes amongst others: books, user manuals, leaflets, business cards, carton packaging, menu cards, posters and advertisement folders. Due to changes in the market there is a need to improve the output of the factory. This can be done by optimizing the production process, increasing capacity or a combination of both. The objective of this research is the following:

Develop a suitable model to evaluate effects of increasing capacity and/or changing priority rules on production KPIs (tardiness, work-in-process, overtime) for a printing company with a process oriented layout subject to a variable demand.

To find effects of changes to the production plant a simulation model is created. This simulation model consists of all the machines on the production floor. Data for the model is acquired from the app that records the action by the printers. This data consists of orders and some properties such as order size, color, double sided and order name. The order type can be derived from the order name in approximately 98% of the cases. This data from the printers was only available for two printers: HP30000 and HP12000. For the HPT240 printer there was no data available, however, since this machine is used to print the inside work of books and brochure the workload of this printer can be derived from the data about covers printed on the HP12000 and HP30000 machines.

The simulation model is built in the Plant Simulation software. Any order (book or manual or leaflet etc.) in the factory are modeled using a Poisson distribution with the amount of copies per order following an Exponential distribution. Order routing and size is depended on the order type. The processing rate at the machines can be dependent on the order type and the size of the order. The following performance measures are considered in running experiments: average work-In-process in the factory, average amount of finished orders/copies at the end of each day (throughput), average and maximum tardiness, utilization of the machines and average amount of overtime.

Multiple simulation experiments were carried out to investigate the impact of the priority rules and the capacity. We found that out of all priority rules that were tested, the earliest due date (EDD) rule works best. Implementing this rule can reduce the average tardiness from 69 minutes to 48 minutes (See figure 0.1) as opposed to the first-come-first-served (FCFS) rule for the current production layout. The EDD priority rule puts a strong emphasis on preventing late orders whilst scoring good on other measures such as overtime, Work-in-process and maximum tardiness

To reduce overtime capacity can be added. 3 machines were considered for increasing capacity: an extra purring machine, extra book trimmer and an extra roll cutter. These machines are tested in various configurations and results are shown in figure 0.2. Experiment 12 shows the current situation, experiment 16 an extra book trimmer, experiment 17 an extra book trimmer and roll cutter and experiment 18 an extra book trimmer, roll cutter and purring machine.

It was found that adding extra machines does not decrease the average tardiness however it can reduce overtime (See figure 0.2). This can be explained because tardiness seems to be constrained by the capacity of the HP T240 printer. This reduction in overtime should be weighed against the costs of adding this extra capacity.
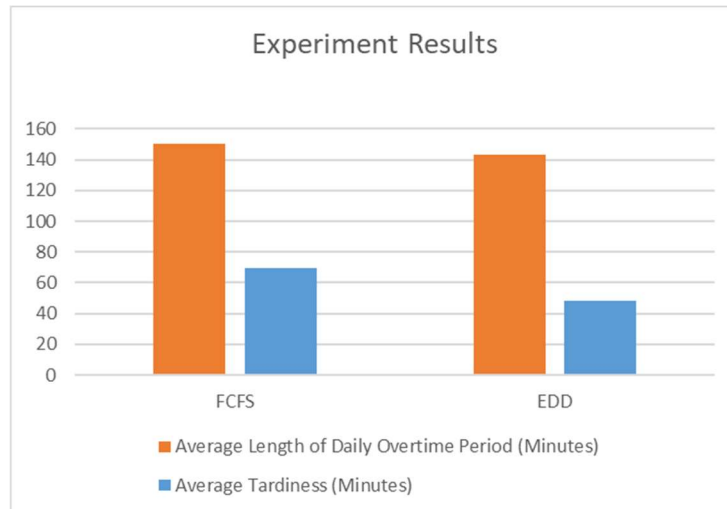
Figure 0.1: Comparison between FCFS and EDD priority rules for the current factory layout

Adding an extra book trimmer can reduce the daily average overtime from 143 to 108 minutes. Therefore if the savings from 33 minutes of overtime are greater than the extra costs of an extra machine, then it is worth to invest in an extra book trimmer. It is found that the costs of adding a new book trimmer to the factory is estimated to save € 4120,- per year while the costs would be € 3500,- per year. Thus the net savings would be € 620,- per year. These figures depend on the costs of the machine, operator, and energy costs. On top of this, an extra book trimmer gives more flexibility in the production process.

From experiments comparing changing priority rules and increasing capacity it can be concluded that changing the priority rules can decrease the average tardiness of orders but keep overtime stable. In contrast, adding extra machine(s) does not improve average tardiness but reduces overtime. Therefore the advice is to add an extra book trimmer to save overtime costs and to change the priority rule to EDD to increase the service level to customers.
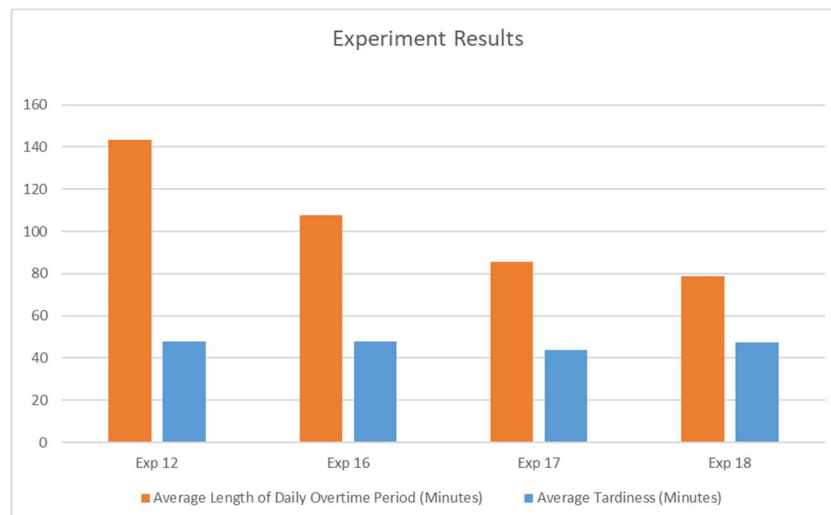

Figure 0.2: Effects of adding extra machines.

PREFACE

This thesis is the final part of my study at the University of Twente. I have completed both the bachelor and master program of Industrial Engineering and Management. I liked the campus and the surrounding area of Twente and it was a great place to do my sports activities as well with the people that I have met over the years. I would like to thank some people for supporting me in completing my thesis.

My Supervisor Engin helped me a lot during writing of my thesis. Unfortunately all of our meetings where via Skype because of the coronavirus situation, however I liked the meetings. His feedback was very helpful and I always looked forward to our conversations. I would also like to thank Ipek for being the second supervisor and reading my entire report and given solid feedback as well.

I did my internship at Ovimex in Deventer. I would like to thank all the people who work there, I could always ask and talk with everyone. And I would like to thank my supervisor from Ovimex, Roland Wolters, for the opportunity.

Finally I will thank my parents and my sister for helping me with everything.

Niels Leliveld

Enschede, 4-11-2020

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GLOSSARY

CR: Critical Ratio.

EDD: Earliest Due Date first.

FCFS: First-Come-First-Served.

HP12000: Printer for sheets of size about 50 x 70 cm. The paper input can be up to medium thickness.

HP30000: Printer for sheets of size about 50 x 70 cm. The paper input can be medium or high thickness.

Job: A job is defined is a single processing step for a single unit (sheet, meter, book) at a certain workstation. A job is sometimes referred to as customer in queueing theory.

LCFS: Last-Come-First-Served.

LPT: Longest Processing time first.

Machine: A machine (or server) is a single machine where a certain processing step is performed.

Workstation: A workstation is defined as a single or multiple machines of the same type.

Order: An order is defined is a certain product type with a certain number of copies (e.g. 800 books).

Processing step: A processing step is defined as the processing at one of the workstations.

Printing on rolls: Printing is done on large rolls of paper that can have a length of up to 84 kilometers. The paper is in the form of a roll at the start and end of the printing process.

Printing on sheets: Printing is done on individual sheets. Sheets are stacked on top of each other before and after printing.

SPT: Shortest Processing time first.

S/RO: Slack per Remaining Operations.

S/RPT: Slack per Remaining Processing Time.

T240: The printer for printing on rolls. This printer prints the pages of books and brochures.

λ: The arrival rate of orders at the factory. Used is the parameter in a Poisson distribution.

β: The expectation of the number of sheets in an order.

1 INTRODUCTION

The introduction of this thesis consists of a brief description of the context, the problem, the research motivation and the research questions.

1.1 CONTEXT

There are several methods to estimate the performance of a manufacturing line. These methods include queueing theory, factory physics and simulation. In this thesis simulation will be used in the context of a printing company with several workstations for printing and printing related support functions.

COMPANY

Ovimex is a printing office located in Deventer. The process consists of printing, finishing and shipping of orders. Products that Ovimex currently makes include: Books, user manuals, leaflets, business cards, carton packaging, menu cards, posters and advertisement folders.

Ovimex started in 1922 as OVerijsselse IMport en EXport maatschappij (Import and export company from Overijssel). By acquiring a printing press in the first years of operation the company has transformed in a printing office and has been one ever since. The company has steadily grown to a small-to-midsized company of about 40 employees. The last decades have been challenging for the printing industry due to the introduction of the internet and smartphones: Newspaper and Magazines have lost subscribers as a consequence. Printing offices have to adapt to this market development. Ovimex is doing this by investing in new printing techniques, IT and exploring new markets.

DIGITAL PRINTING

A recent development in the printing industry is digital printing. This is a different process compared to the traditional offset printing. Offset printing has high setup costs and times thus batch sizes tend to be large. Digital printing has much lower setup times and therefore it is feasible to produce in smaller batches. This offers customers the possibility to order in smaller but more frequent quantities. Digital printing also gives the possibility to customize each sheet, offering increased customer value. This means as well that the company is continuously looking for new customers to offer its products.

Ovimex has gradually been replacing traditional printing presses by digital printers. It has sold its last traditional offset printing press two years ago and replaced it by a new digital printer: HP30000. This printer can print digitally on packaging material, opening new markets. Ovimex is the only company in The Netherlands with this type of printer and has to convince the market of the advantages of digital printing of packages. Challenges at the moment for Ovimex are using the full potential of digital printing and organizing the support processes accordingly.

E-COMMERCE

The printing industry is a competitive market. In the world of today customers expect ever shortening delivery times. A large part of the orders is placed over the internet which puts prices under pressure. Research by CBS (2018) shows that prices for finished products declined last decade whilst the raw material costs remained equal. This makes it vital for printing companies to increase their efficiency in order to stay afloat.

FACTORY LAYOUT

This thesis is aimed at factories with a process-oriented layout. That is processes are grouped according to their function. In practice jobs are moved from station to station. At each station one or multiple machines are available for processing the products. Section 2.2 covers the details of the layout. A sketch of the layout in the factory is given in Figure 1. In this figure the printing operations are marked blue, the cutting operations red, the packaging operations orange and the other operations yellow. The storage spaces are grey and the office is green. In this picture the process-oriented layout is clearly visible: Machines are at a fixed position and there is space for storage near each workstation indicating that products move from station to station in their journey through the factory. At each station a small buffer of work-in-process can be stored. Machines that process similar jobs are grouped together. For example the Printer T240 prints on rolls and the Roll cutters are right next to this machine. Another example is the printer for packages (HP30000) and the finishing operations stamping and folding of packages. Completed orders are stored in the warehouse. Next to the warehouse is the I/O point for transportation. The offices are close to the printers to allow quick communication between office and printing staff. Another interesting note is that there are a lot of different machines, orders typically only require a small subset of machines depending on the needs.
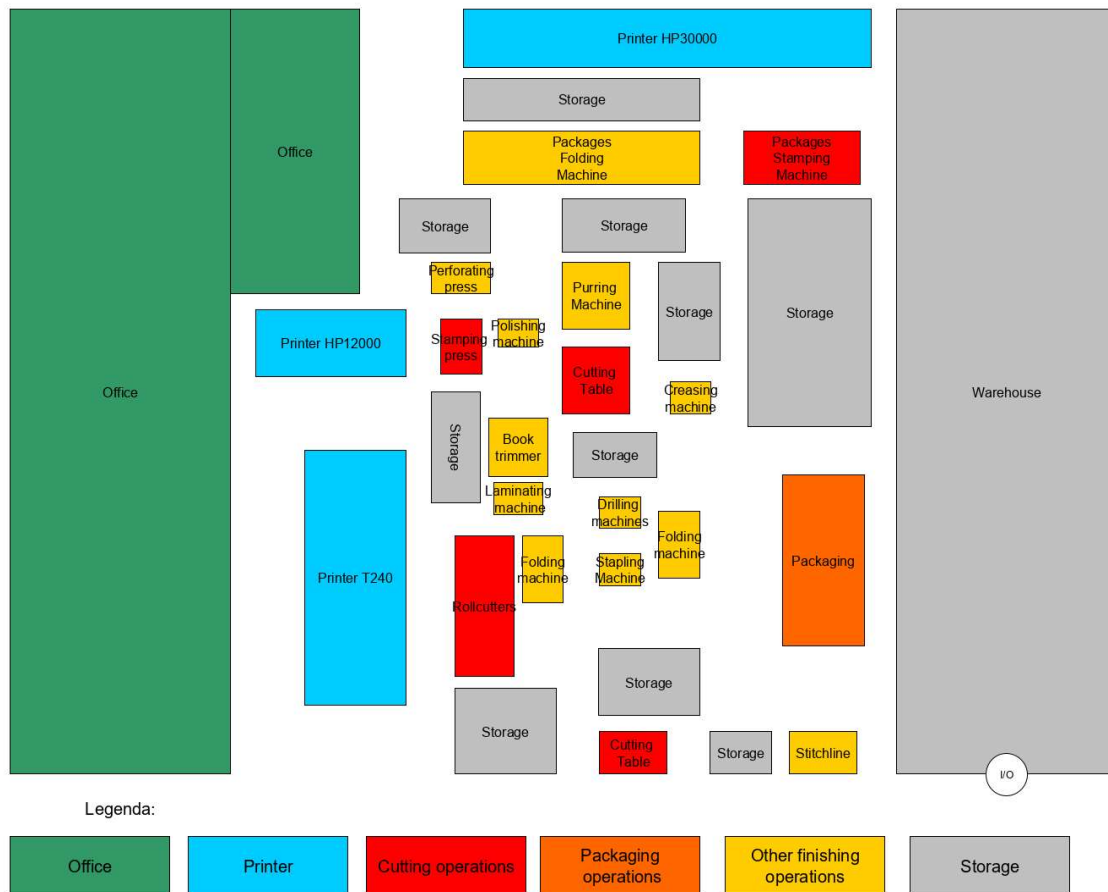
Figure 1. Schematic layout of the factory

1.2 RESEARCH MOTIVATION

As can be seen from the layout there is a large number of different machines. The interaction between the different stations is complex. Some may be overutilized whilst others are underutilized. Some may have peaks in their demand whilst being empty at another point in time. Therefore production planning can be hard to predict. Besides the production planning being complex, the demand side also brings its difficulties. Customers are more demanding than ever and expecting short lead-times. In addition, variability in demand is high. Figure 2 shows the

weekly printed volumes from two of the printers in the factory of the company. The fluctuation in printed volumes indicates a high variability in demand. This has effects on variables such as overtime, late deliveries and utilization of workstations.

There are many different machines for finishing in the company as can be seen from Figure 1. In contrast with printers, these machines are less expensive and can be added or removed based on the capacity needs. Orders have to visit multiple machines. Almost every machines has a buffer to queue up jobs. Hopp & Spearman (2008) mention different priority rules for processing of these queues: First-come-first-served (FCFS), last-come-first-served (LCFS), earliest due date first (EDD), shortest processing time first (SPT), or longest processing time first (LPT). There is value in researching the capacity and priority rules in the factory. Data generated by digital printing offers opportunities that were previously not possible with conventional printing. Would it be possible to find optimizations in the costs of the production process? One could study the effects of adding a certain extra machine or the effects of changing priority rules.
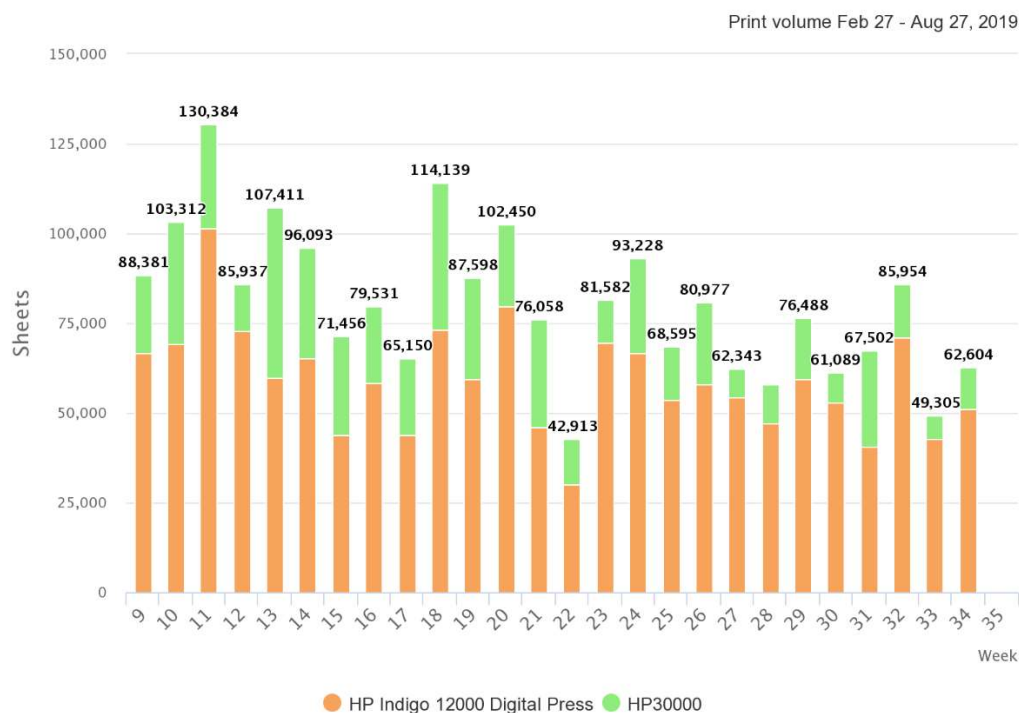
Figure 2. Fluctuations in production

1.3   PROBLEM IDENTIFICATION

To identify a problem in the production process a problem cluster is created (Figure 3). This problem cluster is modeled following the Managerial Problem Solving Method (MPSM) by Heerkens & Van Winden (2017). This method uses a problem cluster to find a root cause of a managerial problem. The idea behind the method is that solving this root cause would solve the end problem. In the picture the root causes are colored in red and the end problems in blue. Yellow indicates intermediate steps. In this picture we can see that there is overtime, late deliveries and increased lead times. These problems are created by the following root causes:

- **Variability in demand:** This issue is due to the nature of the market. The market is volatile and being flexible delivers value to customers. Hence this issue is not a problem that should necessarily be fixed as it creates value for customers. A possibility is to give customers options with respect to lead times and a corresponding price schedule to deal

with variability in demand. Demand forecast is hard since the company is depending on the needs of larger companies such as publishers and web shops.

- **Printer maintenance and failures**: Printers are technically challenging machines. They require regular maintenance like cleaning and replacing parts. Therefore small daily maintenance is unavoidable. Sometimes a component fails and requires repair by a specialized engineer. This situation is unavoidable for the printing company. However if downtime is long it can create problems in the production schedule.
- **Incomplete overview of orders:** Orders are moving through the factory with a physical note attached to it detailing its production details. Downside of this is that the location of orders is not available in a digital program whilst it is in production. This means that it is not immediately clear where bottlenecks are in the system. It also means that there is no detailed overview of the current available capacity. Such that if a new order comes in then the sales person may accept that order whilst there is no capacity for it.
- **Planning in two separate applications**: Ovimex has currently two planning modules: An ERP-system (xGram) for long term planning and a webportal (web2print) for short term planning. Integration of these modules can be improved and lead to more accurate information about capacity usage to assist the sales department and to reduce changes of accepting orders that cannot be met.
- **Printer planning not fully automated**: According to the plant manager the key to efficient production is planning jobs as to minimize setup times. Planning for short term jobs starts at 17:30 in the evening. These orders have to be shipped the following evening. These orders need to be arranged in a cost-effective manner next to the long-term orders. Planning of jobs is a complex process due to multiple workstations and mathematical models/heuristics may assist in planning.
- **Low capacity of some finishing stations:** Some machines in the factory are utilized a lot (cutting, gluing and trimming operations) whilst others (perforating, packaging) are rarely used. This means that demand is not in cooperation with the capacity in the factory. Some of this could be fixed by balancing demand. For example focusing on increasing demand for packages since there is capacity to process more packages orders. To deal with the capacity shortages at some finishing operations it might be useful to increase capacity on these operations.
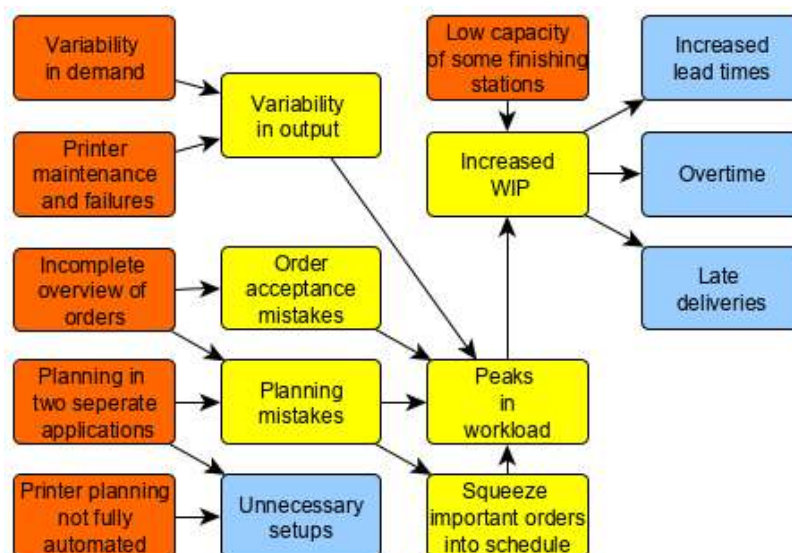
Figure 3. Problem cluster

Concluding, the issue of the increased Work-in-process has several root causes. The issues that can effectively be addressed are the low capacity of some finishing stations, the planning issues and the demand variability. The planning issues can be addressed by integrating both planning

modules into one. The demand variability can partially be addressed by improving the marketing in such a way that new markets are explored to increase demand for packaging. The capacity issues might be addressed by adding capacity or by researcher if there would be a better way to organize the production process. This last point is the most interesting from an industrial management point of view and is thus chosen as subject for this thesis. Improvements to the problems such as overtime and late deliveries might be possible. To find out possible improvements the factory has to be analyzed.

ACTION PROBLEM

One of the above problems can be selected as the action problem. An action problem is a discrepancy between the norm and reality, as perceived by the problem owner (Heerkens & Van Winden, 2017). The action problem should be quantifiable, this way the norm and reality can be compared. For the action problem the end problem "overtime" is chosen. This problem is easily quantifiable: The length of the overtime period can be measured every day and measured in time units. The norm can be defined as: "An average overtime period of x minutes is acceptable". The goal of problem solving is to have the reality to meet this norm. Therefore the processes in the factory have to be analyzed such that both the current situation and the norm can be defined. In the current situation is known that there is overtime and that orders are delivered late. These problems can be solved by either improving the current situation or accepting that the current situation is acceptable (lowering the norm). The problems about overtime and late orders will be analyzed in this thesis.

1.4 SOLUTION APPROACH

There are different methods to analyze a factory. For example queueing models, simulation models and linear programming methods. Currently decisions such as adding/removing workstations and changing priority rules are made without analyzing the effects thoroughly. The advantage of a model is that effects of changes can be analyzed before applying them in practice. The most suitable model for the situation in the company is yet undecided.

QUEUEING MODELS

Several queueing models exists to model the flow of jobs through a network. These include Jackson networks (Jackson, 1963), BCMP networks (Baskett, Chandy, Muntz & Palacios, 1975) and variability model from Hopp & Spearman (2008). Advantages of queueing models are that they give exact results and can be built in a spreadsheet. It becomes easy to change some parameters and see the effects immediately. However the process requires some form of standardization to fit in the queueing model.

SIMULATION MODELS

A Simulation is another way to model a factory. A simulation model offers vastly more customization options compared to queueing models. This means that the simulation model can give more detailed insights in the factory than a queueing model. Obviously a simulation model takes longer to build than a queueing model and changes the parameters and seeing their effects takes more effort. A simulation model can be used to validate a queuing model. Other authors such as Wu (2014) used simulation to verify their queuing models.

1.5 RESEARCH SCOPE AND LIMITATIONS

The scope of this thesis is the entire production process in the factory. However there are some limitations:

- The process is analyzed from printing to packaging. The process before printing (sales, prepress) are left out of the research as well as the warehouse operations.

- Inventory management is not a part of this research. A printing company does not have a complex inventory process. Supplies mainly consists of inks and paper. The company handles this with appropriate reorder policies.
- Processes at suppliers and customers are not taken into consideration.

1.6 RESEARCH OBJECTIVE

The research objective of this thesis is the following:

Develop a suitable model to evaluating effects of increasing capacity and/or changing priority rules on production KPIs (Tardiness, work-in-process, overtime) for a printing company with a process oriented layout subject to a variable demand.

A model of the production process will aid to company in decided which machines to add or remove and give insights into which machines are under- and overutilized. Changing priority rules may lead to an optimized factory performance without investing in capacity. Research sub-questions are created to fulfill this objective step-by-step. The research objective is eventually dealt with at the end of the report in the conclusion.

1.6.1 RESEARCH SUB-QUESTIONS

The research objective is subdivided into several sub questions. Whilst the scope of the research objective is the entire report, sub-questions are answered in a chapter or section of a chapter. The sub-questions guide towards solving the research objective.

CHAPTER 2: CURRENT SITUATION IN THE FACTORY

First the current situation in the factory will be addressed. This section is focused on getting information about machines, production process and the orders at the factory. This is the input for the model of the factory.

- What is the arrival rate of jobs to the factory?
- What are the characteristics of different order types?
- What is the processing rate, setup time and availability of relevant workstations?
- What are the effects of job batching on the setup times?
- How do orders flow through the factory?
- Which properties of the production process should be used in a simulation model?

CHAPTER 3: LITERATURE

Literature is focused on selecting the right model for the research. This model should suit the situation in the factory well. The models that will be considered are queuing models and simulation models. Besides the model we will be looking at priority rules and KPIs.

- What queueing models are available to model the production process of a printing company?
- How to model an arrival process of orders into a production process?
- What priority rules for jobs at workstations are suitable for the production process of a printing company?
- What KPIs are useful for measuring the performance of the production process of a printing company?

CHAPTER 4: MODEL CONSTRUCTION

A suitable model will be constructed based on the data from the factory. The data from the factory requires analysis before it can be used as input for the simulation model. The model requires validation and verification.

- What is a suitable simulation model for the factory?
- What is a good method for the arrival process of orders in the factory?
- Can the simulation model be validated with the factory?
- Can the model be verified?

CHAPTER 5: EXPERIMENTS

After the model is constructed it is ready to run experiments. First relevant settings need to be defined. After that the output of the model can be analyzed.

- What are realistic variations in the input parameters?
- What is the effect of changing capacity on the KPIs?
- What is the effect of changing priority rules on the KPIs?

1.7 RESEARCH METHODOLOGY

Figure 4 shows the method to answer the research question. The main parts of the study are displayed. Input is based on the current situation in the factory, this is described in chapter 2. Chapter 3 gives a literature review, which will give insights into different models. The construction of the model is done in chapter 4. Experiments settings and results are the aim of chapter 5. Finally chapter 6 contains the conclusions of the results and an advice regarding capacity and priority rules to the management of the factory.
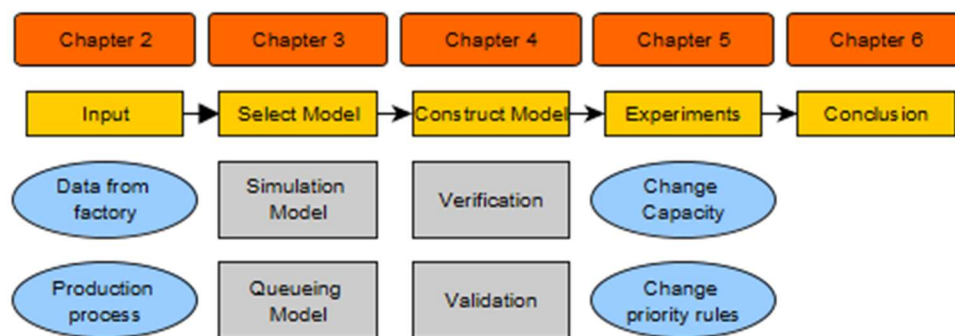
Figure 4. Thesis structure

PLANNING HORIZON

This thesis is aimed at the mid-term planning horizon, that is six to twelve months. In this timeframe an extra machine can be added with accompanying operator or the priority rules can be changed.

2 CONTEXT ANALYSIS

The context analysis contains a detailed view of the processes of the printing company. Besides this the available data is discussed. The machines and workstations are investigated to find values such as processing time and setup time. This chapter seeks to find answers to the following research questions:

What is the arrival rate of jobs to the factory?

What are the characteristics of different order types?

What is the processing rate, setup time and availability of relevant workstations?

What are the effects of job batching on the setup times?

How do orders flow through the factory?

Which properties of the production process should be used in a simulation model?

2.1 PROCESS DESCRIPTION

The production process of a printing company can be divided in three main processes: (i) prepress, (ii) printing, and (iii) finishing. As can be seen in Figure 5.

Figure 5. Three main process steps in a printing company

The factory consists of workstations for printing and finishing. There are three printers and a large variety of workstations for finishing. Prepress is the process of making a document ready for printing. This is performed by a salesperson and/or graphic designer.

2.1.1 PREPRESS

Before a job is ready to print it has to be prepared for printing. This process can consist of the following possible steps:

- Design the graphical document (PDF) based on customer specifications.
- Prepare PDF delivered by client for printing.
- Add order to ERP-system and add to production schedule (for large orders).
- Send batch of jobs to printer (for automated orders).

Most orders are repeating orders or automated orders and thus require few preprocessing.

2.1.2 PRINTING

Printing is the core process of a printing company.

The company has three big printers for production:

- T240: Printing on rolls. Suited only for thin paper such as inside work of books and brochures, but only used for books.
- HP12000: Printing on normal sheets. Suited for covers, flyers, posters, magazines, business cards, etc.
- HP30000: Printing on carton sheets. Suited for packaging materials, covers, posters , etc.

The T240 is suited for large, monotonous jobs such as printing large quantities of books. The other printers are almost identical machines: performance wise and the format of the sheets they can print on are equal. The difference is that printer HP30000 has more options due to using different ink which is suitable for food packaging and can print on thicker sheets. This printer cannot print on thin sheets and is thus unsuitable for printing of pages for magazines or books. The T240 can only print thinner paper (up to 170 gram) and therefore can only print pages of books.

There is some overlap between the HP30000 and the HP12000. They can both print jobs that require medium thickness of paper: Book covers, flyers, promotional material. Also the size of the input paper is equal.

The HP30000 and 120000 give detailed production information via the PrintOS application on job level: name, press, start time, end time, type of paper, number of impressions, job duration, number of failures, and some others. This data can be used to determine setup times, average and standard deviation of processing rates of the printers. The T240 does not give these detailed production statistics and one has to rely on data about orders from the ERP systems to retrieve data.

DATA FROM PRINTERS

A sample of data from the printers containing five records is shown in Table 1. This data is available through the PrintOS application and can be exported to a text file for further data processing. From this data it is possible to extract information about orders.

The order type can be found from the "Job name" entry. This is because the jobname almost always contains a) the order type or b) a strong hint to the order type. Using the Excel macro from Appendix 8.3.1 it was possible to attach an order type based on the job name for 98,5% of the orders.

The "Press Name" entry contains the press where the job was processed.

The "Substrate Units" and "Copies" columns both contain the number of sheets used in the job.

The "Impressions" value counts how many times a photo plate prints on a sheet. For example printing one sheet in black color, one sided takes one impression. Printing in color, two-sided takes eight impressions (four colors times two).

"Inks" refers to the inks used for the job. C (Cyan), M (Magenta), Y (Yellow) and K (Black) are the most common colors. The value behind the character denotes the number of impressions for each color. The inks and impressions can together be used as an estimate for if the order is one-sided, two-sided and black or color.

The "Print Attempts" and "Failures" can indicate mistakes, maintenance and failures. This column can also lead to irregularities in the inks pattern (The 3rd entry in the table has an unequal distribution of ink impressions).

Table 1. Sample of data from printers

Job Name	Press Name	Start Time	End Time	Substrates Types	Sub-strates Units	Inks	Impres-sions	Copies	Print At-tempts	Net Printing Time %	Total Printing Time	Total Job Duration	Failures
853964-C0.PDF	HP Indigo 12000 Digital Press	Mar 12, 2019 14:36:23	Mar 12, 2019 14:38:52	300gr metallica white	34 Sheets	C(68), M(68), Y(68), K(68)	272	34	2	55.7%	00:01:23	00:02:29	0
866562-C4-#4-1 BRIEF A - 46 stuks.pdf	HP Indigo 12000 Digital Press	May 23, 2019 14:02:54	May 23, 2019 14:03:26	Biotop 120	36 Sheets	K(36)	36	12	1	100.0%	00:00:32	00:00:32	0
853394-B3.pdf	HP Indigo 12000 Digital Press	Mar 7, 2019 19:17:31	Mar 7, 2019 19:39:18	Genyous 120	289 Sheets	C(567), M(586), Y(569), K(584)	2306	289	6	50.27%	00:10:57	00:21:47	3
xcardtop-Tweezijdig sulfaatkarton 400MATLMT1-1-B-12_06_2019 _16_12_1.pdf	HP30000	Jun 12, 2019 16:34:05	Jun 12, 2019 16:39:33	2 zijdig sulfaat 400 grs	29 Sheets	C(29), M(29), Y(29), K(29)	116	29	2	11.89%	00:00:39	00:05:28	0
867202-B2.pdf	HP Indigo 12000 Digital Press	May 29, 2019 07:47:07	May 29, 2019 07:48:06	Biotop 120	26 Sheets	C(52), M(52), Y(52), K(52)	208	26	1	100.0%	00:00:59	00:00:59	0

PRINTING ON ROLLS

Printing on rolls is suited for large production runs (e.g. inside work of books) whilst printing on sheets is mostly for smaller orders (e.g. folders, packaging). Figure 6 shows the layout of standard book pages on a roll. Pages are printed next to each other. A normal size for a page of a book is 275 mm. Therefore an estimate for the amount of pages per meter is:

$$\frac{1000}{275} * 2 = 7{,}27 \; pages$$

Sheets on the other hand are large sheets of size 75 cm wide and 53 cm long that fit on pallets. These are printed on the HP12000 or HP30000. They are cut in the end format using cutting tables.
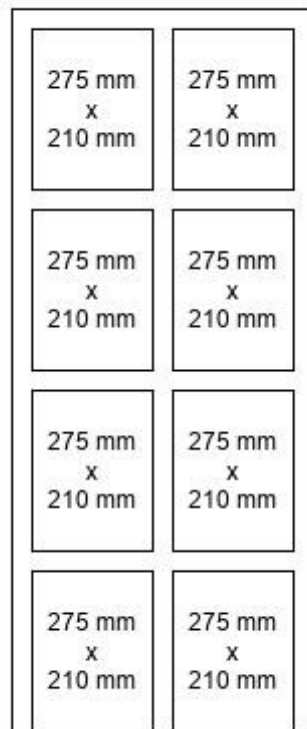
Figure 6. Printing on rolls: 2 pages next to each other on a very long roll of paper (60 to 80 meter).

2.1.3 FINISHING

There are several production steps available for the finishing of the order. Finishing is done after printing. The following steps are available: Coating, laminating, polishing, cutting, stamping, riling, folding, binding, trimming, perforating and packaging. The required operating steps depend on the order specifications.

- Coating: The coating machine is in line with the HP30000 and adds a coating to the sheets. Coating is usually applied on carton packages. This is necessary so glue will stick.
- Laminating: Sheets can be laminated. This adds a plastic protection layer to the material. This optional production step is performed after printing but before cutting the sheets. Book covers are often laminated.
- Polishing: The polishing machine is used to prepare carton packages for gluing. The parts where glue is applied is prepared in such a way that the glue will stick.
- Cutting: Cutting consists of cutting the rolls and sheets into a specified size. Cutting is required for almost all jobs. There are four machines available for cutting: two for the cutting of rolls and two for the cutting of sheets.
- Stamping: This is another way to cut pieces out of sheets. Stamping is done when a certain special shape of the paper is necessary. There are several molds available so a lot of different shapes are available. Stamping is used in the process of carton packages to create papercrafts that can be folded into 3d boxes.
- Creasing: A folding line on a flat sheet of paper is called a crease. Creasing is necessary if the product is printed on thick paper and requires folding.
- Folding: A folding machine automatically folds flat pieces into boxes and adds glue during this process. There is a machine that combines riling, folding and gluing of carton packages.

- Binding: Binding is done to combine pages and covers together to form a book. Binding can be done with glue (purr) or staples (stitching). Binding using wire-O (ring band) is another option.
- Trimming: Books require trimming to align pages and cover correctly. This process consists of cutting the three edges of the books by a machine.
- Perforating: Some orders require perforating. This is done by an operator with a drilling machine.
- Packaging: The orders are packed into boxes at the last processing step. Products may be bonded together using a banding machine. A label is added at the packaging department. Items are usually shipped in the evening after production.

Figure 7 shows the production steps in the order that they can occur. The following observations can be made:

- Each order needs prepress, printing, cutting and packaging[1]. All other production steps are optional.
- The route that a job takes through the factory depends on the order. Simple flyers are just printed, cut and send. Books on the contrary are printed on two different printers and merged together at the "binding" processing step. This is shown in more detail in Figure 8.
- Laminating is only applicable to products that are printed on sheet. Thus, jobs that require laminating are always processed before cutting or stamping.
- The creasing step is an optional step that is sometimes required before folding. This depends on the thickness of the paper (paper of weight x has to be creased before folding).
- Some processing steps are rarely used whilst others are required for every order.
- There are very few orders that require perforating, folding and creasing.

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[1] This is true except for 1 type of orders: Orders that are printed by the company but finished by some subcontractor. However the amount of this type of orders is negligible. These orders are called 'printed sheets'.
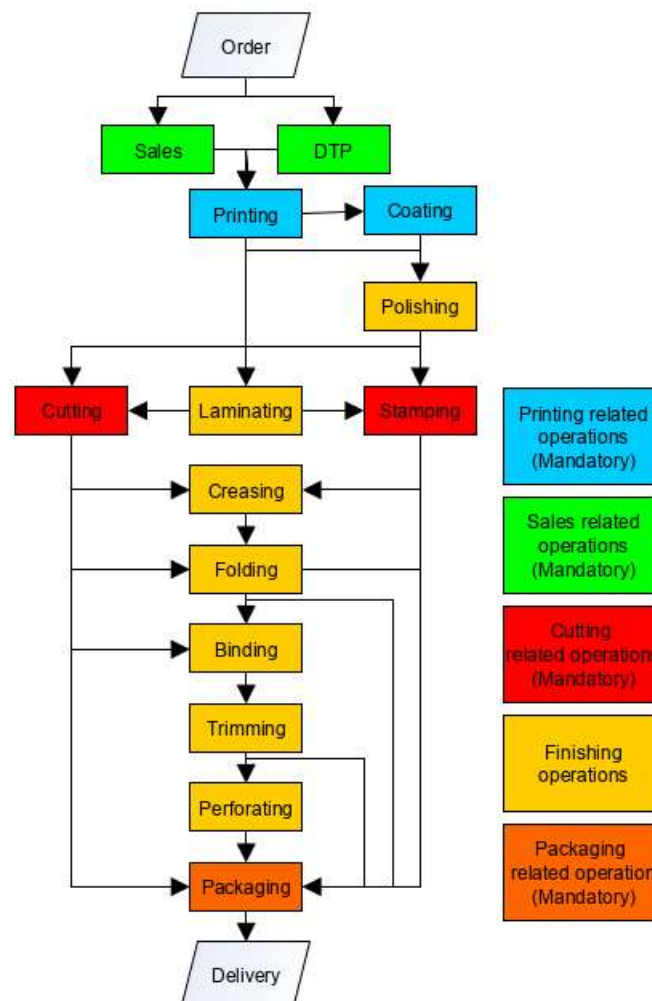
Figure 7. Production processes in a printing company

2.2 FACTORY LAYOUT

There are four basic layout types: process, product, hybrid, and fixed position (Read & Sanders, 2007).

Relevant factory layouts for printing companies are product layout and process-oriented layout.

Product layout: In this layout the products move on e.g. a conveyer belt through the factory. Speed and high throughput are the advantages of this layout type, which makes it appropriate for printing in high volumes and a low cost focus. Downside is that the entire production line is down if one machine is down. This layout is characterized by high automation (Read & Sanders, 2007).

Process-oriented layout: Workstations are in a fixed position and jobs are moved from station to station on e.g. pallets. A workstation can consist of a single machine with operator or several machines that have the same functionality. There is the possibility to store some work in process at the workstations which means that workstations are not idle as long as there is a queue in front of the station. Downside for this layout is that work in process has to be moved manually on pallets

between workstations thus requiring extra labor compared to a production line (Read & Sanders, 2007).

The printing process in the company has a process-oriented layout. This decision is taken to increase flexibility and reduce effects of downtime at the printers. Flexibility and quality are the customer values targets of this company. In a process-oriented layout one can easily swap job priority at each workstation which increases flexibility. This thesis will thus focus on printing processes with a process layout.

The company has one or multiple machines for each production process. The diagram in Figure 8 shows the machines and possible routing through the production process. We can conclude that:

- The sheets printed by the HP12000 and HP30000 use roughly the same machines for finishing.
- The process from T240 is separated at the start from the processes from printer B and C. These processes come together at the purring machines (binding step).
- Steps flow one way: There are no cycles in the process and no station is visited twice.
- Some steps are 'mandatory' i.e. they occur in every order.
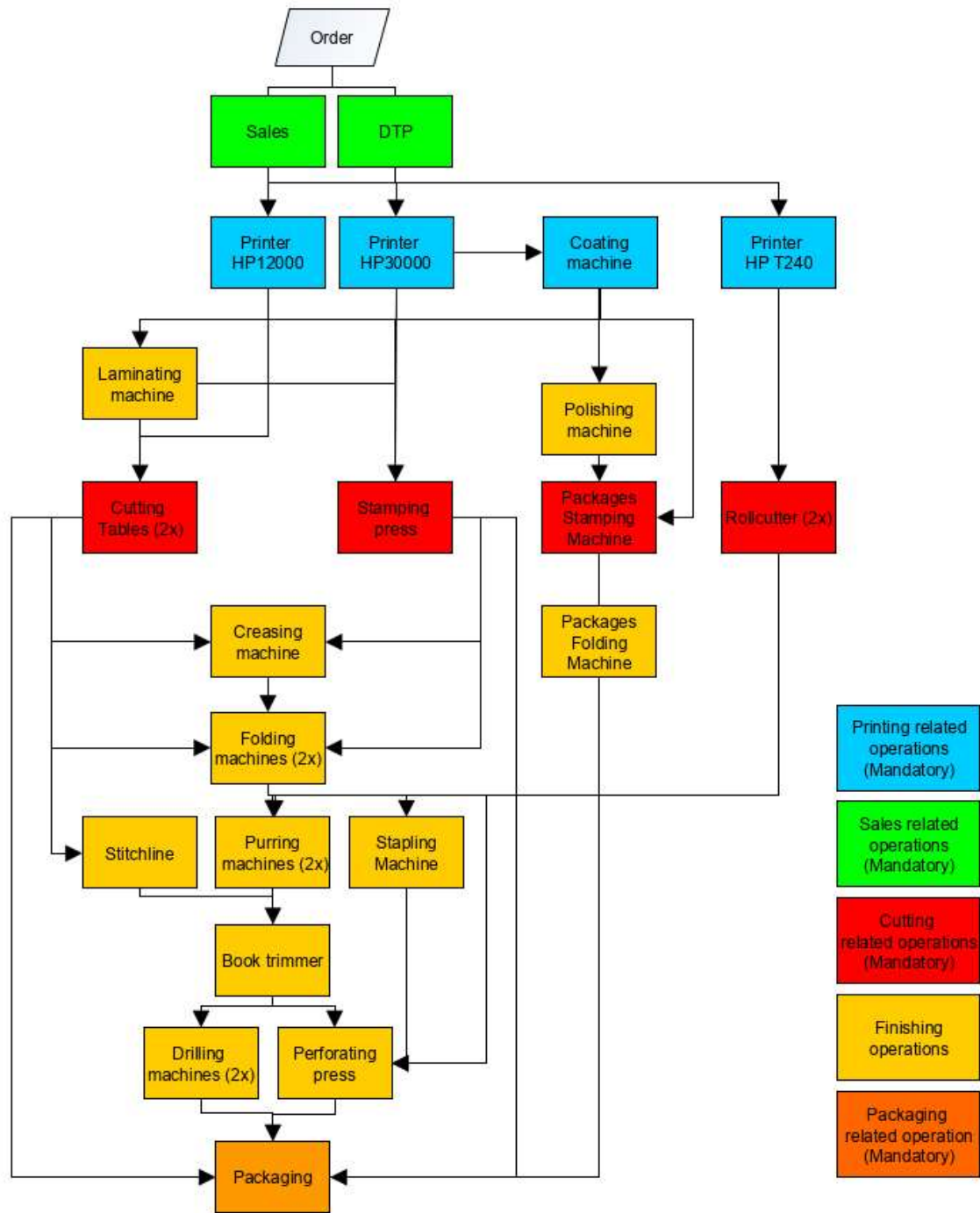
Figure 8. Production process in the company based on each machine.

2.3 MACHINES AND WORKSTATIONS

The company has several machines as is shown in Figure 8. Production process in the company.
A detailed list of these machines is given in Table 2.

15

Table 2. Machine descriptions

Workstation	Short name	Production step	Function	Product type examples
Roll printing station	HP 240	Printing	Printing on rolls. Only thin paper.	Inside work of books
Roll cutting station	Roll cutting machine 1	Cutting	To cut the rolls from the T240 printer into book pages.	Inside work of books
	Roll cutting machine 2	Cutting		
Normal sheet printing station	HP12000	Printing	Printing on sheets. Medium thickness of paper.	book covers, magazines, folders
Carton sheet printing station	HP30000	Printing	Printing on sheets. Thick paper.	Packages boxes
	Coating machine	Coating	Coating paper. This is a protective layer. Machine is in-line with HP30000.	Packaging boxes
Packages stamping station	Packages stamping machine	Stamping	Stamping of sheets into packaging templates.	Packaging boxes
Packages folding station	Packages folding machine	Riling and folding	Riling, folding and gluing of carton packages.	Packaging boxes
Laminating station	Laminating machine	Laminating	Adds a protective plastic layer to the printed sheet.	Book covers, menu cards
Sheet Stamping station	Stamping press	Stamping	Stamping of sheets into special (non rectangular) shapes.	Stamping of sheets into shapes
Perforating station	Perforating press	Perforating	Perforating for ring band binding. Optional step after cutting/stamping.	Products bonded with wire-O
Sheet cutting station	Sheet cutting machine 1	Cutting	Cut sheets into pieces with a rectangular shape.	book covers, flyers, cards, etc.
	Sheet cutting machine 2			
Binding station	Purring machine 1	Binding	Glue cover and inside work together to create a book.	Books
	Purring machine 2			
Stitching station	Stitchline	Binding	Stitches cover and pages together to form a magazine.	Magazines
Trimming station	Book trimmer	Trimming	Trims the edges of books and magazines.	Magazines and books
Creasing station	Creasing machine	Creasing	Adds a riling line to the product so it can be folded easier. Only necessary for thick paper.	Menu cards
Folding station	Folding machine 1	Folding	Folding of products. Old machine that is rarely used.	Menu cards, leaflets
	Folding machine 2	Folding	Folding of products. Old machine that is rarely used.	Menu cards, leaflets
Stapling station	Stapling machine	Binding	Large stapling machine for manual stapling. Is barely used as the Stichline is usually used for stitching.	Custom orders
Drilling station	Drilling machine 1	Perforating	Perforates bonded products.	Magazines, instruction books
	Drilling machine 2	Perforating		
Polishing station	Polishing machine	Polishing	Adds a polished protection layer to printed sheets.	Packaging boxes
Packaging station	Packaging tables	Packaging	Packaging of products and additional manual labor.	All products

2.4   PRODUCT ORDER TYPES

The company produces a wide range of printing products: Books, flyers, magazines etc. These products require different machines and process steps. Therefore it is important to get an

overview of i) quantities of the different order types and ii) the processing steps for each order type. The purpose of this section is to determine the product portfolio of the company.

The different order types that are used frequently are shown in Table 3. These order types are largely categorized on the printer it should be printed at:

- Order codes starting with a 'B' are supposed to be printed on the HP12000.
- Order types with an 'A' are supposed to be printed on the HP30000.
- Order types starting with a 'C' are supposed to be printed on the HP12000 or the HP30000.
- Brochures and books starting without a letter will have their inside work printed on printer HP T240 and the cover at one of the sheet printers.

Order types are also categorized based on their ordering process. Order codes B1 and 65 have the same production process but they are ordered through different means. The same holds for C0 and 'xcard'.

Table 3. Order types at the company

Order code	Order name	Description
B1	Folders	Small folders stitched together. Usually advertisement folders.
B2	Flyers	Simple single sheet advertisement material cut into a rectangle shape.
B3	Brochures saddle stitched	Brochures are small books. Inside work and cover are stitched together.
B4	Brochures PUR	Brochures are small books. Inside work and cover are glued together with PUR.
B9	Printed sheets	Printing of sheets without finishing. Client is another printing company that performs finishing operations.
C0	Business cards	Business cards are small cards. These are printed on sheets in large quantities.
C1	Letter paper	Letter paper are loose sheets of A4 paper with company logos printed on it.
C2	Notebooks	Notebooks are sets of paper glued together at the top. The gluing is performed by workers at the packaging station.
C3	Periodics	These are periodically returning orders. This category is created for administrative purposes by the company however this means that these orders can be any of the other types.
C4	Other	This category includes everything not in the other categories. It can be anything like posters, Wire-O. It is usually promotional material that requires special processing steps.
A1	Commercial carton	This category contains every promotion material meant to be printed on printer C.
A6	Carton Packages	Carton packages that require processing on the special stamping and folding/gluing machine.
50	Brochures printed on rolls	This category includes all brochures with the inside work printed on rolls and the cover printed on sheets. The finishing is usually PUR (80%) but can also be stitching (20%).
54	Books printed on rolls	This category contains books with the inside work printed on rolls and the cover printed on sheets. All books are glued together with PUR.
65	Folders	Same as B1.
xcard	Business cards	Same as C0.
bierkaart	Beercard	These are menu cards usually stamped in a special shape.
N/A	Unknown	This category contains all orders from which there is no code available in the data. It can be any of the other categories.

2.5 ARRIVAL RATES OF JOBS

To build a model of the factory it is necessary to know how many orders arrive each day at the company. Data about arrival rates of orders is an important input for our model. However it proved to be very difficult to obtain this kind of data. There is no data about the date and time orders are placed. Two sources for data about orders are available: Webprint and Printerdata.

2.5.1 WEBPRINT DATA

For the planning of the company due dates are important. The moment of ordering is not stored in a database since this is not important for the production planning. This data can be retrieved

from the Webprint application. Table 4 shows an example of the data that can be retrieved from the Webprint app.

Table 4. Amount of orders with given delivery dates from the Webprint system

Delivery Date	Amount of orders
08/11/2019	177
09/11/2019	1[2]
11/11/2019	126
12/11/2019	126
13/11/2019	106
14/11/2019	65
15/11/2019	43
18/11/2019	22
19/11/2019	16
20/11/2019	26
21/11/2019	1[3]
Grand Total	709

2.5.2 PRINTERDATA

The app from the printer gives more data. An example of this data is shown in Table 5. Data was collected for the same two weeks as in Table 4. There is a noticeable difference between the two tables: The Webprint data shows 709 orders and the printer data show 1668 orders whilst the time interval is the same. Thus, the Webprint data is missing records. This can be explained by the fact that orders are entered in both the Webprint system and the ERP-system. Only automated orders are processed by the Webprint system. Data from the ERP-system is not available. Thus, to predict the amount of orders in the company it is better to use the printer data since this contains all orders. shows the amount of orders each day in the time span of two weeks that were printed. November 7 was an outlier which could be explained by a printer failure. If we remove this datapoint from the set there are 9 observations left. The average amount of orders each day in this time interval was 163,6. The total amount of sheets that were printed was 113.160. Which is 11.316 sheets per day.

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[2] This is a Saturday. This data can be considered as an outlier or error. The company is closed in the weekend.
[3] This data is likely incorrect since it is an outlier and the last day in the interval. Some records may not be included in the dataset.

Table 5. Amount of orders from printer data

Date	Amount of Orders
Nov 7, 2019	3
Nov 8, 2019	139
Nov 11, 2019	183
Nov 12, 2019	237
Nov 13, 2019	186
Nov 14, 2019	209
Nov 15, 2019	153
Nov 18, 2019	166
Nov 19, 2019	217
Nov 20, 2019	143
Grand Total	1636

2.5.3 DOWNTIME AND FAILURES

Printer data will be used to determine the arrival rates of jobs into the system. Downside of this approach is that a day with a low amount of jobs can be explained by another reason than low demand: downtime. This 'noise' in the data could to be taken into account. Downtime can occur in the following situations:

- The factory is closed.
- There is no operator available.
- The printer has broken down.
- The printer is undergoing maintenance.

The factory is operating from roughly 8:00 to 17:00. Printers can operate for a longer time period. Overtime is possible in case demand is high.

SHEET PRINTERS

The app from the printers collects data about maintenance and failures. The app divides the printer uptime into six categories:

- Printing time: The printer is physically printing
- Not-printing time: The machine is awaiting actions by operator such as assigning jobs, emptying paper trays and filling paper trays.
- Supplies time: This category contains regular maintenance. Some components of the machine have a limited lifespan. The PIP (Photo Imaging Plate) and the Blanket have to be replaced multiple times per week. Ink is also replaced regularly but does not require downtime.
- Jams recovery time: This includes jams such as paper getting stuck in the printer.
- Failures recovery time: Other failures and regular cleaning of the machine are included in this category.

This data is shown in Figure 9 (per day), Figure 10 (per month) and for a period of ten weeks in Table 6. This data is available on a day-to-day basis in a spreadsheet. From these figures we can conclude that failure rates are stable on a month to month basis but can fluctuate day-to-day. This means that failures can indeed cause noise into the data and have to be taken into account when constructing a model.
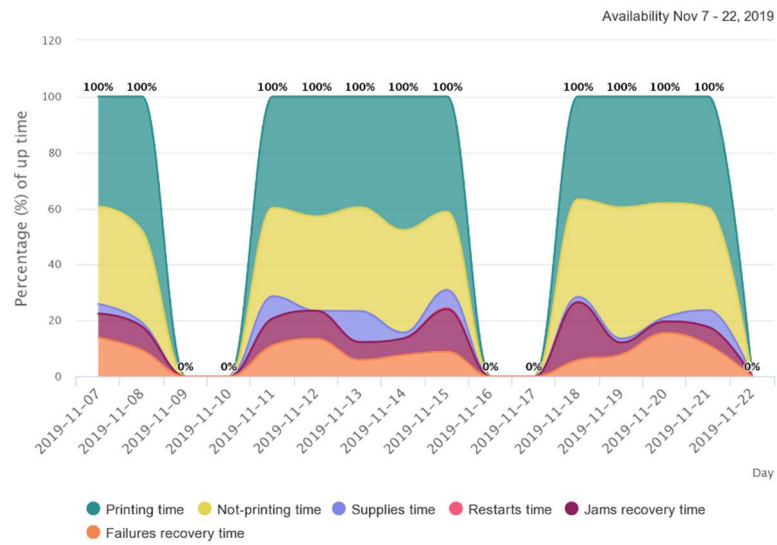
Figure 9. Combined availability of printer b and c per day
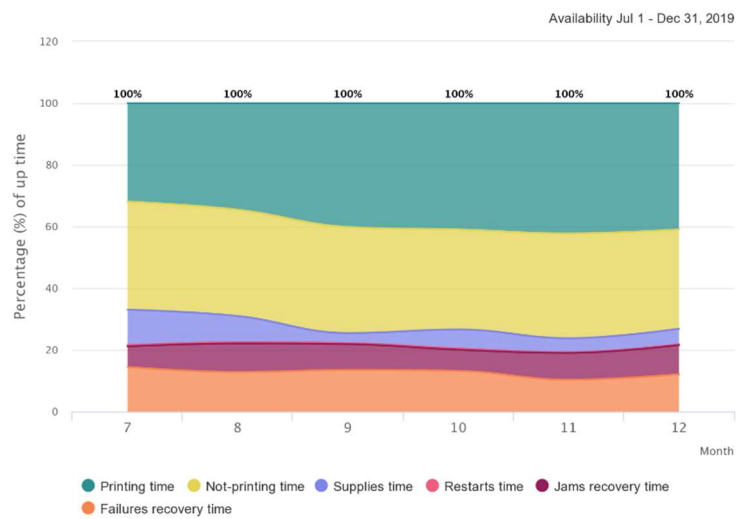
Figure 10. Combined availability of printer b and c per month

Table 6. Fraction of uptime for each failure type

week	Supplies time	Restarts time	Jams recovery time	Failures recovery time	Total
27	13%	0%	7%	16%	36%
28	2%	1%	9%	31%	43%
29	7%	1%	11%	11%	30%
30	8%	0%	10%	9%	27%
31	1%	0%	14%	8%	23%
32	4%	1%	16%	11%	32%
33	6%	1%	13%	8%	28%
34	8%	1%	9%	12%	30%
35	3%	0%	13%	13%	29%
36	4%	0%	12%	6%	22%
Average	6%	1%	11%	13%	30%

OTHER MACHINES

There is no data of failure rates of the other machines. The roll printer (T240) requires maintenance and repairs. The failure rates of this machine can be estimated by the failure rates of the other printers. The other machines require less maintenance and rarely break down.

2.6 CONCLUSIONS ON THE CONTEXT ANALYSIS

A value stream map was created to give an idea how an order is processed. After that we looked for answers to the following question:

> *How do orders flow through the factory?*

We found that the processes can be divided into prepress, printing and finishing. We also found that orders flow through the factory in a flow-shop style without cycles in the process.

> *What is the arrival rate of jobs to the factory?*

Data about orders and their size are available and can be used to determine order arrivals.

> *What are the characteristics of different order types?*

We found data that contains order types. The order types differ in their average size and the machines that have to be visited during the production process.

> *What is the processing rate, setup time and availability of relevant workstations?*

These values have been found using data, measuring and estimates from personnel.

> *What are the effects of job batching on the setup times?*

Job batching is relevant at the printing stations. Using a smart production planning, batches of orders with the same paper type can be grouped together to reduce the processing time at the printers.

> *Which properties of the production process should be used in a simulation model?*

The simulation model should include order types and their characteristics of order size and machines that they will visit since these can vary a lot and have a key influence on the production process. The processing rates are larger independent of the order types, but mostly on the amount of jobs that have to be processed.

Using this information, a model of the factory can be built. What kind of model should be determined based on a literature search.

3 LITERATURE RESEARCH

The literature research is conducted to find information on subjects used further in the thesis. This consists of ways to model a factory, statistics theory, priority rules for scheduling machines and KPIs (Key Performance Indicators). The following sub-questions should be answered in this chapter:

What mathematical models are available to model the production process of a printing company?

How to model an arrival process of orders into a production process?

What priority rules for jobs at workstations are suitable for the production process of a printing company?

What KPIs are useful for measuring the performance of the production process of a printing company?

3.1 MODELS

In this section the following type of models are described: Jackson networks (Jackson, 1963), BCMP networks (Baskett, Chandy, Muntz & Palacios, 1975), factory physics model (Hopp & Spearman, 2008) and simulation models.

3.1.1 QUEUEING MODELS

Queueing theory is the theory of standing in lines. Since jobs 'stand in line' while waiting to be processed, waiting to move, waiting for parts and so on, queueing theory is a powerful tool for analyzing manufacturing systems (Hopp & Spearman, 2008). A queueing network consists of a set of service centers, each formed by a queue and a set of identical servers that provide service to a set of customers (Balsamo, 2011). To apply queueing models to manufacturing we replace 'customers' with jobs and 'servers' with machines. Figure 11 shows an example of a queuing network: Jobs are stored in queue and processed by the station. After processing the job can move to one of the indicated next stations.
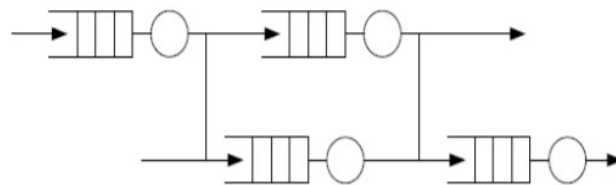
Figure 11. Queueing model. Source: Panda & Reza (2013).

PREVIOUS WORKS

Queuing models have successfully been implemented to model a manufacturing system in the past. Curry & Feldman (2010) describe how to apply queueing theory to factories with multiple stages and multiple products. Marsudi & Shafeek (2014) applied queueing theory to an assembly line for battery lids. Waller (1993) applied queueing theory to the scheduling of service workers to customers. Di Mascolo, Frein & Dallery (1996) showed how to apply queueing theory to a multistage kanban controlled production environment. Semiconductor production facilities were analyzed using queueing theory by Connors, Feigin & Yao (1996).

QUEUEING MODEL CONFIGURATIONS

A queuing network can be blocking or non-blocking. A blocking queue has limited capacity: Jobs that arrive when the buffer of a station is full will either block the previous station or leave the

system. Non-blocking queues have infinite buffer capacity (Balsamo, De Nitto & Onvural, 2001). The printing company will be modeled as an infinite buffer capacity model. This decision is made because orders are usually rejected before entering the production system. Furthermore WIP can be stored in the warehouse in case there is not enough capacity in front of the machine. Thus the process can behave like it has infinite capacity buffer sizes.

A queuing network can be open, closed or mixed. In an open network jobs arrive from an external source and leave the system at some point again. In a closed network jobs stay in a closed loop in the system forever. A mixed network is a network with both types of jobs (Balsamo, 2011). The production process of a printing company is clearly an open network as jobs always leave the system for delivery to customers.

JACKSON NETWORKS

A Jackson network (Jackson, 1963) is a single-class open connected queueing network with M ≥ 1 stations and with the following characteristics:

Station i has c_i ≥ 1 servers and the service times are exponentially distributed with parameter μ_i > 0. The service discipline employed is first-come-first-served at all stations. The jobs arrive from outside the network at station i according to a Poisson process with intensity γ_i. The jobs have a Markovian routing, characterized by an irreducible routing matrix P (Zijm, 2012).

Jackson networks have amongst others the following limitations: (1): All jobs are identical; they all follow the same rules of behavior, and (2) all the service time distributions are exponential (Baskett, Chandy, Muntz & Palacios, 1975). Service times in the factory depend on the type of order and the order size. This means that modeling the factory by means of Jackson networks requires severe simplifications.

BCMP NETWORKS

BCMP networks (Baskett et al, 1975) are a type of queueing models that divide jobs into several classes. Each class can have a separate routing through the factory. The routing can also be stochastic, i.e. a job has probability x to go to station i and a probability of 1-x to go to station j.

In BCMP networks the service rates at stations may depend on the amount of jobs at the station. This is not the case in the situation in the factory: Machines work at a certain rate that does not depend on the amount of jobs in the queue.

In BCMP networks jobs may be subdivided into multiple classes. This is very useful to model the situation at the factory in more detail compared to Jackson networks. The routing through the factory depends on the job type. Each job can be assigned to a certain class and each class has different processing steps.

In BCMP networks, service rates at stations can be different for each class with each job in the class should follow the same probability distribution. This restriction is problematic when applying BCMP networks to the factory as this means that each sheet has to be treated as a different job.

Service stations in BCMP networks can be of four different types:

i.   **FCFS**: The queue is cleared on a First-Come-First-Served basis. Service rates are exponentially distributed and equal and for each job and each class. Service rates may depend on the queue length. A station of this type with multiple machines is equal to a station with one machine with the service rate adjusted to the amount of jobs at the station.
ii. **PS**: Jobs are handled using Processor Sharing. There is no queue and all jobs share the server with the service rate depending on the number of jobs being processed. This type

of server can be used to model e.g. Computing Processor Units (CPUs) but does not exist in the production process of a printing company.

iii. **IS**: There is an Infinite number of Servers available at the station. This means that there can never be a queue. Service rates may depend on the amount of jobs at the station and can be different for each class.

iv. **PR-LCFS**: The queueing discipline is Preemptive-Resume Last-Come-First-Served. Preemptive resume means that jobs can be stopped at some point and be resumed later without restarting from the beginning. Each class of jobs can have a distinct service time distribution. The distribution should have rational Laplace transforms. Deterministic distributions and Erlang distributions have rational Laplace transforms. The exponential distribution is a special case of the Erlang distribution and has therefore also a rational Laplace transform.

For the stations in the factory the FCFS type is the most appropriate.

In the factory the service rates at stations may depend on the order type. The number of necessary cuts determines the processing rate at the cutting station. Number of cuts depends on order type: For example, business cards require more cuts than posters. This also applies to printing on sheets: One-sided is twice as fast as two-sided printing. It is possible to model different service rates per class with the PR-LCFS or IS priority rule but not with the FCFS or IS priority rule.

QUEUEING MODEL WITH PROPAGATION OF VARIABILITY

Hopp & Spearman (2008) present a type of queueing model which handles variability in the production process. Workstation are modeled according to their arrival rate r_a and their departure rate r_d In this model the variability at station i propagates to the next station i + 1.

Figure 12 shows a part of this model with two stations. In this figure r_a, r_e and r_d denote the rate of arrival, effective processing and departure respectively. c_a, c_e and c_d refer to the coefficient of variation of these processes.
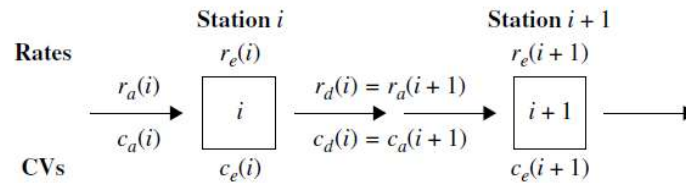
Figure 12. Propagation of variability between workstations in series. Source: Hopp & Spearman (2008)

This model can deal with failures, setup times, rework and batches. The processing rates can follow any arbitrary probability distribution. Drawback of this model is that jobs cannot be classified into multiple classes.

3.1.2 SIMULATION

Another common approach to modeling a production process is simulation. Whereas queueing models give an analytical solution to a problem, simulation gives a numerical solution to a problem. Simulation is defined by Law (2015) as follows:

A technique for using computers to imitate, or simulate, the operations of various kinds of real-world facilities or processes.

In a simulation study the outputs of the computer model are used to make predictions of the behavior of the system resulting from changes in input parameters.

Simulation is a common technique for analyzing manufacturing systems. Work from other authors can be used to explore simulation techniques. Negahban & Smith (2013) give a review of the current state of the simulation in manufacturing environments. They mention amongst others long- and short-term production planning, flow shop scheduling and job shop scheduling. There are many examples for the implementation of simulation in manufacturing environments. Alfieri (2009) used a simulation model to model a cardboard factory with multiple printing and finishing operations. That simulation model is used in conjunction with a tabu search algorithm to make production schedules. Kikolski (2017) used a simulation model to research the effects of different scenarios in a multi-machine shop. The result of the study is details about machine utilization for each different scenario. Grangeon, Tanguy & Tchernov (1999) present a framework for modeling simulation of hybrid flow shops. They suggest using object oriented structure of the software and the performance evaluation of priority rules. They also conducted a simulation study to the effects of different priority rules and found that the shortest processing rule (SPT) gives the best performance for make span. Dileepan & Ahmadi (2010) used simulation to research effects of priority rules on a small job shop.

MODEL CLASSIFICATION

There are several metamodeling and optimization methods in simulation. According to Mourtzis, Doukas & Bernidaki (2014) simulation models are categorized based on three basic dimensions: i) timing of change, ii) randomness and iii) data organization. Law (2015) also distinguishes three dimensions: i) time component, ii) timing of change and iii) randomness. Thus Law (2015) adds a fourth dimension to the ones given by Mourtzis et al. (2014). Currie & Cheng (2013) distinguish simulation models in their finiteness.

The timing of change refers to the way the model progressing through time. A simulation can be discrete or continuous. In a discrete simulation changes happen at certain point in time whilst the time variable is continuous in continuous simulation. Discrete simulation can be event driven or time-stepped. Event driven simulation updates when scheduled events are fired and time-stepped simulation updates with a constant time interval. In the case of a production process of a printing company the simulation is discrete and event driven. Each time a job is started an event is scheduled for completion when the processing time is over.

The randomness property can be either deterministic or stochastic. In a deterministic simulation the outcomes will always be the same whilst in a stochastic simulation outcomes will vary. In this thesis a stochastic simulation will be used. Demand, failures rates and service rates of manual operations are stochastic. Service rates of machines are deterministic as these are producing at a fixed rate.

Data organization refers to a classification into mesh-free and grid-based data. Grid based means that state changes to data can only be based on its neighbors or its own previous state. Mesh-free means that state changes are free from the position of a data point in the simulation (Mourtzis et al., 2014). As you may guess, this is relevant in case of the simulation models of for example fluids but not really relevant for the simulation of a factory. The 'Data organization' dimension of simulation will therefore be omitted from now on.

Time component refers to whether the simulation is static or dynamic. A static simulation is a representation of a system at a particular time, whilst a dynamic simulation is a system that evolves over time (Law, 2015). A model of the processing in a factory changes over time and thus the simulation type that will be used in this thesis is of the dynamic type.

Finiteness refers to whether a simulation is terminating (finite) or non-terminating (infinite). The difference is that a finite simulation has a clear ending period. This ending period can be a certain

state of the system. For example, a simulation of a pandemic which ending condition is set when the amount of infections reaches a certain number. Another example is the behavior of customers in a shop with set open and closing times. Production lines are typically infinite simulations. Orders will keep arriving into the system infinitely and the next workday is a continuation based on the previous day. Non-terminating simulations typically have a warmup period and a run length (Currie & Cheng, 2013).

Concluding, there are 4 dimensions to describe a simulation model. The type of simulation model used in this thesis will be discrete, stochastic, dynamic and infinite.

DISCRETE-EVENT SIMULATION

Discrete-event simulation concerns the modeling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time. These points in time are the ones at which an event occurs, where an event is defined as an instantaneous occurrence that may change the state of the system (Law, 2015). A discrete-event simulation consists of at least the following parts (law 2015):

System state: At some point in time the state is given by a set of variables. For example all the orders in the system and their properties, and location are part of the system state.

Simulation clock: Perhaps the most important variable in a discrete-event simulation is the current time of the system. The clock will increment with each simulated event.

Event list: A list of all events that are scheduled to happen at a certain point in time. An example is part X which is currently being processed at machine Y. The finishing time of part X is one of the items in the event list.

Statistical counters: Variables that store statistics about the system. For example part X had been waiting in the buffer of machine Y for 15 minutes. If this statistic is deemed important it can be stored in a table to be read at the end of the simulation.'

Initialization routine: The simulation needs to be reset at the end of a simulation so a new simulation can be run. For example the simulation clock, event list and all statistics require a reset. This can be done after the statistics from the previous experiment have been stored.

Timing routine: A system that determines the next event in the event list and then advances the simulation clock.

Event routine: To update the event list after each event has occurred.

Library routines: A set of subprograms used to generate random observations. This can be implemented using a random number generator to create random numbers from certain probability distributions. By using a different seed each simulation run we ensure randomness in simulations. For example the arrival rate of orders to the factory can be randomized such that each experiment is different.

Report generator: At the end of the simulation a report with statistics can be created. This report can contain comparisons between the experiments.

Main program: The main program in a software package is the program that contains the main loop: Reset the simulation, run the program generate the report etc.

The components of a simulation as stated above can be implemented using a software package. In this thesis the Plant Simulation package will be used. This program allows to visualize the program and implements the discrete-event simulation routine. This allows us to focus on the implementation of the production process in the factory.

EXPERIMENT SETTINGS

Since the simulation of a factory is a non-terminating simulation a warmup period and run length needs to be set. Also a way to determine the number of replications is required.

- **Warmup:** A non-terminating simulation typically requires a period to move from the initial state to the steady state (Curie & Cheng, 2013). The initial state is for example the first day of the simulation with 0 orders in the system. The steady state is reached when the system is stable. To determine the steady state the Welch method (Heidelberger & Welch, 1983) can be used. This method comes down to plotting an output statistic of the simulation and selecting the point in time that the simulation becomes stable. Then a 20% safety measure is added to it. For an example see Figure 13. Time point 77 is a point when the simulation looks stable. Now add 20% for a warmup period of 92 time units.

- **Run length:** A non-terminating simulation could in theory run forever. However, an end point should be defined since a computer would be calculating until infinity. Law (2015) suggests that the run length should be at least long enough to allow infrequent events such as machine breakdown to occur after a reasonable amount of time. Another sensible approach is to take seasonality into account. A good run length would be for example a year. However, the run length is also limited by the computation time of the simulation model.

- **Number of replications:** Experiments with the same initial settings need to be run multiple times. This is to ensure that the results are valid and not the results of a rare event. Law (2015) suggests to initially start with 5 or 10 replications. From these results a confidence interval of the output values can be constructed. If the confidence intervals are tight enough then the number of replications is sufficient. However if the variance between replications is to large one can consider running more replications.
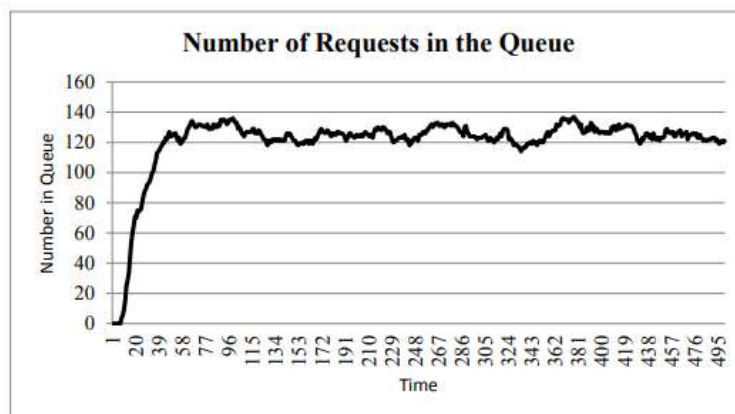
Figure 13. Simulation with warmup period (Source: Currie & Cheng, 2013)

CREDIBILITY

After a simulation is build it is required to be checked if it is a correct representation of the reality. This credibility check can be divided into validation and verification.

- **Validation:** This is concerned with whether the results from the simulation model are corresponding with the results from reality. This can be done by modeling the current situation and comparing its output with data from the actual situation. For example the utilization of machines in the model can be compared with the actual situation.

- **Verification:** Before building a software model a model on paper is constructed. This model on paper is called conceptual model and is the blueprint for the model: It defines

what the intention is when building the model. Verification is concerned with checking whether the conceptual model and the simulation model are equal. Errors can occur due to bugs in the software program. To avoid bugs one can use debugging tools and sensible programming structures. Using a software package including a graphical representation of the model allows to follow orders visually and debug step-by-step. Input data can be compared to the data generated by the simulation model.

3.1.3 CONCLUSION

There are multiple approaches to modelling a factory: Queuing models (Jackson networks, BCMP networks and models with propagation of variability) and Simulation models. Queueing models are easier to make and return exact results. Downside is that these models require simplifications. Simulation models can be customized to fit the situation in a factory. A complication factor is that different order types in the factory follow different paths through the factory. With queueing models the following issues arise:

- **Jackson Networks:** Each job in a Jackson model is of the same type. In this model it is not possible to define different order types and sizes. From Table 1 it is visible that orders can have varying order sizes and custom routing through the factory. Therefore these models are not well suited for the factory.
- **BCMP-network:** There are 4 different types of BCMP networks and the 4th type PR-LCFS looks the most promising as this allows for different product types with their own service rates at stations. However each order type is still supposed to be of the same size.
- **Propagation of variability:** The same issue as with Jackson networks rises with this model. This is mitigated somewhat due to the introduction of arrival rate variance.

On top of this, queueing models do not allow for a change in the priority rules for clearing buffers. Simulation models do not experience these downsides as much as the queuing models. The model can be customized to fit the situation in the factory, resulting in less simplification required. The different paths in the factory can be modelled quite easily in a simulation model. In addition, these models do allow for a change in priority rules. Hence, we can conclude that queueing models are less suited for the complicated process in the factory than simulation models. Therefore, a simulation model will be constructed in Chapter 4.

3.2 PROBABILITY DISTRIBUTIONS

Some probability distributions will be used in this thesis to model the factory. These are Normal distribution, Poisson distribution and the Exponential distribution.

3.2.1 NORMAL DISTRIBUTION

The normal distribution is a continuous probability distribution given by:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \qquad (3.1)$$

With E[X] = μ and standard deviation σ. The normal distribution is symmetrical and values that deviate from the mean are less likely to occur. Figure 14 displays the normal distribution for a few selected parameters. The normal distribution can be used to model processes that handle natural processing that have some variation. In the example of a factory one can think of processing times of machines due to operators.
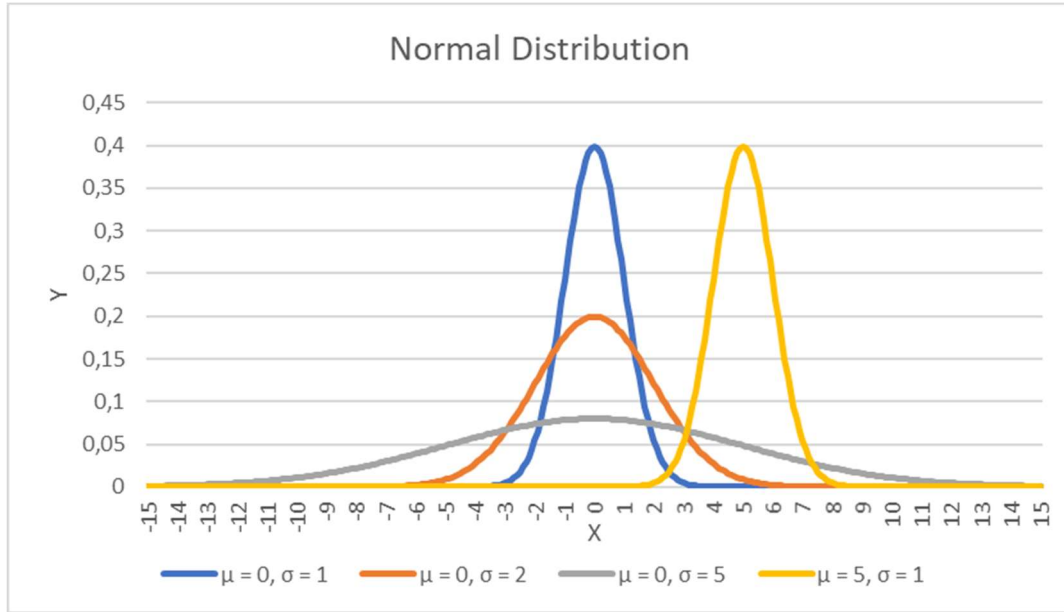
Figure 14. Normal distribution.

3.2.2 POISSON DISTRIBUTION

The Poisson distribution models arrival rates of jobs into a system. A Poisson process is defined as follows:

$$P(X = n) = e^{-\lambda}\frac{\lambda^n}{n!} \qquad (3.2)$$

With

$$E[X] = Var[X] = \lambda \qquad (3.3)$$

Figure 15 shows a Poisson process for various parameters. The horizontal axis shows the number of occurrences in the given time interval and the vertical axis the probability of this number of occurrences. The occurrences are independent of each other and E(X) = λ. External arrivals usually follow a Poisson process (Adan & Reesing, 2015). Therefore the Poisson process is a suitable distribution for the number of orders that arrive into the factory each day. Customers will place orders independently of each other. On the other hand the Poisson distribution is not suitable to model the amount of copies that arrive into the factory. Since each order consists of a certain number of copies the copies individually are not independent.
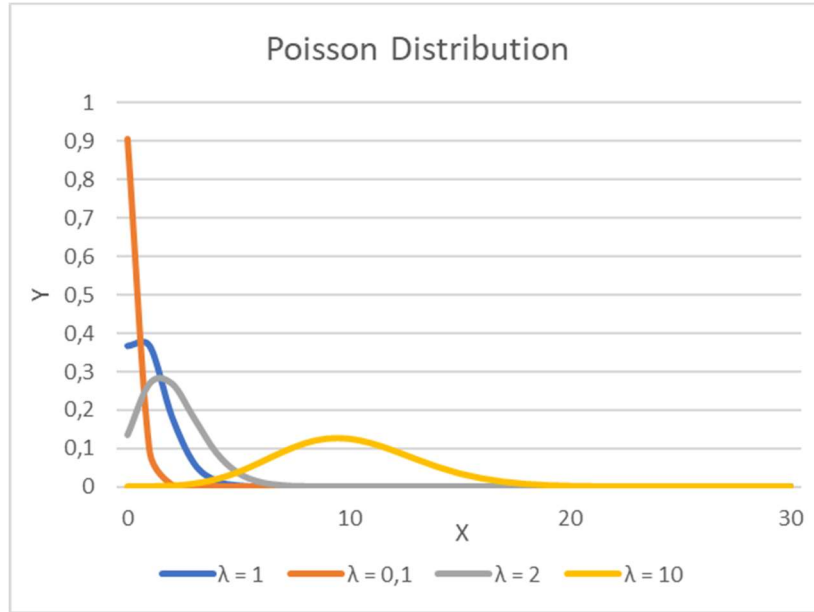
Figure 15. Poisson distribution.

3.2.3 EXPONENTIAL DISTRIBUTION

The exponential distribution is a continuous probability function given by:

$$f(x; \lambda) = \begin{cases} \lambda e^{-\lambda x} & x \geq 0, \\ 0 & x < 0. \end{cases} \tag{3.4}$$

With

$$E[X] = \beta = {}^{1}/_{\lambda} \tag{3.5}$$

$$Var[X] = \beta^2 = {}^{1}/_{\lambda^2} \tag{3.6}$$

The Exponential distribution is a special case of the Gamma distribution and represents the interarrival times in a Poisson process. The Exponential distribution and the Poisson distribution can therefore be interchanged. The exponential distribution follows a different shape (Figure 16) than the normal and Poisson distribution. Therefore it cannot only be used for arrival processes but it can be useful in situation where it is a better fit than the other distributions.
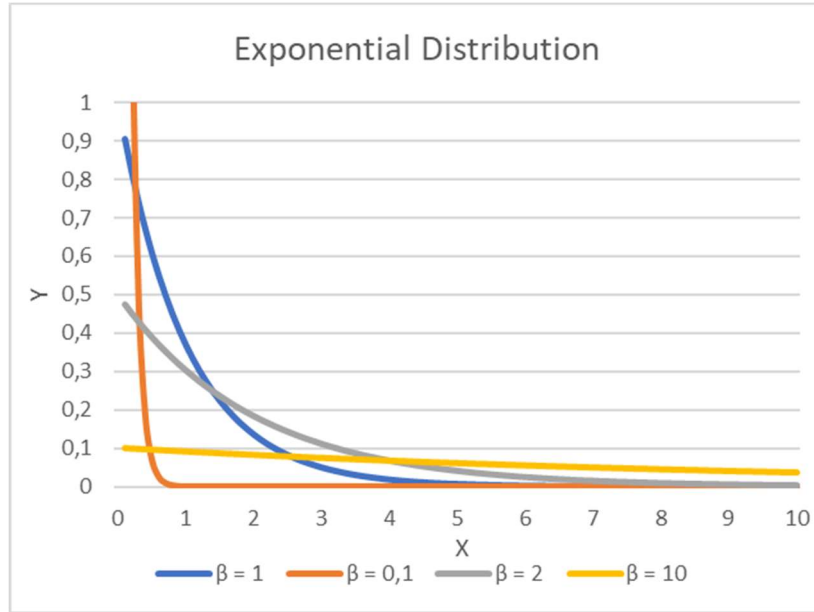
Figure 16. Exponential distribution.

3.2.4 COMPOUND DISTRIBUTIONS

Compound distribution consists of two independent probability distributions. For example the arrival rate of orders follows distribution N and the amount of sheets of the order is given by distribution X. The compound distribution Y gives the distribution of the arrival rate of the sheets. Ross (2007) shows how to derive the expectation and variance of compound distributions from the law of conditional expectation and conditional variance:

$$E[Y] = E[N]E[X] \tag{3.7}$$

$$Var[Y] = E[N]Var[X] + (E[X])^2 Var[N] \tag{3.8}$$

If N is a Poisson random variable the distribution is called a Compound Poisson Distribution and since equation (4.11) the variance can be reduced to:

$$Var[Y] = E[N]E[X^2] \tag{3.9}$$

3.2.5 EXPECTATION AND VARIANCE

For building a queueing model some probability theory is required. If X and Y are random variables then the expectation can be computed as follows (Ross, 2007):

$$E[X + Y] = E[X] + E[Y]$$

Equivalently, in general:

$$E[\sum_i X_i] = \sum_i E[X_i] \tag{3.10}$$

And if X and Y are independent:

$$Var[X + Y] = Var[X] + Var[Y]$$

Equivalently, in general:

$$Var\left[\sum_i X_i\right] = \sum_i Var[X_i] \qquad (3.11)$$

When multiplying the expectation and variance of a random variable we have the following rules:

$$E[cX] = cE[X] \qquad (3.12)$$

And

$$Var[cX] = c^2 Var[X] \qquad (3.13)$$

3.3 GOODNESS-OF-FIT TEST

A goodness-of-fit is a hypothesis test for judging whether or not a frequency distribution conforms to some probability distribution (Jarman, 2013). Data is divided into n buckets. The expected frequency of each bucket is defined by E_i and is given by the probability distribution. These are compared with the observed frequencies defined by O_i in each bucket. With this the value of the test statistic χ^2 can be computed:

$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i} \qquad (3.14)$$

The test statistic compares the expected and observed values. The bigger the difference in frequencies in a bucket the bigger the value of the test statistic. Therefore unless the test statistic surpasses a certain critical value we can conclude that the observed data follows the given probability distribution. The critical value is defined by the Chi-Square distribution with n-1 degrees of freedom and a p-value.

The goodness-of-fit test is used in this report to test which probability distribution fits best with the amount of copies per order.

3.4 COEFFICIENT OF VARIATION

The coefficient of variation for a probability distribution is defined as by Hopp & Spearman (2008):

$$c = \frac{\sigma}{\mu} \qquad (3.15)$$

Hopp & Spearman (2008) separate variability in three different classes: High, moderate and low variation:

- Low variation: c < 0,75. Processes without outages
- Moderate variation: 0,75 ≤ c < 1,33. Processes with short adjustments (setups)
- High variation: c ≥ 1,33. Process times with long outages (failures)

These values can be used to estimate the standard deviation in case no data is available.

3.5 PRIORITY RULES

This section discusses common priority rules for jobs at workstations. Priority rules can be set both at the production planning (prepress) and at the individual workstations. Priority rules are used in production planning. The decision of in which order jobs are processed is called a priority rule.

Reid & Sanders (2007) list the following common priority rules:

- First-come-first-served (FCFS): Jobs are processed in the arrival order.
- Last-come-first-served (LCFS): Jobs are processed from the top of a stack.
- Earliest Due Date (EDD): The job with the earliest due date gets priority. This rule minimizes the maximum lateness among all jobs (Pinedo, 2009).
- Shortest Processing Time first (SPT): The shortest job gets priority. This rule minimizes the average number of jobs waiting for processing (Pinedo, 2009).
- Longest Processing Time first (LPT): The largest job gets priority.
- Critical Ratio (CR): Jobs are prioritized based on the ratio of time remaining until due date and the remaining processing time. This is a more advanced type of EDD priority rule.
- Slack per Remaining Operations (S/RO): The job with the least slack on its remaining operations gets the highest priority.
- Slack per Remaining Processing Time (S/RPT): Job with the least slack divided by the remaining processing time gets priority (Vepsalainen & Morton, 1987).

Other priority rules are available in literature such as First Freed Machine (FFM) and Apparent Tardiness Cost (ATC) (Lamothe et al, 2012). However these heuristics are aimed at situations with parallel machines. The factory in this thesis has mostly machines in series instead of parallel therefore these priority rules will not be considered.

CONCLUSION

There are several priority rules available in literature in varying complexity. Final note is that in practice the priority rule selection is not as straight forward as in literature: Some parts will be processed using LCFS and others FCFS whilst an emergency order might be added in at the last second. The most common priority rule in the printing factory when it comes to rough cut capacity planning is EDD. At the workstations the most common priority rule is FCFS. Finally pallets containing a stack of sheets are handled in a LCFS manner. These different priority rules are more easily implemented in a simulation model than in a queueing model.

3.6   KEY PERFORMANCE INDICATORS

This section discusses performance measures for manufacturing processes. Common performance measures for Jackson networks are throughput and the expected number of customers at a station (Zijm, 2012). The expected number of customers at a station is a useful metric to determine bottlenecks in the system. The throughput and amount of customers at a station of the whole system is the sum of the individual workstations. Pinedo (2009) mentions, amongst others: Throughput, makespan, tardiness, lateness and WIP (work-in-process). Another good measure is amount of overtime. This however requires overtime to be modeled into the model.

Throughput: This is a measure of the amount of jobs that are processed by the factory in a certain time frame. This is a measure of the efficiency of operations. However this value is also strongly depended on the amount of jobs that are entered into the system.

Lateness: This is defined as the difference between the due date and the actual finishes date of an operation. An order that finishes early receives a negative lateness and a order delivered too late receives a positive value. Thus late orders are offset by the early delivered orders.

Tardiness: This is defined the same as lateness, however an order that is delivered too early receives a tardiness value of 0. This is a more valuable metric then lateness since there are usually few advantages of delivering orders too early. The average tardiness and maximum tardiness over all orders can be a performance measure of a factory.

Work-in-process: This value contains of all the orders in the factory or at a certain workstation. This measure can be used to determine if a system is blowing up. If the work-in-process keeps increasing then a certain bottleneck cannot handle the system.

Overtime: Sometimes overtime is necessary to deal with surges in demand. However overtime also induces costs. Therefore overtime can be used to measure costs of a factory and an objective is to minimize overtime.

Make span: This value determines the total time it takes to produce all the current jobs. This metric can be used to schedule a large amount of jobs onto machines. However this value is not applicable to the situation in the factory since new jobs are entering the factory all the time.

3.7 CONCLUSIONS ON THE LITERATURE RESEARCH

The literature search resulted into information and answers to the research questions. The first question was:

> *What mathematical models are available to model the production process of a printing company?*

Literature search resulted in multiple queueing models: Jackson networks, BCMP-networks and Queueing model with propagation of variability. These queuing models are considered to be not applicable to the current situation in the factory. Therefore a discrete-event simulation model will be built. There is a rich landscape of literature into simulation. Results from other authors can be built upon when making the simulation model. For example the literature can be used to determine warmup length, run length and number of replications.

The next question:

> *How to model an arrival process of orders into a production process?*

For the arrival rate of orders a goodness-of-fit test can be used to compare data with probability distributions. Orders can then be generated in the simulation model using this probability distribution.

The next question is:

> *What priority rules for jobs at workstations are suitable for the production process of a printing company?*

In literature the following standard priority rules were found: FCFS, LCFS, SPT, LPT and EDD. Some more complicated rules that might be applicable in the factory are: CR, S/RO and S/RPT. These more complicated rules take besides the due date also the remaining processes into account.

The last research question of this chapter is:

> *What KPIs are useful for measuring the performance of the production process of a printing company?*

It is determined that throughput, work-in-process, tardiness and overtime are important measures that have to be collected in the model of the factory.

4 MODEL DESIGN

This chapter covers the construction of the model. Multiple variables are necessary for the model of the factory: Number of orders of each type, processing times at the machines, setup times, failure rates. Simulation and queueing models are constructed based on this data. The research question which is central in this chapter is the following:

What is a suitable simulation model for the factory?

This chapter is laid out as follows:

- 4.1: General model description: A description of the simulation model.
- 4.2: Model input: Processing of input data and how orders are generated based on this data followed by a description of the setting for the machines (processing time, setup time, failure rate).
- 4.3: Model output: An overview of the statistics that are recorded by the simulation.
- 4.4: Assumption and simplifications: Choices have to be made when building a model. This section describes those choices.
- 4.5: Validation: Check if the output from the model meets output from the factory.
- 4.6: Verification: Check if the model is implemented as it was defined on paper in sections the sections 'model input' and 'model output'.

The research question:

Can the simulation model be validated with the factory?

Is the subject of section.

4.1 GENERAL MODEL DESCRIPTION

A simulation model of the factory was built in the Plant Simulation software package. The model is depicted in Figure 18 and a screenshot of the software model is displayed in Figure 17
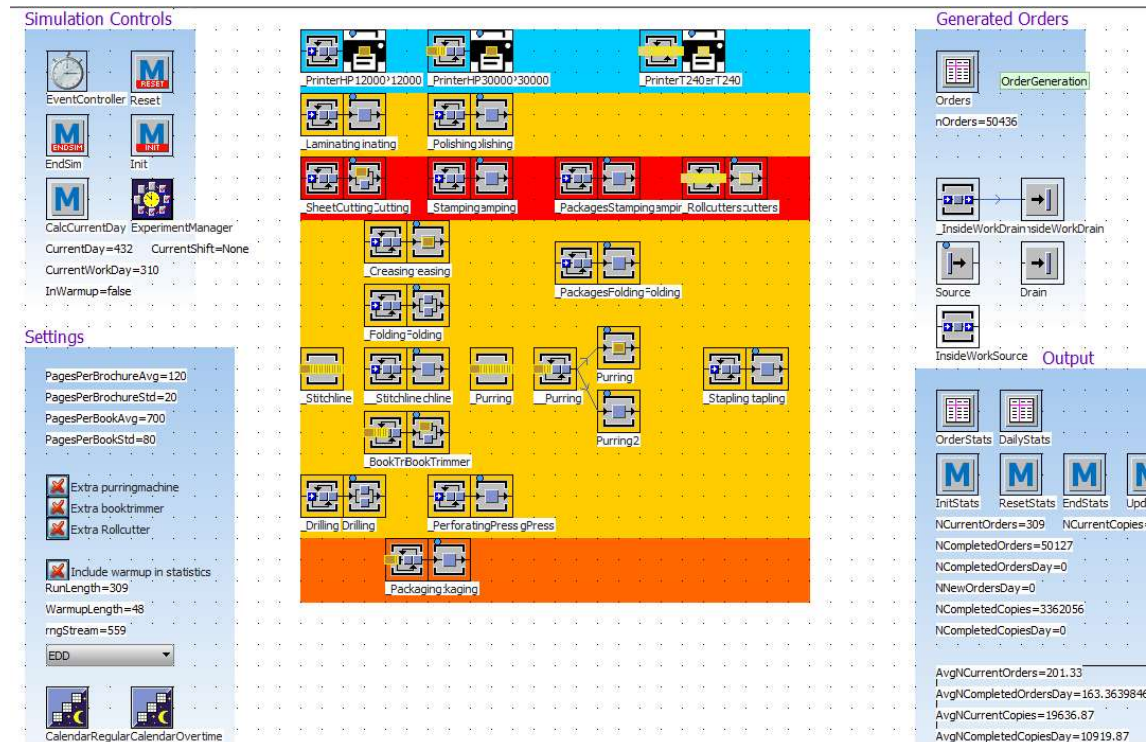
Figure 17. Simulation model screenshot

Figure 18 show the input to the model. This contains all the variables that can be changed between simulations. So the simulation length, machine configuration, priority rules and the pages in books/brochures can be changed between simulation runs. Settings about machines and orders are parameters to the model. The output of experiment runs are graphs and statistics such as work in process, throughput, overtime, and tardiness.
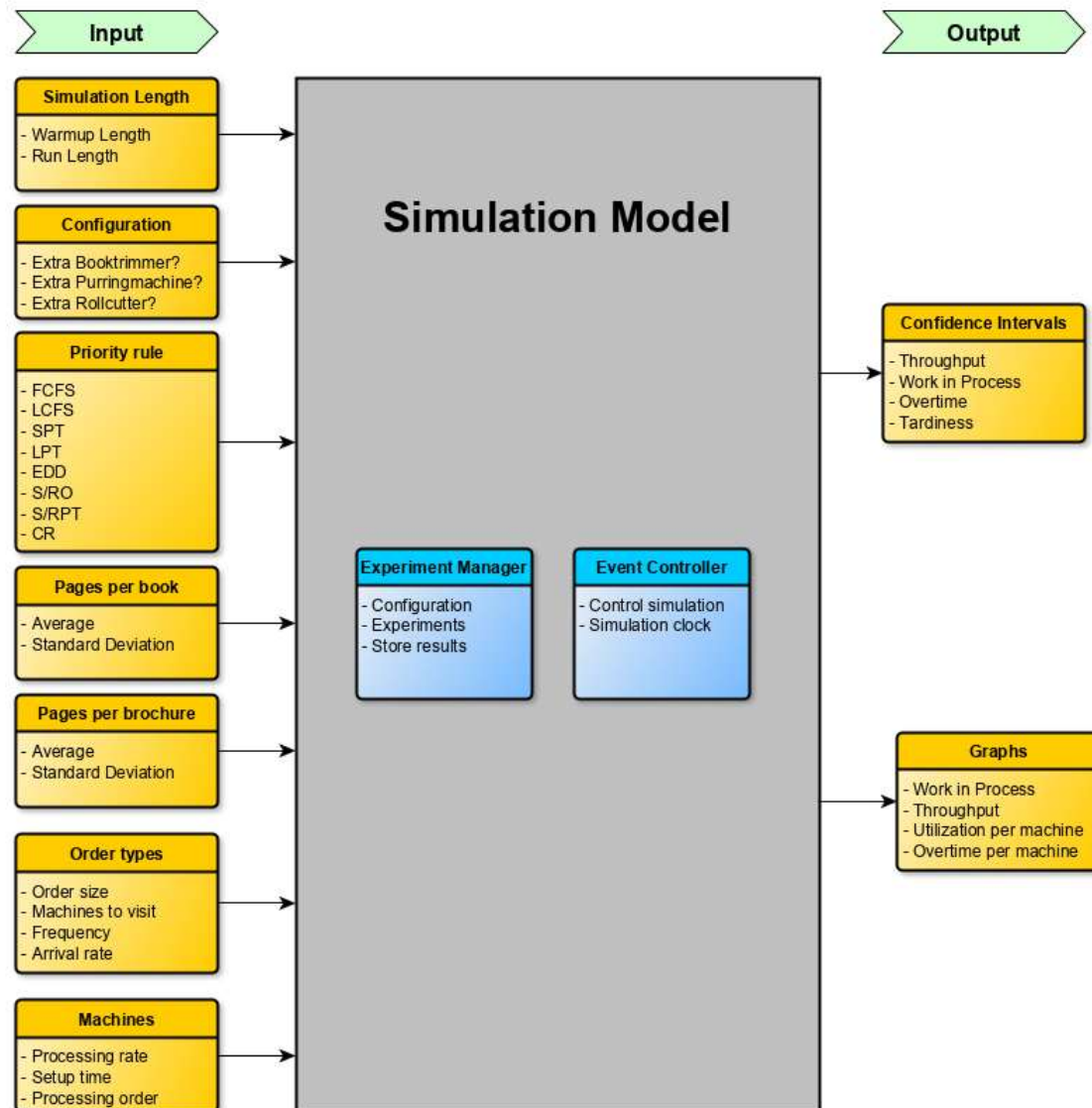
Figure 18: Overview of simulation model

Orders are generated based on data and routed through the factory in the same order as in the real situation. Processing times and failure rates are based on real data. This model can be used for the following:

- Effects of adding a certain machine: New machines can be added to analyze their effects.
- Effects of changing priority rules: Priority rules for handling inventory can be changed to analyze the effects.
- Effects of changing parameters such as run length, warmup length, average amount of pages in a book.

4.2 MODEL INPUT

The input for the model is subdivided in: Data, order generation and machines. The goal is to create a realistic order portfolio and machines with accurate processing rates, setup times and failure rates.

4.2.1 DATA

This section contains the processing of the data from the factory.

Data from HP12000 and HP30000: Table 7 shows an analysis from actual orders in the company. This table is based on data from the printers that print on sheets (HP12000 and HP30000). The HP T240 does not give such detailed data. Data was collected in the timespan of two weeks. The column 'orders' contains the total amount of each order type that was printed in the period. The total copies column contains the number of printed sheets.

Table 7. Categorization of orders 8 nov - 20 nov 2019

Order type	Total Copies	% of Total copies from printer	Total Orders	% of Total Orders	Average of Copies	StdDevp of Copies	Sum of OneSided (PT)	% One-sided of total	Sum of Color (PT)	% Color of total
Beercard	1030	0,91%	11	0,66%	94	81	11	100,00%	11	100,00%
Books printed on rolls	2846	2,52%	21	1,26%	136	109	21	100,00%	20	95,24%
Brochures printed on rolls	7475	6,61%	67	4,02%	112	181	17	25,37%	54	80,60%
Brochures PUR	423	0,37%	22	1,32%	19	33	2	9,09%	22	100,00%
Brochures saddle stitched	19522	17,25%	54	3,24%	362	729	1	1,85%	53	98,15%
Businesscards	9313	8,23%	456	27,34%	20	50	124	27,19%	447	98,03%
Carton Packages	2127	1,88%	17	1,02%	125	139	17	100,00%	17	100,00%
Commercial carton	22967	20,30%	159	9,53%	144	737	156	98,11%	159	100,00%
Flyers	16297	14,40%	400	23,98%	41	78	212	53,00%	346	86,50%
Folders	10845	9,58%	170	10,19%	64	152	41	24,12%	124	72,94%
Letter paper	367	0,32%	8	0,48%	46	36	4	50,00%	8	100,00%
Notebooks	1194	1,06%	4	0,24%	299	151	2	50,00%	4	100,00%
Other	13636	12,05%	219	13,13%	62	124	107	48,86%	207	94,52%
Periodics	1507	1,33%	3	0,18%	502	151	0	100,00%	3	100,00%
Printed sheets	1917	1,69%	25	1,50%	77	90	16	64,00%	25	100,00%
#N/A	1694	1,50%	32	1,92%	53	122	25	78,13%	26	81,25%
Grand Total	113160	100,00%	1668	100,00%	67,84	287,30	756	45,32%	1526	91,49%

Data from T240: For the printer that prints on rolls this information is not available but there is a workaround: This printer only prints the inside work of books and the workload can be predicted from the other printers. The covers are printed on the other two printers from which information is available. From Table 7 it can be read that 2846 sheets with book covers were printed in this period. From practice it is known that each sheet contains two covers. Therefore 5692 books were

produced in this period. The number of pages and the proportions of the book are unknown. The processing time at the T240 printer and the Rollcutters is dependent on the proportion and number of pages of books.

Copies: Each order contains a certain amount of copies (i.e. the number of sheets). This data is available for each individual order. To be able to generate random orders it is helpful to find an appropriate probability distribution for the number of sheets per order. Exploratory statistics are shown in Table 7. Categorization of orders 8 nov - 20 nov 2019. From the table we can conclude that there are differences in the amount of copies for each order type. The maximum value is 7558 and only 9 out of the 1668 orders are larger than 1000 sheets.

Color: The column "color" contains the number of sheets that were printed in color. This data was not readily available in the data but can be derived from it. Data per order is given in the following format: *C(68), M(68), Y(68), K(68)* (See Table 1). Every order that uses more than one color is categorized as "Color" and every order that has only 1 color is categorized as "black and white". We can see in Table 7 that most orders (91%) are printed in color.

One-sided vs two-sided: The processing time at the printers is twice as long when printer double sided. It is possible to estimate if an order is one- or two-sided. This is based on the amount of impressions and the amount of different colors used. For each order a value is computed:

$$Ratio = \frac{Amount\ of\ Impression}{Amount\ of\ different\ colors} * \frac{1}{Amount\ of\ Copies} \qquad (4.1)$$

This ratio is an estimate for the order being one-sided or two sided. Let us consider the following example: an order of 10 one sided sheet in 4 colors. This order would have had 40 impressions (4 per sheet). This would thus give a ratio of: 40/4 * 1/10 = 10/10 = 1. The same example but double-sided would have had 80 impressions (8 per sheet) but still 10 copies and would thus return a ratio of: 80/4 * 1/10 = 20/10 = 2. So a ratio of 1 indicates single sided printing and a ratio of 2 indicates double sided printing. It appeared that due to failures in the machine or the data that not every order returns a ratio of exactly 1 or 2. Therefore each order with a ratio smaller than 1.5 is categorized as one-sided and the other orders are categorized as double-sided. Using this method it is possible to determine what fraction of orders of a certain order type were one-sided and two-sided.

Printer: There is data of which order has been printed on which machine. This data is relevant since these printers are different in the type of orders they can handle. Therefore orders are assigned on generation to a printer.

4.2.2 ORDER GENERATION

Each order gets its characteristics assigned on creation. This paragraph contains an enumeration of the parameters assigned upon order generation. As there is no data about interarrival times of orders it is assumed that the arrival rate of orders follows the Poisson distribution. The Poisson distribution is a commonly used probability distribution to model an arrival process. Orders are generated with this distribution in the model. In section 0,

Arrival rates of jobs there were 1636 jobs in a period of two weeks. It is assumed that orders arrive between 8.00 and 17.00 on weekdays. The frequency of arrivals is set equally over this time period. The arrival rate λ is therefore equal to:

$$\lambda = \frac{Amount\ of\ jobs}{Time\ period\ (weeks)} = \frac{1636}{2} = 818\ orders\ per\ week = \frac{818}{9 * 5} \qquad (4.2)$$
$$\approx 18{,}18\ orders\ per\ hour$$

The interarrival time be defined by:

$$\beta = \frac{1}{\lambda} \approx \frac{1}{18,18} \approx 0,055 \; hours \approx 3 \; minutes \; and \; 18 \; seconds \qquad (4.3)$$

Therefore during regular workhours, on average, every 3 minutes and 18 seconds an order is generated by the system. The interarrival times of a Poisson distribution are exponentially distributed (Adan & Reesing, 2015). Therefore the orders are generated following the exponential distribution with β = 3 minutes and 18 seconds.

Number of units per order: Each order type has specific characteristics. For example the number of products that fit on one page. This data is displayed in Table 9. The first column indicates the number of sheets produced in the period from 8 to 20 November 2019. The number of pages per job indicate an estimate of the number of pages necessary for a certain order type. Pieces per sheet indicate the amount of pieces that fit on one sheet. This can be used to get an estimate for the total amount of pieces of a certain order type were produced in the time interval. This information is necessary to get an estimate of the processing time at the various machines. In the table a red highlight indicates uncertainty and green indicates certainty about the estimate.

Workstations to be visited for each order: Each order has to visit multiple workstations. This is decided at the moment the order is generated. **Error! Reference source not found.** displays the probability that an order has to visit a certain station. The bold value indicate that they are based on data and the normal values are estimates. The estimated values are based on experience from within the company and have to be taken with care. The data is from the printer app or experience.

Number of sheets: The data from Table 7 contains the amount of copies for each individual order. The number of sheets for each order are generated using an exponential distribution. This was determined using a Pearson Chi-square goodness-of-fit test for this distribution. Each order type has its own parameter β which is equal to the average number of copies for this particular order type. Figure 19 plots the actual amount of pages in the orders and the expected amount for each bucket based on the exponential distribution. The Chi-square test yields a p-value. This value is the probability that the data is independent. In this case the data consists of the amount of copies and the expected values from the exponential distribution. Results of the test are displayed in Table 8. Bold p-values indicate statistical significance. Details of the Chi-square test can be found in appendix 8.4. The 'Flyers' and 'Others' order categories follow the Exponential distribution. The 'Folders' and the 'Business cards' categories do not follow this distribution. Reason for this can be that these products are ordered in fixed amounts, i.e. a folder is usually of a certain size. For simplicity it is assumed that all orders follow the Exponential distribution with parameter β equal to the sample mean.

Figure 19. Histogram of sheets per order (zoomed in: 0-300).

Table 8. P-values for chi-square tests

Order type	Amount of orders (n)	Average of copies (β)	Critical value	Value of test stastic (χ^2)	P-value
All order types	1667	63,34853	10,851	11,72325	0,925272183
Businesscards	456	20,42324561	10,851	59,44098558	0,000008689
Flyers	400	40,7425	10,851	6,996553	**0,996696**
Other	219	62,26484	10,851	9,149659	**0,981108**
Folders	170	63,79	10,851	27,01697	0,134787

Pages per book/brochure: There is no data available about the number of pages per job for books and brochures printed on rolls. It is estimated that these have 500 and 80 pages respectively. It is estimated that 7,27 pages fit on one meter (See section 2.1.2). The estimated length of paper per order can be computed with this information: Number of pages * meter per page * covers per sheet.

Order type: Different orders have different workstations that they have to visit. To model this the workstations that an order have to visit are determined when an order is created. An order is of certain type e.g. "Books" or "Flyers". The categories and their probability of occurrence are selected using the frequencies of order types from Table 7. The categories "Periodics" and "unknown" are set to a probability of 0 since these categories are for administration purposes only.

One-sided or double-sided: An order can be one-sided or double-sided. This is determined by the method from the 'data' section. Each order has a certain probability to be one-sided based on the order type. The probability to be one-sided is equal to the fraction of orders of this type that are one-sided according to the data from Table 7.

Color: The color or black/white of each order is determined by the same method as one-sided and double-sided and based on the data from Table 7.

Table 9. Info for each order type. Used to compute the amount of sheets/rolls used for each piece of a certain order type.

Order types	Number of sheets	Number of pages per job	pieces per sheet	total number of pieces	Length in m on rolls per order	Notes
Flyers	16297		4	65188		
Brochures saddle stitched	19522	40	0,1	1952		Estimated 4 pages per sheet and 40 pages per brochure.
Brochures PUR	423	40	0,1	42		Estimated 4 pages per sheet and 40 pages per brochure.
Printed sheets	1917		1	1917		
Businesscards	9313		40	372520		
Letter paper	367		4	1468		
Notebooks	1194	80	0,05	60		Estimate is 4 pages per sheet and 80 pages.
Other	13636		4	54544		
Commercial carton	22967		1	22967		
Carton Packages	2127		4	8508		
Brochures printed on rolls	7475	80	2	14950	22	
Books printed on rolls	2846	500	2	5692	138	
Folders	10845		1	10845		
Beercard	1030		2	2060		
Subtotal	**109959**			**562713**		
Periodics	1507					This category can be anything of the above types.
Unknown	1694					This category can be anything of the above types.
Total	**113160**			**562713**		

Table 10. Stations visited per order type. Bold values indicate that they are based on data. Non-bold values are estimates.

Order types	Amount of sheets	Roll printing station	Roll cutting station	Normal sheet printing station	Carton sheet printing station	Packages stamping station	Packages folding station	Laminating station	Sheet Stamping station	Perforating station	Sheet cutting station	Binding station	Stitching station	Trimming station	Creasing station	Folding station	Stapling station	Drilling station	Polishing station	Packaging station
Beercard	1030				1			0,5	1	0,1										1
Books printed on rolls	2846	1	1		1			1			1	1		1						1
Brochures printed on rolls	7475	1	1	0,95	0,05			0,9			1		1	1				0,1		1
Brochures PUR	423			1				0,5			1	1		1				0,1		1
Brochures saddle stitched	19522			1				0,5					1					0,1		1
Businesscards	9313			0,82	0,18						1									1
Carton Packages	2127				1	1	1												0,1	1
Commercial carton	22967				1			0,1	0,5	0,1	0,5				0,1	0,1				1
Flyers	16297			0,84	0,16						1									1
Folders	10845			0,94	0,06			0,1			1				0,5	1				1
Letter paper	367			1							1									1
Notebooks	1194			1							1									1
Other	13636			0,85	0,15			0,25	0,5	0,1	0,75		0,05		0,25	0,25	0,05	0,05		1
Printed sheets	1917			1																1
Subtotal	109959	10321	10321	73635	36323	2127	2127	26851	19331	3763	70471	3269	27679	10744	11128	16551	682	3424	213	109959
Periodics	1507	0,09	0,09	0,67	0,33	0,02	0,02	0,24	0,18	0,03	0,64	0,03	0,25	0,10	0,10	0,15	0,01	0,03	0,00	1,00
Unknown	1694	0,09	0,09	0,67	0,33	0,02	0,02	0,24	0,18	0,03	0,64	0,03	0,25	0,10	0,10	0,15	0,01	0,03	0,00	1,00
Total	113160	10621	10621	75779	37381	2189	2189	27633	19894	3873	72522	3364	28485	11057	11452	17033	702	3523	219	113160

4.2.3 MACHINES

Processing rates: This data is acquired by measurements in the factory and data from machines. Most machines have a fixed processing rate. Processing and setup times can be found in Table 12. Most machines have a fixed constant speed. For machines where processing rate is dependent on human input the processing rates are based on measurement in the factory or estimates. The printers HP12000 and HP3000 have their processing rates set to a base 3000 (for one-sided – color) without setups instead of their actual processing rate including setups. This is due to irregular setup times which are based on the paper type and complicated to re-engineer from data. 3000 sheets per hour is a good estimate of the actual processing rate according to the operators.

Setups: Each machine has its own unique setup time. Setup times are based on estimates from the operators. Setups are done by the operator and therefore have some variability. Setups may be necessary after an order is finished or a certain number of sheets. Because orders are performed by operators and each order is slightly different there can be some variability in the setup times. This variability is likely very low. Furthermore setup times are a small part of the total processing. Therefore the variability of the setup times is set to 0 in the simulation model.

Failure rates: Failure rates for printers are set based on the data from section 2.5.3. Table 11 show a summary of this data. These are average fractions of time that a sheet printer is down for failure or maintenance. Printer downtimes for the T240 printer is set based on this data as well. Printers can only fail or require maintenance during uptime. Other machines do not have failures modeled.

Table 11. Failure rates

week	Supplies time	Restarts time	Jams recovery time	Failures recovery time	Total
Average	6%	1%	11%	13%	30%

Table 12. Machine list

Short name	Production step	processing rate	setups
HP T240	Printing	152 meter/minute	15 minutes (change rolls)
Roll cutting machine 1	Cutting	60 meter/min (per machine)	10 minutes (change rolls)
Roll cutting machine 2	Cutting	60 meter/min (per machine)	10 minutes (change rolls)
HP 12000	Printing	One-sided:57 sheets/minute Double-sided: 114 sheets/minute	Filling paper trays
HP 30000	Printing	3000 sheets/hour one-sided. 1500 sheets/hour double-sided	Filling paper trays
Coating machine	Coating	3000 sheets/hour one-sided. 1500 sheets/hour double-sided	Filling paper trays
Packages stamping machine	Stamping	20 sheets/minute	10 minutes (between orders)
Packages folding machine	Rilling and folding	400 products/minute	5 minutes (between orders)
Laminating machine	Laminating	11 sheets/minute	2 minutes (between orders)
Stamping press	Stamping	6 sheets/minute	15 minutes (between orders)
Perforating press	Perforating	20 products/minute	20 minutes (between orders)
Sheet cutting machine 1	Cutting	150 meter/minute	2 minutes (between orders)
Sheet cutting machine 2	Cutting	150 meter/minute	2 minutes (between orders)
Purring machine 1	Binding	2 books/minute	30 minutes (between orders to change the clamps)
Purring machine 2	Binding	2,95 books/minute	No setup times. Specifications are determined automatically.
Stitchline	Binding	66 magazines/minute	2 minutes (between orders)
Book trimmer	Trimming	2,2 books/minute	4 minutes (between orders)
Creasing machine	Creasing	40 products/minute	5 minutes (between orders)
Foldingmachine 1	Folding	25 products/minute	10 minutes (between orders)
Foldingmachine 2	Folding	25 products/minute	10 minutes (between orders)
Stapling machine	Binding	10 products/minute	no setup times.
Drilling machine 1	Perforating	6 books/minute	2 minutes (change drill size)
Drilling machine 1	Perforating	6 books/minute	2 minutes (change drill size)
Polishing machine	Polishing	55 sheets/minute	5 minutes (between orders)

4.2.4 PRIORITY RULES

The priority rules as described in chapter 3 are used in the model. The standard rule is First-Come-First-Served. At each station the orders are ordered based on priority rules. In this section the implementation of each rule is described. In this section we use the following definitions:

- J_i: The set of all jobs at station i
- a_{ij}: The arrival time of job j at station i
- d_j: The due date of job j
- t: The current time
- k: The index of the current machine

- **m:** The total amount of machines
- **p_{ij}:** The processing time of job j at machine i
- **R_j:** Number of operations remaining of job j

First come first served (FCFS):

$$\min_{j \in J_i} a_{ij} \tag{4.4}$$

Last come first served (LCFS):

$$\max_{j \in J_i} a_{ij} \tag{4.5}$$

Earliest due date (EDD):

$$\min_{j \in J_i} d_j \tag{4.6}$$

Shortest processing time first (SPT):

$$\min_{j \in J_i} p_{ij} \tag{4.7}$$

Longest processing time first (LPT):

$$\max_{j \in J_i} p_{ij} \tag{4.8}$$

Critical ratio (CR):

Critical ratio is defined as follows by Berry & Rao (1975):

$$Critical\ ratio = \frac{Time\ remaining\ until\ schedule\ delivery\ date}{Remaining\ processing\ time}$$

The job with the lowest ratio is selected first. The job with the highest priority will be selected with the following formula:

$$\min_{j \in J_i} \frac{d_j - t}{\sum_{i=k}^{m} p_{ij}} \tag{4.9}$$

The nominator in the formula is equal to the time remaining until due date and the denominator is equal to the total remaining processing time over all remaining operations. The job with the least slack is selected for processing. A ratio lower than 1 means the job is behind schedule and will finish late whilst a ratio higher than 1 means there is some slack left on the operation.

Slack per remaining operations (S/RO):

$$S/RO = \frac{Time\ remaining\ until\ schedule\ delivery\ date - Remaining\ processing\ time}{Number\ of\ operations\ remaining}$$

The job with the lowest ratio is selected first. Thus if more operations are remaining then a job is selected first. The job with the highest priority will be selected with the following formula:

$$\min_{j \in J_i} \frac{(d_j - t) - \sum_{i=k}^{m} p_{ij}}{r_j} \tag{4.10}$$

Slack per Remaining Processing Time (S/RPT):

The slack per remaining processing time is given by:

$$\min_{j \in J_i} \frac{(d_j - t) - \sum_{i=k}^{m} p_{ij}}{\sum_{i=k}^{m} p_{ij}} \tag{4.11}$$

4.3 MODEL OUTPUT

Statistics are collected during a simulation run. The goal of the simulation is to research the effects of adding machines and changing priority rules. The output of the model is given in operations management related KPIs such as Overtime, amount of late orders and work-in-process. This output can be used to compare the effects of changing the inputs. The results can be displayed in the form of confidence intervals comparing different model settings.

Table 13: Simulation model output

Key Performance Indicator	Description
Average work in process (orders)	This statistic collects at the end of each day (at 17.00) the amount of orders in the system. The average is then calculated over each day.
Average work in process (copies)	This statistic collects at the end of each day the amount of copies (sheets) that are in the system.
Average Throughput (Orders)	This measure is the amount of orders finished at each day.
Average Throughput (Copies)	This measure is the amount of copies that are finished each day.
Average Length of Daily Overtime Period	The moment that the factory is closed at the end of the day is recorded. The length of this overtime period is used in this statistic.
Average Total Sum of Overtime at Workstations	At each day the sum of the overtime over all machines is computed. The average is taken over this sum.
Max Tardiness	Tardiness is the amount of time an order is finished past its due date. If the order is on time this value is 0, otherwise it is the lateness of the order.
Average Tardiness	Each order has a tardiness value. The average is computed over all orders.
Utilization of Machines	For each machine the average utilization is recorded.

4.4 ASSUMPTIONS AND SIMPLIFICATIONS

Availability: The factory is operational for 12 hours a day for 5 days per week. Work that is partially completed on one day is completed on the next day.

Operational hours: Processing of jobs can be stopped during processing and continued on a next day. Therefore it is a reasonable simplification to model the simulation as a continuously operating plant.

Due Dates: As there is no data on due dates of orders some educated guesses had to be made. Orders can be divided into two categories: Those that require the T240 printer and those that do not. The first category has a longer due date due to longer processing time and requirements of planning. The second type of orders are typically with shorter due dates (Web2print). The books and brochures have a due date of 11 and 21 days respectively. Other order types have a due date of one day.

Roll cutting: The Roll cutting machines are modeled as one machine instead of two. These machines have a processing rate of 60 meter per minute per machine. Therefore the processing rate is set to 120 meter per minute. The reason for this simplification is that in practice both machines are usually performing work on the same order at the same time. This is possibly since an order consists of multiple rolls.

Buffers: Each machine in the model has a buffer in front of it. This buffer is used to temporarily store the order in case the machine is busy. The buffer is emptied using a first-come-first-serve principle. The Stitchline and Purring machines are assembly steps and therefore they have a second buffer. This second buffer is used to wait for the inside work in case the cover of a book or brochure is finished first. When the inside work arrives, the order is ready for assembly and moved to the buffer of the machine. This also means that statistics about blocking and starving of machines are not relevant in this study.

Operators: Operators are not part of the scope of this study. The focus is an adding machines and/or priority rules. It is often easier to shift workers around machines since employees are cross-trained to be able to operate multiple machines.

4.5   VERIFICATION

Checking whether the simulation model is doing the same as it is was supposed to be on paper is called verification. The model and its assumptions was written in the previous section. This is the model on paper. The simulation model was built in the Plant Simulation software. Verification is performed in the following way: Model development, Arrival process verification, copies per order verification, priority rules verification.

4.5.1 MODEL DEVELOPMENT

During the building of the model verification was carried out continuously. The software package offers opportunities for this since it is highly visualized: Simulations can be carried out step-by-step and have the orders are visible whilst moving through the factory. This was used to closely watch orders to see if they indeed follow their intended path through the factory. The tables that are filled with data during a simulation help find errors: If data is missing it is easily visible. Also these tables can easily be exported to Excel. This tables can than checked if values such as moving average or computed correctly. Multiple graphs are created from the data. Irregularities are easily visible in the graphs. The Plant Simulation model follows the object oriented programming (OOP) paradigm. This is a modular way of programming and allows for testing of parts of the software individually. For example each order is an object. This order has properties attached to it such as order size, type, machines to visit, arrival time, finishing time, etc. as well as methods such as the calculation of processing time at a certain station given the order properties. These properties and methods can then be checked for each order individually. This OOP structure allows to add inheritance to the model: For example each machine inherits from a standard global machine type with certain properties and methods. Changing the definition of these properties and methods in the 'parent' also changes those in its 'children' that derive from it. This is helpful since we can change the priority rules for all machines with one click.

4.5.2 CROSS VALIDATION

Cross validation consists of validating multiple scenarios. For example if adding a machine X gives a certain amount of performance improvement. If we use a different priority rule, will this setting still give a comparable improvement. Cross validation could be caried out after running experiments.

4.5.3 ARRIVAL PROCESS

In Section 2.4 data about orders was reviewed. The average amount of orders per workday is 163 Since the simulation ran for 309 workdays the expected amount of orders is 50552. A simulation run yielded 50699 orders. This is a plausible value since $P(X \leq x) = 0,74$ for a Poisson distribution with $\lambda = 50552$ and $X = 50699$. Thus it is expected that in 26% of the simulation runs the amount of orders are larger than X.

4.5.4 COPIES PER ORDER

A simulation run yielded a total of 780421 orders. Table 13 shows the average amount of copies for a few order types. This can be compared with the expected amount of copies per order. The expected amount of copies is the parameter β from the Exponential distribution. This is the same as the average amount of copies from Table 7. There is some discrepancy in the average and expected values for individual order types. However averaging over all order types in the last row shows a very small discrepancy of only 0,34%, indicating that the amount of copies per order are modelled correctly.

Table 14: Verification of amount of copies per order

Order type	Average	Expected	Difference (%)
Businesscards	18,61	20	-6,94%
Flyers	39,66	41	-3,26%
Commercial carton	152,12	144	5,64%
Brochures saddle stitched	406,95	362	12,42%
Other	61,07	62	-1,50%
Folders	63,45	64	-0,87%
All order types	68,07	68	0,34%

4.5.5 VERIFICATION OF PRIORITY RULES

There are five different priority rules implemented in the simulation model: FCFS, LCFS, EDD, SPT and LPT. To verify that these results are implemented correctly an analysis is conducted. The analysis takes place at the book trimming station. Once the buffer at the station consists of 20 items their statistics are collected. These statistics are shown in Table 15. The times in the table are denoted in the format DAYS:HOURS:MINUTES:SECOND.XX. The priority rule that was used in this experiment was SPT (Shortest Processing Time first). The orders are sorted by their processing time. To verify that the rule is implemented correctly, we can check the "Start time processing" column. Close inspection of this column confirms that this column is in ascending order as well, indicating that the order with the shortest processing time is processed first. Verification for the other processing rules can be found in section 8.5. Close inspection of the tables in that section leads to the conclusion that the priority rules or implemented correctly.

Table 15: Verification of SPT priority rule

Order number	Due date	Arrival time at buffer	Start time processing	Processing time
11741	100:17:0.0	99:8:59.59	99:12:15.15	0:1.1
11726	109:17:0.0	99:9:24.24	99:12:17.17	0:4.4
11765	120:17:0.0	99:11:36.36	99:12:21.21	0:4.4
11794	110:17:0.0	99:11:49.49	99:12:25.25	0:4.4
11701	109:17:0.0	99:9:28.28	99:12:30.30	0:5.5
11608	109:17:0.0	99:9:45.45	99:12:36.36	0:10.10
11704	119:17:0.0	99:11:31.31	99:12:46.46	0:10.10
11654	109:17:0.0	99:9:35.35	99:12:57.57	0:11.11
11626	109:17:0.0	99:9:57.57	99:13:9.9	0:17.17
11687	109:17:0.0	99:10:56.56	99:13:26.26	0:27.27
11619	109:17:0.0	99:10:14.14	99:14:25.25	0:34.34
11721	109:17:0.0	99:11:20.20	99:16:20.20	0:43.43
11559	116:17:0.0	99:10:0.0	99:19:34.34	0:55.55
11536	116:17:0.0	99:11:19.19	100:9:57.57	1:10.10
10717	109:17:0.0	92:11:59.59	101:13:36.36	3:53.53
2273	38:17:0.0	81:12:30.30	105:8:54.54	4:5.5
10068	105:17:0.0	95:11:55.55	105:14:25.25	4:6.6
10266	106:17:0.0	91:13:8.8	106:12:7.7	4:6.6
10379	107:17:0.0	99:8:57.57	115:14:54.54	4:18.18
9124	98:17:0.0	94:16:24.24	141:14:19.19	5:9.9

4.6 VALIDATION

Validation is concerned with whether a simulation model fits with the actual situation. Thus the simulation model is compared with the situation in the factory. Validation is divided into utilization and throughput.

4.6.1 UTILIZATION

It is known from the factory that machines with high utilization are the T240 printer, Rollcutters, Purring and Book trimmer. In fact an additional Purring and/or Book trimming machine is already in consideration and the T240 printer is running in teams of two. Machines with notoriously low utilization are the printer HP30000, packages stamping and gluing, drilling and perforating. This should be seen in the simulation model as well. This is confirmed later in Section 5.1. Figure 24 shows the utilization for machines and this confirms the situation in the factory. The T240, Rollcutters, Purring and Book trimmer machines have the highest utilization. Another important validation metric is checking whether no machines has utilization > 100%. In this case the system would be exploding according to queueing theory. This was a good validation metric during the construction of the model since an exploding system is an indicator of bugs.

4.6.2 THROUGHPUT (ORDERS)

In a serial production line without yield loss or rework, the arrival rate to every workstation is equal to the throughput (Hopp & Spearman, 2008) for each scenario or priority rule. Therefore throughput can be used for verification purposes. In the factory, there is no yield loss in the form of lost orders or rework. Thus fiddling with the experiment settings should not give a difference in

throughput. In chapter 5 experiments will be carried out. The expected result is that there will not be any significant differences in throughput.

4.6.3 THROUGHPUT (COPIES)

The amount of copies from the printers over a longer time period is shown in Figure 2. The simulation model keeps track of the amount of copies completed each day. These two figures are compared in Figure 20. The data is sorted in descending order for easier comparison. Unfortunately there is some discrepancy between the data sets:

- The average from the simulation is lower than the average from the factory. This can be explained as the order data (Table 7) for the model is based on a two week period. This period was apparently a period with lowered throughput.
- There is more variability in the data from the factory compared to the simulation. The simulation is based on a compound Poisson distribution with order arrivals following the Poisson distribution and the amount of copies per order exponentially distributed. There is no data for the order arrival process and therefore it is not possible to find a more accurate probability distribution.

Another explanation for the discrepancy is that the data is not measuring the exact same thing: the data from the factory are the copies completed by the printers each week and the data from the simulation model are the amount of copies in finished products each week. To handle concerns a sensitivity analysis can be performed, increasing the arrival rate of orders to the system to check if there is any effect on the conclusions if demand was increased.
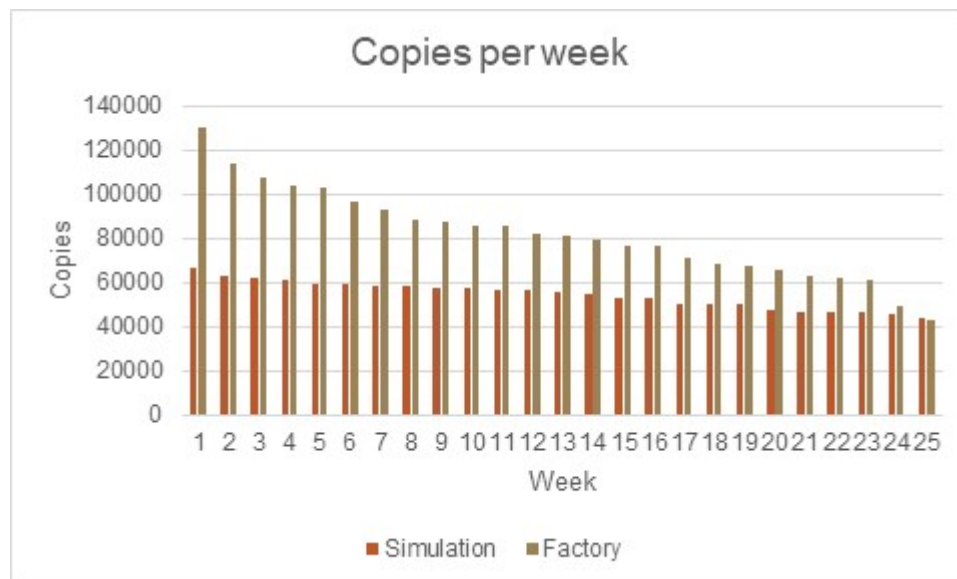
Figure 20: Comparison of number of copies per week

4.6.4 QUEUEING MODEL

A queueing model can be used for validation. In this section the arrival rate mean and average are calculated using compound distributions. The following data is necessary to validate our model using queuing theory as stated in (Hopp and Spearman, 2008):

- Arrival rate of jobs at each workstation
- Processing time and variance per machine
- Availability per machine
- Failure rates per machine
- Average batch size per machine
- setup time per machine

Machines are grouped together based on the jobs they perform, e.g., there is one sheet printing station containing both HP12000 and HP30000.

Workstations in the queueing model operate at a rate based on sheets, products or meters. This is called a job. E.G. printer 1 meter is 1 job, binding 1 book is 1 job etc. This is contrary to the simulation model which works per order.

- $r_{a,i}$ = Arrival rate of jobs at station i
- $t_{a,i}$ = time between arrival of jobs at the station i
- $\sigma_{a,i}$ = arrival standard deviation of jobs at the station i
- $c_{a,i}$ = arrival CV at the station i
- m,i = number of machines at the station i

ARRIVAL RATE OF JOBS AT EACH WORKSTATION

For the first machines in the production process the arrival rate of jobs is based on external arrival rates. These rates are based on the order data. For the other machines, the arrival rate and variability are based on the departure rate and variability of the previous station. In this section formulas for both the expectation and variance of the number of sheets at the printers are derived.

EXTERNAL ARRIVAL RATE AT SHEET PRINTING STATIONS

The external arrival rate is based on the order data. From Section 4.2.2 we get $1/\lambda$ = 3 minutes 18 seconds between orders. Therefore:

$$\lambda = E[N] = \frac{1}{3:18} = 0,3030303 \; orders \; per \; minute \tag{4.12}$$

in which E[N] is the expected amount orders per minute. And $N \sim Poisson(\lambda)$. Let X denote the number of sheets per order. From section 4.2.2: $X \sim Exponential(\beta)$ in which β = E[X]. The total number of sheets to the printing stations per minute is denoted by Y and thus has Compound Poisson (λ,β). For Compound Poisson, E[Y] and Var[Y] can be computed as follows (See Section 3.2.4):

$$E[Y] = E[N]E[X] = \lambda\beta \tag{4.13}$$

And:

$$Var[Y] = E[N](Var[X] + (E[X])^2) \tag{4.14}$$

For the Exponential distribution the expectation and variance are given by:

$$E[X] = \beta$$

And

$$Var[X] = \beta^2$$

Therefore (4.11) can be reduced to:

$$Var[Y] = 2E[N](E[X])^2 = 2\lambda\beta^2 \tag{4.15}$$

With this the arrival rate and variance at the sheet printing station can be computed:

- $\lambda = {}^1/_{3,30}$ (see Section 4.2.2)

- $\beta = 67.84172662$ (see Table 7)

Entering into the formulas gives the arrival rate at the sheet printing station:

- $r_{a,Sheetprinting} = E[Y] = 20,56 \; sheets \; per \; minute$
- $\sigma_{a,Sheetprinting} = \sqrt{Var[Y]} = 52.81$
- $CV_{a,Sheetprint} = \dfrac{\sigma_{a,Sheetprint}}{r_{a,Sheetprint}} = 52.81$

ARRIVAL RATE AT ROLL PRINTING STATION

To compute the arrival rate at the roll printing station (T240) more steps are necessary. Let Z be the random variable defining the amount of jobs in meters arriving at the station each minute and Z_j denote the amount of jobs of order type j in meters arriving at the station each minute. The sum of two random variables (3.10) is given by:

$$E[Z] = \sum_j E[Z_j] = E[Z_{books}] + E[Z_{brochures}] \tag{4.16}$$

Note that books and brochures are the only order type that require inside work printed on the T240 printer. The number of meters arriving at the station is a compound distribution consisting of the arrival rate of orders for books (Y_i) and the size of the books in meters (M_i). Using the rules for compound distributions from Section 3.2.4:

$$E[Z_j] = E[2Y_j]E[M_j] = E[2X_j]E[N_j]E[M_j] = 2\beta_j\lambda_j E[M_j] \tag{4.17}$$

$E[X_j]$ denotes the number of sheets per order of type j. This is multiplied by 2 since there are 2 book covers per sheet. N_j denotes the distribution of the arrival rate with mean λ of order type j. λ_j is equal to:

$$\lambda_j = f_j\lambda \tag{4.18}$$

M_j denotes a random variable modeling the amount of meters per order of type j. $E[M_j]$ can be computed with:

$$E[M_j] = E\left[\frac{1}{q}P_j\right] = \frac{1}{q}\mu_{P_j} \tag{4.19}$$

In which q is a constant denoting the number of pages that fit on 1 meter of paper and P the distribution of the number of pages per book/brochure. This is assumed a normal distribution. The variance can be computed as follows:

$$Var[M_j] = Var\left[\frac{1}{q}P_j\right] = \frac{1}{q^2}\sigma_{P_j}{}^2 \tag{4.20}$$

Substituting formulas into (4.17) yields:

$$E[Z] = \sum_j 2E[X_j]E[N_j]E[M_j] = \sum_j 2\beta_j f_j \lambda \frac{1}{q}\mu_{P_j} = \frac{2}{q}\lambda \sum_j \beta_j f_j \mu_{P_j} \tag{4.21}$$

Now let us move on to the variance of the arrivals. Since there is no reason arrival rates of order types are dependent on each other they are assumed independent. Therefore, using the rules for the sum of random variables (3.11) the variance is given by:

$$Var[Z] = \sum_j Var[Z_j] = Var[Z_{books}] + Var[Z_{brochure}] \tag{4.22}$$

Similarly to the computation of the expectation. We use the rule for the variance of compound distributions (3.8):

$$Var[Z_j] = E[2Y_j]Var[M_j] + E[M_j]^2 Var[2Y_j] \tag{4.23}$$

Again, Yj is multiplied by 2 since there are 2 covers per sheet. Because of (3.12) and (4.11) we get:

$$Var[Z_j] = 2E[Y_j]Var[M_j] + 4E[M_j]^2 Var[Y_j] \tag{4.24}$$

Substitution (4.13) and (4.15) in (4.11) for E[Yj] and Var[Yj] gives:

$$Var[Z_j] = E[N_j]E[2X_j]Var[M_j] + E[m_j]^2 \left(4\left(2E[N_j](E[X_j])^2\right)\right) = $$
$$2E[N_j]E[X_j]Var[M_j] + 8E[M_j]^2 E[N_j]E[X_j]^2 \tag{4.25}$$

Now since $N_j \sim Poisson(\lambda_j)$, $X \sim Exponential(\beta_j)$ and $M_j \sim Normal(\mu_j, \sigma_j)$:

$$Var[Z_j] = 2\lambda_j \beta_j \frac{1}{q^2}\sigma_{P_j}^2 + 8(\frac{1}{q}\mu_{P_j})^2 \lambda_j \beta_j^2 = 2\lambda_j \beta_j \frac{1}{q^2}\left(\sigma_{P_j}^2 + 4\mu_{P_j}^2 \beta_j\right) \tag{4.26}$$

And:

$$Var[Z] = \sum_j = 2\lambda_j \beta_j \frac{1}{q^2}\left(\sigma_{P_j}^2 + 4\mu_{P_j}^2 \beta_j\right) \tag{4.27}$$

The input for the formulas is:

- f_{books} = 4.02% (Table 7)-
- $f_{brochures}$ = 1.26% (Table 7)
- $P_{books} \sim Normal(500, 80)$ (Section 4.2.2)
- $P_{brochure} \sim Normal(80, 20)$ (Section 4.2.2)
- q = 7,27 pages per meter (Section 2.1.2)
- β_{books} = 136 (Table 7)
- $\beta_{brochures}$ = 112 (Table 7)
- λ = 0,3030303 (Formula (4.12))

Which results in:

- $r_{a,Rollprinting} = E[Z] = 101.37 \; meter \; per \; minute$
- $\sigma_{aRollprinting} = \sqrt{Var[Z]} = 1678.78$
- $CV_{a,Rollprinting} = \frac{\sigma_{a,Rollprinting}}{r_{a,Rollprinting}} = 16.56$

Thus every minute, on average, 101,37 meter of job is arriving at the Printer T240. This is a plausible value since it is lower than the processing rate of 152 meter per minute.

4.7   WARMUP PERIOD

In this section we will define the warmup period of the simulation. The simulation starts without any orders in the system. This is not a realistic situation since the factory starts each day filled with the work-in-process from the previous days. Therefore it will take some time before the steady state is reached. This period is known as the warmup period. To determine the length of the warmup period various statistics can be used: Utilization, Throughput and Work-in-process. Because a graph with the utilization of 20 different machines yields a messy graph throughput will be considered as a measure. The throughput of orders is shown in Figure 21 for both the amount of orders and the amount of copies. The moving average for each week and month is shown in thicker lines. Although the daily values may fluctuate heavily the monthly average stabilizes quickly. This graph stabilizes quickly.
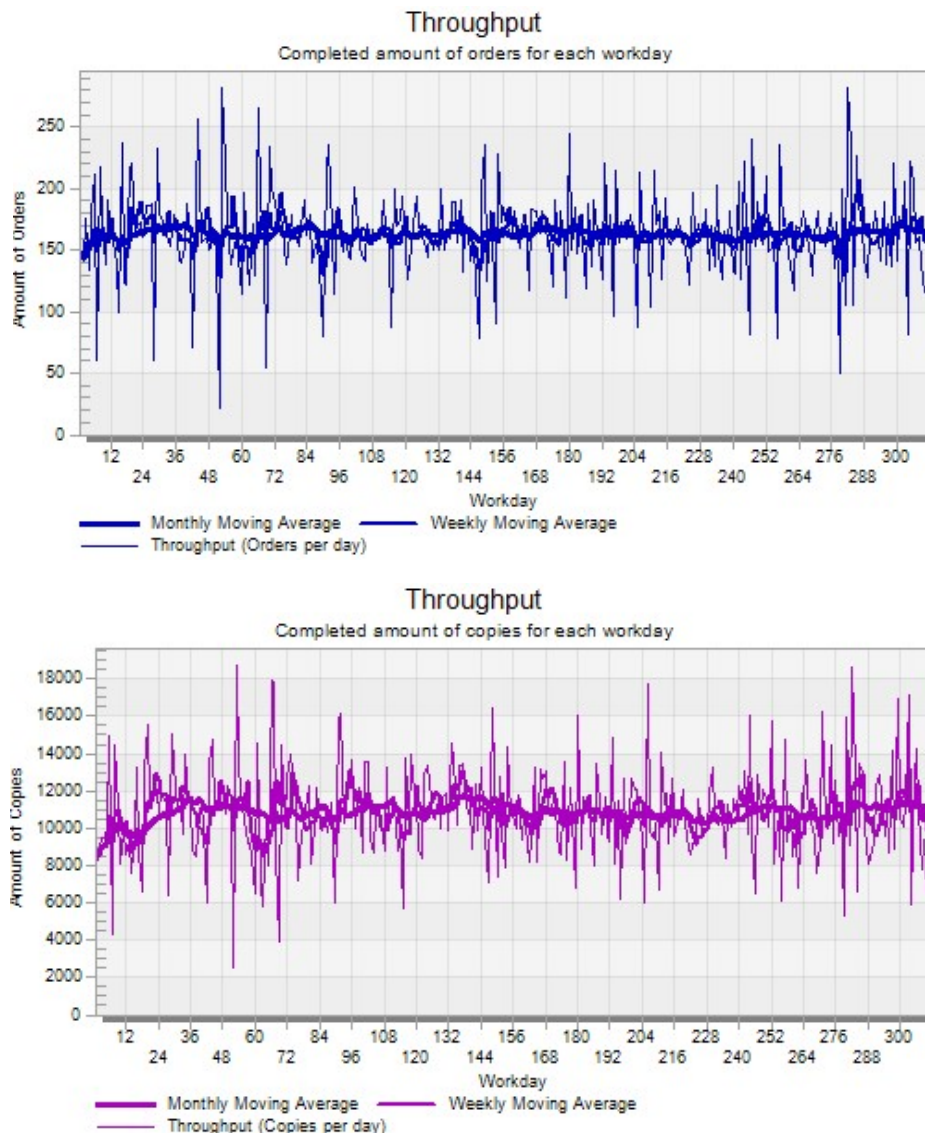
Figure 21. Throughput (orders and Copies)

So let us now consider the work in process. The Work in process (Figure 22) is measured as the amount of orders in the factory at the end of a day at regular time (17:00). This statistics fluctuates more heavily than the throughput. The first peak is reached at around day 30 and ends around

day 40. There does not seem to be a peak that is significantly higher in the rest of the time period. Therefore the conclusion is that the system is stable at day 40.
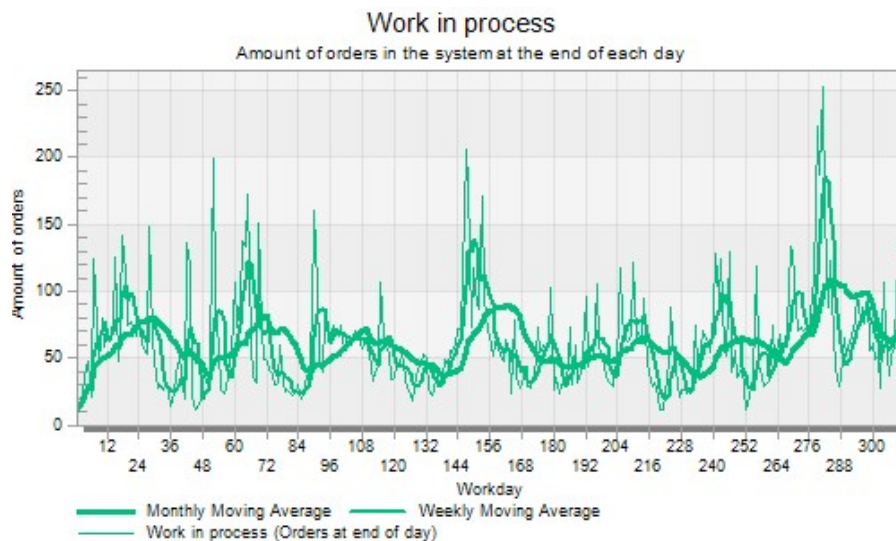
Figure 22. Work in process

As a safety measure 20% is added to this value for a total warmup time of 48 workdays (67 days). To confirm the steady state has been indeed been reached a very long simulation run (3 years: 830 workdays) is performed. The results are displayed in Figure 23. This figure plots both the monthly moving average of the throughput and work in process. The dashed line indicates the average excluding the warmup period. That the values fluctuate around the average indicates a steady state. In this figure it is also visible that both throughput and work in process follow the same pattern after one year is passed. So the initial assumption that a warmup length of 48 days is sufficient is confirmed.
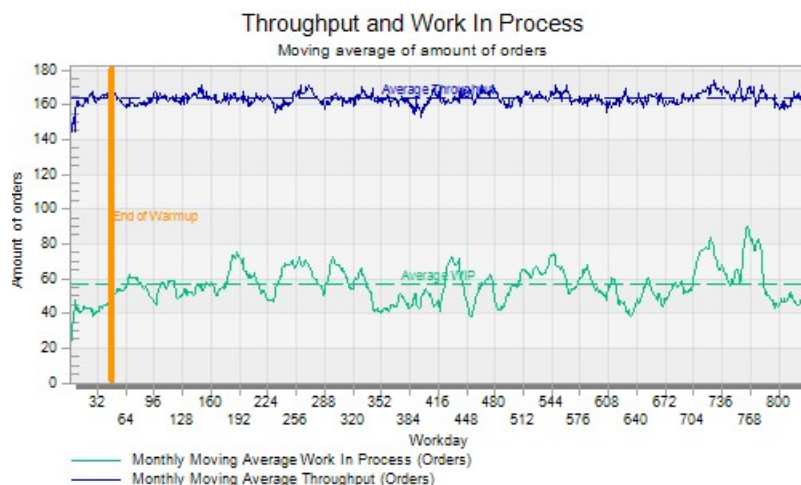
Figure 23. Simulation run of 3 years

4.8 CONCLUSIONS ON MODEL DESIGN

In this chapter the simulation model was designed. The model construction was divided into: General model description, model input, model output, validation and verification. The first research question was:

What is a suitable simulation model for the factory?

Effort has been made to represent the situation in the factory in the model. The model is designed to measure effects of adding machines, changing priority rules, changing arrival rate and parameters such as run length, warmup length and the number of pages per book. Important simplifications are that the arrival process of orders is assumed Poisson and that buffers have infinite capacity.

The other research question for this chapter was:

Can the simulation model be validated with the factory?

We saw that the utilization of machines in the simulation model followed the same pattern as observed in the factory. Also the throughput and order sizes was realistic. However there was slight deviation when comparing data from amount of copies over a longer period of time with the output from the simulation model. This concern can be addressed by doing a sensitivity analysis over the results and varying the mean amount of orders arriving to the factory.

The length of the warmup period was determined at 48 workdays,

5 EXPERIMENTS AND NUMERICAL STUDY

This chapter includes the analysis of the current situation in the factory as modeled in the simulation model. Experiments consists of adding extra machines and comparing their effects. But first a suitable warmup period needs to be found. The research question is:

What are realistic variations in the input parameters?

This is the subject of section 5.2. The research questions:

What should capacity be to maximize output KPIs?

And:

What is the effect of changing priority rules on the KPIs?

Are the subject of sections 5.2.2 and 5.2.3.

5.1 CURRENT SITUATION

The current situation is simulated using a warmup length of 48 and a run length of a year (261 workdays) For a total length of 309 workdays. Results from this simulation are displayed graphically in Figure 21, Figure 22, Figure 24, Figure 25, Figure 26, Figure 27 and Table 16.
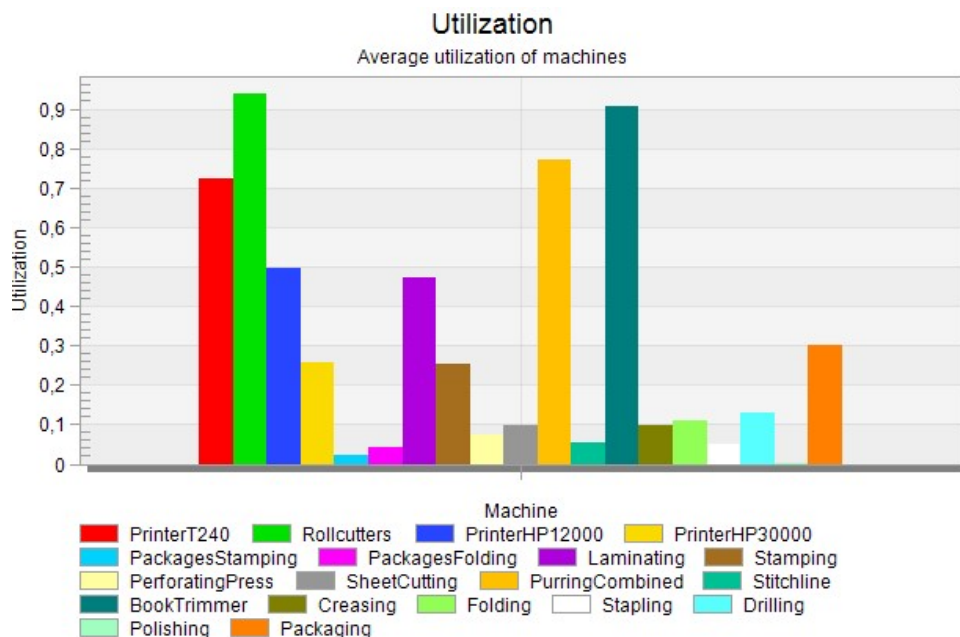

Figure 24. Average Utilization

Some observations from these statistics:

- From Figure 24 it is clear that the machines with the highest utilization are: Roll cutting, PrinterT240, Book trimmer and Purring (named PurringCombined in the bar chart). These are displayed in more detail in Figure 26 and Figure 27. This is in line with the situation

as is in practice. Currently the T240 printer and the Roll cutters are operating for two shifts per day. A new Book trimming and Purring machine are considered by management.

- Some machines have very low utilization (< 10%). This is due to the nature of the factory. There are a lot of machines that do different key steps in the process that are only required for few orders. Low utilization is not efficient but it is necessary to provide diversity to the customers.
- The sheet printers have a lower utilization (50 % and 25% respectively) compared to the T240 printer (72%). This means that there is capacity left on these machines. This is also what is visible in the factory. Especially the HP30000 printer which is specialized in printer on carton is underutilized. More customers have to be acquired to deal with this inefficiency. Both the stamping and folding machines for packages are also underutilized. Thus by increasing the demand for carton packages the capacity could be utilized more efficiently.
- Despite a relatively low utilization of the PrinterT240 (Figure 26), there is a considerate amount of overtime on this printer (Figure 27). This can be explained by failures and maintenance. From practice it is known that printers have more frequent downtime for repairs than other machines. Data about printer failures is available in Section 2.5.3. The repair time is time where the machine is not working and reducing the utilization. Another factor is that overtime is necessary after a downtime to deal with the backlog. There is no data about failures of other machines than printers but these are negligible.
- The Roll cutters have very high utilization values (Figure 26) but the amount of overtime is relatively low compared to the Purring and Book trimming machines (Figure 27). This is a consequence of the way overtime is implemented in the model. Whenever there are more than 10 orders at a buffer the machine will use overtime to clear it. Because the trimming machine is next in the chain after printing and cutting it will still be receiving new orders from these stations during the overtime period whilst the others do not receive new orders.
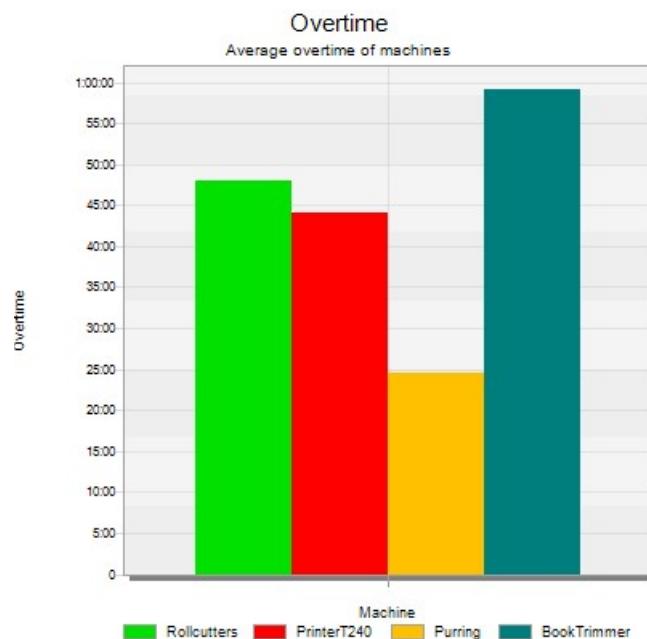
Figure 25. Average overtime for selected machines

60
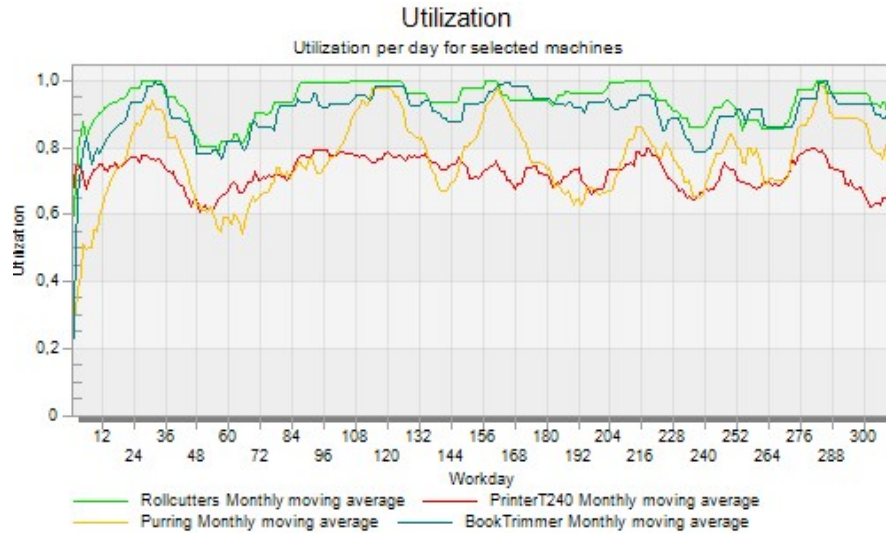
Figure 26. Utilization for selected machines
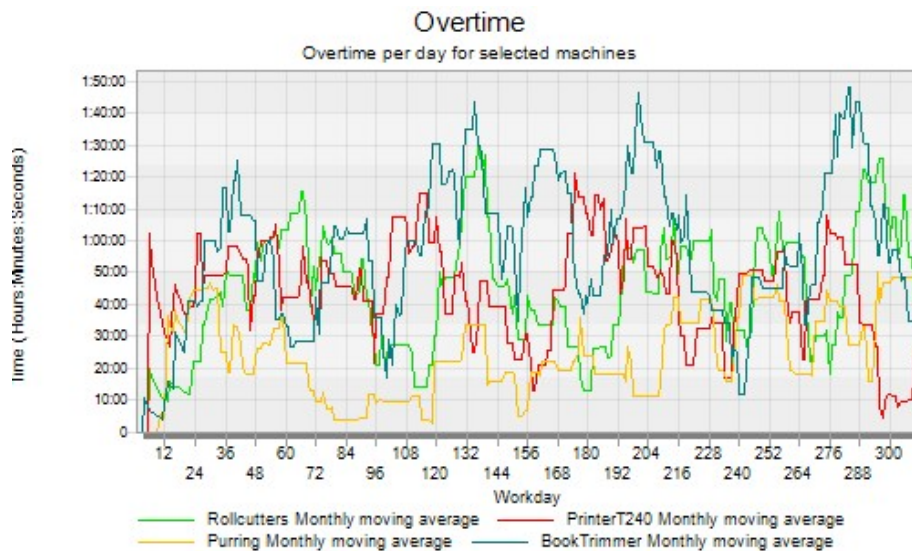
Figure 27. Overtime for selected machines

Table 16 shows the statistics collected at the end of the simulation run. 50699 is the total amount of orders in the system. The work in process is recorded each workday at 17:00 and the average indicates the average over all workdays. The same counts for throughput. The average overtime statistic is based on the time that the last machine stopped working overtime on each day. Average total overtime is based on the sum of overtime over all machines at the end of each day. Tardiness is calculated for each order with following formula:

$$\max(0, \quad Completion\ time - Due\ date)$$

Therefore tardiness is 0 when the order was finished before the due date was over and equal to the lateness if the order was completed too late. The statistics from Table 16 are collected at the end of each simulation run and can be used to compare different simulations.

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Table 16. End of simulation statistics

Including warmup period	
Total amount of orders	50699
Total amount of finished orders	50564
Amount of orders currently in system	135
Excluding warmup period	
Average work in process at end of day	62,41
Average throughput per day (orders)	164,10
Average throughput per day (copies)	10963,48
Average overtime (hours:minutes:seconds)	2:23:16
Average total overtime	2:57:20
Max tardiness (days:hours:minutes:seconds)	5:15:01:134
Average tardiness (hours:minutes:seconds)	1:39:37

5.2 INTERVENTIONS

Possible interventions include adding more capacity (machines) and changing priority rules. This section starts with adding machines and showing the results and will then study effects of changing priority rules. The test will contain a run length of one year excluding the warmup period. Every experiment setting will be run 10 times independently for 309 workdays with a different random number seed each.

5.2.1 EXPERIMENT OUTPUT

The results of the experiments are divided into the following parts: Work in process, overtime, tardiness and throughput.

- Work in process is a metric that counts the amount of orders in the system at the end of each day. High values of work in process usually lead to other problems such as long lead times, overtime, and late delivery of orders. Low values of work in process mean that the machines in the factory are not being used efficiently.
- The total overtime and average overtime both measure the amount of overtime. The average length of overtime measures the moment the factory closes at the end of each day whilst the average total overtime is the sum of overtime over all the machines at the end of each day. In case a particular machine is the bottleneck we can expect that both values are close to each other. However if multiple machines require overtime than expect the total overtime to be much higher than the length of overtime. Overtime is on important measure for management as overtime increases costs.
- Tardiness measures the lateness of orders. Expect that increasing capacity will reduce tardiness. Tardiness is an important measure for management as it is a measure of customer satisfaction.
- Throughput measures the amount of orders going through the system. Throughput is an important measure for validation as explained in section 4.6.2.

5.2.2 ADDING CAPACITY

From the analysis in the previous section it is clear that the four machines with the highest utilization are: Printer T240, Roll cutters, Book trimmer and Purring. Therefore it is logical to try adding an extra of those machines to the system and measure the effects. Because adding an extra printer is not feasible due to the size and costs involved in doing so this option is not considered. The possible combinations that will be tested are shown in Table 17. The scenarios can be divided into 4 groups: Current situation (experiment 1), adding an extra machine

(experiments 2, 3 and 4), adding two extra machines (experiments 5, 6 and 7) and adding three machines (experiment 8).

Table 17. Scenarios

Scenarios	Extra Purring machine	Extra Book trimming machine	Extra Roll cutting machine
1	No	No	No
2	Yes	No	No
3	No	Yes	No
4	No	No	Yes
5	Yes	Yes	No
6	Yes	No	Yes
7	No	Yes	Yes
8	Yes	Yes	Yes

WORK IN PROCESS
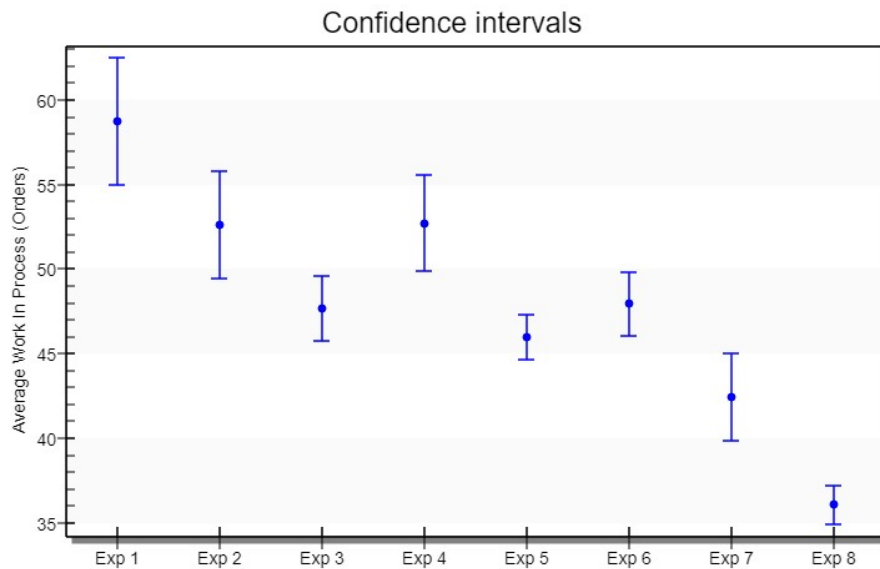
Figure 28. Confidence intervals for Work in Process

Table 18. P-Values comparison for Work in Process

	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8
Exp 1	0.012	0	0.01	0	0	0	0
Exp 2		0.008	0.97	0.001	0.012	0	0
Exp 3			0.004	0.125	0.804	0.002	0
Exp 4				0	0.006	0	0
Exp 5					0.07	0.017	0
Exp 6						0.001	0
Exp 7							0

The first metric to consider is the work in process. Figure 28 plots 95% confidence intervals for the values whilst Table 1 plots p-values from the scenario results. Values < 0.05 indicate a statistical significant difference between scenarios. From Figure 28 it is visible that there are significant differences between scenarios. Scenario 1 (current situation) scores the weakest whilst

adding 3 extra machines scores best which is expected. Remember scenario 2-4 adding 1 machine. From these three experiments scenario 3 (Add Book trimmer machine) gives the best results of these three options. Adding a Book trimmer in combination with an extra Roll cutting machine works best in case of adding 2 additional machines.

OVERTIME
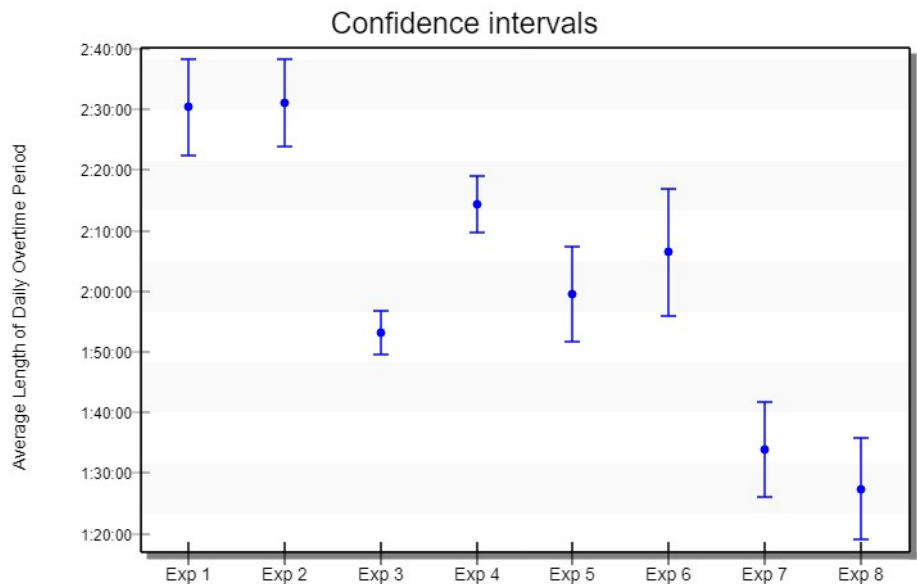
Figure 29. Confidence intervals for Overtime

Table 19. P-Values comparison for Overtime

	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8
Exp 1	0.888	0	**0.001**	0	**0.001**	0	0
Exp 2		0	0	0	0	0	0
Exp 3			0	0.121	**0.02**	0	0
Exp 4				**0.002**	0.146	0	0
Exp 5					0.244	0	0
Exp 6						0	0
Exp 7							0.209
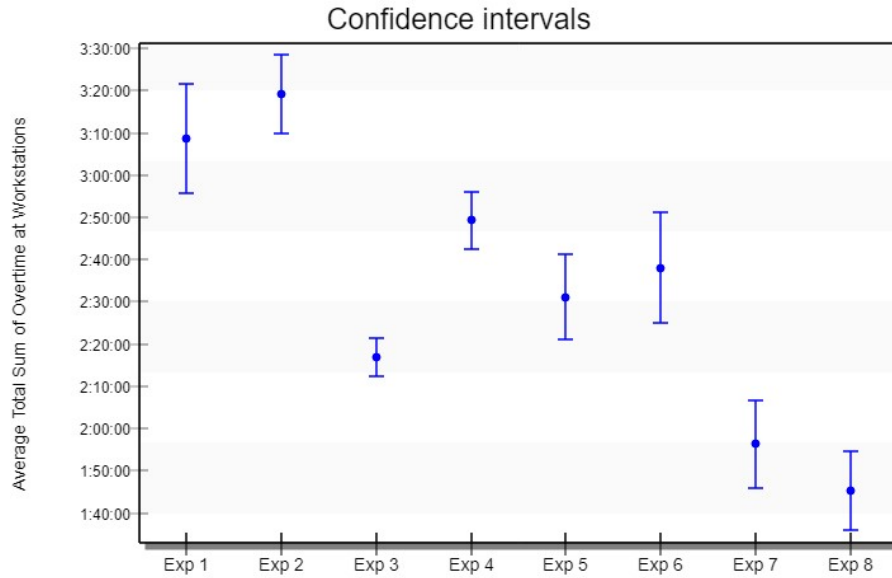
Figure 30. Confidence intervals for total overtime

Table 20. P-Values comparison for total Overtime

	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8
Exp 1	0.153	**0**	**0.009**	**0**	**0.001**	**0**	**0**
Exp 2		**0**	**0**	**0**	**0**	**0**	**0**
Exp 3			**0**	**0.013**	0.005	**0.001**	**0**
Exp 4				**0.004**	0.107	**0**	**0**
Exp 5					0.359	**0**	**0**
Exp 6						**0**	**0**
Exp 7							0.093

The average length of overtime denotes the average time after regular time that the factory can close in the evening, i.e. when all machines have stopped working. From Figure 29 it can be concluded that both scenario 3 and 7 perform relatively well. The sum of overtime is given in Figure 30 and Table 20. P-Values comparison for total Overtime denotes the average total overtime over all machines at the end of each day. Again the scenarios 3 and 7 perform well compared to the other scenarios. Both overtime measures are surprisingly similar in their results.
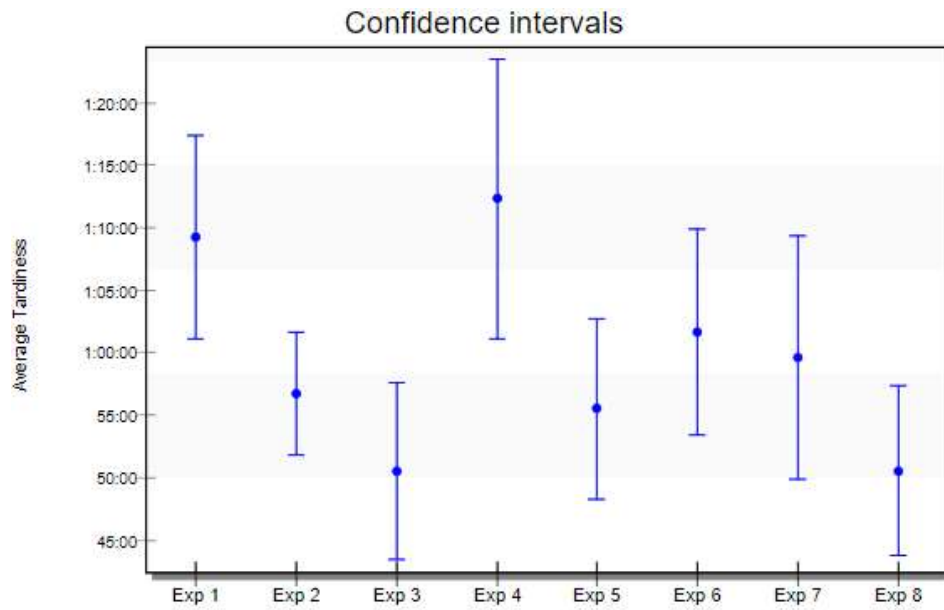
Figure 31. Confidence intervals for average tardiness

Table 21. P-Values comparison for average tardiness

	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8
Exp 1	**0.01**	**0.001**	0.617	**0.011**	0.156	0.104	**0.001**
Exp 2		0.121	**0.013**	0.756	0.265	0.562	0.116
Exp 3			**0.002**	0.277	**0.032**	0.105	0.988
Exp 4				**0.012**	0.1	0.068	**0.002**
Exp 5					0.221	0.455	0.275
Exp 6						0.721	**0.031**
Exp 7							0.104
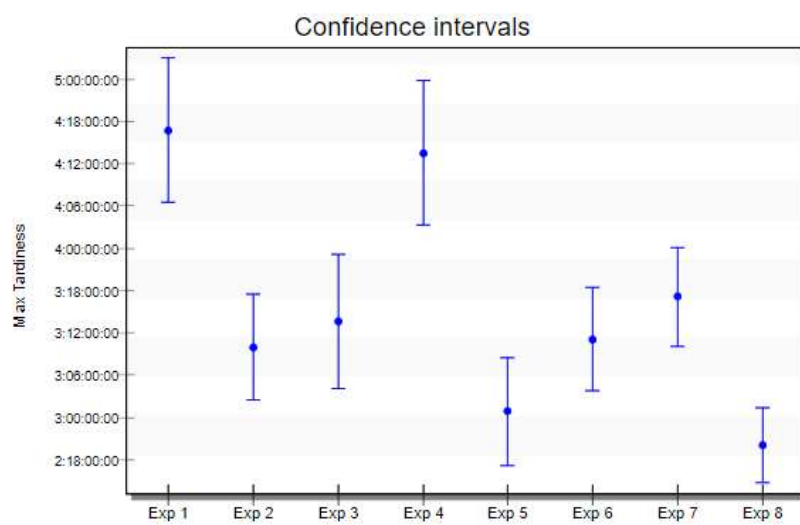
Figure 32: Confidence intervals for maximum tardiness

Table 22: P-values for maximum tardiness

	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8
Exp 1	0	0	**0.622**	0	0	0.001	0
Exp 2		**0.502**	0	**0.068**	**0.807**	**0.131**	0.003
Exp 3			0.001	0.029	**0.639**	**0.513**	0.003
Exp 4				0	0	0.002	0
Exp 5					0.041	0.002	**0.256**
Exp 6						**0.195**	0.002
Exp 7							0

Tardiness is a measure of how much too late an order is. The maximum and average tardiness give a similar pattern in their results. Results are surprising in that scenario 3 (Add Book trimmer) performs very well. Adding extra machines besides a Book trimmer seems not to yield extra reduction of the average tardiness.
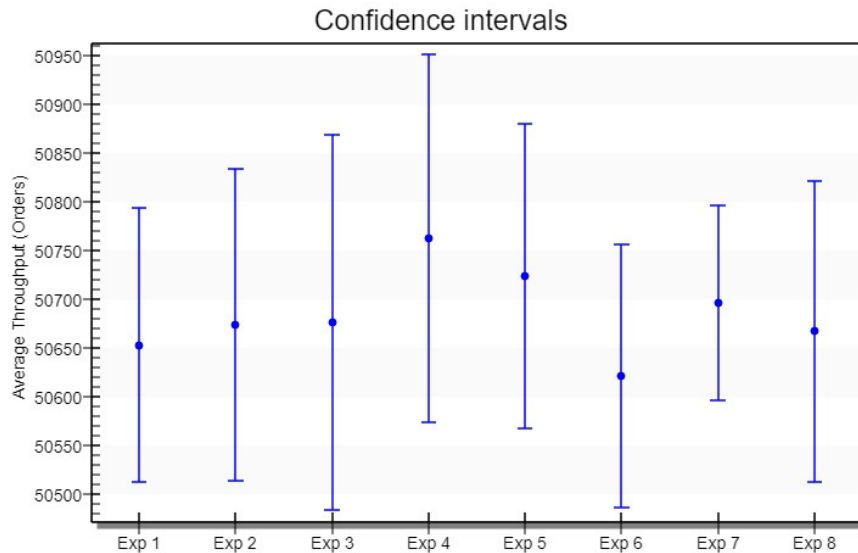
THROUGHPUT

Figure 33. Confidence intervals for throughput

Table 23. P-Values comparison for Work in Process

	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8
Exp 1	0.829	0.828	0.307	0.455	0.716	0.579	0.882
Exp 2		0.981	0.427	0.616	0.578	0.791	0.946
Exp 3			0.478	0.669	0.604	0.839	0.933
Exp 4				0.726	0.187	0.493	0.387
Exp 5					0.275	0.738	0.565
Exp 6						0.328	0.621
Exp 7							0.725

In section 4.5.5 it was stated that throughput can be used to verify the simulation model. Results are shown in Figure 33. There are no significant differences between scenarios (see Table 23). This result is as expected. An explanation is that each scenario uses the same distribution for the

arrival process of orders. Therefore each scenario has roughly the same amount of orders at its disposal. Since each order is processed eventually the throughput figures are equal.

CONCLUSION

Table 24. Results of experiments for changing capacity.

	Settings				Results				
	Second Purring Machine	Second Trimming Machine	Third Roll cutting Machine	Priority Rule	Average Work In Process (Orders)	Average Length of Daily Overtime Period (Minutes)	Average Total Sum of Overtime at Workstations (Minutes)	Max Tardiness (Days)	Average Tardiness (Minutes)
Scenario 1				FCFS	58,74	150	189	5	69
Scenario 2	X			FCFS	52,63	151	199	3	57
Scenario 3		X		FCFS	47,66	113	137	4	50
Scenario 4			X	FCFS	52,70	134	169	5	72
Scenario 5	X	X		FCFS	45,98	120	151	3	56
Scenario 6	X		X	FCFS	47,57	127	158	3	62
Scenario 7		X	X	FCFS	42,46	94	116	4	60
Scenario 8	X	X	X	FCFS	36,06	87	105	3	51

To reduce the average tardiness, adding an extra Book trimmer is a good option. Overtime can be most effectively reduced with the settings of experiment 7 (Extra Book trimmer and Roll cutting machine) and 8 (Extra purring machine, extra Roll cutting machine and extra book trimming machine).

5.2.3 CHANGING PRIORITY RULES

It may be possible to improve the performance of the factory be changing the priority rules at the factory. Section 4.2.4 listed 8 priority rules. These rules are: FCFS, LCFS, SPT, LPT, EDD, CR, S/RO and S/RPT. These rules have been implemented in the simulation model and are applied at each workstation. The configuration of the factory as in the current situation, i.e. with no extra added machines. Experiment setting are again 10 experiments per configuration with warmup length of 48 workdays and run length of 309 workdays.

WORK IN PROCESS
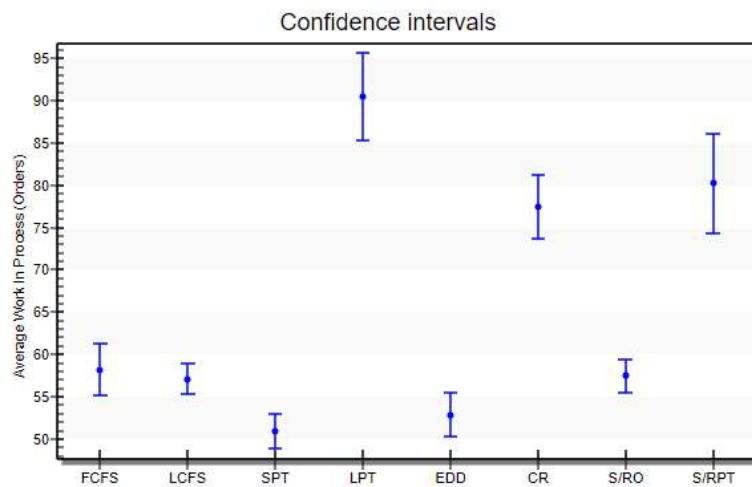
Figure 34. Confidence intervals for average work in process

The shortest processing time (SPT) rule minimizes the average number of jobs waiting for processing (Pinedo, 2009). This is confirmed by the simulation results, verifying that the rule has indeed been implemented correctly. Also the more complex rules CR and S/RPT do not yield good results on this measure.

OVERTIME

Figure 35. Confidence intervals for average overtime

LPT performs best at the overtime measure. Overtime can be reduced by about half an hour using the LPT rule over FCFS.
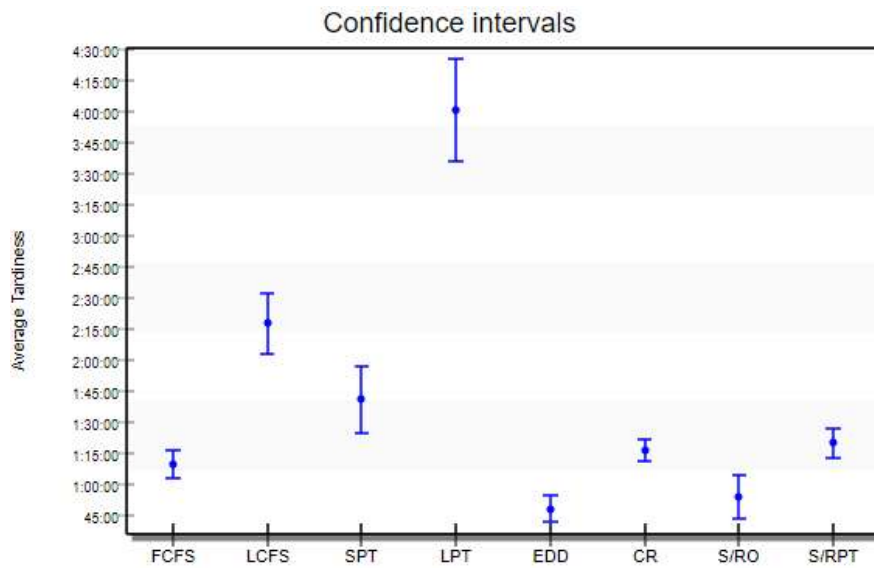
Figure 36. Confidence intervals for average tardiness
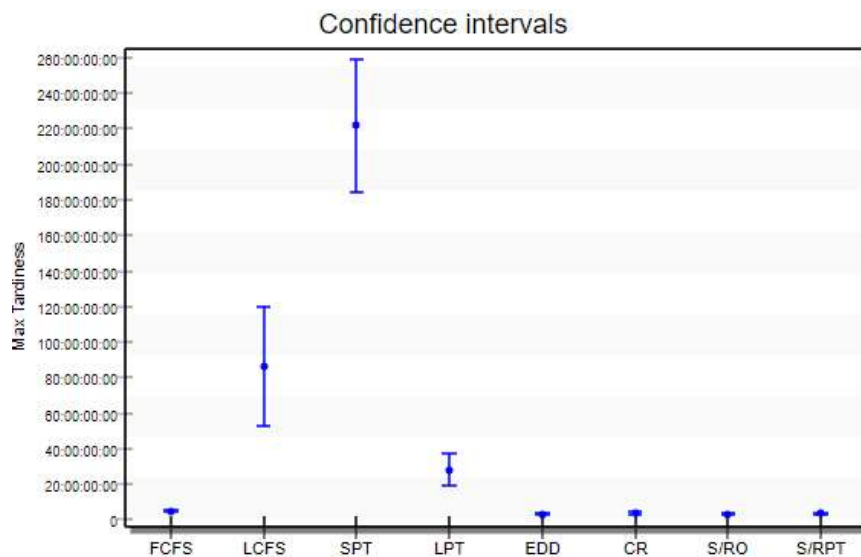
Figure 37. Confidence intervals for max tardiness

The EDD rule minimizes the maximum lateness among all jobs (Pinedo, 2009). This is confirmed by the results from Figure 37. The CR, S/RO and S/RPT rules are ba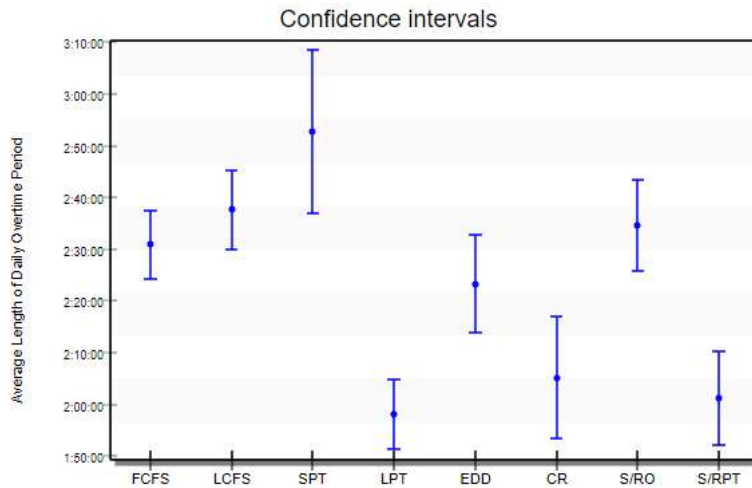sed on the due date and perform strong on the tardiness measure as well. The LPT rule performs notoriously bad on average tardiness. This can be explained because the small orders are pushed back after the large orders and therefore a lot of small orders are delivered late, hence the average increases. The SPT rule on the other hand performs bad on the max tardiness measure. This can be explained by certain large orders with large processing time being pushed back continuously. Lastly, the EDD rule performs better than FCFS and LCFS on both average and maximum tardiness measures. Experiments with combining the capacity changes and priority rules will be performed in the following section.

5.3 CONCLUSIONS ON THE EXPERIMENTS

5.3.1 SUMMARY OF PREVIOUS RESULTS

In total 150 experiments of 15 different scenarios have been carried by the simulation model of the factory. An overview of the results is given in Table 25. This table also contains a definition of the settings of the different scenarios. This data shows the average values over all experiments per scenario. This data is presented visually in Figure **38**. The following conclusions can be drawn from the results:

- For each performance measure, it holds that a lower value is better. Less overtime means lower costs, less tardiness means better customer service and lower work in process means lower costs.
- In the conclusion of section 5.2.2 it was reasoned that the most promising options are scenarios 3 (Extra Book trimmer), 7 (Extra Book trimmer and Roll cutter) and 8 (Extra Book trimmer, Roll cutter and Purring machine) are the most realistic scenarios and therefore the options 4,5 and 6 do no longer have to be considered.
- Scenarios 9 (LCFS) and 10 (SPT) score very bad at the maximum tardiness measure and are therefore not a realistic scenario to implement in the factory. Therefore these scenarios are no longer considered from now on.
- Scenarios 13 (CR), 14 (S/RO) and 15 (S/RPT) are a more complicated version of the earliest due date rule. However these scenarios do not perform significantly better than scenario 12 (EDD), see also the figures from the previous section. Given to the added complexity of implementing these priority rules on the work floor it is safe to assume that these priority rules are not a realistic solution for the company. Why would one implement a complicated rule that does not perform better than an easier rule? Therefore these scenarios are no longer considered.
- The 11th scenario (LPT) performs really bad at the average tardiness measure and is therefore not a realistic solution.
- There is a correlation between the performance measure "Average total sum of overtime" and "Average length of daily overtime period": Scenarios that score high on the first one also score high on the second one and vice versa. Therefore only one of these measures has to be taken into account.
- The scenarios that perform bad on maximum tardiness are no longer considered therefore this performance measure con be omitted.
- The most important cost measure out of overtime and work in process is overtime. Therefore the focus will be on this measure when it comes to depicting costs of a scenario.

Concluding, the scenarios 1, 2, 7, 8 and 12 can be considered in more depth. This comes down to 4 different configurations of machines and 2 different priority rules. Extra experiments can be run since the EDD priority rule was only used for the standard configuration without extra machines. The performance measures that will be focused on will be "Average length of daily overtime period" and "Average tardiness".
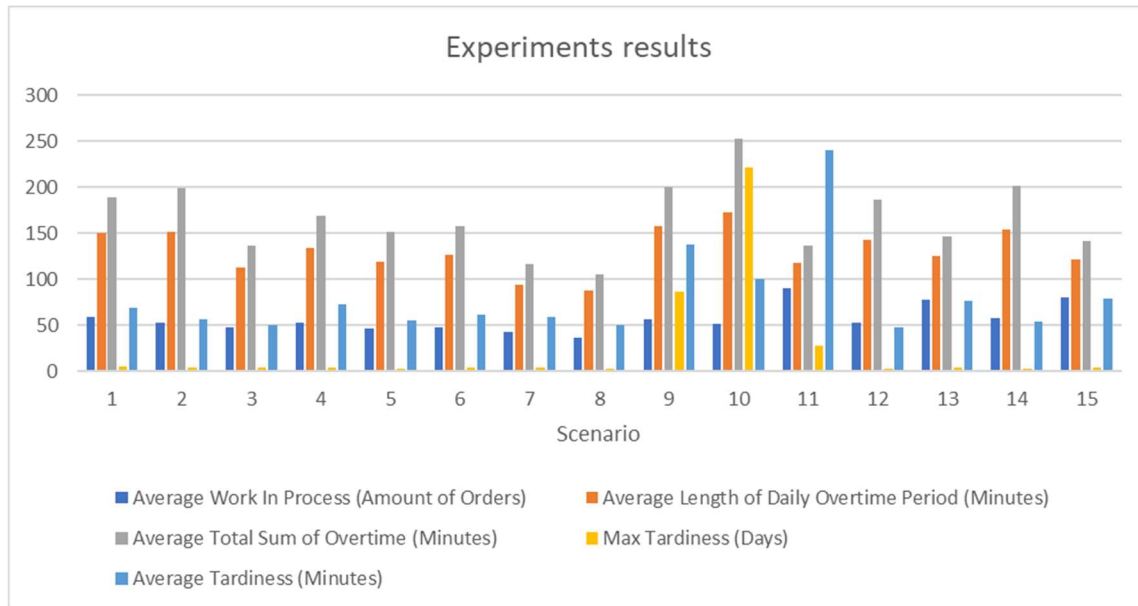
Figure 38. Experiment Results

Table 25. Experiment results

	Settings				Results				
	Second Purring Machine	Second Trimming Machine	Third Roll cutting Machine	Priority Rule	Average Work In Process (Orders)	Average Length of Daily Overtime Period (Minutes)	Average Total Sum of Overtime at Workstations (Minutes)	Max Tardiness (Days)	Average Tardiness (Minutes)
Scenario 1				FCFS	58,74	150	189	5	69
Scenario 2	YES			FCFS	52,63	151	199	3	57
Scenario 3		YES		FCFS	47,66	113	137	4	50
Scenario 4			YES	FCFS	52,70	134	169	5	72
Scenario 5	YES	YES		FCFS	45,98	120	151	3	56
Scenario 6	YES		YES	FCFS	47,57	127	158	3	62
Scenario 7		YES	YES	FCFS	42,46	94	116	4	60
Scenario 8	YES	YES	YES	FCFS	36,06	87	105	3	51
Scenario 9				LCFS	57,09	158	200	86	138
Scenario 10				SPT	50,92	173	253	222	101
Scenario 11				LPT	90,46	118	137	28	240
Scenario 12				EDD	52,84	143	186	3	48
Scenario 13				CR	77,46	125	147	4	76
Scenario 14				S/RO	57,47	155	201	3	54
Scenario 15				S/RPT	80,22	121	142	4	80

COMPARISON OF FINAL SCENARIOS

In the previous section the simulation is reduced to the following scenarios:

- Current Situation FCFS
- Extra Book trimmer FCFS
- Extra Book trimmer and Roll cutter FCFS
- Extra Book trimmer, Roll cutter and Purring machine FCFS
- Current Situation EDD
- Extra Book trimmer EDD
- Extra Book trimmer and Roll cutter EDD
- Extra Book trimmer, Roll cutter and Purring machine EDD

These scenarios are simulated and the results are displayed visually in Figure 39 and in Table 26. The most important conclusions from these experiments is that the Earliest Due Date rule performs better than the First-Come-First-Served rule for all scenarios on both the tardiness and

overtime performance measure. A sensible advise would therefore be to focus on the Earliest Due Date in the production planning. Advice regarding whether extra capacity should be invested in depends on the gains that can be made. It is evident that overtime is decreased by buying new machines, however it depends on the costs of these machines. This is discussed in the final chapter.
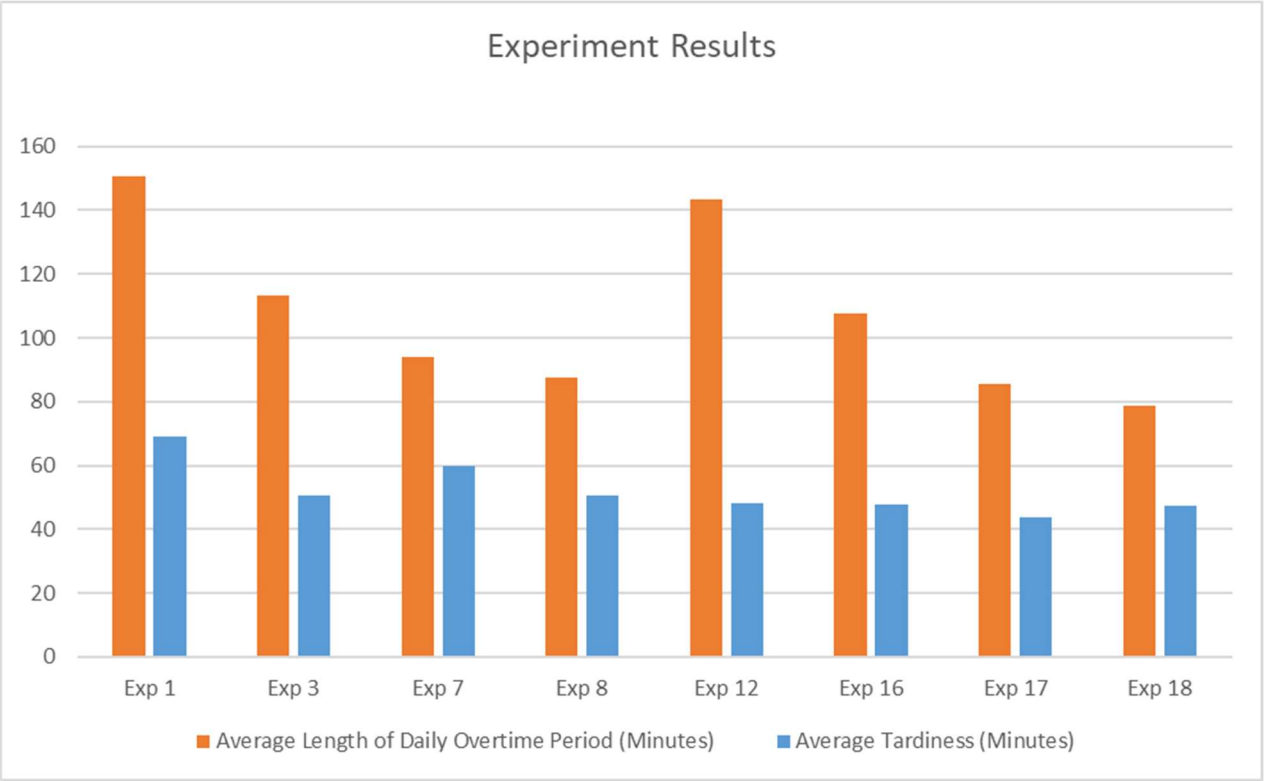

Figure 39. Experiment Results

Table 26. Experiment Results

	Second Purring Machine	Second Trimming Machine	Third Roll cutting Machine	Priority Rule	Average Work In Process (Orders)	Average Length of Daily Overtime Period (Minutes)	Average Total Sum of Overtime at Workstations (Minutes)	Max Tardiness (Days)	Average Tardiness (Minutes)
	Settings				**Results**				
Scenario 1				FCFS	58,74	150	189	4,70	69
Scenario 3		YES		FCFS	47,66	113	137	3,57	50
Scenario 7		YES	YES	FCFS	42,46	94	116	3,71	60
Scenario 8	YES	YES	YES	FCFS	36,06	87	105	2,83	51
Scenario 12				EDD	52,84	143	186	3,11	48
Scenario 16		YES		EDD	44,66	108	132	3,05	48
Scenario 17		YES	YES	EDD	36,87	86	108	2,67	44
Scenario 18	YES	YES	YES	EDD	35,75	79	98	2,51	47

5.3.2 TRADE-OFF BETWEEN PRIORITY RULES AND CAPACITY

Adding extra capacity involves buying new machines whilst changing priority rules involves changes the way of working. Figure 39 shows that adding more capacity reduces the overtime. This is because jobs can be completed during regular time due to the extra capacity. Changing the priority rule from FCFS to EDD reduces the tardiness. Tardiness is a measure of service level: A lower tardiness means that orders arrive on time, keeping customers satisfied. Thus to increase the service level the priority rule can be changed whilst the overtime can be reduced by adding capacity.

5.4 SENSITIVITY ANALYSIS

Lejmi & Sabuncuoglu (2002) researched the effects of processing time variation, load variation and due date variation on the relative performance of priority rules. Their conclusion was that the relative performance of priority rules is not threatened much by changes in these variables. Therefore a sensitivity analysis of results of priority rule changes is not deemed necessary. What might be interesting though is to see whether changing some estimated parameters give a different result. During the model construction phase, it was decided that the amount of pages that a book or brochure has would be estimated. This was because of a lack of data. It was estimated that books have 500 pages on average with a standard deviation of 80. For brochures this was estimated at 80 and 20. However what if this estimate was wrong? What implication does this have for the results of this research? Are they still valid? We can find that out by changing the parameters in the model and check for the results.

10 different experiment settings were simulated and their results are displayed in Figure 40. The amount of pages per book/brochures was changed from low to high. The default setting is 500 pages per book and 80 pages per brochures. The variance was kept constant at 80 and 20 respectively. One would expect that the workload of the factory increases as bigger books mean a longer production time on the printer and cutting stations. This can indeed be found from the figure. The experiments for FCFS and EDD follow the same pattern. One interesting result is that when the average amount of pages gets large the average work in process increases significantly and the confidence interval becomes very wide. This indicates that the workload of the system is too large to handle properly. i.e., the workload is larger than it can properly handle. Therefore the conclusion of the sensitivity analysis is as follows: The results from the experiments are valid as long as the average amount of pages per book/brochure does not exceed 600 and 100 respectively.
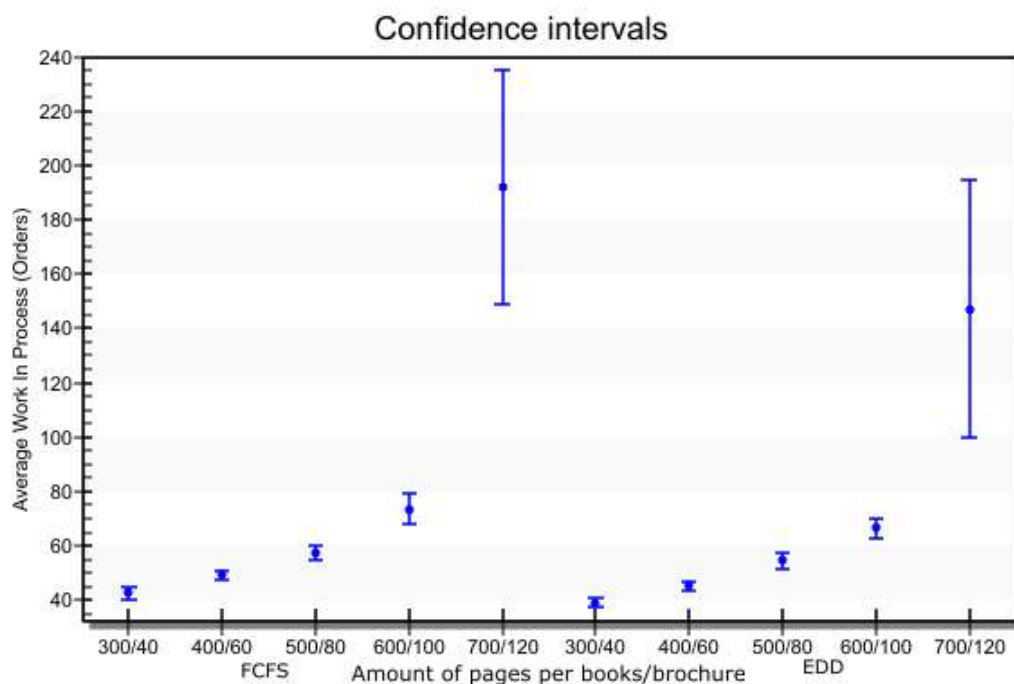

Figure 40. Sensitivity analysis comparing changing amount of pages and priority rules.

6 CONCLUSIONS AND RECOMMENDATIONS

This chapter consists of a summary of the results of this research. The findings and their implications for the company and for science will be discussed. Finally there will be a discusses of the main research objective:

Develop a suitable model to evaluating effects of increasing capacity and/or changing priority rules on production KPIs (Tardiness, work-in-process, overtime) for a printing company with a process oriented layout subject to a variable demand.

After that ideas for future research can be discussed.

6.1 SUMMARY

The objective of this thesis is to develop a suitable model to evaluating effects of increasing capacity and/or changing priority rules on production KPIs. This is done by building a simulation model. This simulation model consists of all the machines on the production floor. Data for the model is acquired from the app that records the action by the printers. This data consists of orders and some properties such as order size, color, double sided and order name. The order type can be derived from the order name in 98% of the cases. This data from the printers is only available for two printers: HP30000 and HP12000. From the HPT240 there is no data available, however, since this machine is used to print the inside work of books and brochure the workload of this printer can be derived from the data about covers printed on the HP12000 and HP30000 machines.

6.1.1 SIMULATION MODEL

The simulation model is built in the Plant Simulation model. The orders in the factory are modeled using a Poisson distribution with the amount of copies per order following an Exponential distribution. Order routing and size is depended on the order type. The processing rate at the machines can be dependent on the order type and the size of the order. The following statistics can be collected by running experiments: Average Work-In-Process in the factory, average amount of finished orders/copies at the end of each day (throughput), Average and maximum tardiness, utilization of the machines and average amount of overtime.

The simulation model is verified during the model construction. The software package allows for visual tracking of products which helps in debugging and follows the Object-Oriented Programming structure which allows for fragmentation of the code. The model is validated by comparing about from the simulation model with expected output based on data from the print app and expected values from queueing theory. Also the utilization values of the machines are compared with the actual situation in the factory and these are comparable.

Multiple simulation experiments were carried out. This model was used to evaluate the influence of changing the priority rules and the capacity.

6.1.2 EXPERIMENT RESULTS PRIORITY RULES

We found that out of all priority rules that were tested, the earliest due date (EDD) rule works best. Implementing this rule can reduce the average tardiness from 69 minutes to 48 minutes (See Table 26) as opposed to the First-Come-First-Served (FCFS) rule for the current production layout.

6.1.3 EXPERIMENT RESULTS CAPACITY

The experiment results show that adding extra machines does not decrease the average tardiness (See Figure 41) if the EDD priority rule is applied. A possible explanation is that the capacity of the system is limited by the T240 printer and that late orders are therefore late regardless of adding extra machines. What adding extra capacity does however, is reducing the overtime. An explanation for this is that adding an extra machine reduces the workload and

therefore the jobs can be completed in the regular hours. This also means that savings are possible because overtime means extra costs.

6.1.4 Adding capacity vs changing priority rules

From the experiment results it was found that tardiness can be reduced by changing the priority rule from LCFS to EDD. The amount of overtime can be reduced by increasing capacity. Overtime reduction gives potential costs savings but need to be weighted against the costs of adding a new machine. Reducing tardiness increases value for customers.
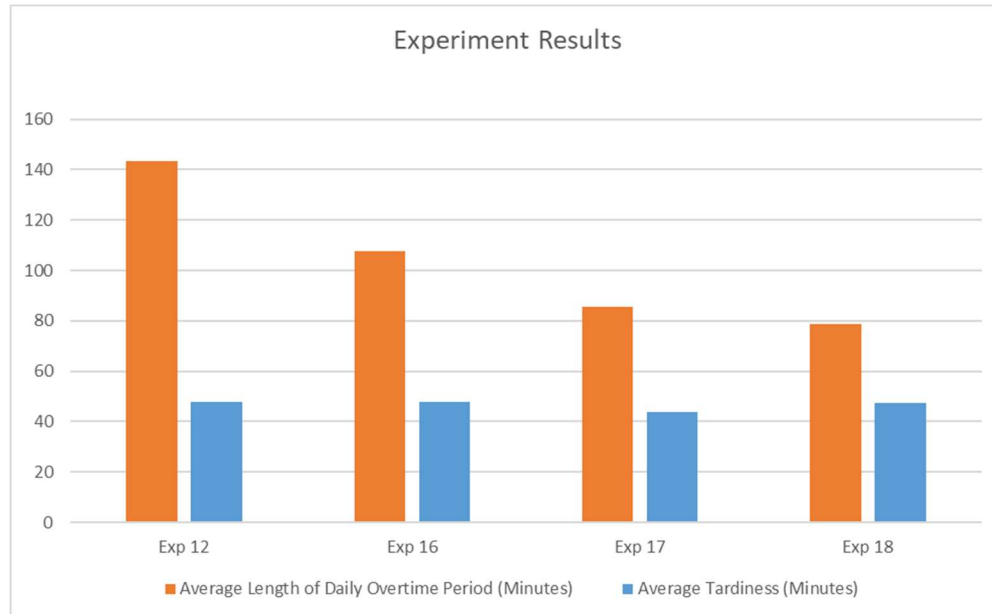

Figure 41. Experiments results for EDD

Table 27. Experiment settings

	Second Purring Machine	Second Trimming Machine	Third Roll cutting Machine
Exp 12			
Exp 16		YES	
Exp 17		YES	YES
Exp 18	YES	YES	YES

6.2 RECOMMENDATIONS

The results of the experiments show that the company can improve it's performance by adding extra capacity and changing priority rules. One recommendation is the implementation of the earliest due date (EDD) rule. This priority rules showed strong performance compared to FCFS and the other six priority rules that were tested. This priority rule is relatively easy to use in practice: A priority does not require capital investments. Also the EDD rule does not require any computations as compared to some more complex priority rules. For adding extra capacity it showed that adding an extra book trimming machine yields a big step forward in reducing overtime. Therefore recommendations is to change the priority rule to EDD and to get an extra book trimming machine.

The costs of an extra machine have to be offset with the extra profit that can be gained from having that extra machine. If the profit is larger than the costs than it is worth to get this extra machine. Adding extra machines reduces the overtime. This reduction in overtime should be weighed against the costs of adding this extra capacity. Adding an extra book trimmer can reduce the daily average overtime from 143 to 108 minutes. Therefore if the savings from 35 minutes of overtime are greater than the extra costs of an extra machine, then it is worth it to get an extra book trimmer. An estimate of the costs and benefits of an extra machine is given in **Table 28**. The costs of adding a new book trimmer to the factory is estimated to save € 4120,- per year while the costs would be € 3500,-.

Table 28. Implementation benefits/costs estimate for extra book trimming machine.

Costs		
Type	**Explanation**	**Costs per year**
Machine	Total costs of € 50.000 over a lifetime of 20 years.	€ 2.500
Operator	None. An operator from a different machine can be used as the total workload does not increase.	€ 0,-
Energy	Yearly energy costs of the machine (estimate).	€ 500,-
Maintenance	Estimated costs of repairs, replacing parts.	€ 500,-
Total		**€ 3.500,-**
Benefits		
Type	**Explanation**	**Benefits per year**
Operator	Base salary of 2.350 per month based on 40 hours/week and overtime increase of 25%. Costs per overtime hour: € 18,36. No more overtime pay for 33 minutes per day and a total of 309 workdays per year.	€ 3.120,-
Closing of plant	The entire plant can be closed 33 minutes earlier each day on average. Saves energy and presence of support personnel. Estimated savings: € 1000,- per year.	€ 1.000,-
Total		**€ 4.120,-**

6.3 LIMITATIONS

The simulation model consisted of the entire production layout. Each machine in the factory is included in the simulation model. The limitations of this research include:

- The interventions in the factory are limited to 3 machines: extra book trimmer, extra roll cutting machine and extra purring machine and priority rules.
- The buffers in the model are set to infinite capacity since researching buffer sizes was not the purpose of this research. Of course this can be an issue if the order arrival rate is increased significantly as this would lead to capacity issues.
- Personnel is not implemented in the simulation model. In the actual situation operators can work on multiple machines.
- Overtime can only be possible on 4 machines: printer T240, roll cutters, Book trimmer and purring machine. In practice this is no issue since these machines are the machines with the highest utilization. If however, the order portfolio would change significantly than this may be different.

- The workhours for the plant are set from 8:00 to 17:00 on workdays. In reality this is a bit more fluid. For example some operators start early and are replaced in the afternoon such that a machine can be utilized in shifts.

6.4 CONTRIBUTION TO PRACTICE

This research showed how to create a simulation model of a factory, how to create experiments and how to draw conclusions from the experiments. This simulation model can be adjusted when parameters such as demand change. Machines can be added or removed to reflect future situations. Such a simulation model can be helpful to predict effects of making changes to the setup of the production plant. This research also showed what data can retrieved from the print app. Each order that has been printed are available in the app as soon as printing has started. The following information can be deducted for each order: Order type, color, one-sided vs double-sided, amount of sheets, printing time, amount of failures and time of printing.

6.5 CONTRIBUTION TO SCIENCE

In this research various priority rules have been compared using simulation. These results can shed some light into the effectiveness of those priority rules. The full results are in Figure 38. These results confirm previous results. It was confirmed that the Earliest Due Date (EDD) rule minimizes the maximum lateness of all the jobs and that the Shortest Processing Time (SPT) rule minimizes the average amount of waiting jobs. It was also found that the maximum tardiness is significantly higher for the SPT rule and that the average tardiness is significantly higher for the LPT rule compared to the other priority rules. Both maximum and average are important measures for customer satisfaction, therefore these priority rules are not suitable in production environments. A last contribution is that priority rules that try to improve the EDD rule such as CR (Critical Ratio), S/RO (Slack per Remaining Operations) and S/RPT (Slack per Remaining Processing Time) do not perform significantly better than the EDD rule. As these rules are more complex to implement one could question the point of implementing such a priority rule.

6.6 FUTURE RESEARCH

The following points might be interesting for future research:

- Collecting data that would make the model more accurate, such as data about the pages per book and brochure and failure rates of machines.
- Develop new scheduling rules for the planning of the printers and evaluating them using the simulation model. These rules could optimize the planning such that orders with equal paper type are planned in succession as to reduce setup times.
- Use the simulation model to find the effects of changes in the product portfolio. For example it is known that there is capacity left to produce more packaging materials. Research could find out how much capacity us remaining before the production plant starts to see negative effects to KPIs.

7   LITERATURE

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8 APPENDICES

8.1 DEFINITIONS

Table 29. Definitions

Dutch	English	Description
Garenloos gebrocheerd	Adhesive binding	Inside work of book is glued together with the cover. Also called pur or glued.
Gehecht gebrocheerd	Saddle stitching	Inside work and cover are stitched together.
Genaaid gebrocheerd	Paperback	Inside work of book divided in multiple individual stitched sections and glued together with the cover.
Binnenwerk	Inside work	The pages inside a book or brochure. So the entire book except for the cover.

8.2 SIMULATION MODEL MANUAL

The simulation model models the factory. A screenshot of the model is depicted in **Figure 42**. This model shows the machines in the factory. The blue layer contains the printers, the yellow layer the finishing operations, the red layer the cutting operations and the orange layer the packaging operations.
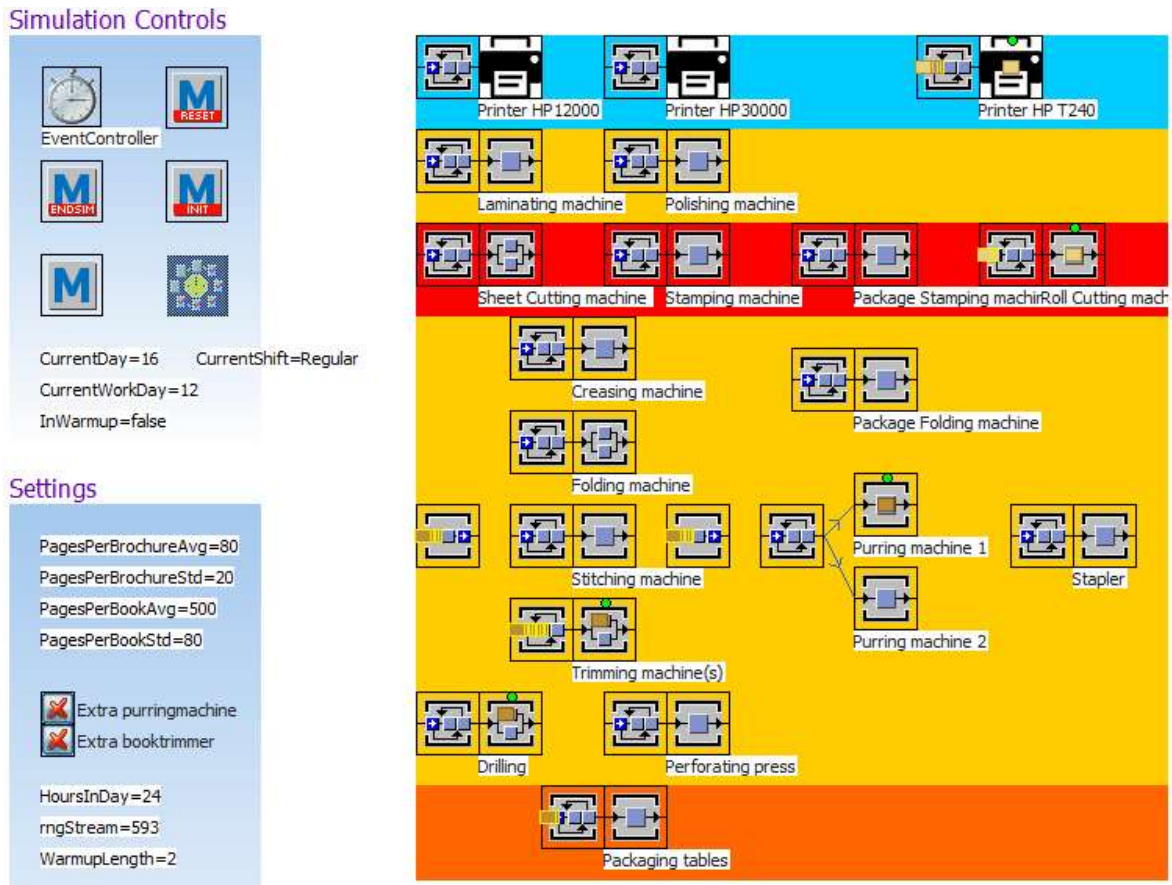

Figure 42. Simulation Model

The general idea behind the model is that orders are generated randomly and routed through the factory. Each machine has a buffer in front of it to store inventory. **Table 30** contains a legenda.

Table 30. Legenda simulation model

	Workstation with 1 machine.
	Workstation with 1 or 2 machines.
	Printer
	Buffer: Each workstation has a buffer or sorter in front of it to store work-in-process.
	Sorter: Buffer that allows sorting options.
	Source: Orders are generated by the source.

→|	Drain: Orders are removed by the source.
▨	Order: An order as it is moving through the factory. One order consists of multiple sheets. A yellow border indicates waiting.
▢	Inside Work: The inside work of books and brochures. A yellow border indicates waiting.

8.2.1 SETTINGS

The settings of the model can be changed in the Settings pane. The following settings can be changed:

- Pages per book/brochure (average and standard deviation): The amount of pages of a book and brochure follow a normal distribution. This variable influences the production times at the printing and cutting of the inside work.
- WarmupLength: This variable sets the warmup period in workdays.
- OvertimeTreshold: This number is the maximum amount of orders allowed in the buffers before overtime is triggered. A values of 0 means that overtime is run until the buffer is empty and a very high value means that there is no processing in overtime.
- Extra Purring machine: This toggle enables an extra purring machine.
- Extra Book trimmer: This toggle enables an extra trimming machine.
- Include warmup in statistics: If this toggle is enabled the warmup period is included in the statistics. This should be turned off for experiments.

It is not advised the make changes to the other parameters as this may lead to errors in statistics calculations. Experiments run with the experiment Manager do not use the settings defined in the interface but are defined in the Experiment Manager itself.

8.2.2 SIMULATION CONTROLS

For control of the simulation the Event Controller and Experiment Manager objects are relevant.

EVENT CONTROLLER

The Event Controller can be used to start and reset experiments. The green button starts experiments and the red button resets the experiment.

Figure 43. Event Controller

Under settings the end time of the simulation can be set. This is in a days:hours:minutes:seconds.miliseconds format. For example 100:0:0:0.0 sets the end of the simulation at 100 days. Some statistics (averages) are collected when the end of the simulation is triggered.
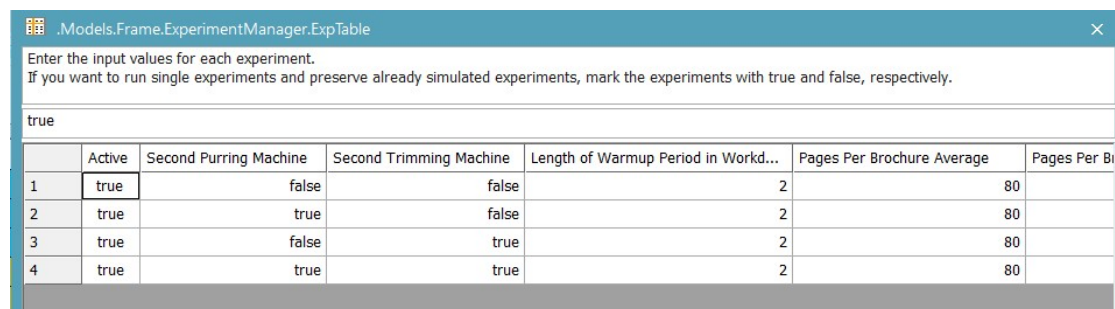
EXPERIMENT MANAGER

Figure 44. Experiment Manager

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The Experiment Manager is used to perform multiple simulations in one go. It is as an Event Controller with extra options. Open it by clicking the icon. The "observations per experiment" value in the Experiment Manager defines how often an experiment with the same settings will be repeated. Each repetition uses a different random number seed.

To configure the different experiments the "Define Experiments" option is available in the Experiment Manager. The Define Experiments button leads to the table shown in Figure 45. In this table there are 4 experiments defined. The column "Active" indicates if the experiment will be run or not. The others columns set the parameters of the simulation. For example the first experiment will not use a second purring machine whilst the second experiment will.

Figure 45. Define Experiments

The Experiments can be start and reset in the Experiment Manager using the "Start" and "Reset " buttons respectively.

8.3 SOURCE CODE

This section contains the source code for the Excel sheets. The source code for the simulation model is too large to put in the appendix.

8.3.1 CATEGORIZING ORDERS

This code binds data from three sources together in Excel:

- Data from the printers (PrintOS app)
- Data from completed orders (Webprint app)
- Table with ordercodes and their ordertype

The purpose of this data binding is to get statistics of the frequencies of order types.

```
Private Sub CommandButton1_Click()
    Dim printOSjobname As String
    Dim ordernumber As String
    Dim ordertype As String
    Dim testOrdernumber As Boolean
    Dim numOrdertypes As Integer
    Dim ordertypes() As String
    Dim testOrdertype As Boolean
    Dim numRows As Integer
    Dim i As Integer
    Dim j As Integer

    Application.ScreenUpdating = False

    numOrdertypes = Worksheets("Ordertypes").Cells(2, 5).Value
    ReDim ordertypes(numOrdertypes)
    For k = 1 To numOrdertypes
        ordertypes(k) = Worksheets("Ordertypes").Cells(k + 1, 1).Value
    Next k

    'Main Loop to fill ordernumbers and types'
    numRows = Range("C1", Range("C1").End(xlDown)).Rows.Count
    For i = 2 To numRows

        printOSjobname = Cells(i, 3).Value
        ordernumber = Left(printOSjobname, 6)
        ordertype = Mid(printOSjobname, 8, 2)

        'check if the first 6 numbers indicate an ordernumber'
        testOrdernumber = False
        If (IsNumeric(ordernumber)) Then
            testOrdernumber = True
        Else
            ordernumber = ""
        End If

        'check if the stuff in the middle indicates an order type. This is true
if it is in the list with orders'
        testOrdertype = False
        For j = 1 To numOrdertypes
            If (ordertypes(j) = ordertype) Then
                testOrdertype = True
            End If
        Next j

        'Check for other common types such as 'xcard and bierkaart. '
        If (Left(printOSjobname, 5) = "xcard") Then
            ordertype = "xcard"
            testOrdertype = True
        ElseIf (Left(printOSjobname, 9) = "Bierkaart") Then
            ordertype = "bierkaart"
            testOrdertype = True
        End If

        'set default order type as it could not be recognized'
        If (testOrdertype = False) Then
```

```
                ordertype = ""
            End If

            'Add to workbook. Extra check for correct column'
            If (Cells(1, 1).Value = "Ordernumber") Then
                Cells(i, 1).Value = ordernumber
            End If
            If (Cells(1, 2).Value = "Ordertype") Then
                Cells(i, 2).Value = ordertype
            End If
    Next i

    Application.ScreenUpdating = True

End Sub
```

8.4 DISTRIBUTION FITTING

Histograms of the data from table 3 are shown in Figure 46 and Figure 47 and Figure 50. From the histograms we can conclude that the data is skewed with a long tail. From Figure 50 we can conclude that for 3 out of 4 of the most frequent orders (Flyers, Business cards, Other) that their distribution follow a similar shape.

Common probability distributions with different parameters are shown in Figure 14, Figure 15 and Figure 16. The Normal distribution and the Poisson distribution do not seem to fit the histograms. The Normal distribution does not fit as it is symmetrical whilst the data is skewed. The Poisson distribution does not fit the data well because of the high probability of X=0. Order size is always greater than 0, except for errors. The Exponential distribution and the Gamma distribution however might fit the data. Therefore the exponential distribution is considered first as this is a special case of the Gamma distribution. The Exponential distribution roughly fits the data as can be seen from **Figure 47**. A Pearson Goodness-of-fit test is performed to test this hypothesis.
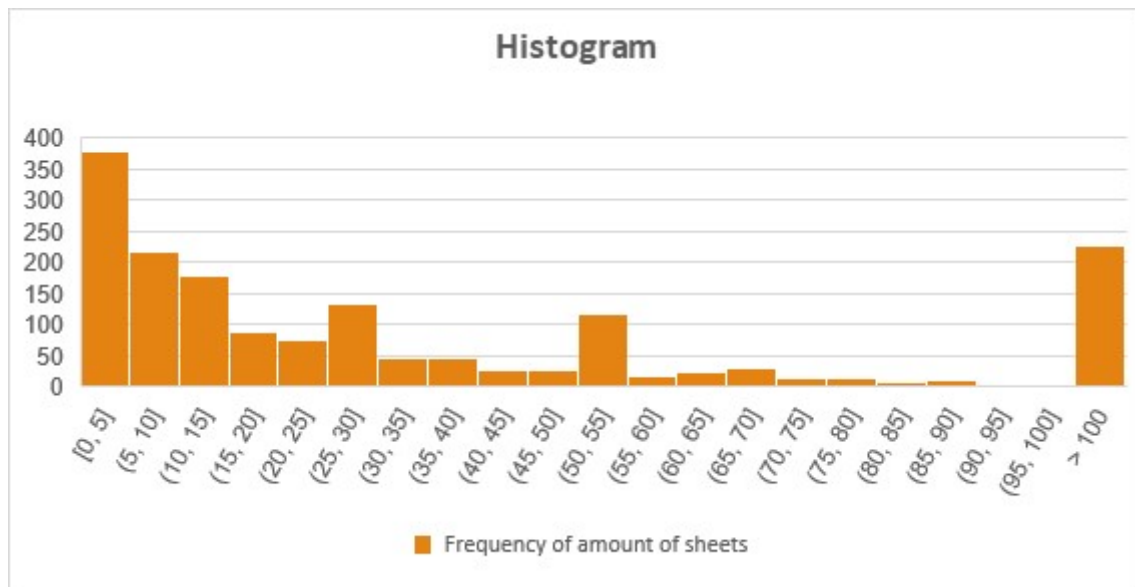

Figure 46. Histogram of sheets per order

Figure 47. Sheets per order vs Exponential distribution

8.4.1 CHI-SQUARE GOODNESS OF FIT TEST FOR EXPONENTIAL DISTRIBUTION

A Chi-Square test is used to test the hypothesis that the data fits the exponential distribution.

- There are 20 buckets with a size of 5 and limited to 100 copies since the Chi-Square test requires a sufficient size of the buckets.
- The last bucket contains all orders with more than 100 copies.
- There are 20 degrees of freedom (21 buckets – one parameter (β)).
- The hypothesis is rejected if the p-value is lower than 0,95.
- The parameter β is estimated with the mean of the sample data.

The value of the test statistic χ^2 is calculated with:

$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i}$$

In which n is the amount of buckets, O_i the observed amount of values in this bucket and E_i the amount of expected values based on the test statistic. The p-value of the test statistic is than found using the Chi-Square distribution in Excel using:

=CHISQ.DIST.RT(<TESTSTASISTICKVALUE>;<DEGREESOFFREEDOM>)

Which returns the corresponding probability from the Chi-Square distribution gives the value and the degrees of freedom. Results of the Chi-Square test are displayed in Table 31. Tests are performed for all orders and the four biggest order types. **Bold** p-values indicate statistical significance.

Table 31. Results of Chi-Square tests

Order type	Amount of orders (n)	Average of copies (β)	Critical value	Value of test stastic (χ^2)	P-value
All order types	1667	63,34853	10,851	11,72325	0,925272183

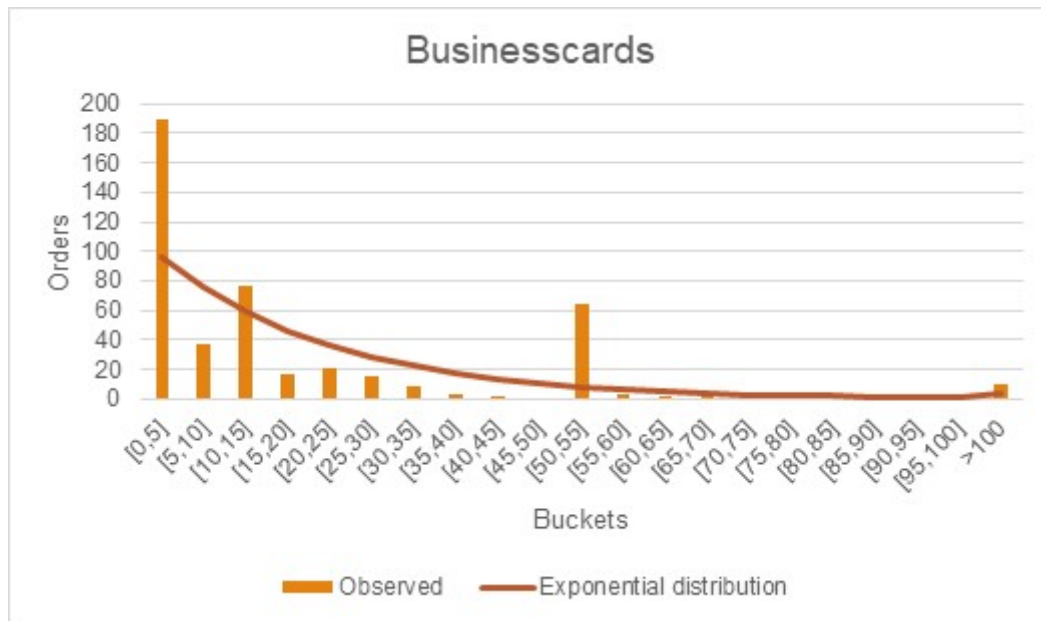|					
Businesscards	456	20,42324561	10,851	59,44098558	0,000008689
Flyers	400	40,7425	10,851	6,996553	**0,996696**
Other	219	62,26484	10,851	9,149659	**0,981108**
Folders	170	63,79	10,851	27,01697	0,134787

Figure 48. Histogram for Businesscards
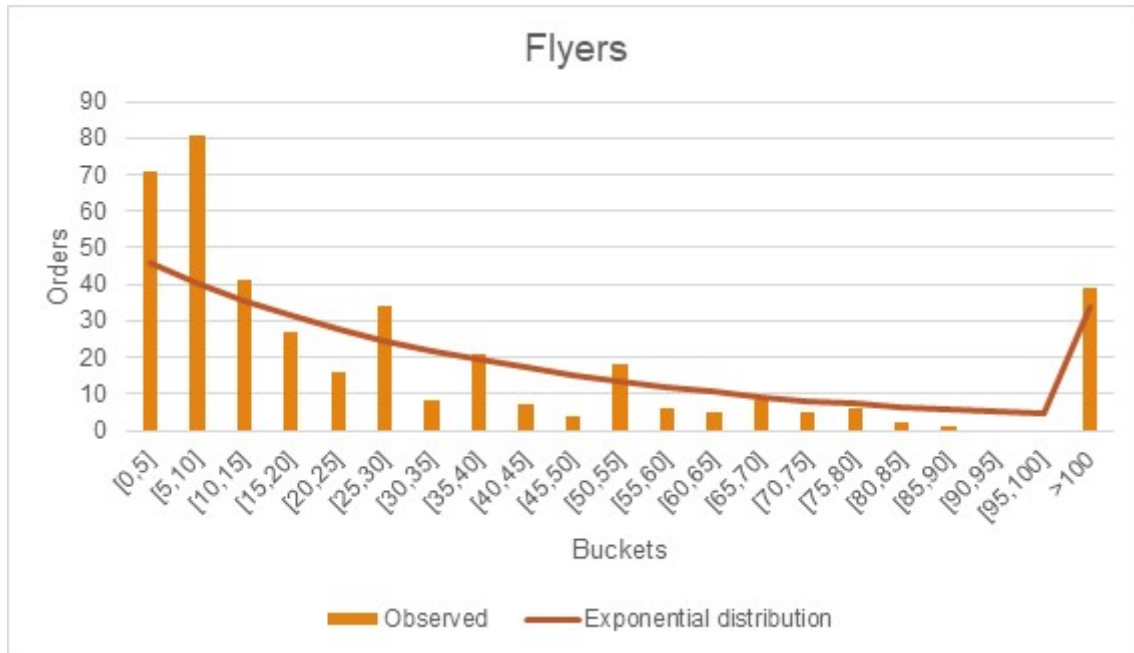
Figure 49. Histogram for Flyers

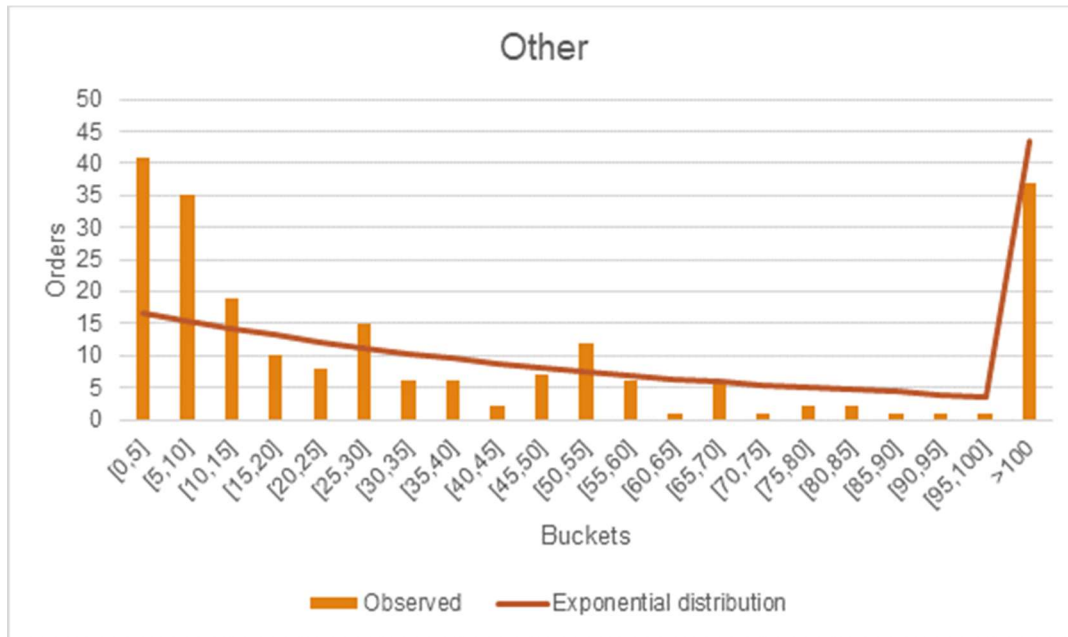
Figure 50. Histogram for Folders

Figure 51. Histogram for Other

8.5 VERIFICATION OF PRIORITY RULES

Section 4.5.5 contained information about how verification of priority rules is conducted. The SPT priority rule was verified in that section. This section contains the verification of the other priority rules: LPT, EDD, FCFS and LCFS. A subset of 20 orders is followed at the Book trimming station. These orders are all a certain point in time together in the buffer. Table 32 is created with an experiment using the LPT (Longest Processing Time first) rule. The orders are sorted by their processing time. The start time of the longest order is indeed before all other the other orders. Table 33 shows the verification of EDD (Earliest Due Date first) rule. **Table 34** shows the verification of FCFS (First Come First Served) rule. **Table 35** shows the verification of FCFS (First Come First Served) rule. In these last tables the arrival time at the buffer is compared with the start time of the processing.

Table 32: Verification of LPT

Order number	Due date	Arrival time at buffer	Start time processing	Processing time
44	11:17:0.0	7:8:9.9	7:17:19.19	1:38.38
677	15:17:0.0	7:8:17.17	7:20:23.23	1:18.18
734	15:17:0.0	7:8:24.24	7:21:41.41	1:11.11
796	15:17:0.0	4:16:46.46	7:22:52.52	1:8.8
312	12:17:0.0	7:8:31.31	8:8:1.1	1:2.2
281	12:17:0.0	4:8:23.23	8:13:25.25	0:57.57
592	14:17:0.0	4:12:4.4	8:20:11.11	0:57.57
516	14:17:0.0	4:9:45.45	8:21:8.8	0:51.51
539	14:17:0.0	7:8:35.35	8:22:42.42	0:41.41
394	13:17:0.0	7:8:39.39	9:12:47.47	0:39.39
271	12:17:0.0	7:8:41.41	9:19:17.17	0:26.26

93

175	11:17:0.0	7:8:44.44	9:19:43.43	0:24.24
79	11:17:0.0	7:8:46.46	9:20:31.31	0:22.22
663	14:17:0.0	7:8:48.48	9:20:53.53	0:20.20
488	13:17:0.0	7:8:50.50	9:21:34.34	0:18.18
317	12:17:0.0	7:8:52.52	9:22:11.11	0:16.16
739	15:17:0.0	7:8:53.53	9:23:11.11	0:12.12
632	14:17:0.0	7:8:54.54	9:23:31.31	0:7.7
255	12:17:0.0	7:8:54.54	9:23:46.46	0:7.7
689	15:17:0.0	7:8:55.55	9:23:39.39	0:7.7

Table 33: Verification of EDD

Order number	Due date	Arrival time at buffer	Start time processing	Processing time
6107	63:17:0.0	58:14:46.46	59:10:27.27	0:29.29
6091	63:17:0.0	58:14:35.35	59:10:57.57	0:14.14
6083	63:17:0.0	58:14:34.34	59:11:14.14	0:6.6
6075	63:17:0.0	58:14:33.33	59:11:20.20	0:47.47
6364	64:17:0.0	59:9:10.10	59:12:7.7	0:2.2
6376	64:17:0.0	59:9:10.10	59:12:10.10	0:26.26
6333	64:17:0.0	59:9:7.7	59:12:36.36	0:56.56
6286	64:17:0.0	59:8:48.48	59:13:33.33	1:3.3
6239	64:17:0.0	58:16:59.59	59:14:37.37	0:51.51
6345	64:17:0.0	58:15:6.6	59:15:28.28	0:6.6
6479	67:17:0.0	59:10:2.2	59:18:53.53	0:2.2
6473	67:17:0.0	59:10:1.1	59:18:56.56	1:30.30
6475	67:17:0.0	59:9:51.51	59:20:26.26	0:0.0
6466	67:17:0.0	59:9:26.26	59:20:27.27	0:23.23
6441	67:17:0.0	59:9:20.20	59:20:50.50	0:33.33
6644	68:17:0.0	59:9:2.2	59:22:57.57	2:6.6
6830	69:17:0.0	59:9:35.35	60:12:9.9	0:0.0
6329	74:17:0.0	59:8:56.56	60:12:11.11	0:25.25
6293	74:17:0.0	59:8:27.27	60:21:8.8	3:17.17
6438	77:17:0.0	59:9:21.21	63:22:39.39	0:22.22

Table 34: Verification of FCFS

Order number	Due date	Arrival time at buffer	Start time processing	Processing time
1125	30:17:0.0	16:13:19.19	17:10:47.47	6:56.56
1147	30:17:0.0	16:13:30.30	17:17:43.43	0:10.10
1774	15:17:0.0	16:13:32.32	17:17:53.53	0:1.1
1354	21:17:0.0	16:15:48.48	17:17:55.55	0:17.17
1357	21:17:0.0	16:16:4.4	17:18:12.12	0:24.24
1364	21:17:0.0	16:16:10.10	17:18:37.37	0:20.20
1434	22:17:0.0	16:16:40.40	17:18:57.57	0:22.22

1207	30:17:0.0	16:18:55.55	17:19:20.20	4:53.53
1230	30:17:0.0	16:20:17.17	18:8:13.13	1:14.14
1904	16:17:0.0	16:20:19.19	18:9:28.28	0:1.1
1911	16:17:0.0	16:20:19.19	18:9:28.28	0:0.0
1255	31:17:0.0	16:23:3.3	18:9:30.30	2:29.29
1279	31:17:0.0	16:23:55.55	18:11:59.59	0:47.47
1442	22:17:0.0	17:8:1.1	18:12:46.46	0:11.11
1444	22:17:0.0	17:8:1.1	18:12:57.57	0:4.4
1490	22:17:0.0	17:8:11.11	18:13:2.2	1:37.37
1509	22:17:0.0	17:8:12.12	18:14:40.40	0:15.15
1533	22:17:0.0	17:8:18.18	18:14:55.55	0:55.55
1537	22:17:0.0	17:8:23.23	18:15:51.51	0:45.45
1302	31:17:0.0	17:8:27.27	18:16:36.36	0:29.29

Table 35: Verification of LCFS

Order number	Due date	Arrival time at buffer	Start time processing	Processing time
1471	32:17:0.0	14:11:31.31	14:14:54.54	2:13.13
1272	20:17:0.0	14:11:18.18	14:20:5.5	0:25.25
1256	20:17:0.0	14:11:11.11	14:20:31.31	0:16.16
1206	20:17:0.0	14:11:4.4	14:20:47.47	0:6.6
1201	20:17:0.0	14:11:3.3	14:20:53.53	0:47.47
1647	25:17:0.0	14:10:34.34	14:21:40.40	0:38.38
1078	19:17:0.0	14:8:58.58	14:22:19.19	0:41.41
1365	31:17:0.0	14:8:27.27	14:23:0.0	2:36.36
1480	22:17:0.0	14:8:14.14	15:11:6.6	0:46.46
1520	22:17:0.0	14:8:9.9	15:19:50.50	0:4.4
1504	22:17:0.0	14:8:9.9	15:19:54.54	0:22.22
1049	19:17:0.0	14:8:6.6	16:8:22.22	1:6.6
1245	20:17:0.0	10:9:56.56	16:10:27.27	0:11.11
1172	20:17:0.0	9:12:26.26	16:12:4.4	0:25.25
1051	9:17:0.0	8:16:19.19	16:12:30.30	0:0.0
786	25:17:0.0	8:16:19.19	16:12:30.30	0:0.0
820	25:17:0.0	8:16:18.18	16:12:30.30	0:50.50
787	25:17:0.0	8:15:22.22	16:13:21.21	1:26.26
954	18:17:0.0	8:10:32.32	16:14:48.48	0:16.16
724	15:17:0.0	8:9:7.7	16:15:5.5	0:13.13