AUTOMATING AND IMPROVING THE PRINTING PLANNING PROCESS

Jongbloed BV

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Management Summary

Jongbloed is a company that is known for its ability to manufacture books on very thin paper. Nowadays, it consists of two business units namely a publishing and a book manufacturing unit. The book manufacturing business unit uses an almost manual production planning which is labour-intensive. Jongbloed would like to purchase a production planning software package, such that the production planning can be automated and improved. However, there is a wide variety of production planning rules that can be used in various production planning packages. Therefore, we were asked to analyse these rules and select the best performing rule given several performance indicators.

After studying the current situation, we formulated the following main research question:

"*What production planning rules should be used to automate and improve Jongbloed's production planning?"*

First, we analyse the current situation. We want to know the magnitude of improvement of a new production planning software package, and we therefore need to quantitatively describe the current situation. We compute that in approximately 62 percent of the leadtime, a project is waiting for either materials or the next process. Obviously, zero waiting time is impossible because machines fail and need maintenance, suppliers do not deliver raw materials and other projects also need to be processed. All these reasons cause waiting time. Still, the improvement potential is quite large.

Literature provides us with several methods to automate and improve the production planning. Roughly speaking, there are two methods of 'simple' production planning namely global and local. A local production planning is a production planning per machine, whereas a global production planning is an overall planning for the complete factory. However, not a single method outperforms all the others. Therefore, we build a computer model that has the same characteristics as the production process of Jongbloed. It allows us to analyse different production planning rules, without actually implementing them.

After running the computer model with the different types of production planning, we conclude that local methods outperform global production planning approaches. Global production planning methods do not automatically reschedule, whereas local production planning are able to do so.

There is one major drawback of local production planning. As the planning is per machine and only includes projects that are present in the queue (and thus not future projects), its horizon is very short. Therefore, it is impossible to react to future spikes in the number of waiting projects and plan preventive maintenance. So, we would like to implement the best performing global production planning rule namely global forward planning. This rule makes a complete planning for the factory and adds the projects to all the necessary processes, at the first possible time slot.

If we compare the global forward planning method to the current situation, given the four performance indicators Work In Progress (WIP), lead time, tardiness, and percentage projects tardy, it gives an overall improvement of 22 percent. Especially the WIP performance increases, the performance on the other three performance indicators remains stable. Therefore, we would like to advise the global forward planning method to improve and automate Jongbloed's production planning.

Preface

This report is the result of a graduation project at Jongbloed, located at Heerenveen. I started approximately six months ago, with virtually no knowledge of the book printing and binding process. During this internship, I learned several terms and processes that are specific for the printing- and binding industry. I am very grateful for all the time that the employees at Jongbloed spent to explain them to me. Especially Jan Egas, my supervisor at Jongbloed, has been very helpful by reviewing the content of my research and enabling me to get the research to a higher level. I would also like to thank Sipke Boschma, head of the pre-production department and responsible for the production planning, for explaining the current practice and reviewing my computer model.

Besides the support at Jongbloed, I would like to thank Peter Schuur and Martijn Mes. Peter Schuur has been very helpful by reviewing my research and providing valuable suggestions for the next step in my research. Martijn Mes reviewed my report and helped me to fix errors in the computer model. It would have still been a buggy model without his help.

Finally, I thank all my friends for their endless support.

Arjen Colijn, September 2013

Glossary

- **Bookblock** – A set of section, which contains the full content of the book.
- **Book block manufacturing department** – In this department, the different sections are collected and sewn.
- **Bindery department** – Department where the bookblock is attached to the cover.
- **Cover department** – Department where the covers are manufactured, which are afterwards used in the bindery department.
- **Gauze** – Gauze is used to strengthen the spine of the book.
- **Printing department** – The sections are printed in the printing department, one-by-one.
- **Ribbon** – One ‘track’ of paper in the printing press.
- **Section** – A section is collection of several pages, the size depends on the book.

Contents

1 Introduction

This report describes a master research project to complete the study of Industrial Engineering and Management at the University of Twente, performed at Jongbloed BV which is located in Heerenveen. We first give a description of the company in Section 1.1, continue with an introduction to the research in Section 1.2, discuss the research questions in Section 1.3, then describe the used research method in Section 1.4 and end with a conclusion in Section 1.5.

1.1 Company description

Jongbloed was founded in 1862 as a printing house in Leeuwarden. Nowadays, it is located in Heerenveen, employs about 100 employees and is transformed to a publishing group which focuses on the publishing of Christian books and magazines. Over the last two decades, they took over some publishers such as 'J.J. Groen en Zoon' and Medema. Also, they introduced several new brands such as Columbus, which focuses on books for children between the age of four and 17.

Nowadays, Jongbloed consists of two business units, namely the publishing business unit and the printing house. This research focuses solely on the printing house unit which make books. The publishing unit does marketing for bibles, bible software and serious games for educational purposes, provides educational material for children, and publishes both Christian magazines and books in the Netherlands.

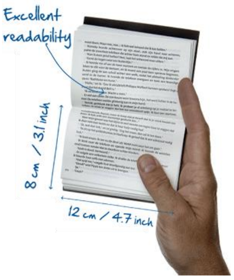

Figure 1: Dwarsligger

Jongbloed is specialised in printing on thin paper, which only a few companies in the world are able to do. Over ninety percent of the total production is exported, even to China. Bible sales are nowadays declining, and therefore Jongbloed introduced a new product. It is called the 'Dwarsligger', which is a book of eight by twelve centimetres where the text is printed turned ninety degrees compared to a 'normal' book.

1.2 Research topic

The broad topic of this report is the planning of the different orders at the printing house. Making a book consists of several steps, such as printing, sewing of the book blocks, making the book cover and finally combining the book cover and the book block. These are some of the activities that need to be planned, in order to deliver to the customer on time. However, reality is far more complex than these 'simple' activities suggest. Jongbloed's customers have a large amount of options to customize books. Examples of customization are the type of cover, which is either hardcover or softcover, the material of the cover, such as leather or paper, and the cover of a book, which can be gold plated. All the different varieties affect the complexity of the production planning. The different types of books have different lead times, different operations and different resources such as machines, materials and machine operators. What makes production even more complicating, is that one project often contains various editions. For example, a project can contain an inexpensive paperback and also a luxurious edition, with a leather cover. Often, all different editions within one project are shipped at once. This makes planning even more complicating, as different editions have different lead times.
Nowadays, this planning is made by hand using Excel. The core of this research is to find out whether there are algorithms to facilitate the production planning.

1.3 Research questions

We have just given a small introduction to the problem. We now define the main research question and continue with several sub research questions, which are more manageable compared to the main research question. The answers to the sub research questions combined answer the main research question.

Given the problem formulation in the previous chapter, the following main research question can be stated:

"*What production planning rules should be used to automate and improve Jongbloed's production planning?*"

As discussed earlier, this main research is still quite 'vague'. Therefore, we defined several sub research questions:

1. How does Jongbloed manufacture books?
2. How is Jongbloed's current production planning performing?
    a. What is the average waiting time, as a percentage of the average lead time?
    b. What is the estimated distribution of the four categories, which are material availability, machine issues, employee capacity and planning, which cause the waiting time?
    c. What failures occur at the two printing presses?
    d. What is the workload per week per department?
3. What production planning rules are available in literature?
4. How do the different production planning rules perform on Jongbloed's production?
5. How can the best performing production planning rule be implemented?
6. How can the best performing production planning rule be evaluated?

As the main research question suggests, we would like to recommend a set of production planning rules that can be used to automate Jongbloed's production planning. We now briefly discuss our approach to answer each sub research question.

1. For the first sub research question, we work at each department for some time. This gives us the opportunity to interview a lot of different employees in a casual setting.
2. To answer this question, we gather all the required data and perform a data analysis.
3. We do a structured literature research to answer this question.
4. There are different ways to analyse the performance of production planning rules. After evaluating the possible manners to do so, we describe a model to assess the performance of the production planning rules.
5. After evaluating the different production planning rules, we discuss the implementation of the best performing rule. It contains some guidance how to do the implementation.
6. In the last sub research question, we discuss some guidelines to evaluate the performance of the chosen production planning method.

Ultimately, we would like to answer the main research question. This is a set of rules that can be used to automate Jongbloed's production planning.

1.4 Research method

In this section, we describe the method that we use in this research. We choose the Managerial Problem-Solving Method (MPSM) and the accompanying methodological checklist (Heerkens, 1998). The MPSM is a broad framework that supports doing research and this generality is the great strength of the framework. It can be applied to a large variety of issues that a company may face. The Managerial Problem-Solving Method comes with another supplementary framework called the methodological checklist. The MPSM is the main framework. The methodological checklist is used when a problem needs more research. The checklist is often used to find information that is currently not available in the organization. A graphical representation of the research frameworks and their relation is shown in Figure 2.

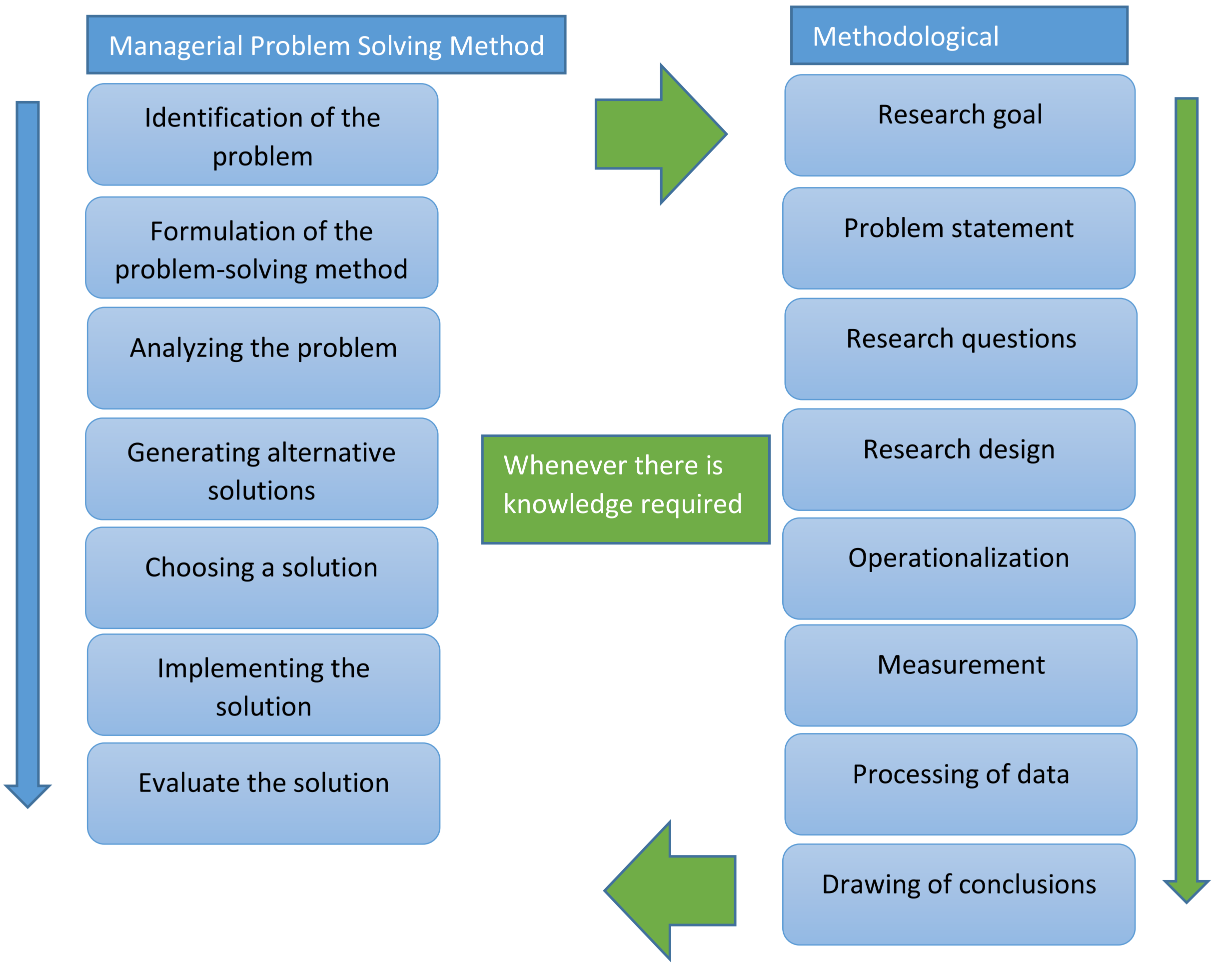

Figure 2: Graphical representation of the research frameworks and their relation

Whenever there is knowledge required, such as 'What is the average lead time of book X', we enter the methodological checklist cycle. Starting the methodological checklist is possible in any step of the MPSM, except for the 'Implementing the solution' phase. After executing the methodological checklist, we return back to the same phase as where we left. With the new knowledge that we gained from executing the methodological checklist, we can continue with the MPSM. A detailed description of all the topics of both the MPSM and the methodological checklist can be found in Appendix A.

1.5 Conclusions

In this chapter, four subjects have been discussed namely the company description, the research topic, the research questions and the used research method. Especially the research topic, the research questions, and the research methods are important for this research. The research topic is the planning of the production. Using the research method, a combination of the MPSM and the methodological checklist, enables us to systematically analyse the current situation and provide recommendations to improve the current situation.

2 Identification of the problem

In this chapter, we give an overview of the production process and its complexity. After describing the current situation in section 2.1, we visualize the problems in the problem diagram in section 2.2, continue with the desired situation in section 2.3 and then do a comparison between the current and the desired situation in section 2.4.

2.1 Current situation

We first give a broad introduction of the production process; how do they actually make a book. This description is continued with an in-depth analysis of each department, in a chronological order from the sales order to the end product. Finally, we visualize all problems in one flowchart to provide an overview.

2.1.1 Production of a book

The making of a book starts several weeks before the production. First, the customer comes to Jongbloed (or the other way around) to negotiate about a new (or reprint) book. After negotiation, the order is confirmed. We describe a more-or-less ‘standard’ book.

Next, the pre-production department starts to formulate the work instructions and orders the necessary materials (which highly depends on the chosen book, as the degree of customization is high). Furthermore, the pre-production department is responsible for the planning. The exact routing of the book through the factory highly depends on the degree of customization.

The next department is where the actual production of the book starts, it is called the Prepress department. They check the files, which contain the content of the book, and correct them if necessary. The customer then gets an example book, either digitally or by regular mail. If the result is satisfactory, the file is converted and sent to a machine that transforms UV-sensitive plates into plates that can be used in the printing house department. These plates allows Jongbloed to transform plain paper into printed paper.

The subsequent department is the printing house. Plates that were made at the ‘previous’ department are loaded into the machine. The machines then prints the text that is on the plates on paper, cuts the paper to several ribbons (Dutch: baan), gathers the ribbons, cuts the paper, folds the paper and then all the sections (Dutch: katernen) are collected and stored in a waiting area or transported to the next department. A section contains one, two or three copies of a book, depending on the size of the book. Whether the sections are stored or immediately transported to the next department depends on whether the printed sections are directly required in the next department or not. Often, the paper needs to rest for a couple of days before the next production step can start.

The succeeding department is the book block department. It actually consists of two successive production steps, namely gathering and sewing. First, all the different sections and flyleaves (Dutch: schutbladen) are collected and combined in a book block, thereafter the book blocks are sewed. While the sections are gathered and sewed, the cover department starts producing the cover. The specific production steps depend on the type of cover.

If all activities are done at both the cover department and the book block department, it is time for the final production step. Here, the book block and the cover are brought together. This is done in the bindery department. First, the book blocks are glued and gauze is applied. The book bocks then dry and then the book blocks are sawn into pieces, where each piece is the content of one book. Books are transported via a transportation belt to the next station, where on the three sides (each side excluding the spine of the book) a small piece is cut off. Now, it is possible to browse through the content of the book.

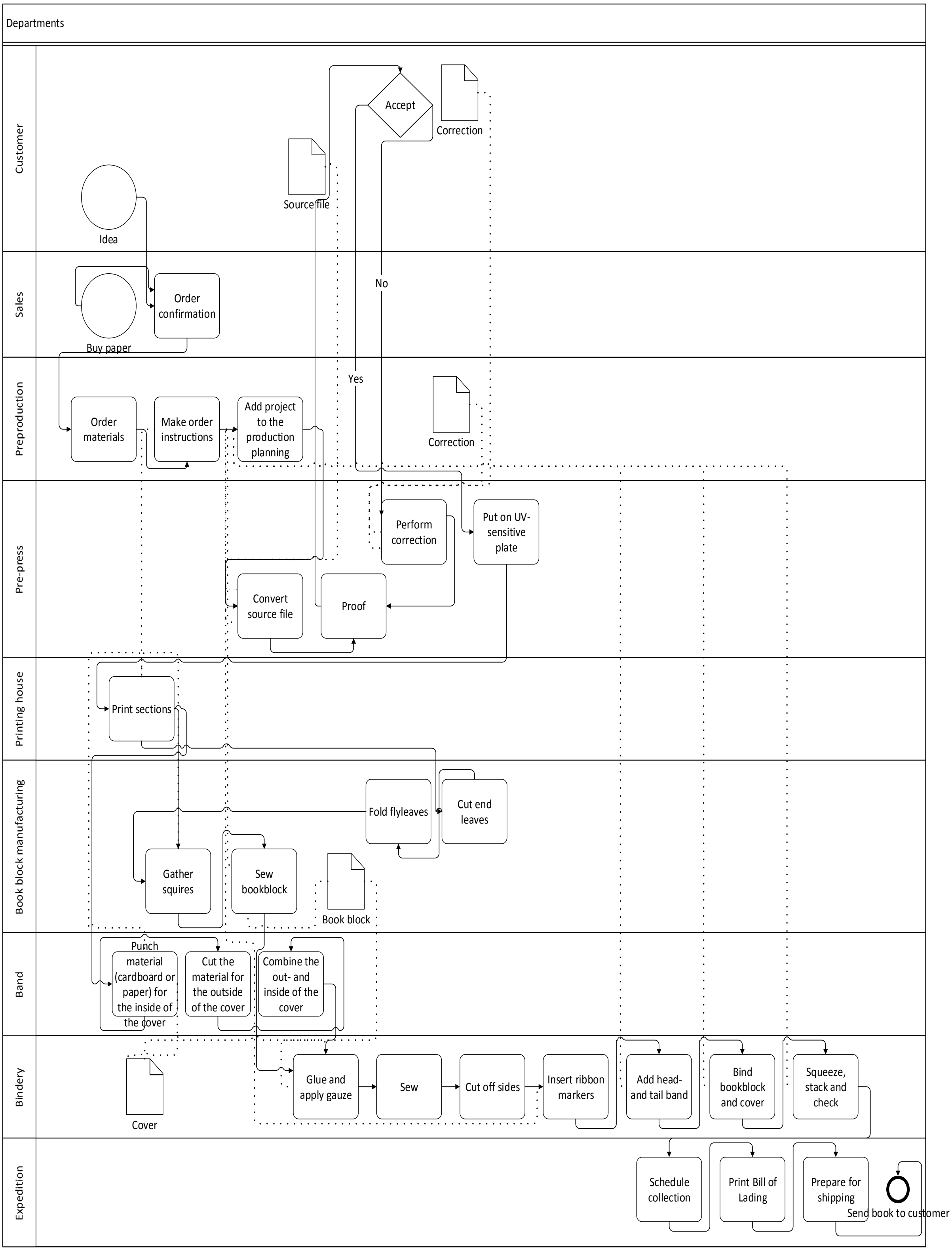

Figure 3: Flowchart production of a book

If it is a more luxurious book, it is taken of the production line and the edges of the book can be gold plated. Besides gold plating on the edges of the book, corners can also be rounded and a layer of paint can be applied on the three sides on the book. More luxurious books are now processed by hand.

The next station is the ribbon marker machine, which inserts the required number of ribbons into the book. Thereafter, a layer of glue is applied to the spine of the book. A small sucker (vacuum cleaner) than grasps the ribbon markers and fixes them on the spine of the book. Next, the head- and tail band is applied. In the next step, the book block (which now has gauze, is sawn, is cut, has ribbon markers, and has a head- and tail band) is combined with the cover. The last four steps include applying pressure on the book, stacking the books, visually inspecting the books and stacking it on a pallet. All these different production steps are summarized in Figure 3.

2.1.2 Challenges of the departments

In this section, an in-depth description per department is given. We skip the sales department because it is not relevant for our problem. Still, they are affected by the production planning. It determines the lead time of the products, which sales needs to pass on to their customers. In each of the departments below, we have spent one day talking, observing and helping to get to know the process. Per department, we describe their processes from three different points of view namely the current situation, information flows and how the planning supports the processes per department. These different views enable us to give a proper description of the current situation.

2.1.2.1 Pre-production department

The pre-production department is the second department in line, right after the sales department. They make the work instructions for all the departments, order the necessary materials and make the production planning. We first discuss the current situation, continue with the information flows and finish with the role of the production planning.

Current situation

The pre-production department is an important department. The degree of customization is high, and therefore the materials often need to be ordered specifically for an order. After ordering the required materials and making the work instructions, all the production steps need to be added to the already existing production planning. Doing so is a responsible job, as the results of forgetting to order material or not adding a production step to the production planning can be devastating.

Information

There are all different sorts of information flows. Order confirmations do not always contain all specifications, so communication is required in order to ‘fix’ this. Also, there is quite some communication between the pre-production department and the actual production department. The subject often concerns material that is not available or work instructions that are not completely clear.

Role of the production planning

The pre-production department defines the production planning. Currently, they try to minimize the total setup time and make the production planning, which takes the machines capacity into account. This is done in Excel. Twice a week all those who are involved have a planning meeting, where the sequence of the orders on all machines is discussed. The sequence is often changed, because either the raw materials are not present or the previous processes have not been finished yet. A lot of effort is therefore put into the production planning. Also, because the production planning is changed frequently the production planning is perceived as a wish list instead of a planning.

2.1.2.2 Pre-press

In this section, we describe the current situation, the information flow and the role of the production planning for the pre-press department.

Current Situation

The pre-press department is where they make the required plates for the printing house department. Their responsibilities concern the correction of the files that the customer sends, convert the file to a local format and finally a file for the machine, uploading a digital version of the book-proof to the customer or sending it by mail, receiving a confirmation from the customer that the file or printed book looks ok and then sending the digital file to the machine that makes the plates for the printing house.

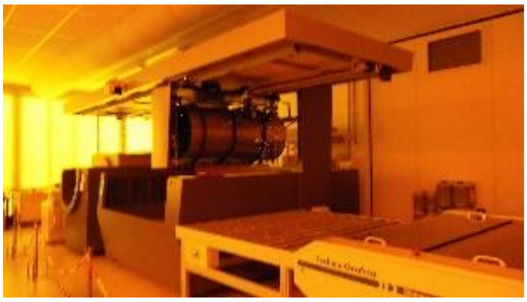

Figure 4: CTP Machine

Information

The information that flows in and out of the pre-press department is not yet ideal. Confirmation that the uploaded file or printed proof-book is okay, often first arrives at the pre-production or sales department, before being forwarded to the pre-press department. This is not directly related to this report, however this disturbance surely does affect the processing time at the pre-press department. If a confirmation mail gets stuck, it obviously takes more time to process a new order. Furthermore, the communication is not always clear. Even in the production planning, the name of the project is sometimes stated wrong. Not each employee has the same term for the exact same book, this is also quite confusing. Additionally, corrections (from either customers or Jongbloed itself) are only applied to the local copy of the file. The source file is unchanged, therefore in case of a reprint, the corrections are not included. Moreover, orders are not always complete. All necessary information of an order is occasionally missing and therefore requires searching for the correct information.

Role of the production planning

The pre-press department has its own section in the production planning. However, the planning for the pre-press department does not show the complete planning. Sometimes, the production planning shows old data and sometimes it only displays a part of the production planning. Therefore, the pre-press department does not work with their own part of the production planning anymore. They decided to let the planning of the printing house also be their planning. In the current situation, the pre-press department needs the following resources in order to manufacture aluminium sheets:

- Files from the customer.
- Order instruction, which contains information such as the name of the customer, the number of colours and pages and other technical printing information.
- A confirmation of the customer that the printed proof-book or the digital file is correct.
- UV-sensitive press plates.
- Chemicals, to develop the plates and also gom, which is a thin protection layer on the plates.

The last two resources might be outside of the scope of this research, but have been added for the sake of completeness.

2.1.2.3 Printing house

The printing house department is the department which uses the sheets that are made by the previous department, the pre-press department. First, we describe the current situation, continue with the information that is currently used and finish with the role of the production planning.

Current situation

The printing house can be seen as the bottleneck of the factory. The overall equipment effectiveness (OEE) consists of three factors, namely availability, performance and quality (Pintelon & Muchiri, 2006). The OEE is approximately forty percent, slightly varying over the two machines. There is a difference between the two machines in terms of specifications. The younger of the two, called the Timson 3, has an exchangeable cylinder and folding machine. The other one, called the Timson 2, has a fixed cylinder and folding machine. Especially the setup-times, changing equipment and failures are responsible for a large part of the non-productivity. After the sections are processed, they are collected and strapped. Depending whether the project is necessary in the next department, the project is either transported to the next department or stored in a storage area.

Figure 5: Printing press

Information

There is only one leading source of information, which is the production planning. There is not really any other source of information, which is important for this study.

Role of the production planning

The printing house department is the bottleneck of the factory, and therefore they follow the production planning quite strictly. This planning is leading for the printing house department.

2.1.2.4 Book Block Manufacturing Department

The book block manufacturing department consists of two processes, namely the gathering of sections and the sewing of the book blocks. First, we describe the current situation, then the information that is present and the role of the production planning.

Current Situation

As discussed earlier, the book block manufacturing department consists of two processes. Input for the book block manufacturing department are sections and flyleaves. Sections are produced by the printing house, flyleaves are supplied by a supplier. They are first cut into the correct size and then folded (and glued) on a section.
First, the different sections and flyleaves (the combination depends on the book) are loaded onto the stations from one to twenty. The maximum number of stations that can be gathered from simultaneously is twenty. If there are more than different twenty sections, the book block is gathered in more than one step. The machine collects one of each section using a transportation system. At the end of the machine, a complete book block arises. The book

Figure 6: gathering machine

Figure 7: Sewing machine

blocks are stacked onto pallets and stored in a waiting area. The second step of this department, namely the sewing of the book blocks is the next step in producing a book. A pallet with book blocks is collected from the storage area and fed into the machine. The machine then sews the book block. The final step at this department is firmly squeezing the book blocks. Again, the sewed book blocks are stacked onto pallets. They are stored in yet another waiting area, until they are required by the next department.

Information

Each pallet of book blocks is accompanied by a paper that states the project number, project name and other useful information. This is used to identify projects. Again, the production planning is another source of information.

Role of the production planning

The production planning is not always followed, for example, when the gathering machine is not yet finished on a certain project. The sewing machines that normally would continue with this project than continues with another project. If they would not do so, they would have to wait. Therefore, the sewing machines highly depend on the gathering machine. If the gathering machine is not finished, because the flyleaves are not yet ready or they simply did not gather the sections yet, the sewing machines starts with a different project. This example illustrates the highly dependent relation between the gathering machine and the sewing machines.

2.1.2.5 Cover department

Figure 8: Machine for adding embossing

The cover, combined with the book block, basically makes a book. First, we describe the current situation, continue with the information and finish with the role of the production planning.

Current situation

Not all covers are produced at Jongbloed. Covers that are cheaper to import, such as softcovers, are outsourced to China. Sometimes the finishing, such as gold embossing, is done inhouse. Generally, hardcovers are produced inhouse. The hardcovers start with producing the inside of the cover. The 'body' is punched out of a sheet of cardboard. Next, the outside of the cover is cut into the right dimension and the final step is to glue the inside to the outside of the cover, thus combining the two semi-finished products.

Figure 9: Machine that produces hard covers

Information

As described before, the production planning is the main source of information. Besides this paper flow of information, there is a lot of communication between the pre-production department and the cover department about for example order specifications and missing material.

Role of the production planning

The band department is comparable to the luxury department, in terms of dependence on material (both raw and semi-finished). If the correct raw material in the right quantity is not present, they simply cannot start producing.

2.1.2.6 Luxury department

Figure 10: Machine for rounding spines

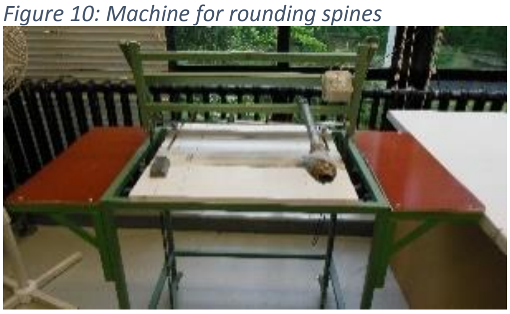

Figure 11: Machine for rounding covers

Jongbloed offers a lot of customization to its customers. Some of them are more luxurious, these are processed by the luxury department. First we describe the current situation, continue with the information section and end with the role of the production planning.

Current situation

There is a lot of variation in the luxurious products that Jongbloed offers to its customers. These products are often labour intensive. Often, books start as similar products but the subsequent production steps differ. An example is an expensive cover with leather, which are frequently combined with other more expensive production processes such as adding a thumb index or a zipper.

Information

The luxury department is placed almost at the end of the production process. Therefore, this department is highly relying on previous activities and raw materials. Thus, the production planning is important source of information. Besides the production planning, another source of information is communication about for example the delivery date of raw material and so on.

Role of the production planning

The luxury department is highly dependent on the materials and the previous activities. Consequently, the production planning cannot always keep up with the actual situation. Raw material is not available or the previous activities have not yet been finished. As a result, the short term production planning is changing quite often.

2.1.2.7 Bindery department

Figure 12: Machine that cuts off three sides

One of the last steps to produce a book is binding the book block and the cover. First, the gauze is attached to the book, the book is then sawed, the three sides (all except the spine) are cut off, the ribbon markers are attached and glued to the spine of the book, the head- and tail band is applied, the book block and the cover are combined and finally the book is squeezed, stacked and visually inspected. In essence, this is an overview what the bindery department does. First, we discuss the current situation, continue with the information flow and finish with the role of the production planning.

Current situation

Figure 13: Machine that gilds sides

The bindery department features two binding lines. Both contain a set of production steps, such as cutting or adding gauze. These steps can be used separately or sequentially, which gives Jongbloed a high flexibility to mix-and-match the different production orders on to the binding lines. However, this also gives a lot of options to plan the production orders onto the two binding lines.

Information

As for all the other departments, the bindery department is highly relying on the production planning. Again, communication is also an important source of information.

Role of the production planning

The bindery department requires a lot of materials, such as ribbon markers, head- and tail bands, cover and book blocks. Therefore, missing material can have a large impact on the production schedule of this department. 'Rush' orders can have the same effect. The binding lines than need to be setup twice, one time for the rush order and another time to pick up the previous job. So, as for all the other departments the production planning is also vital for the bindery department.

2.1.2.8 Expedition

The expedition department is necessary at least one time in the production of a book, namely when the shipment is being prepared (wrap the books in plastic, print a bill of lading and schedule a collection for the shipment). Besides sending a shipment to the final customer, it is also possible that an outsourcer needs to perform a certain activity. The expedition department than also ships the batch to the outsourcer and after the activity has been performed they receive the shipment again. We first discuss the current situation, continue with the information flows and finish with the role of the production planning.

Current situation

The expedition department for the graphic business unit is only a few months old. This department is not only responsible for receiving and sending shipments, but is also accountable for storing and retrieving pallets in a storage facility and transporting batches between departments.

Information

An important source of information is, as for most of the departments, communication and the production planning.

Role of the production planning

The production planning is basically an importance ranking for all shipments, which are ordered per week. They are however missing a shipping address, which would be convenient for expedition.

2.2 Visualization problems

We just described a lot of different challenges. They are linked together using a causal (cause-result) relationship. This is shown in Figure 14.

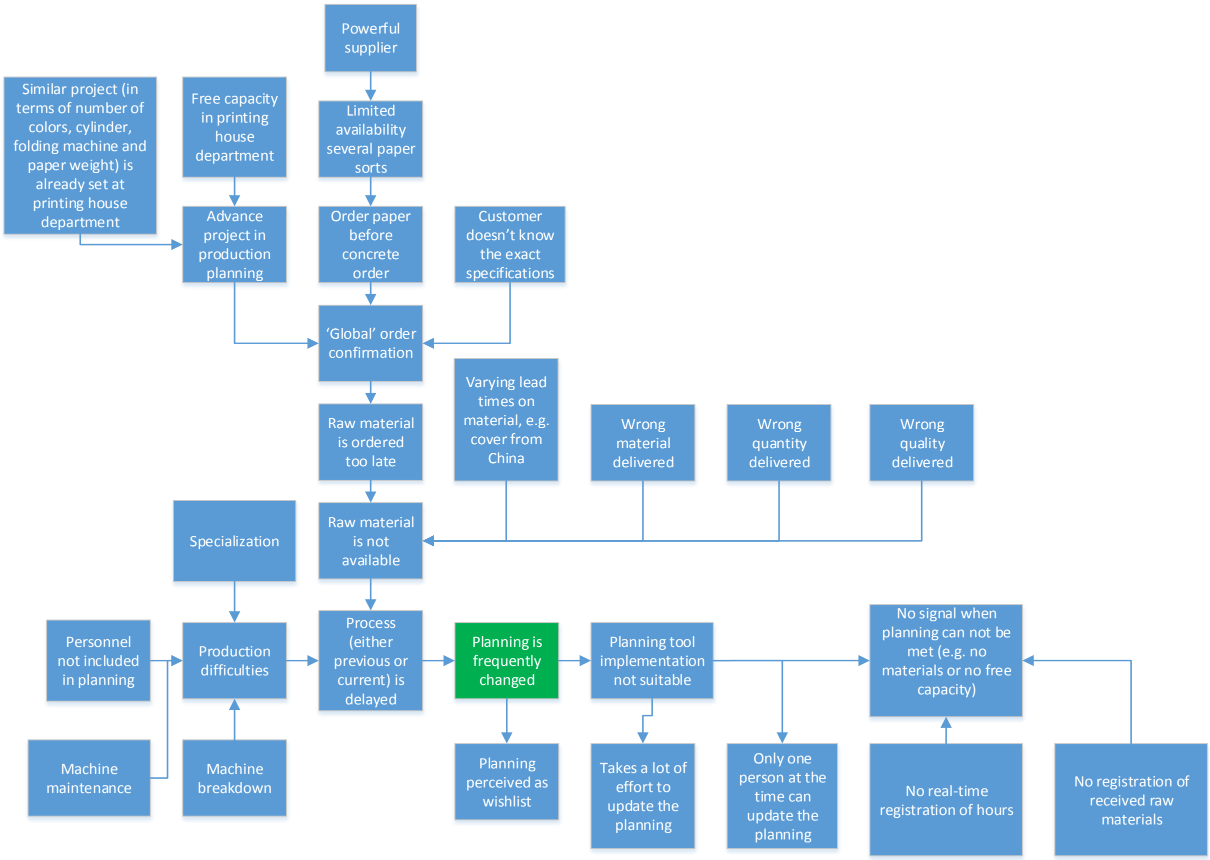

Figure 14: Problem diagram

In Figure 14, the green block is the main problem. We now discuss the different problems that require further explanation, starting at the bottom of the figure and finishing at the top.

- **Only one person at the time can update the planning.** Due to the restrictions of both Excel and Windows, editing the planning with more than one person at the time is not possible. Also important is that the person exits the planning file after editing/viewing, otherwise no one else is able to edit the planning.
- **Takes a lot of effort to update the planning.** A modification in the sequence of jobs at one machine does not automatically alter the sequence of jobs at succeeding machines. Therefore, updating the planning takes a lot of effort. Also, adding a new project to the production planning is not an easy job. All production steps need to be added manually, one-by-one. Furthermore, there is no real check to verify the correctness of the sequence of the production steps.
- **Planning tool implementation not suitable.** Excel, which is the planning tool, is capable of coping with simple and stable production planning. However, the implementation of the production planning in Excel is not suitable for a frequently updating production planning.
- **No signal when planning cannot be met (e.g., no materials or no free capacity).** The planning tool, Excel, does not warn when the production planning cannot be met. It is simply not configured to do so.
- **Planning perceived as wish list.** Rather than being perceived as an enabling tool for production, the production planning is seen as a wish list. The reason is that the planning is frequently changing.

- **Planning is frequently changed.** This is the main problem. The production planning is frequently updated, to reflect delays in production and the availability of raw materials and semi-finished products.
- **Process (either previous or current) is delayed**. Either or both (current or previous) processes cannot be executed, and therefore the process is delayed.
- **Production difficulties.** This can range from a low throughput rate, high setup times to maintenance and machine breakdowns. These difficulties leads to a delay of the current and/or previous process.
- **Specialization.** Jongbloed is one of the few companies in the world that can print on light and thin paper. However, it is quite complex to do so, and processing the thin material sometimes results in low throughput times, failures and high setup times.
- **Machine breakdown.** The same reasoning applies as for machine breakdown. A breakdown of a machine directly affects the production planning. The machine is simply unable to produce.
- **Personnel not included in planning.** Currently, the planning only takes into account the machines. Personnel to operate the machines is assumed to be infinite, they are not included in the production planning. One exception is the luxury department, where the number of employees determine the capacity of this department.
- **Varying lead times on material, i.e. cover from China.** The soft covers that are produced in China is just an example, but lead times on a lot of raw materials tend to vary.
- **'Global' order confirmation.** The order confirmation does not the specific materials. They are specified in a later stage.
- **Advance project in production planning.** A project is advanced in the production planning, when the project meets one or two of the following requirements:
    - Free capacity in printing house department. Another project is not ready to start (for example the paper or plates are not ready yet), or there is simply a gap in the planning. The presses in the printing house department are the bottleneck of the factory and therefore its capacity is fully utilized.
    - Similar project (in terms of number of colours, cylinder, folding machine and paper weight) is already set-up at printing house department. Therefore, another project can follow up this project with almost no setup times.
- **Order paper before concrete order.**
    - Limited availability several paper sorts. Not all paper can be bought off the shelf at the supplier. There are some special paper sorts that need to be ordered in advance, without an order for the paper. The 'normal' process of selling books is than the other way around, Jongbloed is trying to find a customer for this paper. Normally, a customer comes to Jongbloed with an idea in mind for a new book. Now, they do not yet have this idea and therefore the order confirmation is quite 'global'.
    - Powerful supplier. Jongbloed only represents a small part of the supplier's revenue. Therefore, they are not that important to them.
- **Customer doesn't know the exact specifications.** This problem can be seen as a plain service to Jongbloed's customers. They do not yet have to know all specifications for a new book, this can be decided later on.

2.3 Desired situation

We just described the current situation. We would now like to discuss the desired situation, so that we can compare the current and the desired situation. The difference between the desired situation and the actual situation is that what should be changed. The desired situation has the following characteristics:

1. Possibility to request the estimated due date for a quotation. The planning tool should take the current production planning and the lead times of raw materials into account, such that the planning tool gives an accurate estimate of the expected delivery date.
2. Feedback on the production processes. If a certain process is ahead/behind schedule, this delay should be known. This notification has two results, as we could increase/decrease the capacity of a machine by adding or subtracting employees to keep up with the pace of the production planning and Jongbloed can report the lead/delay to the customer.
3. The production planning should be perceived as a tool that supports their daily activities, provides clarity concerning the sequence of the projects and the presence of the required materials, both raw materials and semi-finished products.
4. The production planning facilitates in narrowing the gap between the estimated production costs and the actual production costs. This helps to state a realistic price to Jongbloed's customers.

2.4 Difference between the current and the desired situation

The difference between the current and the desired situation is a gap that needs to be closed, in order to attain the desired situation. We use the four characteristics of the desired situation to explain the difference between the desired and the actual situation.

1. A feature of the production planning should be that it is possible to put a potential order in the production planning, which takes into account the current schedule and the lead times on raw materials.
2. There should be (real time) feedback from the production floor, in order to keep track on the production processes.
3. The production planning should be fixed on the short term (say one week), so everyone feels that the production planning is not merely a wish list instead of a production planning.
4. An accurate production planning, which includes accurate processing and setup times, can facilitate closing the gap between the estimated production costs and the true production costs.

2.5 Conclusions

In this chapter we first described the current situation. The production planning is highly affected by the availability of raw materials and semi-finished products. Next, we described all the problems in a cause-effect diagram. Next up was the description of the desired situation; what would be the ideal situation? The difference between the desired situation and the actual situation was described in the last section. Finding out how the current situation can evolve into the desired situation is one of the main goals of our research.

3 Problem analysis

This chapter can be considered as the body of this report. An extensive analysis is useful and structures the upcoming chapters. We first discuss several indicators that make the problem measurable and then investigate the second sub research question: “How is the Jongbloed’s current production planning performing?”

3.1 Indicators

Indicators are meant to make the problem measurable. They can be used to quantitatively express the current situation and future situation, so the effects can be measured. We believe that the following indicators express the described problem:

- Lead time of the products, which is the sum of the production- and the waiting time. It reflects the uncertainty in the production planning. For example, if raw material is not available this most likely increases the waiting time of the project.
- Workload per department per bucket of time.

3.2 Jongbloed’s current production planning

Here, we briefly describe the eight steps of the research cycle to research Jongbloed’s current production planning.

3.2.1 Research goal

We research the effects of Jongbloed’s current production planning. The previous chapter contains a cause effect diagram of all observed problems. However, this is a purely qualitative analysis. We would like to add quantitative information to this diagram, using the research cycle.

3.2.2 Problem statement

A lot of information is currently being tracked. However, this information is not so easy to retrieve. Some info is easy to access, while other is quite hard to find. Therefore, we started the research cycle. All the information needs to be combined in order to add quantitative information to the cause effect diagram. The sort of research is more descriptive, as we would like to know what the effect of Jongbloed’s current production planning is on the waiting time and the workload. Normally, combining several variables in one group is not possible according to the Managerial Problem Solving Method. However, we are unable to find the individual influence of for example material availability. Therefore, we use two ‘steps’ that are shown in Figure 15.

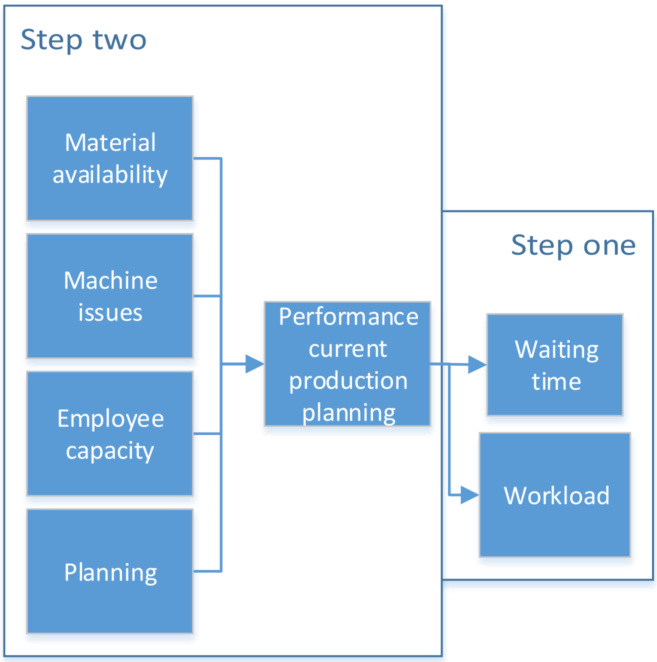

Figure 15: Approach in research cycle

Figure 15 also shows the structure of the problem. There is a direct relation between the performance of the current production planning and both waiting time and workload. A low performance of the production planning automatically results in a higher waiting time. Here, waiting time is defined as the time that the product is not being processed. Workload is defined as the total number of hours that is worked at a department per bucket of time, which could be either in days, weeks or months.

3.2.3 Research questions

Here, we discuss the research questions that this research cycle is going to answer. They are exactly the same as the questions that are stated in chapter one. They are as follows:

1. What is the average waiting time, as a percentage of the average lead time?
2. What is the estimated distribution of the four categories, which are material availability, machine issues, employee capacity and planning, which cause the waiting time?
3. What failures occur at the two printing presses?
4. What is the workload per week per department?

Each of these research questions has its own section, where we research and answer each research question.

3.2.4 Research design

Research design involves some technical description of the research cycle. The basic setup of this research design is a longitudinal research, which follows multiple objects for several moments in time. We investigate a large set of projects from the first activity to finally shipping the product and therefore we include multiple points in time. The analysis is based on historic data from 2012 and only includes fully completed projects. After receiving the data, we do a quantitative analysis. As expected results, we would like to have a distribution of the four categories over the total lead time. Besides this, we would like to find an average percentage of the lead time where the project is waiting and the workload per department per month.

3.2.5 Operationalization

All relevant variables are already explicit, however the four uncertainty categories and the term workload needs some further explanation. Here is a small description of the four categories and the term workload.

- **Material availability.** The availability of material, for whatever reason. The wrong quantity, quality or material results in that a process cannot start. This affects the production planning.
- **Machine issues.** When machines do not function properly, they do not produce the desired output, have increased set-up times or do not work at all. There are several reasons for this behaviour such as difficult to handle material, breakdowns or maintenance.
- **Employee capacity.** Planning is not only about machines, employees also need to be taken into account. They need to operate the machines, and therefore determine the capacity of the machines.
- **Planning.** There is a large variety of planning possibilities. The appropriate variety depends on the performance indicator that we would like to maximize/minimize and the production process itself. A simple production process demands a complete different way of planning, compared to a complex and variable production process.
- **Workload.** Another result of uncertainty, besides the waiting time, is workload. A high degree of uncertainty leads to a variable workload, whereas a low degree of uncertainty leads to a stable workload.

3.2.6 Measurement

There are actually two ways to retrieve the data. One way is by using the overall equipment effectiveness of each machine and using this in combination with the expected number of orders and the expected setup- and throughput times per machine to find the expected waiting time per project and the workload per department. However, not all machines keep track of their overall equipment effectiveness. Also, the level of detail is often not specific enough. However, there is a second way to find the waiting time per project and the workload per department per bucket of time. Jongbloed's Enterprise Resource Planning (ERP) system is a rich source of information. Time for each process is recorded, which can be used to compute the expected waiting time using the start- and end date/time. This same information can also be the basis to calculate the workload per bucket of time per department.

3.2.7 Processing of data

As discussed earlier, there is a lot of data available. Getting the necessary and correct data took us quite some time. If we did not succeed to get the necessary data, we were unable to draw conclusions. We used two sources of information, namely a new business intelligence (BI) tool and the overall equipment effectiveness of several machines. The BI tool extracts data from Jongbloed's ERP System and exports it to pivot table in Excel, such that the data can be analysed. As discussed earlier, this research cycle is done in two steps.

3.2.7.1 What is the production waiting time, as a percentage of the average lead time?

We made one analysis to answer the research question stated above. At Jongbloed, a project consists of multiple production orders. Currently, there are four types of production orders namely the GK (pre-press and printing)-, BB (book block manufacturing)-, BD (manufacturing of covers) - and BK (binding of the book block and the cover) production order. Depending on the number of editions, we can have several production orders of each type. A combination of a set of corresponding production orders gives an edition of a book. At Jongbloed, one project can (and often does) contain multiple editions. Figure 16 shows the analysis.

Figure 16: Production- and waiting time in working days of editions in 2012, given based on revenue

In Figure 16, DL stands for Dwarsligger, HC for hard cover, SC for soft cover, L for luxurious products and Overall for all editions. The allocation of the different projects to calculate the score and lead time is based on revenue. First, the allocation was only based on the order quantity. However, this ignores the value and importance of luxurious books. Therefore, we now use revenue to calculate the score.

Both graphs show that the Dwarsligger has a relative small lead time and luxurious products have a longer lead time. The graph is counter intuitive, as luxurious products have a smaller amount of production time compared to hardcover products. This is due to the fact that the edition quantity of hard covers are simply greater than the edition quantity of luxurious products. The total amount of work is larger for hard covers compared to luxurious products. We would like to mention that both figures use a project point-of-view. This view is completely different from a machine point-of-view, as this view looks at passing projects.

While doing the analysis, we made the following assumptions:

- Waiting time is defined as lead time, subtracted by the production time. However, the lead time is rounded up to days. Therefore, the true ratio between the waiting time and the production time is likely to include a higher share of production time.
- We do not take sending a project in different shipments into account. Lead time is defined as the first activity till the last shipment. Different shipments are common in the BK production order, as this often is the last part of the production process. Again, the true ratio between the waiting time and the production time is likely to include a higher share of production time.

The answer to the first research question, which is '*What is the average waiting time, as a percentage of the average lead time?'* is 62.1 percent. We use revenue as a scale, which means that we think that projects with more revenue are more important compared to other projects with lower revenue.

3.2.7.2 What is the estimated distribution of the four categories, which are material availability, machine issues, employee capacity and planning, which cause the waiting time?

This question is actually about explaining the waiting time, found in the first research question. However, we can only partly explain the waiting time as not all causes are logged. Figure 17 visualizes the logged causes, which is based on the overall equipment effectiveness (OEE) of several machines.

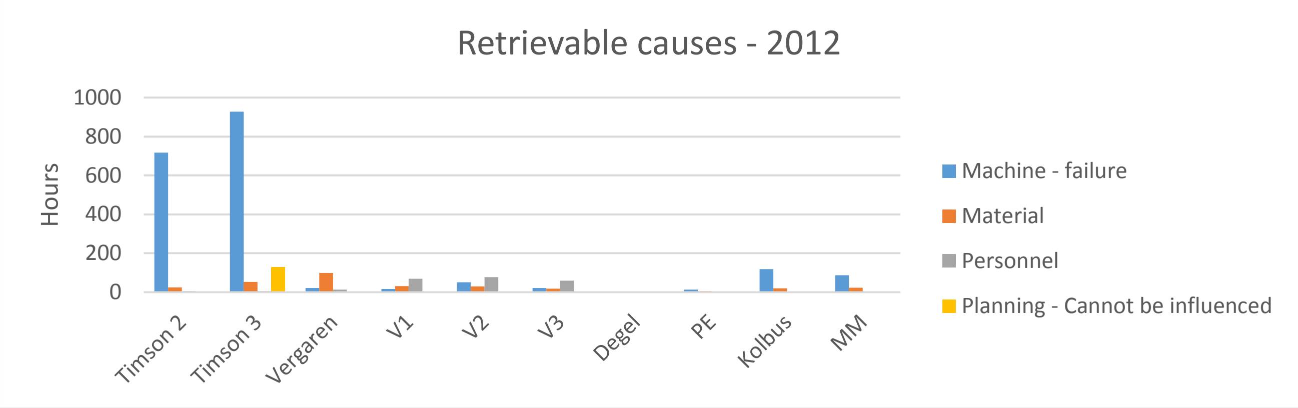

Figure 17: Retrievable causes waiting time in 2012

On the x-axis in Figure 17, the different machines that log the OEE are shown. On the y-axis, the total amount of hours is shown. These are grouped in several groups, which are shown on the right side of the figure. Machine failure is a common cause, especially at the two printing presses in the printing house. Material is another cause, which is defined as the time that the machine has to wait before the machine can start producing. Reasons can be the quality or quantity of material. The third group is the personnel cause, which can be ill personnel, personnel that is working on another machine or a shift is dropped. These three reasons combined is the cause personnel. The fourth and final group is 'planning – cannot be influenced'. This is the amount of time that an order is advanced, due to the fact that one of the two printing presses (the so-called Timson 3) uses exchangeable cylinders and folding machines. The changeover times are huge, up to 24 hours for a cylinder exchange. Therefore, projects that use the same cylinder and folding machine are clustered. Therefore, means that we cannot put the order on the press at the desired time. We approximated the expected time using the data of 2012. The other printing press, the Timson 2, has a fixed cylinder and folding machine. Therefore, the Timson 2 only has 'normal' waiting time and not 'forced' waiting time. While making the above graph, we assumed that the machines that log the OEE are representative for all machines.

3.2.7.3 What failures occur at the two printing presses?

The previous section shows that failure at the two printing presses has a large impact on the waiting time for projects. Therefore, we would like to investigate the different types of failure. For instance, what are common failures at the printing presses? We first look at Timson 2 and continue with Timson 3. Timson 2 is the older printing press of the two, with a fixed cylinder and folding machine. Timson 2 uses heat to dry ink. Timson 3 is a bit more modern, it has an exchangeable cylinder and folding machines, so this printing press is able to print a wide range of books.

Timson 2

We would like to have an overview of all the different types of failure. Furthermore, we would like to know whether the total amount of failure increased or decreased over the last few years. All this is shown in Figure 18.

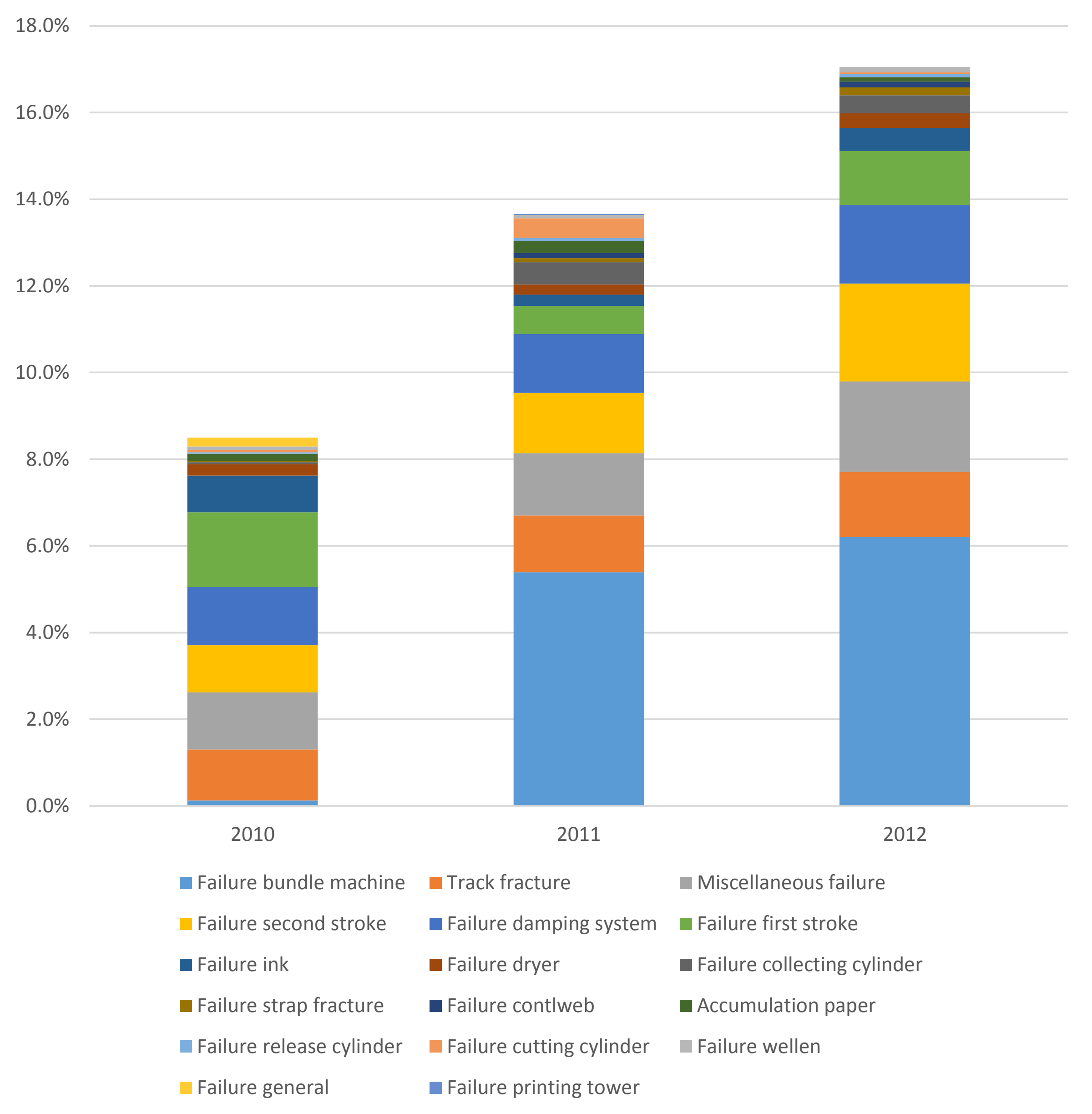

Figure 18: Failure as a percentage of total available time - Timson 2

Figure 18 shows the total amount of failure, as a percentage of the total available time. Further, the amount of failure as percentage of the total available time increased over the last three years. Especially the new category called 'Failure bundle machine' is responsible for a significant share of the total failure time. Furthermore, the percentage of failure doubled between 2010 and 2012. However, the order portfolio has changed between 2010 and 2012. Thus, the comparison above in not completely fair. Order quantities have dropped and the number of orders have increased, which means more setups. We now have an overview of the complete problem and would like to know whether the production rate increased at the same pace as increase in failure. This is shown in Figure 19.

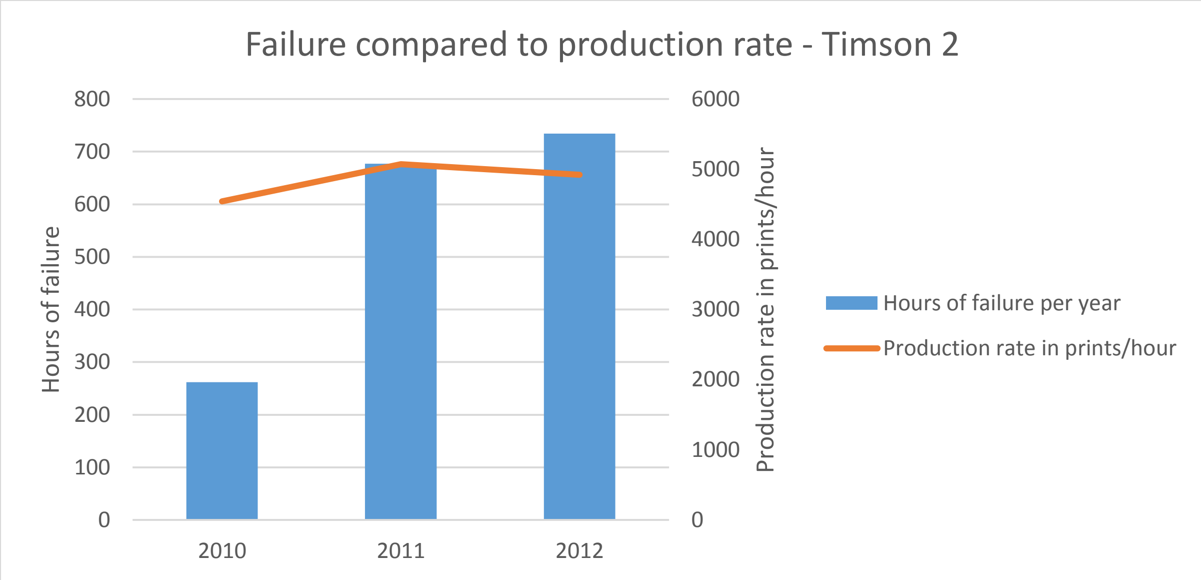

Figure 19: Total amount of failure compared to the production rate per hour - Timson 2

Figure 19 tells us whether the production rate increased at the same rate as the total amount of failure. We can easily see that this is not the case. There is a modest increase in the production rate, whereas the total amount of failure shows a huge growth. A method to quantify a relation between two variables is called a correlation. A correlation is a number between minus one and one, where zero indicates no correlation at all. One indicates that there is a positive correlation, which means that the variables 'follow' each other. If one variable increases, the other one mimics this behaviour. A correlation of minus one shows that there is a negative correlation. This means that if one variable increases, the other decreases.
The two variables in the figure above have a correlation of 0.926, which is a positive correlation. This means that our visual analysis is not correct, as this means that there is a link between the total amount of failure and the production rate.

Especially the increase between 2010 and 2011 is remarkable. The figure with the different types of failures shows that is almost solely due to the new bundle machine. Before, all sections were bundled by hand. The bundle machine was installed in the first half of 2011. A bundle machine automates this, which allows the employee at the bundle machine to check the quality or tweak a machine.

Still, we only indirectly compared the throughput rate and the total amount of failure. In Figure 20, we present a new performance indicator which is the total throughput per year, divided by the total hours of failure per year. Intuitively, this performance indicator should be maximized.

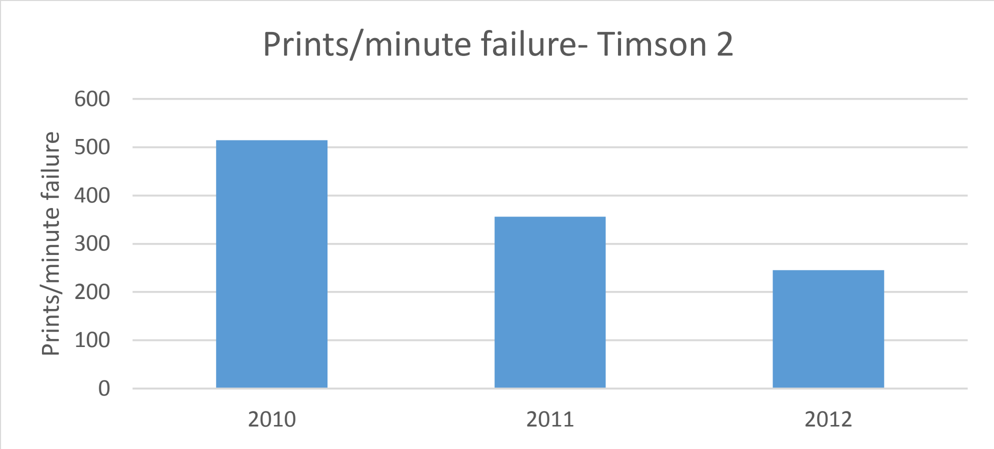

Figure 20: Prints / minute failure – Timson 2

Figure 20 shows a great decrease in the number of prints per minute failure. Therefore, the performance of the Timson 2 between 2010 and 2012 sharply declined. We would like to further investigate the decrease in performance. The bundle machine that we just discussed allows Timson 2 to run at a higher production rate. Bundling by hand is limited to a certain production rate, as bundling faster is simply not possible. A bundle machine does not have this issue and is able to run at higher production rate. However, the bundle machine is responsible for a significant amount of failure. Figure 21 shows the relation between the increase in production rate and failure.

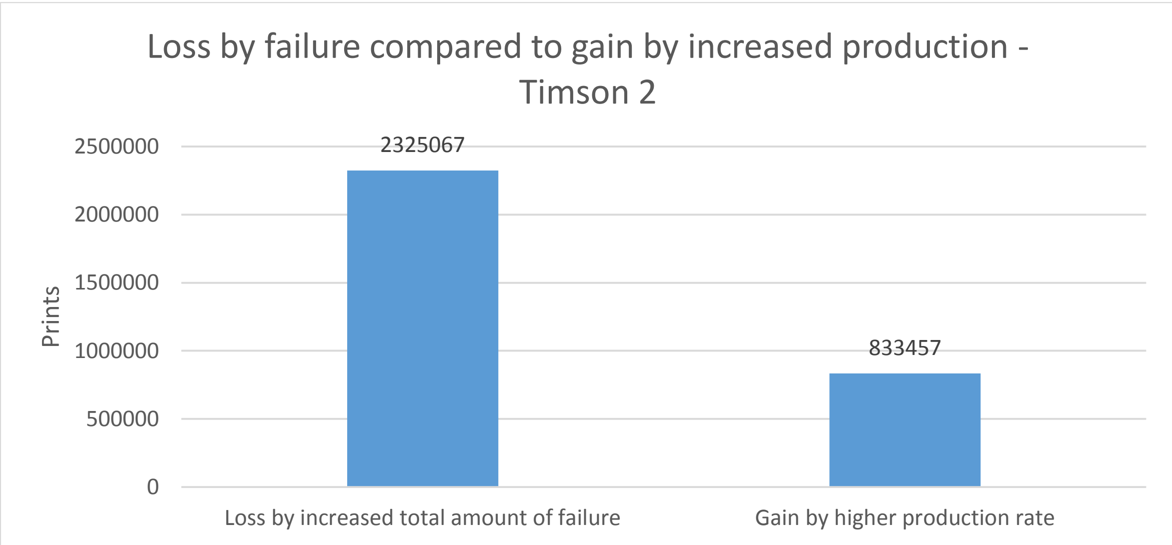

Figure 21: Loss by increased total amount of failure compared to the gain by higher production rate between 2010 and 2012

Both parameters are expressed in the number of prints. Figure 21 shows that the increased total amount of failure is not compensated by the gain of a higher production. We could conclude that the bundle machine of the Timson 2 is a bad investment, but that would be a blunt conclusion. The bundle machine has a number of advantages, which cannot be quantatively expressed. One advantage of a bundle machine is the improved ergonomics for an employee at the bundle machine. Also, he/she is able to perform other activities such as tuning the machine. The bundle machine was bought secondhand and has been programmed specifically for the Timson 2. However, this was not done correctly. One of the two carts was continuously braking, which caused a lot of failure. Two years after installing the bundle machine, this issue was finally fixed. The bundle machine causes a tremendous decrease in total amount of hours failure on the bundle machine. To illustrate the decrease, we present Figure 22 which shows the total amount of hours failure in March 2013.

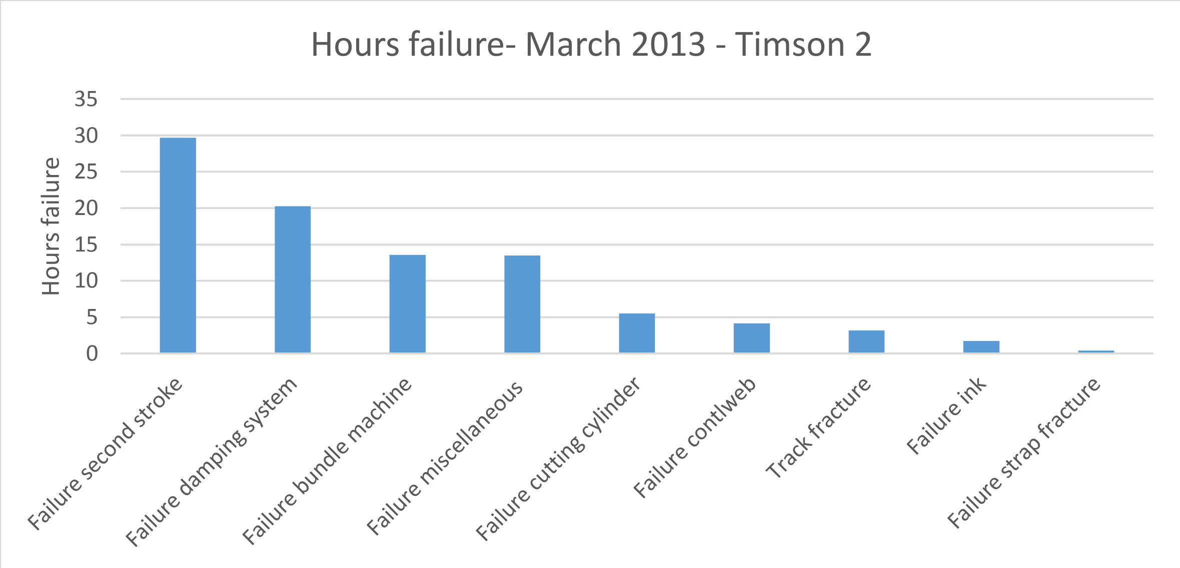

Figure 22: Hours failure - March 2013 - Timson 2

Normally, the category 'failure bundle machine' was strictly number one in terms of failure. In March 2013, the total amount of hours failure decreased till 13.6 hours whereas it still accounted for 37.8 hours in January 2013.

We now return to the different causes of failures. We now compare these between 2010 and 2012. We take two pairs containing two consecutive years, namely 2010-2011 and 2011-2012. They are shown in Figure 23.

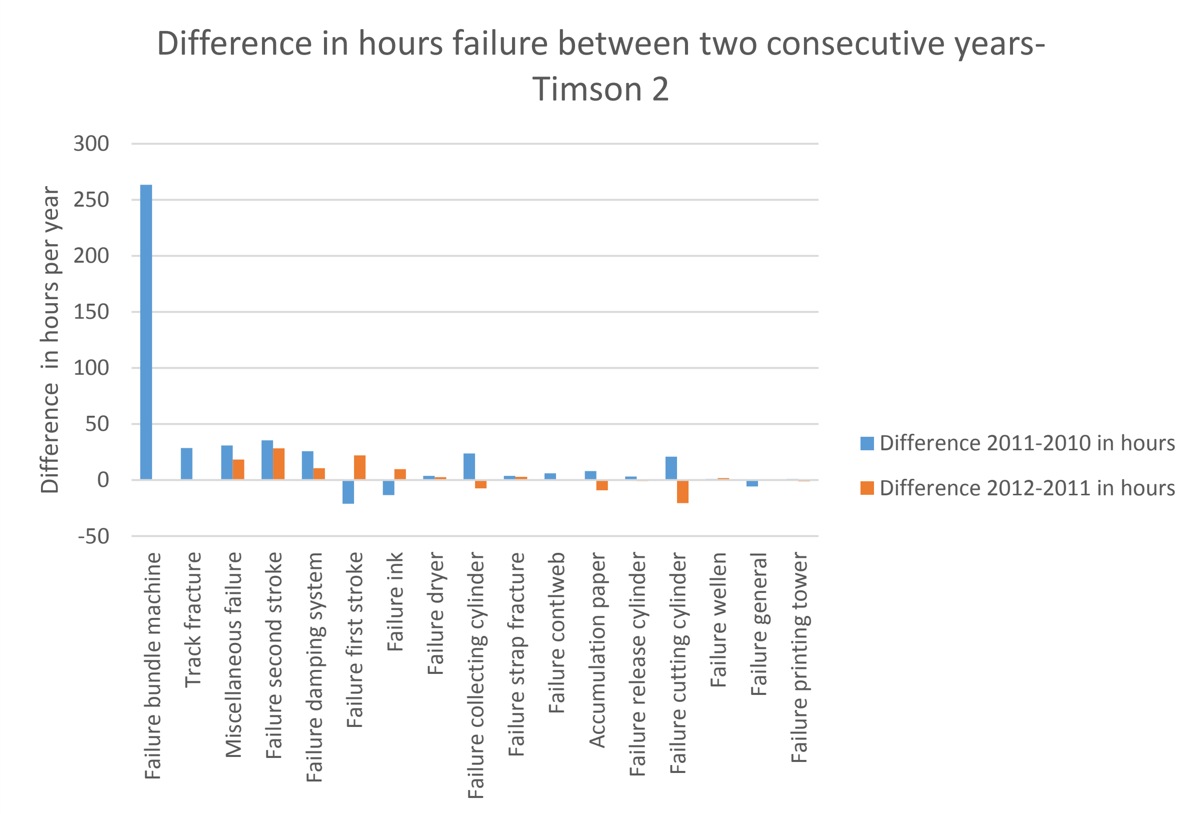

Figure 23: Difference in total amount of hours between two consecutive years – Timson 2

Figure 23 shows the different categories of failure on the x-as. The y-axis is shows the difference between two consecutive years. A positive difference represents an increase, while a negative difference means a decrease in failure.

Timson 3

We just researched Timson 2 and continue with Timson 3, again we first give an overview of the development of failure on Timson 3 over the last three years. They are shown in Figure 24.

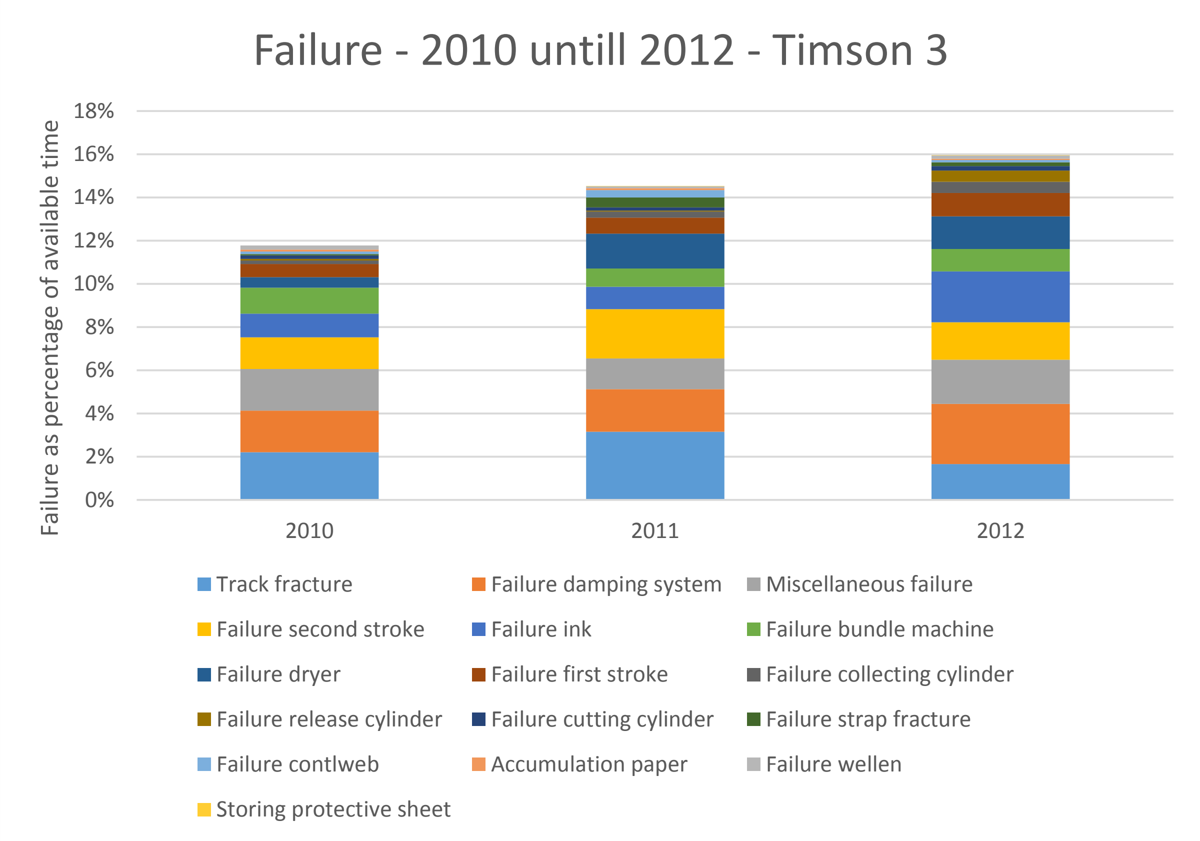

Figure 24: Failure as a percentage of the total available time – Timson 3

The failure behaviour of Timson 3 is similar to Timson 2. However, the total increase in failure is nowhere as large as for the Timson 2. The increase in failure is modest, percentage-wise. We now look at the relation between failure and production rate. This is done in Figure 25.

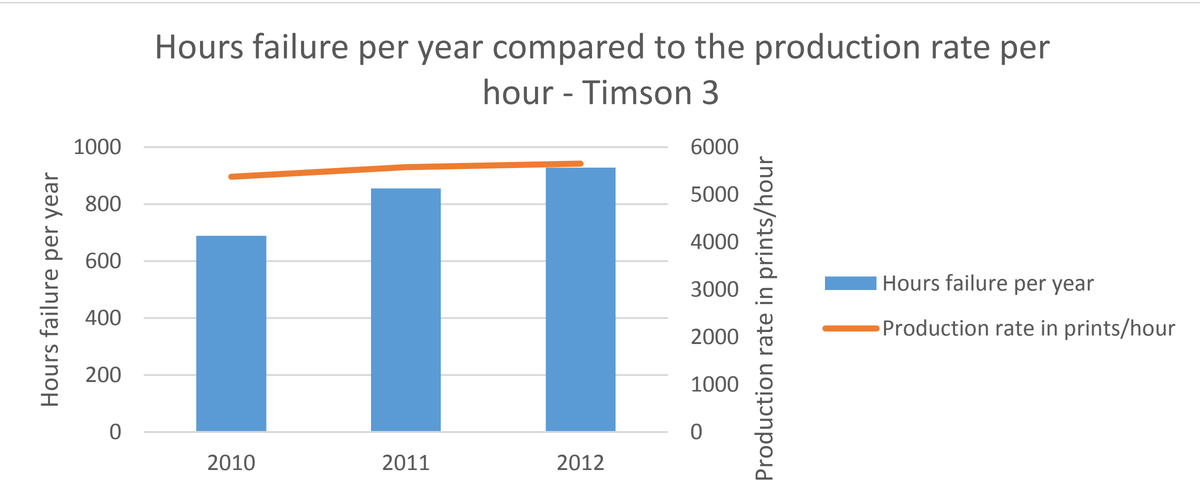

Figure 25: Total hours failure per year compared to production rate per hour - Timson 3

Figure 25 shows a similar relation as the Timson 2, however the increase in total hours failure is not so steep. We again look at the correlation between failure and production rate. The explanation for the correlation is exactly the same as for the Timson 2. 0.999 is the correlation between the production rate and failure, this means that there is a nearly perfect correlation. An increase in failure leads to an increase in production and the other way around.

Still, the graph above does not show the performance of Timson 3. Therefore, we use the same performance indicator as we used for the Timson 2. This is shown in Figure 26.

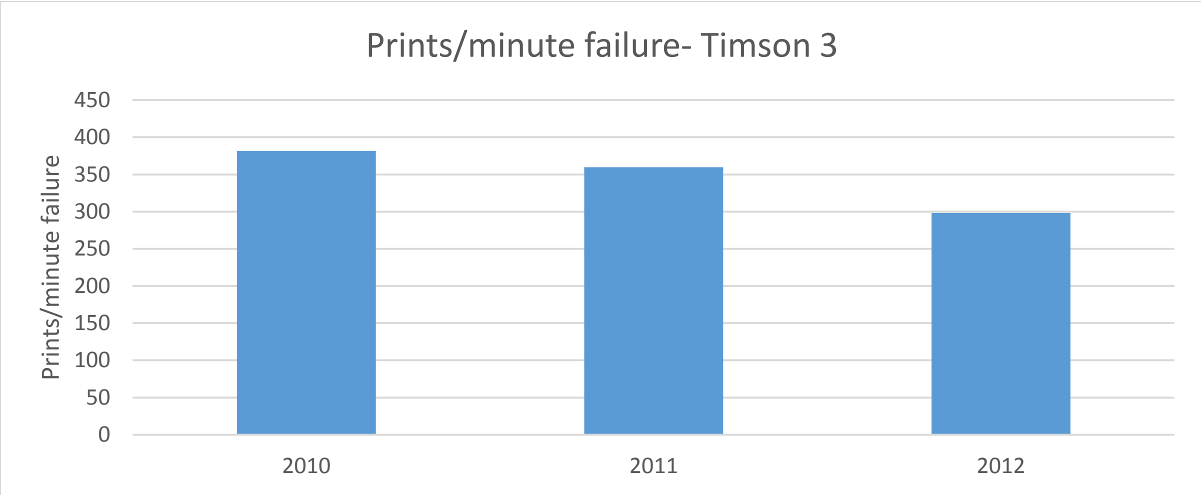

Figure 26: Prints per minute failure – Timson 3

As for the Timson 2, the performance of the Timson 3 is decreasing between 2010 and 2012. Over time, employees are able to let the printing press run at a higher production rate. Does the increase in production rate compensate for the increase in failure? Figure 27 shows that this is not the case.

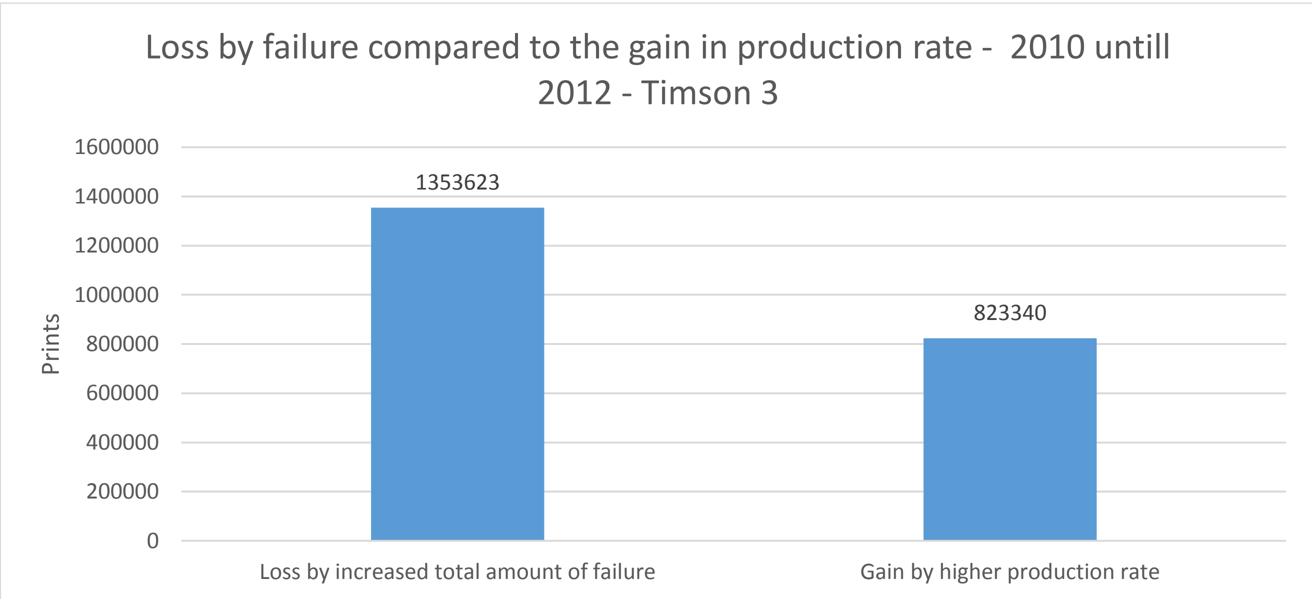

Figure 27: Loss by increase failure compared to gain in production rate - 2010 till 2012 - Timson 3

We again express the performance indicator in number of prints. However, the gap between the loss in failure and the gain in production rate is much smaller compared to the Timson 2. This means that performance of Timson 3 did not decline as hard as decline of performance did for the Timson 2. We now look at the difference of two consecutive years, between 2010 and 2012. This means that we compare both 2011-2010 and 2012-2011. This is visualized in Figure 28.

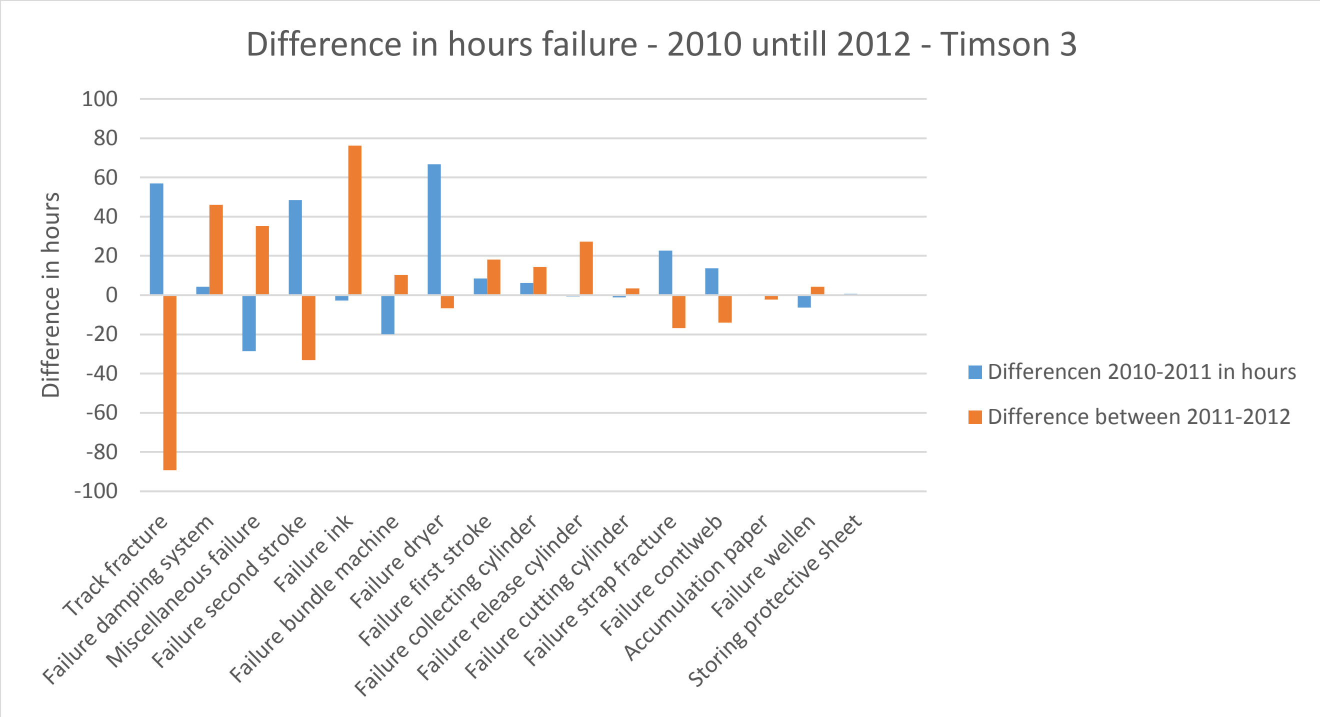

Figure 28: Difference in hours failure for two consecutive years - Timson 3

Timson 3 shows a completely different image, compared to the Timson 2. We use the same definitions as we used for the Timson 2, this means that an increase is positive and decrease in failure is negative. If we for instance look at the failure category 'second stroke', this category shows a great increase between 2010-2011 and a great decrease between 2011-2012.

3.2.7.4 What is the workload per week per department?

The previous research question is answered from a machine point-of-view. We analyse this research question using a personnel point-of-view. We look at the number of hours that are spend on the four departments, which are as follows:

- **8042** – Number of hours spend on book block manufacturing and cover manufacturing
- **8049** – Number of hours spend in the binding- and luxury department
- **8056** – Number of hours spend in the pre-press and printing house department.

We looked over a period of approximately 14 months, starting in January 2012 and finishing fourteen months later in February 2013. We picked 14 months, as it also shows the tremendous decrease in the numbers of hours per week per department in January and February 2013. An overview of the number of hours spend per week per department is shown in Figure 29.

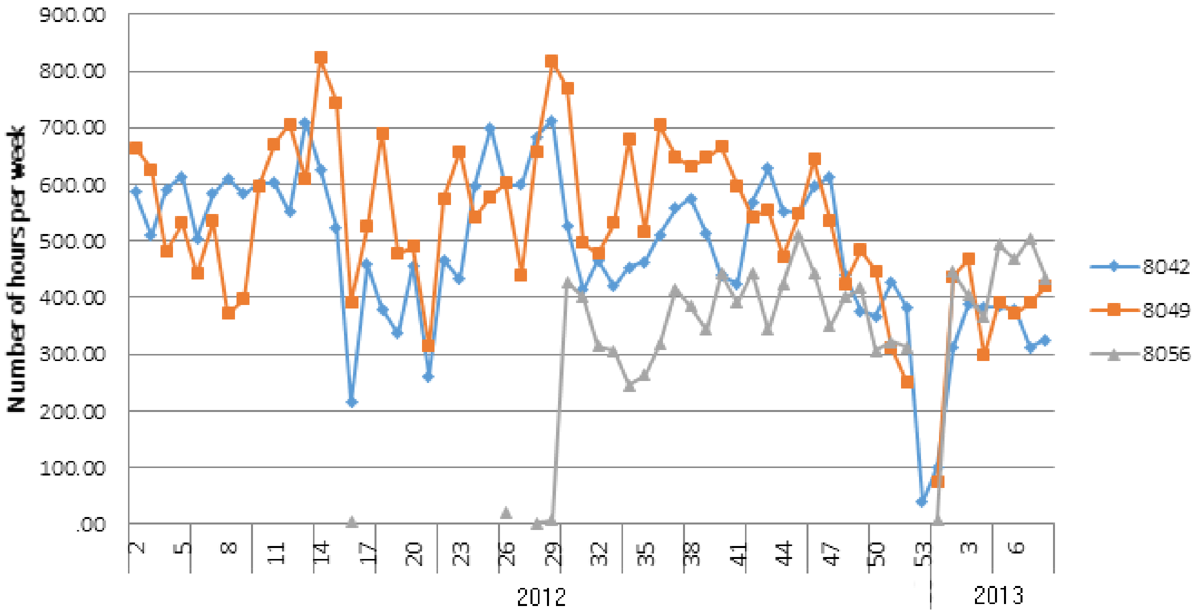

Figure 29: Number of hours per week per category from early 2012 to February 2013

Inspecting Figure 29 shows the follows interesting facts. For instance, in the first half of 2012 there are no registered hours for the pre-press and the printing house department. This is correct, during that period of time all hours were registered using one general code. Furthermore, we see that the fluctuations are enormous during the first half of 2012. In the second half, the spikes are reduced. One reason is that they allowed to dynamically schedule personnel over all departments. Before, employees could only be scheduled within departments. The spikes in 2013 are even smaller, as they try to avoid to use temporary personnel. We would say that the workload is quite stable in 2013, whereas the workload was not stable the year before.

3.3 Conclusions

In the previous section, we answered the four research questions. We briefly summarize the answers. The average waiting time for an edition, based on 2012, is 62.1% based on revenue. Additionally, the most common retrievable cause for waiting time is machine failure. We further researched the machine failure category for both printing presses, and this analysis shows that both presses have an increased failure rate in the last three years. Furthermore, the number of hours per week can be considered stable in the first part of 2013.

4 Generating alternative solutions

The previous section revealed that there is a significant amount of waiting time, for each project. Different ways of scheduling affect not only this performance indicator, but also others. Therefore, this section investigates all the different applicable ways of scheduling. This allows us to answer the following sub research question: “What production planning rules are available in literature?” We first describe Jongbloed’s production from a theoretical perspective and continue with several scheduling rules.

4.1 Theoretical type of production

According to Pinedo, there are five different planning models (Pinedo M. L., 2005). In literature, resources are known as machines and an activity on a machine is called a job. Also, the time between the first and the last job is referred to as the makespan. The five different planning models are as follows:

- **Project planning and scheduling.** These manufacturing models include large projects, for example building a new bridge over the Thames in London or manufacturing the new aircraft such as the Joint Strike Fighter (JSF). Such projects consist of many stages, often they include precedence relations. If we set the JSF as an example, we cannot attach the wings before the body of the airplane is constructed. Project planning and scheduling models often assume to have an infinite capacity, which is not always correct in the real world. The objective in such models is to minimize the make span.
- **Single machine, parallel machine, job shop and flow shop models.** The single- and parallel machine can be considered as the simplest manufacturing models. This model only consists of one job that can be performed on any machine that does not have a job. The difference between a single machine model and a parallel machine model is that there are multiple machines with the exact same specifications. Job shops are more complex, compared to single- and parallel machine models. Each job in a job shop has its own route, which consists of several different activities. A special case of a job shop is a flow shop, where each job has the exact same route. Examples of a job shop manufacturing model can be found in both the service- and manufacturing industries. Job shop models are generally present when there is some sort of customization. In the service industry, job shop models are present in for example hospitals, whereas job shop models are present in the manufacturing industry in for example the manufacturing of shoes (where the exact route depends on the type of shoe).
- **Production systems with automated material handling.** This manufacturing model is comparable to the flow shop, but as the name suggests material handling is automated. The form of automation varies, but possibilities include conveyors and automated guided vehicles. Examples include the manufacturing of cars and food such as bread.
- **Lot scheduling models.** These models don’t focus on the short term planning, but concentrate on the medium- and long term planning. The main topic is the batch size. When does a machine need to switch to a different product and how does this affect the supply, changeover- and inventory costs? This type of manufacturing model is the process industry, examples include steel manufacturing plants and paper mills.
- **Supply chain planning and scheduling models.** These manufacturing models do not look at just one company, but consider the whole supply chain. If we look again at the shoe example, the supply chain does not exist of just one company that manufactures the whole shoe. For example, laces and soles are manufactured at different companies. Supply chain

planning and schedules models look at all these different factories and include inventory-, setup- and transportation costs.

If we take the above definitions into account, we can conclude that Jongbloed uses a job shop manufacturing model. Each edition within a project has its own route. Furthermore, they only look at their own production planning and do not include suppliers. Therefore, the production planning is not a supply chain planning and scheduling model.

4.2 Scheduling

We first give a small introduction in scheduling history, continue with the scheduling rules and order release and finish with several ways of due date setting.

4.2.1 History

Scheduling has been around for ages. Starting in the second half of the nineteenth century, companies became aware of the fact that humans are not capable of making the whole planning themselves. The range of products and volumes increased during the industrial revolution, thus creating a demand for planning. This was not until the First World War, when Frederick Taylor 'created' production planning offices. Individuals working in such an office took away the planning from the foremen and were busy keeping track of the inventory and oversee operations. Gantt even further specified the production planning, by introducing a schedule per foremen. Such a schedule contains a list of the jobs that need to be done per day, in chronological order. This can also visually expressed, which is called a Gantt chart. It comes in a wide variety, such as "man's record" which shows per worker what he/she did and still has to do. Gantt charts are still used in planning, as they are a powerful and visual tool for planning. A few decades later, computers were introduced to support the scheduling. Companies were now capable to make much more advanced planning. The next major innovation within planning were manufacturing resource planning (MRP) systems. These systems enabled planners to include for example include future orders (Hermann, 2006). These systems later on evolved, first to MRP-II (which also includes for instance finance) and later on to enterprise resource planning.

4.2.2 Scheduling rules

We first discuss the different available types of scheduling, the definition and classification of the different scheduling rules and continue with reviewing the available scheduling rule.

4.2.2.1 Types of scheduling

Roughly, we could say that there are three ways to make a production planning schedule. The first are heuristics, which do not necessarily lead to the optimal solution but take little computation time. Another technique to make a production planning schedule is an exact method which guarantee the optimal solution, but take significant more computation time. The last category are meta heuristics. These are more complex compared to 'normal' heuristics and aim to find an optimal solution, but they do not guarantee that. Examples include tabu search and simulated annealing. They start with an initial solution, which could be based on a simple heuristic, and then try to improve the initial solution (Blazewicz, Domschke, & Pesch, 1996).

We research simple heuristics, as we would like a reasonable solution within a minimum amount of time. Jongbloed is coping nowadays with a lot of uncertainty which results in a high number of schedule changes. A production planning schedule that takes a long computation time result in an unworkable solution.

4.2.2.2 Definition and classification

Now that we know the history of scheduling, we continue with the scheduling rules. We look at the Job Shop literature and give an overview of all the different algorithms and heuristics that are available, ranging from a simple algorithm such as the shortest processing time rule to more complex ones such as the apparent tardiness cost rule. First of all, we define all the different terms which are priority rules, heuristics and scheduling rules. We use the definition for the priority rule and scheduling by Gere (Gere, 1966). However, we think that the Gere's definition for a heuristic is broad. Therefore, we use the definition by Kuehn and Hamburger instead (Kuehn & Hamburger, 1963). The definitions are as follows:

- **Priority rule.** "A priority rule or priority function is that function which assigns to each waiting job a scalar value, the minimum of which, among jobs waiting at a machine, determines the job to be selected over all others for scheduling. In the case of a tie, the job with smaller job number is selected." (Gere, 1966)
- **Heuristic.** "A problem solving approach, where the emphasis is on working towards optimum solution procedures rather than optimum solutions." (Kuehn & Hamburger, 1963). Gere simply states that heuristics are rules of thumb, which we believe is a summary of the definition by Kuehn and Hamburger.
- **Scheduling rule.** Represents a combination of one or more priority rules or heuristics (Gere, 1966).

To structure the different rules, we made our own classification scheme based on work by Ramasesh (Ramasesh, 1990), Panwalkar and Iskander (Panwalkar & Iskander, 1977), Conway and Maxwell (Conway & Maxwell, 1962) and Haupt (Haupt, 1989). We think that each of these classification schemes has its benefits and downsides. Combining all the benefits of these classification schemes gives us a solid foundation to analyse the scheduling rules. Therefore, we use a variety of classification schemes from literature to construct our own classification scheme which has five dimensions in total. The different dimensions are as follows:

- **Dependent on time in the shop.** Does the time that the job is in the system affects its priority (Ramasesh, 1990)?
  - Yes. The priority rule is classified as dynamic.
  - No. The priority rule is classified as static.
- **Dependent on state of the shop.** Does the scheduling rule take into account the workload of the job shop (Ramasesh, 1990)?
  - Yes. The priority rule is classified as dependent.
  - No. The priority rule is classified as independent.
- **Structure of the rules.** There is an extensive variety of priority rules. They can be classified as follows (Panwalkar & Iskander, 1977):
  - Simple priority rule. Any rule that uses information of a specific job is considered a simple priority rule.
  - Combination of single priority rules. Two or more different priority rules that are not combined, but each one is applied under different conditions.
  - Weighted priority indexes. This is a true combination of two (or more) priority rules, combination is done based on weights.
  - Heuristic scheduling rules. These are more sophisticated rules, not only looking at the job characteristics but also taking for example the effect on other machines into account.

    - Other rules. Rules that simply cannot be categorized in the other categories. Mathematical functions to combine priority indexes would be an example of such a rule.
- **Information content of the rules.** What does the priority rule take into account?
    - Arrival time (Ramasesh, 1990). The priority rule only takes arrival time into account as a decision factor.
    - Processing time (Ramasesh, 1990). The priority rule only takes processing time into account.
    - Number of operations. The rule looks at the number of operations (Panwalkar & Iskander, 1977).
    - Setup times. The rule takes setup times into account (Panwalkar & Iskander, 1977).
    - Slack. The amount of time that is still left to finish the production order, minus the necessary amount of time to process the production order. Slack can be seen as the amount of time 'to play around with' (Ramasesh, 1990).
    - Due date information (Ramasesh, 1990). Due date is taken into account.
    - Cost or value added (Ramasesh, 1990). Cost or value added as a decision factor.
    - Combination of one or more of the above (Ramasesh, 1990).
    - Miscellaneous. Rule don't fall in any other category (Panwalkar & Iskander, 1977).
- **Amount of information.** Does the rule only look at the machine that requires scheduling (Conway & Maxwell, 1962)?
    - Yes – The priority rule is a local rule.
    - No – The priority rule is a global (non local) rule.

4.2.2.3 Review scheduling rules

In this section, we discuss several scheduling rules and continue with classifying the different schedules among the dimensions that we just discussed. As argued earlier, there is a wide variety of scheduling rules. For instance, Panwalkar and Iskander discuss a total of 113 priority rules. We would like to model the most promising scheduling rules according to the literature in our model. Baker, Montazeri, van Wassenhove, Kanet and Hayya provide us with an excellent overview of several papers (Baker K. R., 1984) (Montazeri & van Wassenhove, 1990) (Kanet & Hayya, 1982).

Shortest processing time (SPT)

This is quite an 'easy' priority rule. It looks at all the different jobs that are waiting are in the queue for a certain machine and looks at the processing time for each job at this machine. This rule picks the minimum of all processing times, and then picks the job with the minimum amount of processing time. Originally, this priority rule is designed for computers. If a number of jobs is waiting to be processed, the computer picks the job with the shortest amount of processing time. Thus, the rule minimizes the number of jobs waiting to be processed. The shortest processing time rule performs great in terms of lead time, but is known to let jobs with a long processing times wait (Rose, 2001).

Longest processing time (LPT)

As with the SPT rule, this rule also looks at the processing time, but picks the job with the longest expected amount of processing time on the machine that needs a new job to process. The idea is that the jobs with longer processing times are processed first, whereas jobs with a smaller processing times are used for balancing the load (Pinedo M. L., 2012).

Earliest due date (EDD)

The earliest due date is another simple priority rule. This rule does not look at the processing time of jobs, but instead look at the due date of the job. The job with the earliest due date is given the highest priority. The idea behind this priority rule is jobs that should finish first, are processed first (Wein & Chevalier, 1992).

First come first serve (FCFS)

The first come first serve priority rule is a simple priority rule. The rule only looks at the arrival time of a job and gives the highest priority to the job that first arrived at the queue. Computation-wise, the FCFS scheduling rule is efficient and therefore often use as a so-called “reference” priority method to check the performance of other priority rules (Schwiegelshohn & Yahyapour, 1998).

Weighted Shortest Processing Time (WSPT)

The weighted shortest processing time priority rule is a weighted priority rule. WSPT uses two simple priority rules, namely the weight of a job and the processing time of a job for the machine that needs to be scheduled. The priority is the ratio between those two priority rules; a high weight is given to a job that has a low processing time. Weight can be anything, ranging from revenue to importance of the customer. The WSPT rule does not explicitly use the due date criterion, but still manages to keep the number of tardy jobs to a minimum by delaying jobs that have a long processing time and a low weight (Vepsalainen & Morton, 1987).

Minimum Slack (MS)

The minimum slack rule is a simple priority rule which takes slack into account. Slack is the time between the due date and the current time, minus the processing time of the job on the machine. The highest priority is given to the machine that has the lowest amount of slack (Pinedo M. L., 2012).

Apparent Tardiness Cost (ATC)

The apparent tardiness cost rule is classified as another heuristic. ATC uses the mathematical operator multiply to combine the WSPT rule with the slack of a job. The slack of a corrected by factor *k,* this means that *k* determines the weight of the two rules (Volgenant & Teerhuis, 1999).

Service In Random Order (SIRO)

According to Pinedo, in this priority rule “no attempt is made to optimize anything”. The priority rule randomly picks a job and processes it. Still, this priority rule is common in practice.

Least Number of Operations Remaining (LNOR)

This priority rule is another simple priority rule. LNOR looks at the number of operations that the product still requires and gives the highest priority to the product that still needs the least number of operations (Blazewicz, Domschke, & Pesch, 1996).

Most Number of Operations Remaining (MNOR)

The MNOR rule is similar to the previous priority rule. MNOR also looks at the number of operations that the product still needs, but the rule gives the highest priority to the product that still requires the largest number of operations. In this sense, this rule and the LNOR are similar to the SPT- and the LPT-rule (Blazewicz, Domschke, & Pesch, 1996).

First Arrival At Shop, First Served (FAASFS)

The FAASFS is similar to the first come, first serve priority rule. However, the FAASFS rule does not take the arrival time of a job at a processing station into account. FAASFS only looks at the arrival of the job at the entrance of the job shop. The production orders are sorted ascending on arrival time of the job at the shop (Panwalkar & Iskander, 1977).

Total Work (TW)

Another simple priority rule. TW looks at the total processing time that a jobs needs and gives a high priority to jobs that have a large total work content (Haupt, 1989).

Critical Ratio (CR)

Critical Ratio is a composite priority rule, which takes into account the allowance and the remaining setup and processing time. CR divides the allowance by the remaining the setup- and processing time and gives the highest priority to the lowest critical ratio (Berry & Rao, 1975).

Allowance / Number Of Remaining Operations (A/NORO)

A different way to determine the urgency of a job is to look at the number of remaining jobs. The logic is the higher the number of remaining jobs, the higher the possibility that a job is delayed (Baker K. R., 1984). Unfortunately, a negative allowance which gives undesirable effects is possible. A negative allowance makes it possible to get a high priority for jobs that have a few remaining jobs, but a negative slack/allowance. The critique is applicable to any rule with a ratio and allowance or slack, such as the critical ratio or the slack / work remaining (Kanet J. J., 1982).

Slack / Number Of Remaining Operations (S/NORO)

The denominator is exactly the same, compared to the last priority rule. However, the numerator is different. S/NOO uses slack as the numerator, which is more complex because the rule also includes processing times (Weeks, 1979).

Slack / Work Remaining (S/WR)

Again, similar to the previous priority rule. The S/WR priority rule does use slack as a numerator, but a different denominator namely work remaining. Again, a more difficult priority rule compared to the previous one because S/WR also takes the processing time into account (Haupt, 1989).

Earliest Operation Due Date (EODD)

The earliest operation due date priority rule is the counterpart of the Earliest Due Date priority rule. The EODD rule looks at the separate processes, and determines the due date per process in order to finish on time. According to Kanet and Hayya, the performance of the EODD priority rule is superior in terms of mean lead time and lead time standard deviation to its counterpart that focuses on the duedate of the job (Kanet & Hayya, 1982).

Smallest Operation Slack (SOS)

Another priority rule with a counterpart is the SOS priority rule. The contrary of the SOS priority rule is the Minimum Slack rule. The only difference between these two rules is that the SOS priority rule looks at the slack between the due date of the upcoming process and the necessary processing time, whereas the MS rule looks at the slack between the due date of the job and the total remaining processing time. Again, according to Kanet and Hayya the SOS priority rule is outperforming the MS rule in terms of lead time (Kanet & Hayya, 1982).

Operation Critical Ratio Rule (OCRR)

The OCRR priority rule is the last variant of an already existing priority rule, namely the critical ratio priority rule. Again, the OCRR looks at the ratio between the allowance and the necessary setup- and processing time for the next process. The 'normal' critical ratio rule looks allowance and the necessary setup- and processing time for the complete job, which is the subtle difference (Kanet & Hayya, 1982).

4.2.2.4 Global and local production planning

Often, orders are released immediately. Material Resource Planning systems are known to be push, whereas a fancy Just In Time (JIT) systems use a backward planning called pull (Karmarkar, 1991). The first immediately plans the from the order confirmation date and onwards. The other one looks at the delivery date, and plans all the activities backwards. Both of them have their up- and down sides. For instance, the push method is 'famous' to provide reasonable lead times but the amount of work in progress is quite high compared to JIT systems. Ming-Wei and Shi-Lian distinguish a third type of order release, namely a hybrid system (Ming-wei & Shi-lian, 1992). They believe that combining MRP, which focuses on planning, and JIT, which focuses more on the execution phase, gives the ultimate tool. MRP-II distinguishes two types of manufacturing, namely process (which basically is continuous) and discrete manufacturing. Discrete manufacturing is further divided in project manufacturing, job shop manufacturing and repetitive manufacturing. Examples of a process industry is the oil refinery, where the automotive industry can be seen as discrete manufacturing. Ming-Wei and Shi-Lian recognize three different type of hybrid systems, depending on the type of manufacturing. The first type is a combination of job shop and repetitive manufacturing. The second variant is especially for repetitive manufacturing, whereas the third category is exclusively for job shop manufacturing. We are interested in the last category, as this is the category that is applicable for Jongbloed. Their model states that common components should be pushed, whereas special parts should be scheduled pull.

Razmi, Rahnejat and Kahn analyse what system to pick, using the Analytic Hierarchy Process (AHP). AHP takes several criteria such as inventory cost, operating cost, product quality and external factors into account and advises one system based on the importance ranking of the criteria and the score on each criteria (Razmi, Rahnejat, & Khan, 1998).

All the scheduling rules that we discussed in section 4.2.2.3 are local rules, which need to be used with a type of order release that we just mentioned namely forward, backward or hybrid. However, we can also solely use these three planning methods for a global production planning. If we for example use the global forward production planning method, a new production order will be added at the earliest possible time to the already existing production planning for all necessary production steps. Another variety is the global backward production planning, where the new project is added at the latest possible time for all operations in the production planning. The difference between an order release strategy in combination with a scheduling rules compared to a global planning method is shown in the flowchart in Figure 30.

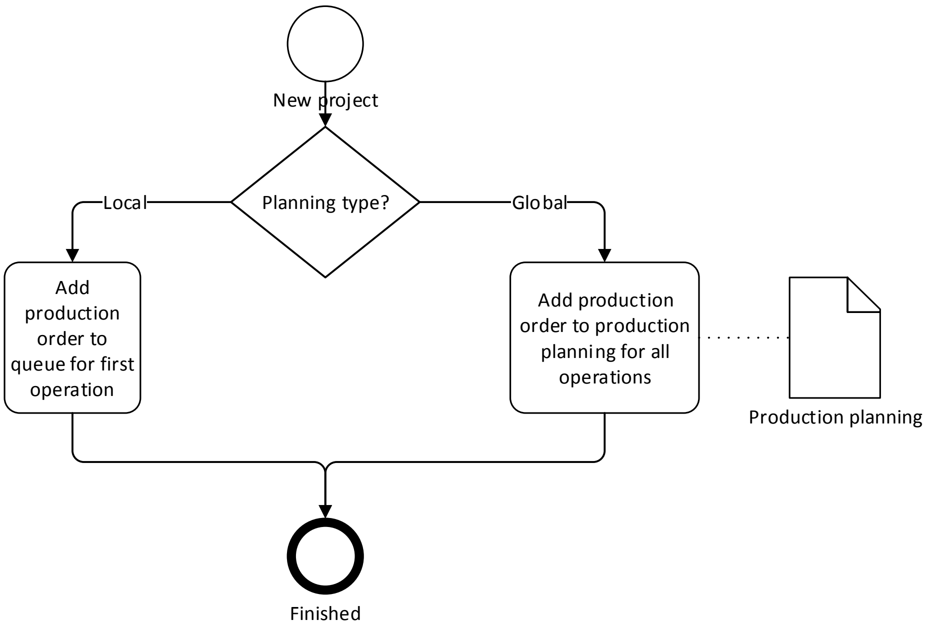

Figure 30: FLowchart global and local production planning

Figure 30 does not directly show another difference between local and global production planning rules. A global production planning rule is only updated if a new project arrives, whereas local production planning are updated every time that a job finishes processing on a machine. This feature of local production planning is called automatic rescheduling, which global production planning rules do not feature.

Classification scheduling rules

We just described a large variety of scheduling rules and three global planning types. For the sake of clarity, we put all these rules in Table 1 with the different dimensions that we discussed earlier in this report. We also include the global planning methods, namely global forward (GF), global backward (GB) and global hybrid (GH) to compare them to the local scheduling rules. We use the following abbreviations, to make Table 1 readable. They are as follows:

- **Stat.** – Static
- **Dyn.** – Dynamic
- **Indep.** – Independent
- **Dep.** – Dependent

Schedule rule	Time dependent	State of shop	Type of rule	Information	Amount of information
SPT	Stat.	Indep.	Simple rule	Processing time	Local
LPT	Stat.	Indep.	Simple rule	Processing time	Local
EDD	Stat.	Indep.	Simple rule	Due date	Local
FCFS	Stat.	Dep.	Simple rule	Arrival	Local
WSPT	Stat.	Indep.	Weighted	Combination: Processing time and miscellaneous (weight)	Local
MS	Dyn.	Indep.	Weighted	Combination: Processing time and due date	Local
SIRO	Stat.	Indep.	Simple rule	Miscellaneous (random number)	Local
LNOR	Stat.	Indep.	Simple	Number of operations	Local
MNOR	Stat.	Indep.	Simple	Number of operations	Local
FAASFS	Dyn.	Indep.	Simple	Arrival	Local
TW	Stat.	Indep.	Simple	Processing time	Local
Allow	Dyn.	Indep.	Simple	Due date	Local
CR	Dyn.	Indep.	Weighted	Combination: Due date, processing time	Local
A/NORO	Dyn.	Indep.	Weighted	Combination: Due date, number of operations	Local
S/NORO	Dyn.	Indep.	Weighted	Combination: Due date, number of operations	Local
S/WR	Dyn.	Indep.	Weighted	Combination: Due date, processing times	Local
EODD	Dyanmic	Indep.	Simple	Due date	Local
SOS	Dyn.	Indep.	Weighted	Due date	Local
OCRR	Dyn.	Indep.	Weighted	Combination: Due date and processing times	Local
GF	Dyn.	Dep.	Other	Miscellaneous	Global
GB	Dyn.	Dep.	Other	Miscellaneous	Global
GH	Dyn.	Dep.	Other	miscellaneous	Global

Table 1: Classification of the scheduling rules

4.2.3 Due date setting

If we would change the type of planning, the release and due dates automatically change. Therefore, we need to look at the different ways of setting due dates. If we know the 'new' due dates, we automatically have our new release dates. Baker and Bertrand provide three ways of due date setting, which are as follows (Baker & Bertrand, 1981):

- **Constant allowance.** The production order is given a constant amount of slack, regardless of the necessary process time.
- **Slack.** The production order is given a constant amount of slack, on top of the necessary processing time.
- **Total Work Content (TWC).** The necessary process time of a production order is multiplied by a factor, which is the total amount of time that is available to process the production order.

They conclude that the TWC due date setting rule is the best performing of all three. Therefore, we use this rule in the next chapter.

4.3 Conclusions

In the literature review, we looked at several ways for production planning. We basically find two types of production planning, namely global and local. A global production planning makes a production planning, whereas a local production planning does not make a 'real' production planning.
In case of a local production planning, there are two levels. The highest level is order release, which comes in three varieties namely push, pull and hybrid. The second level is order sequencing, which determines the priority of the jobs that are waiting to be processed on a certain machine. There is a wide assortment of so-called priority rules, ranging from simple priority rules such as the shortest processing time priority rule to more advanced ones such as the apparent tardiness cost rule.

The global production planning is different in the sense that the schedule is immediately generated, while a local production planning picks a new job 'on the fly' if a machine is empty.

Furthermore, we looked at three different due date setting rules. We use the TWC rule for modelling, as this is the most powerful rule according to Baker and Bertrand.

5 Solution approach

In this chapter, we discuss the method that we can use to compare the different scheduling rule. First, we discuss the different methods that are available to determine the performance of the scheduling rules from chapter 4. We continue with a description of our model and the data that it uses. We continue with the verification and validation of the model, where we describe whether it behaves as expected and according to the predetermined specifications. Finally, we discuss some technical aspects of the model such as warm-up, the replication length and the number of replications.

5.1 Choosing a method to evaluate production planning rules

There are different ways to evaluate the production planning rules. We give an overview of common tools in literature and their benefits and drawbacks.

- Simulation is quite often used in literature to analyse the performance of different production planning rules. A simulation model is a simplified model of reality and is used to test out different production planning rules. A great benefit of simulation is the ability to include stochastic variables, such as the inter arrival time of orders and the breakdowns of machines (Wein & Chevalier, 1992).
- Analytical analysis of the production planning rules. Analytic analysis guarantees the performance of a production planning rule, whereas a simulation study only shows the average performance (Schmidt, 2000).

We would like to use simulation to analyse the production planning methods, because it requires no restrictive assumptions and simulation is a very transparent method (Robinson, 2004). Other methods, such as queuing, require restrictive assumptions to analyse queuing networks. An analytical analysis is basically a set of formulas, where simulation is a graphical tool of analysis. This feature enables us to analyse the impact of several events such as a new machine or a breakdown of a machine in future research.

5.2 Conceptual model

In this section, we discuss the conceptual model that we use to build our simulation model. The conceptual model is based on the current situation, as we described earlier on in this report.
We first describe the basic components of the model, continue with a description of the conceptual model and finish with the different assumptions that we made while modelling.

5.2.1 Basic components

Our simulation model requires five basic components, which are deterministic variables, stochastic variables, input, output and scenarios. We briefly discuss these four basic components. Stochastic variables are variables that are random. 'Normal' variables can be influenced in the simulation model; these are settings that can be changed. Input is all the data that is fixed. Output is the data that the simulation model generates, which is the basis for decision making. The foundation for all the experiments are the different scenarios. They are based on a set of variables, each with its own specific range. A combination of a set of variables with specific values is called a scenario. These four categories are visualized in Figure 31.

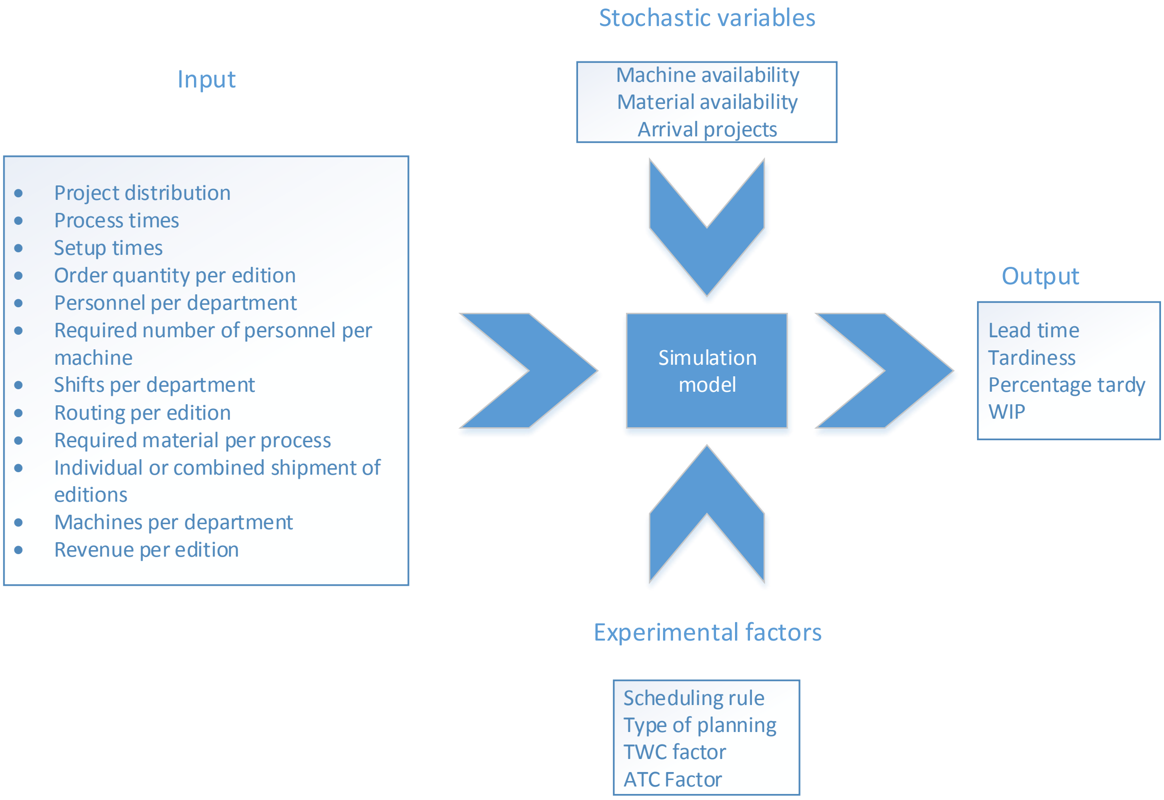

Figure 31: Overview components simulation model

We now give a short description of the four components.

5.2.1.1 Input

As explained earlier, input variables are basically the data that the model needs in order to run. We are using the following input data:

- **Project distribution.** The simulation model take into account a lot of historic data. This data includes information like the delivery date and the number of editions per project.
- **Process times.** Per process, a certain amount of time is necessary in order to process a production order. This input table contains the required amount to do so.
- **Setup times.** Especially for both print presses, setup times are vital. An 'efficient' planning takes these setup times into account, and clusters production orders with the same characteristics in order to avoid unnecessary changeovers.
- **Order quantity per edition.** The order quantity determines the amount of time necessary process an order, and can also be used as an allocation formula to get the performance of certain scheduling methods.
- **Personnel per department.** The number of people that work at a department.
- **Required number of personnel per machine.** This is the required number personnel that is necessary in order to let the machine run.
- **Shifts per department.** The current number of shifts per department.
- **Routing per edition.** All the different processing steps per edition.
- **Required material per process.** The required number of material, in order to start the process.

- **Individual or combined shipment of editions**. Editions are shipped individually or per project.
- **Machines per department.** We need to know which machines are on which department, as the personnel is organized per department.
- **Revenue per edition.** Revenue is used as an allocation formula to get a single performance indicator.

5.2.1.2 Stochastic variables

The simulation model uses three stochastic variables in total, they are as follows:

- **Machine availability.** This includes for example machine breakdowns. When is the machine available to produce?
- **Material availability**. Often, material is specifically ordered for a certain production order. Therefore, material has a huge impact on the production process. The wrong quality or quantity of a product results in that a certain activity cannot start.
- **Arrival projects.** We analysed the inter arrival times of projects and use this stochastic variable to 'generate' new projects.

5.2.1.3 Experimental factors

A combination of a set of experimental factors is called an experiment. The interpretation of the different factors is as follows:

- **Scheduling rule**. As discussed before, there are a lot of different scheduling rules. We use the rules that we found earlier in our literature research.
- **Type of planning.** There are basically two levels in production planning, namely order release and the order sequencing. The type of planning is about order release, which can be done forwards, backwards and hybrid.
- **TWC factor.** The total work content factor is a multiplier, which multiplies the total amount of work that needs to be done with a TWC factor. The result is used in the production planning, where the TWC factor is used to determine when a production order should be released.
- **ATC factor.** This is the factor for the scheduling rule apparent tardiness cost. The ATC factor determines the ratio between the weights of the two scheduling rule minimum slack and the weighted shortest processing time.

5.2.1.4 Output

We use four performance indicators, namely lead time, tardiness, percent tardy and work in progress. Lead time is defined as the time between the first and the last activity of a production order. If a whole project is shipped at once, the model takes the maximum lead-time of all individual production orders. The second performance indicator is tardiness. This is defined as the time that production order is finished beyond its due date. The same logic that goes for lead time applies here, as the simulation model takes the maximum tardiness of all editions if the project is shipped at once. We specifically do not use lateness, as it is defined as $Lateness = Completion\ date - Due\ date$ (Li, Yang, & Ma, 2011). This means that theoretically delivery beyond due dates can be compensated by delivering before due date, as lateness gives an average. Percentage tardy is the percentage of projects that is shipped beyond the due date.

5.2.2 Description conceptual model

In this section, we are going to discuss our conceptual model. We start with an overview of our model, and later on tell more about some specific parts of the model.

Our model starts when a new project arrives. As described earlier, one project can contain multiple editions. For instance, the French bible contains nineteen editions. These different editions often share the printed pages, but the cover is different. Each production order is given a set of characteristics, such as the order quantity, release- and due date. This is visualized in Figure 32.

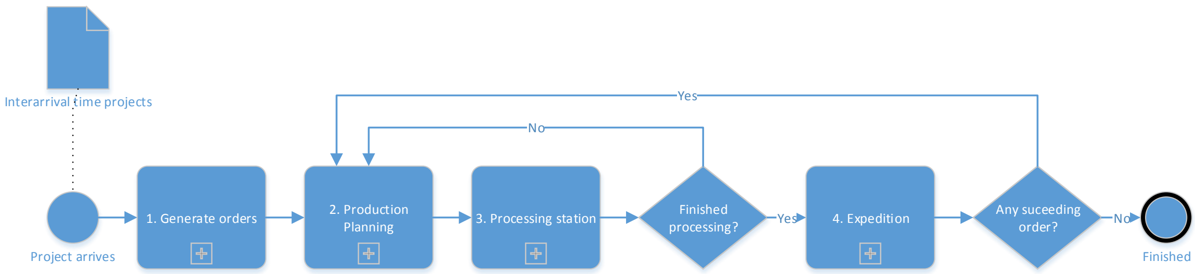

Figure 32: Global overview of our simulation model

The next step is to update the production planning. Production orders are added to the production planning and the affected machines are rescheduled. The production order is processed, until all steps are finished. The production order is shipped to the expedition, regardless whether it is finished or not.

If there is any succeeding production order, the production planning is triggered again. The method checks whether the succeeding production order is allowed to start. If so, the method adds the succeeding order to the planning.

As we announced earlier in this report, we now look at all the individual steps. We start with generating orders. Again, projects arrive according to the inter arrival time of orders. This is shown in Figure 33.

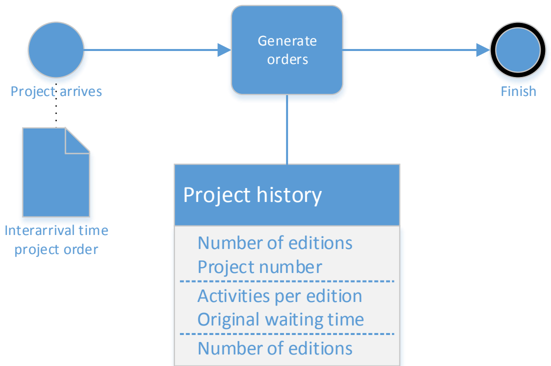

Figure 33: 1. Generate orders

After a new project arrives, all the production orders are created. All the necessary information is written into the production order. Next is the planning of the production orders. They are added to the production planning (or scheduled for a start in the future if the type of planning is either backwards or hybrid). We first discuss the local production planning, which is shown in Figure 34.

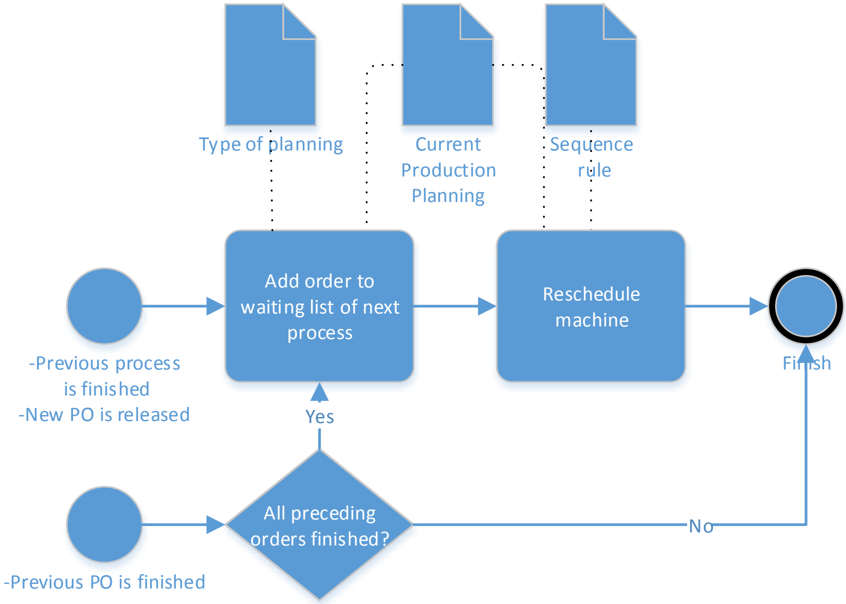

Figure 34: 2. Production Planning – Local planning

There are two different start events. The first one is the 'normal' start event, which is triggered if a process is finished or a new production order is released. The second start event is triggered whenever a complete production order is finished. The method checks whether all required semi-finished products (which in fact are production orders) are ready. We now use the French bible as an example to illustrate the second start event.

The French bible just finished at the sewing stations. All the covers were already present, as they were outsourced to China and only needed a blind embossing. This means that the two semi-finished products are present, together making it possible to start with the final production order which is binding the book. Basically, the book block (which just finished at the sewing station) is inserted into the cover.

If a production order is added to a machine, the concerned machine is rescheduled using the sequence rule. The production order is processed immediately if the machine is free. If not, nothing is done.

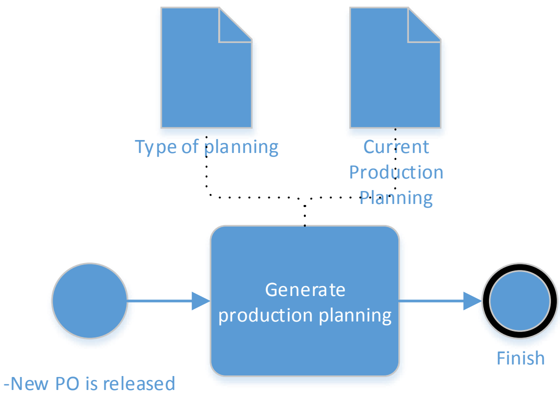

Figure 35: 2. Production Planning - Global planning

We just described the production planning for the local production planning. Now we continue with the global production planning shown in Figure 35, which is simple compared to the local production planning. The production planning method is only triggered if a new production order is released. If this is the case, this order is added the already existing production planning given the type of global planning (which is forward, backward or hybrid). The actual processing is shown in Figure 36.

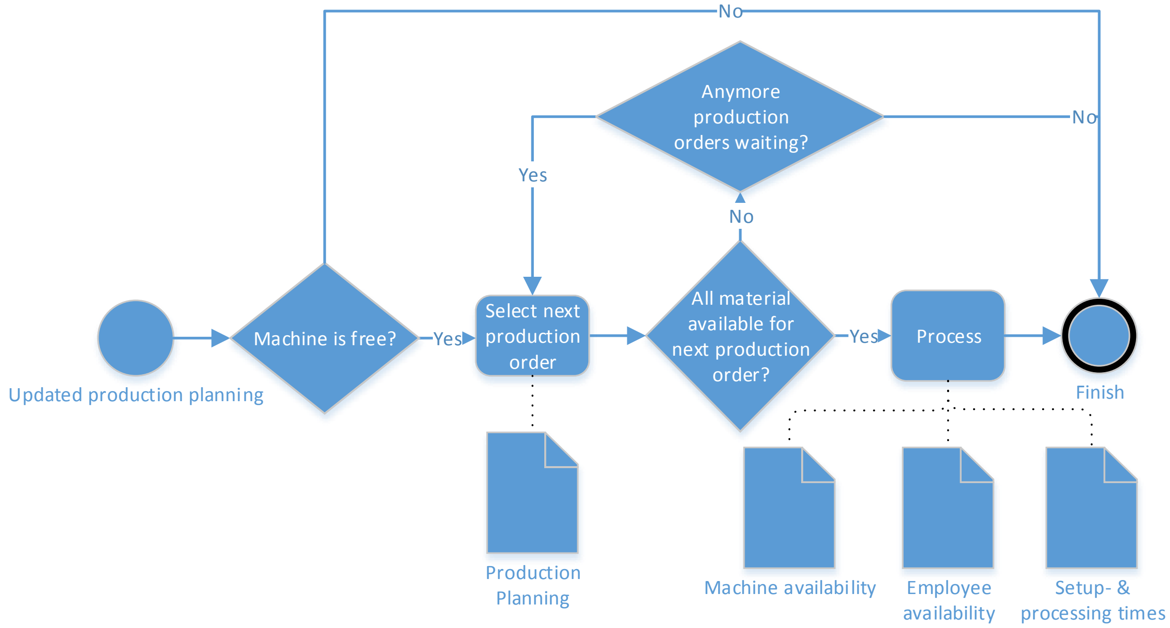

Figure 36: 3. Processing Station

The method in Figure 36 starts a trigger, which is an updated production planning. The next job is selected, and the simulation model checks if all necessary material is available. If so, the model processes the production order using employee availability and the corresponding setup- and processing times. If not, the method checks whether there are any other production orders waiting. The next production order is processed, if there is any. If not, the method stops here.

If production order that just arrived is the last one, an edition is transported to the expedition department. A flowchart of this department is presented in Figure 37.

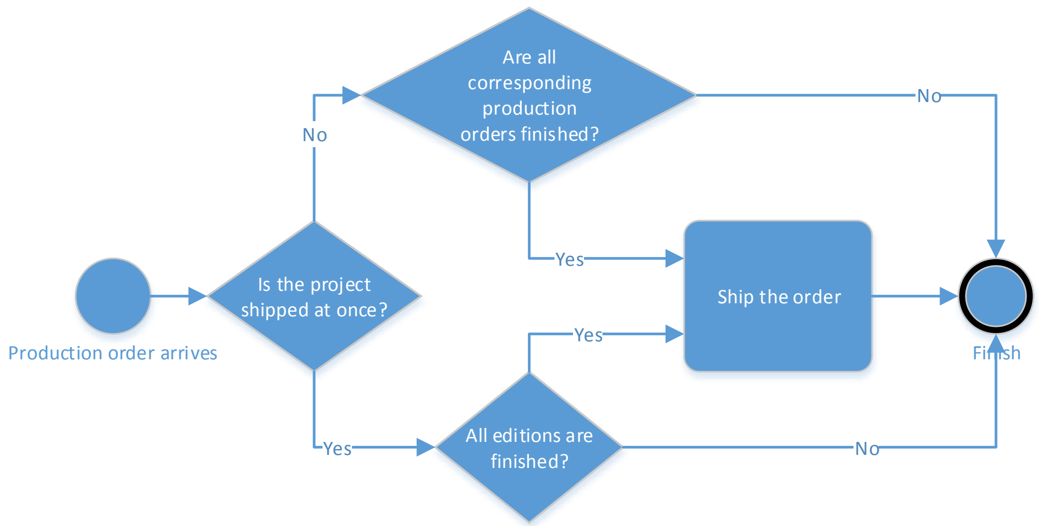

Figure 37: 4. Expedition

The first gateway contains a confusing question. Sometimes, editions are shipped individually. This is quite logical, as softcovers have a smaller lead time compared to luxurious books. The manufacturing of the book starts at the same time, as the content of the book is often the same. This means that 'simple' books finish early and are therefore shipped in advance. This is not always true, occasionally orders are expedited. To summarize, if all editions are shipped at once means that the complete project is shipped at once.

5.2.3 Assumptions

It is impossible to include the complete reality in a simulation model, as such a model takes forever to execute. Therefore, during modelling, we made several assumptions to produce a model. The different assumptions are:

- Infinite space to store products, in both buffers and waiting areas.
- People do not get ill or take a day off.
- The order confirmation contains all specifications.
- Information is freely available, and always up to date.
- Processing times are fixed. The simulation model uses the actual number of hours, instead the expected amount of hours.
- The average mean time to failure and the mean time to repair of the last three years for machines that keep track of the OEE is representative.
- Machines that do not track OEE do not fail.

5.3 Simulation model

This section includes a description of all aspects of our simulation model. We start with the data analysis, which is necessary in order to get input for the model, continue with a general description of the simulation model, and finish with discussing several technical details of the simulation model.

5.3.1 Data analysis

The simulation model needs quite a large amount of data in order to run. This section is different compared to section 3.2.7 because we here analyse the necessary data for the simulation model. In section 3.2.7, we investigated the causes for the waiting time. This is not directly related to for example processing times. Every single variable that was earlier stated as input needs to be defined, in order to get a working model. A lot of data can be obtained easily, as the data is formatted in the correct way. An example of data that was easy to access are the required materials per process per production order. We used the new Business Intelligence tool to get this information, which luckily could be almost directly imported into our simulation model.

Not all information was freely available. An example is the hierarchy of production orders. We need the hierarchy of production orders, in order to know which production orders starts when and what production order 'consumes' one another. The hierarchy of a 'normal' production order is shown in Figure 38.

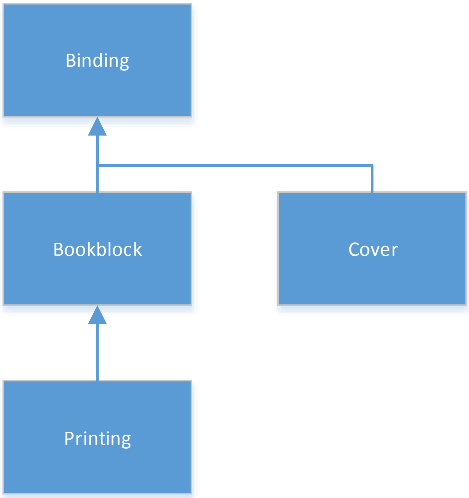

Figure 38: Hierarchy production orders within one edition

The logic behind Axapta (which is Jongbloed's ERP system) is as follows. The binding production order consumes two production orders, namely the bookblock- and the cover production order. Furthermore, the bookblock production order consumes the printing book block order. After using an incredible amount of Excel formulas, we were able to figure out the complete route of all production orders.

Once we got the hierarchy of all production orders per edition, we wanted to know all the processes per production order. Again, after some programming in Excel we got the chronological order of process per production orders. However, finding the setup time and the process time per activity was not so easy. We wanted to find a theoretical distribution for the processing time of each process, such that the processing times vary. However, finding a suitable theoretical distribution is not always possible. Therefore, we use a combination of the empirical and theoretical distributions. In total, we need to test 76 datasets. Due to the large amount of testing that needs to be done, we use Plant Simulation's statistical software to find a theoretical distribution for the processing time of each process. It is able to test twelve common theoretical distributions, which are binomial, geometric, poisson, beta, Erlang, negative exponential, gamma, log normal, normal, triangle, uniform and Weibull. The complete description of all datasets is done in Appendix B.

A final hurdle for us was the theoretical distribution for the interarrival time of projects. The idea of a simulation model is the arrival of new projects use some kind of pattern, which is called the interarrival distribution. A theoretical distribution is always preferred to using the historic data, as historic data is always limited. For instance, we 'only' have access to five years of interarrival times. Therefore, we would like to find a theoretical distribution that represents our interarrival data. Such a distribution is not limited to five years of history, but is able to simulate years of arrival of projects and the distribution can easily be modified. We first plotted the interarrival times, to possibly recognize the pattern of a known theoretical distribution such as the Poisson distribution (Law, 2007). An overview of the interarrival time of the projects is visible in Figure 39.

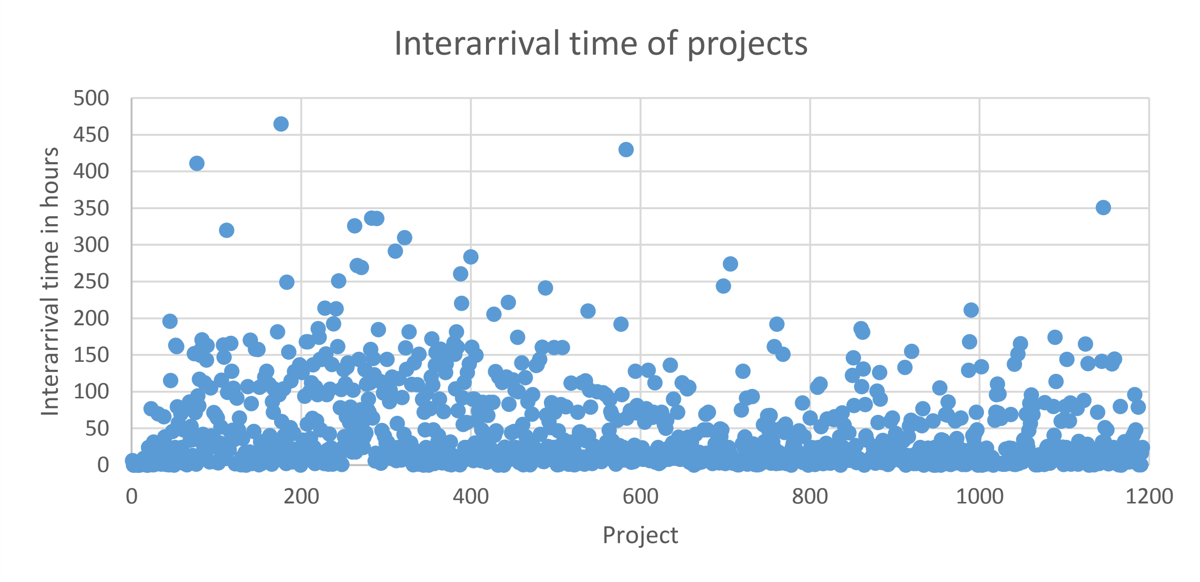

Figure 39: Interarrival time projects

We chronologically plot the arrival of projects in the past on the x-axis. The y-axis contains the interarrival time in hours. We define the arrival of a project as the first time that a project is processed. The graph above looks quite random, therefore we construct a histogram. To construct a histogram, we need the number of bins and the bin ranges. The number of bins is calculated using the square root of n rule, which is a common rule of thumb. Our data has 1192 observations, which gives us 35 bins after rounding. We use a technique called the chi-square test later on, to check the fit between the real data and the theoretical distribution. To give us an idea about a suitable theoretical distribution, we first make a histogram. This is shown in Figure 40.

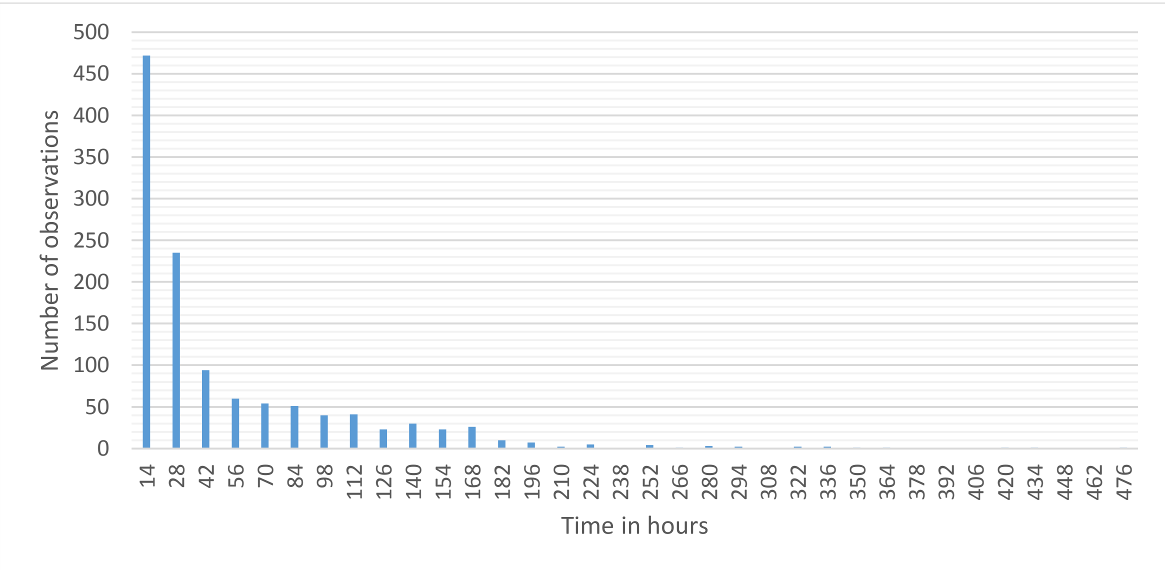

Figure 40: Histogram of interarrival data

Figure 40 looks like an exponential distribution. We hypothesize the exponential distribution and use this distribution to calculate the bin ranges. We use the chi-square test to check the fit between the real data and the theoretical distribution. We find a chi-square test value of 377.62. If the fit between the theoretical distribution and the data is reasonable given an α of five percent, the test value should be below 48.6. α is used as a variable to measure the fit between the theoretical distribution and the real data. It is common in statistics to use five percent for alpha. A good fit is certainly not the case. We now use the statistical software called MiniTab to check whether there is a theoretical distribution that fits the data. The program analyses the data, and picks four theoretical distributions that are most likely to represent the data. The result of this test is shown in Figure 41, which tests the interarrival times against for the following distributions: a normal distribution, a 3-parameter log normal, a 2-parameter exponential and a 3-parameter weibull distribution. Figure 41 shows two test statistics and a P-P plot for each distribution that we test.

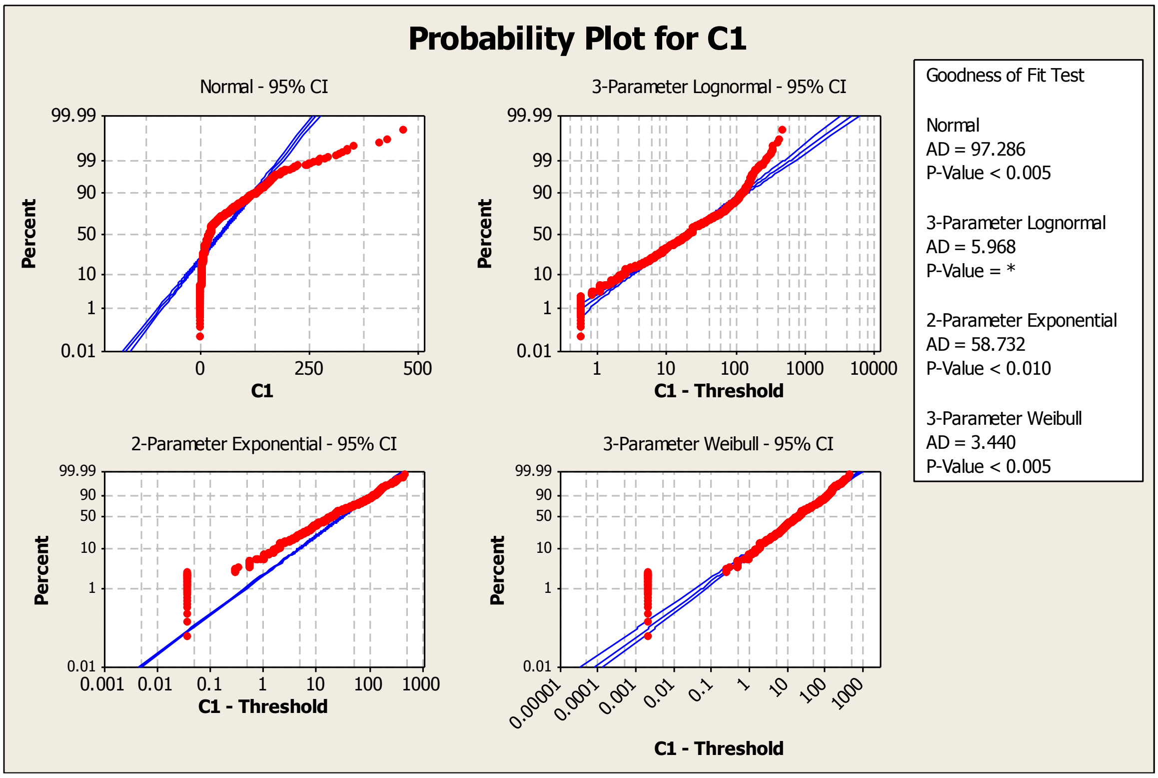

Figure 41: MiniTab result with C1 as the variable for interarrival times

MiniTab uses two test statistics, namely Anderson-Darling (AD) test and Pearson's goodness of fit test. The AD test is similar to the chi-square test with regard to accepting or rejecting a certain theoretical distribution. If the test statistic exceeds a given critical value, the tested theoretical distribution can not be used. The test result above show a promising fit between the data (red line) and the theoretical distribution (blue line). Especially the 3-parameter lognormal distribution appears to have a good fit with the data. However, if we compare the AD values which are show on the right side of the picture, none of the tested theoretical distributions are suitable. Also, the value of Pearson's goodness of fit test does not surpass a conventional value of alpha of 0.05.

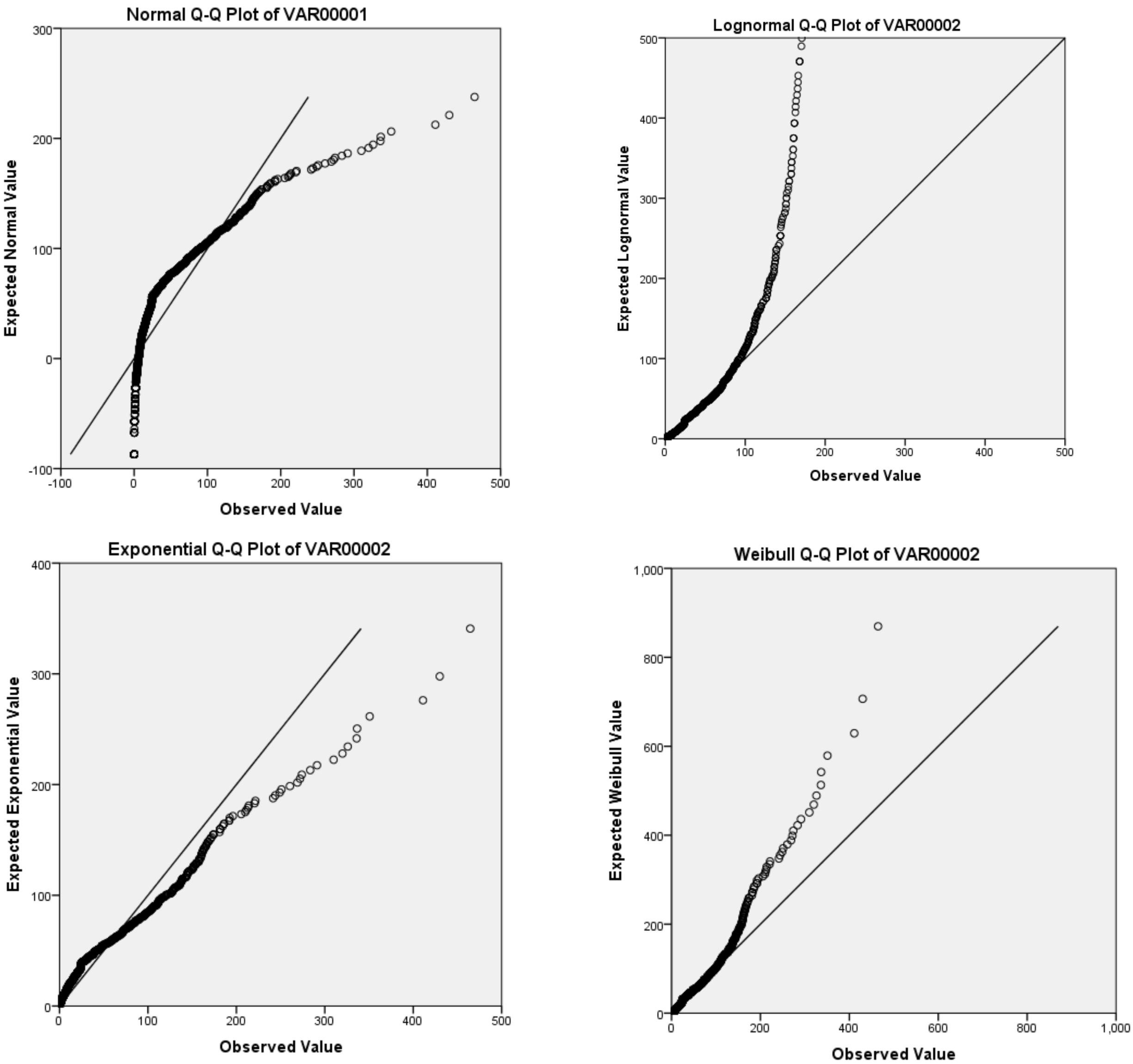

Figure 42: Q-Q plots of the four distributions

Figure 42 shows a Q-Q plot of the four distributions that we test, in the same order as Figure 41. Noticeable is the bad fit of the lognormal distribution. In Figure 41, it uses a different scale and therefore the fit of the lognormal distribution in Figure 41 looks fine. Still, none of the four distributions show a great fit. We must note that we have a total of 1192 observations, hence finding a fitting distribution is nearly impossible. To conclude, we are forced to use the empirical distribution as shown in Table 2. We constructed this table using Plant Simulation's DataFit.

Each bin has the a probability of $\frac{Number\ of\ observations\ in\ bin}{Total\ number\ of\ observations}$ to be drawn. After drawing a bin, the model picks a random value within a bin and uses that value as the next interarrival time. Therefore, the distribution is continuous.

Bin	Left bound (Day:Hours:Minutes:Seconds. Milli Seconds)	Right bound (Day:Hours:Minutes:Seconds. Milli Seconds)	Number of observations
1	0	13:39:42.4	462
2	13:39:42.4	1:03:19:24.7059	243
3	1:03:19:24.7059	1:16:59:07.0588	91
4	1:16:59:07.0588	2:06:38:49.4118	58
4	2:06:38:49.4118	2:20:18:31.7647	52
5	2:20:18:31.7647	3:09:58:14.1176	53
6	3:09:58:14.1176	3:23:37:56.4706	36
7	3:23:37:56.4706	4:13:17:38.8235	38
8	4:13:17:38.8235	5:02:57:21.1765	32
9	5:02:57:21.1765	5:16:37:03.5294	26
10	5:16:37:03.5294	6:06:16:45.8824	24
11	6:06:16:45.8824	6:19:56:28.2353	27
12	6:19:56:28.2353	7:09:36:10.5882	13
13	7:09:36:10.5882	7:23:15:52.9412	7
14	7:23:15:52.9412	8:12:55:35.2941	4
15	8:12:55:35.2941	9:02:35:17.6471	5
16	9:02:35:17.6471	9:16:15:00.0000	2
17	9:16:15:00.0000	10:05:54:42.3529	2
18	10:05:54:42.3529	10:19:34:24.7059	2
19	10:19:34:24.7059	11:09:14:07.0588	3
20	11:09:14:07.0588	11:22:53:49.4118	2
21	11:22:53:49.4118	12:12:33:31.7647	1
22	12:12:33:31.7647	13:02:13:14.1176	1
23	13:02:13:14.1176	13:15:52:56.4706	2
24	13:15:52:56.4706	14:05:32:38.8235	2
25	14:05:32:38.8235	14:19:12:21.1765	1
26	17:01:51:10.5882	17:15:30:52.9412	1
27	17:15:30:52.9412	18:05:10:35.2941	1
28	18:18:50:17.6471	19:08:30:00.0000	1

Table 2: Interarrival times

5.3.2 Description

In this section, we give a small description of the model. The full description is done in appendix C, an overview is given in Figure 43.

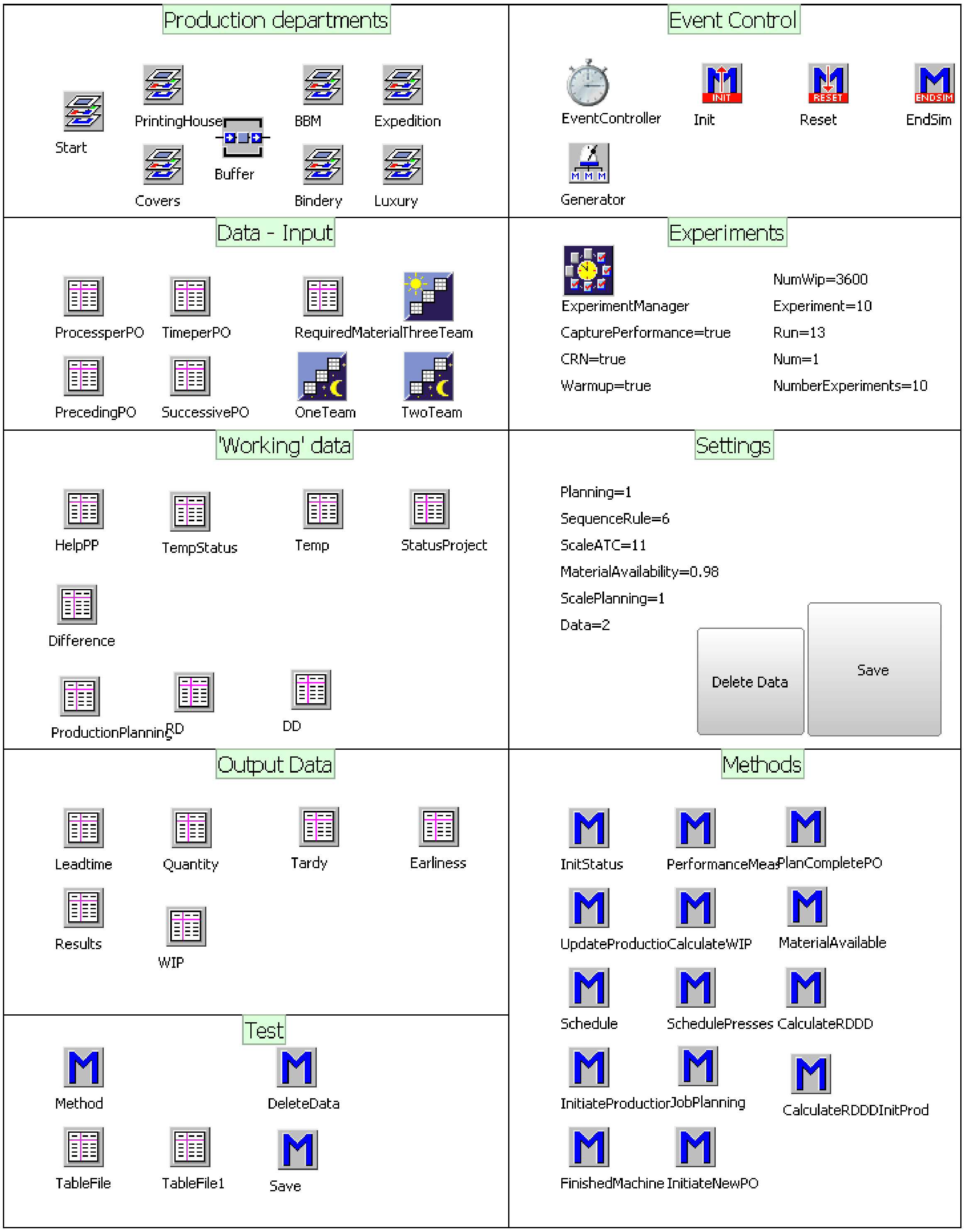

Figure 43: Simulation model main screen

All the green comments in Figure 43 represent different 'categories'. We give a short description of each category.

5.3.3 Production departments

The production departments contains all the different departments. The 'category' Start is the department where production orders are generated, after processing they are transported to the expedition department. This is exactly the same as discussed earlier in the conceptual model. New projects arrive according to the interarrival time that we just discussed. After arrival of a new project, the simulation model randomly picks a new project and produces all the production orders and starts generating the production planning. Once all production orders are processed, the project is shipped and the performance is registered.

5.3.4 Event Control

Event Control is the backbone of the simulation. Especially the Event Controller is important. An Event Controller coordinates all the different processes and makes simulation possible. The init and reset method are used to bring the simulation to its initial and thus empty state. These methods, together with the Experiment Manager, allow us to do multiple so-called replications without having to manually reset the simulation model. Each replication uses a different set of random numbers, which means that we get different results from every replication. One replication means running the simulation model for a certain amount of time, so that we can evaluate the performance of the system.

5.3.5 Data input

Most of the data input is stated in this category. However, the input data that is necessary for creating projects is somewhat 'hidden' under production departments. All the data on the main screen is gathered from Jongbloed's ERP system and the OEE of several machines. Some tables with data have cryptic names, such as OneTeam. OneTeam, TwoTeam and ThreeTeam contain the working for respectively one, two and three shifts. These working hours are linked to the different departments.

5.3.6 Experiments

As described earlier, an experiment is defined by a set of variables. Executing different experiments enables us to give advice on the best production planning rules. The experiment manager is used to enter all the experiments and controls these, such that these do not have to be entered manually. In the experiment manager, we define the settings for the simulation models which are experimental factors. An example of an experimental factor is the type of production planning, which could be either global or local. Thus, an experiment is a set of experimental factors, each with a certain value.

5.3.7 'Working' data

'Working' data contains all the tables that are used to store and retrieve data. One example is the StatusProject table, which contains the relation between production orders. This table is used when a production order is finished, if there is any succeeding production order. Programming this relationship was hard, as normally one production order contains all the different processes. However, at Jongbloed processing two production orders simultaneously is possible. An example is embossing covers and sewing bookblocks, which can be done at the same time.

5.3.8 Settings

Settings contain all the experimental factors and settings, which are used by the experiment category. In total, we now have five variables. We briefly discuss them:

- **Planning** – We state in the literature chapter that there are basically two types of production planning, namely local and global. For both global and local planning, there are three types namely forward, backward and hybrid.
- **SequenceRule** – This is the lower planning, if the production planning type is local. If a machine has more than one job waiting to be processed, there are numerous strategies to process them. We just state them here, as we already discussed them in the literature chapter.
    - Shortest Processing Time.

    - Longest Processing Time.
    - Earliest Due Date.
    - First Come First Serve.
    - Weighted Shortest Processing Time.
    - Minimum Slack.
    - Service In Random Order.
    - Least Number of Remaining Operations.
    - Most Number of Remaining Operations.
    - First Arrival At Shop First Served.
    - Total Work.
    - Allowance.
    - Critical Ratio.
    - Allowance / Number Of Remaining Operations.
    - Slack / Number Of Remaining Operations.
    - Slack / Work Remaining.
    - Earliest Operation Due Date.
    - Smallest Operational Slack.
    - Operational Critical Ratio Rule.
- **ScaleATC** – This parameter is specifically for the Apparent Tardiness Cost rule. Earlier, we argued that this rule actually is a combination of two scheduling rules, namely the Weighted Shortest Processing Time rule and the Minimum Slack rule. ScaleATC determines the ratio between these two rules.
- **MaterialAvailability** - Often, material is missing at Jongbloed. The reason could be due to the wrong quantity, quality or even ordering the wrong product. The MaterialAvailability parameter is linked to a binomial distribution, which checks whether all materials are present to start a process. If not all material is available, the production order is taken of the production planning and scheduled to be processed in the future. The event in the future simulates the arrival of the missing materials.
- **ScalePlanning** - If we do not take the 'standard' production planning method, we need to recalculate the due date. In the literature chapter, we discussed that the TWC method is the best way of setting due dates of all reviewed methods. ScalePlanning is the TWC factor.
- **Data** - The variable data indicates what data the planning method uses. If Data is set to one, the simulation model uses the exact processing times to make a planning. However, if Data is set to two the simulation model uses estimates of the processing times to generate the production planning.

5.3.9 Output Data

In the output category, all the performance of the four performance indicators (Leadtime, tardiness, percentage tardy and work in progress) are captured if CapturePerformance is true and the simulation time is higher than warm up period if we set WarmUp to true. Furthermore, the simulation model keeps track of the quantity of all editions that are finished.

5.3.10 Test

This is purely for testing our model. This method collects data about the production orders that are the buffer on the main screen, and prints this into the table 'TableFile1'. Furthermore, there are two methods that save the model and delete all data. These are linked to the buttons on the main screen.

5.3.11 Methods

The methods, combined with the data and the event controller together form the simulation model. They take care of organizing the planning process, both order release and the planning of waiting jobs per machine. The complete description of all the methods is done in appendix C.

5.3.12 Verification and Validation

Verification and validation is an important part of any simulation study. A verified and validated model means that we can safely use our model to run our experiments, as it is programmed according to the specifications and has similar behaviour to the real world. Therefore, we discuss the verification and the validation in the next two sections.

5.3.12.1 Verification

Verification is an important part of the programming the simulation model, which is commonly known as debugging the program. Plant Simulation provides several tools to do so. Especially the tracing function is helpful, as this feature allows us to walk through the programming code (Kleijnen, 1995). This functionality allows us to debug the code and fix mistakes. Kleijnen furthermore addresses modular programming, which is the opposite of so-called 'spaghetti programming'. Our model is divided into a lot of different methods. Each methods covers only one specific topic, for example the schedule method reschedules a machine if the method is triggered by another method. Another way to validate our model is by comparing the output of the simulation model of a statistical distribution to the input. We use a graphical Q-Q plot to compare the processing times of the simulation model to the theoretical distribution. This is shown in Figure 44.

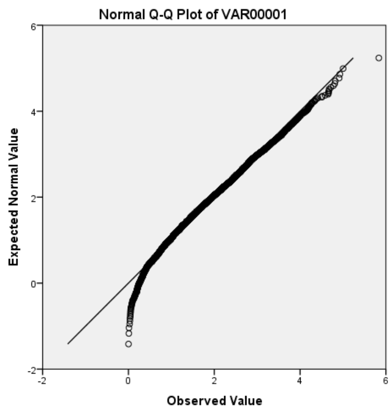

Figure 44: Q-Q Plot Processing times machine 6280

The fit between the theoretical distribution and the processing times around zero is not great. A negative processing time is not possible and we programmed a while loop to find a positive processing time. This specific while loop keeps picking a value from the normal distribution, until the value is positive. Still, the fit beyond the value of 0.25 is good between the observed and the expected values. Another manner to verify the model is by looking at the animation of the simulation model, while the animation is running. The model animation for example made us aware that several MU's (which are production orders in our simulation model) were not being processed. We programmed an error when we added a new MU to the production planning, which made the MU disappear from the production planning. Therefore, the production order was not processed. The last method that we used to verify our model is by doing extreme conditions tests. An example that Sargent states is by checking whether the model produces output while there is no input (Sargent, 2005). We checked this and indeed, if there is no input the model does not produce anything. Another extreme condition that we made up is by reducing the availability of a machine to the almost zero (because an availability of zero is not possible in Plant Simulation), and checking whether the machine was almost always in failure. Indeed, this was the case.

5.3.12.2 Validation

Validation is about checking whether the simulation model represents the modelled system, given the required accuracy. There are several methods available that enable us to validate the model. We briefly discuss them here and argue what we have done to validate our simulation model. Sargent (Sargent, 2005) states that one possible method to check the simulation model is by using one period of all available historical data to build the simulation model and use another period to validate the correctness of the model. In our case, we use the available data of 2012 and earlier to build our model. We did not take 2013 into account because we use the data of 2013 to validate our model. 2013 is similar to 2012 in terms of the production planning method, the number of projects and the distributions. Therefore, we can use the data of 2013 to check our simulation model. If we look at our simulation model, the average lead time in days is 68.6. The data of 2013 has an average lead time of 65.8 days. Given the goal of our study, this difference is sufficiently small.

5.3.13 Experimental setup

We just described the simulation model itself and the verification and validation of the model, but did not yet discuss the other technical aspect of the model. Before running the experiments, we need to know the replication length, the warm-up period and the number of replications. Therefore, discussing the replication length, the warm-up period and the number of replications is done in the subsequent sections.

5.3.13.1 Replication length

There are two types of simulation, namely terminating and non-terminating simulations. According to Law, a simulation is terminating if either of the following applicable to the model:

- A system is emptied, after a certain point in time. An example is the daycare center of a hospital, where the patients leave at the end of the day.
- A point in time, when no further useful information is gathered.
- A time specified by management (Law, 2007).

None of these three statements applies to our model, and therefore our simulation model is non-terminating. We are interested in the steady-state, which is the ‘average’ performance, and thus need a warm-up period. The replication length should be sufficiently long, and we therefore choose for a replication length that is ten times the warm-up period namely 4000 days.

5.3.13.2 Warm-up period

Initially, a simulation model starts empty. If the model is executed, the model ‘fills’ with production orders and eventually turns into a steady state. The time between the empty system and the steady state is the warm-up period and needs to be deleted from the gathered statistics, because in reality we are studying a system in steady state. There are many methods to determine the warm-up period, but Law states that Welch’s procedure is the “simplest and most general” (Law, 2007).

Each experiment has its own specific warm-up period. We would like to find the highest warm-up period, such that we do not need to set it for each individual experiment. A high variability in lead times yields a higher warm-up period, because the output is unstable. A local production planning method provides a high variability in lead times, because the schedule is not ‘fixed’ compared to a global production planning method. Therefore, we only look at local production planning methods. However, we were uncertain what type of local planning and sequence rule gives the highest warmup period. After testing the most ‘extreme’ experiments, we found that the hybrid local production planning method in combination with the apparent tardiness cost as sequence rule returns the highest warm-up periods. Using Welch's procedure, we did ten replications and calculated the moving average using a width of one hundred. This is visualized in Figure 45.

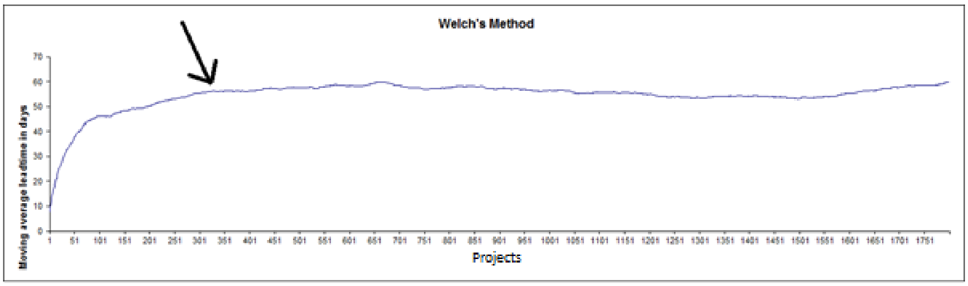

Figure 45: Warm-up period local hybrid planning and apparent tardiness cost as sequence rule

Welch's graphical method states that the simulation model can be considered in a steady state, once the graph becomes stable. In our opinion, this is the case after approximately 320 projects. Using the average interarrival time, which rounded up is thirty hours, we can compute the necessary warm up period. So, the minimal warm-up period is

$$\frac{30\text{ (Interarrival time in hours project)}}{24\text{ (hours per days)}} * 320\text{ (necessary number of projects)} = 400\text{ days}$$

5.3.13.3 Number of replications

To determine the number of replications, we use the replication deletion method. The replication deletion procedure starts with executing two replications. The method divides the confidence interval half width by the average over the two replications, and compares it to the required precision. We use the following formula to compute the required precision: $\alpha' = \frac{1}{1+\propto}$. We use a value of five percent for α, which is common in statistics. The required precision is α'.
If the precision is not sufficient, another replication is executed in order to decrease the confidence interval half width until the required precision is achieved. The same logic that we used to determine the warm-up period is used here, a local production planning rule has more variability in lead time and thus needs more replications in order to achieve the specified precision. We tested all the different local production planning methods and sequence rules, and we found that the forward production planning method in combination with the apparent tardiness cost sequence rule requires the highest number of replications. This is shown in Table 3, the required precision is $\frac{1}{1+0.05} =$ 4.762%

				Confidence interval		
Replication	Result	Cum. mean average	Standard deviation	Lower interval	Upper interval	% deviation
1	70.726539	62.96	n/a	n/a	n/a	n/a
2	62.870634	66.80	5.555	16.89	116.71	74.72%
3	62.008956	65.20	4.804	53.27	77.14	18.30%
4	60.505682	64.03	4.571	56.75	71.30	11.36%
5	69.100931	65.04	4.563	59.38	70.71	8.71%
6	57.580039	63.80	5.093	58.45	69.14	8.38%
7	62.963405	63.68	4.660	59.37	67.99	6.77%
8	68.533493	64.29	4.643	60.40	68.17	6.04%
9	70.536518	64.98	4.817	61.28	68.68	5.70%
10	54.56843	63.94	5.610	59.93	67.95	6.28%
11	66.376	64.16	5.372	60.55	67.77	5.63%

12	63.227513	64.08	5.129	60.82	67.34	5.09%
13	63.232896	64.02	4.917	61.05	66.99	4.64%
14	60.226102	63.75	4.831	60.96	66.54	4.38%
15	71.080027	64.24	5.026	61.45	67.02	4.33%

Table 3: Replication deletion procedure

Table 3 states that we require at least 13 replications, in order to achieve the required precision.

5.4 Experimental design

In this section we describe the method that we use to design our experiments and we then state all the experiments that we execute with our simulation model. There are several methods to create an experimental design. A common method is the 2^k factorial design or classical experimental design. Each individual factor is evaluated at two different values, a high value and a low value. Using the high and low values of each factor, the expected outcomes can be computed. A different experimental design method is the fractional-factorial design method, where only a subset of all possible experiments are executed (Kelton, 2000). The 2^k factorial design and the fractional-factorial design always yield estimates of the performance indicators. We however use a full experimental design as we have enough time available to run all possible experiments. This design requires a lot of computation time. In total, we have four experimental variables that we vary. They are shown in Table 4.

Experimental factor	Minimum	Maximum	Interval	Applicable?
Planning	1	8	1	Always
Sequence Rule	1	19	1	Only if planning is local
Total Work Content Factor	1	10	1	Only if the planning method is not forward or push
Scale ATC	1	10	1	Only if Sequence Rule is ATC

Table 4: Experimental factors and their ranges

Table 4 shows that the experimental factor Planning has minimum value of one and a maximum value of eight, with an interval of one. Therefore, the experimental factor Planning has eight possible values in total. A value between one and four means a local planning method, and a value between five and eight means a global planning method. Earlier, we discussed that local planning methods need a sequencing rule to function because a local planning method does not determine the sequence in which a machine needs to process production orders. Therefore, a sequence rule is only necessary if the planning method is local. The total work content factor is only an experimental factor if the planning method is not forward or push. The scale of the sequence rule apparent tardiness cost is used if the sequence rule apparent tardiness cost is selected and the planning method is local. According to Vepsalainen and Morton, the Scale ATC should be somewhere between one and four and a half (Vepsalainen & Morton, 1987). Just to be sure, we vary the Scale ATC between one and ten. If we would execute all experiments, we would need a total of $8 * 19 * 10 * 10 = 15200$ experiments. However, we can exclude some experiments because they are irrelevant or not plausible.

Factor one (Number)	Factor two (Number)	Factor three (Number)	Factor four (Number)	Number of experiments

Global planning methods (3)	Total Work Content Factor (10)			30
Global planning methods (1)				1
Local planning methods excluding forward/push (3)	Total Work Content Factor (10)	All sequence rule excluding apparent tardiness cost (18)		540
Local planning methods excluding forward/push (3)	Total Work Content Factor (10)	Apparent tardiness cost sequence rule (1)	Scale ATC (10)	300
Local planning forward/push (1)	All sequence rule excluding apparent tardiness cost (18)			18
Local planning forward/push (1)	Apparent tardiness cost sequence rule (1)	Scale ATC (1)	Scale ATC (10)	10

Table 5: Overview experimental design

Table 5 shows an overview of all factors that we vary, for each subset of experiments. We put the number of levels for each factor in parentheses. The number of experiments can easily be calculated by multiplying the four factors.

Using the formula that we just stated, we need a total of 899 experiments. Given that one experiment (with 13 replications and a run time of 4000 days that we found earlier) takes approximately one minute and 45 seconds to execute, we have a total run time of

$$26.22\ hours = \frac{Number\ of\ experiments\ (899) * 1{:}45\ (Run\ time\ in\ minutes\ one\ experiment)}{60\ (Convert\ minutes\ to\ hours)}$$

5.5 Conclusions

We started this chapter with an assessment of two possible methods to analyse the production planning methods and then a description of the model, where we for example described how the different departments interact and what data we use in our model. We looked at the processing times and interarrival times, and concluded that we are unable to find a fitting distribution for the interarrival process. We continued with the verification and validation of the model, where we concluded that the model is suitable for its purpose. The last section in this chapter is the experimental design section, where we discussed the type of experimental design that we used and the number of experiments that we needed. Our simulation model is non-terminating, which means that we had to set a replication length of 4000 days. In each replication, the first 400 days were necessary to get the simulation model in a steady state. We are interested in the steady-state performance of the simulation model, and therefore the performance during the warm-up period is not recorded.

6 Results

In this chapter, we discuss the results that we retrieved from our simulation model. We answer the following research question: "How do the different production planning rules perform on Jongbloed's production?" First, we give a short introduction how we compute the score and then look at the scores of the planning methods. We then continue with the sensitivity analysis, where we vary the weights and test several scenarios. Finally, we give an advice keeping the results of the sensitivity analysis and the analysis of the scores in mind.

6.1 Computation scores

We use this section to explain how we compute the score for each planning method. This would be easy if we would have just one performance indicator. We could then pick the planning method that has the best score on this indicator, as there is no trade-off between two or more indicators. If we would have two performance indicators, we could use a so-called efficient frontier to express the performance of two performance indicators (Merton, 1972). This method is mainly used in the financial field to analyse portfolios of assets. All planning methods then can be plotted in a graph such as Figure 46. Each dot represents a planning method, with for example lead time on the x-axis and work in progress on the y-axis. All the dots that are located on the line are Pareto efficient. Dots that are not placed on the line are not optimal, as we could improve either lead time or work in progress by using a planning method that is located on the efficient frontier.

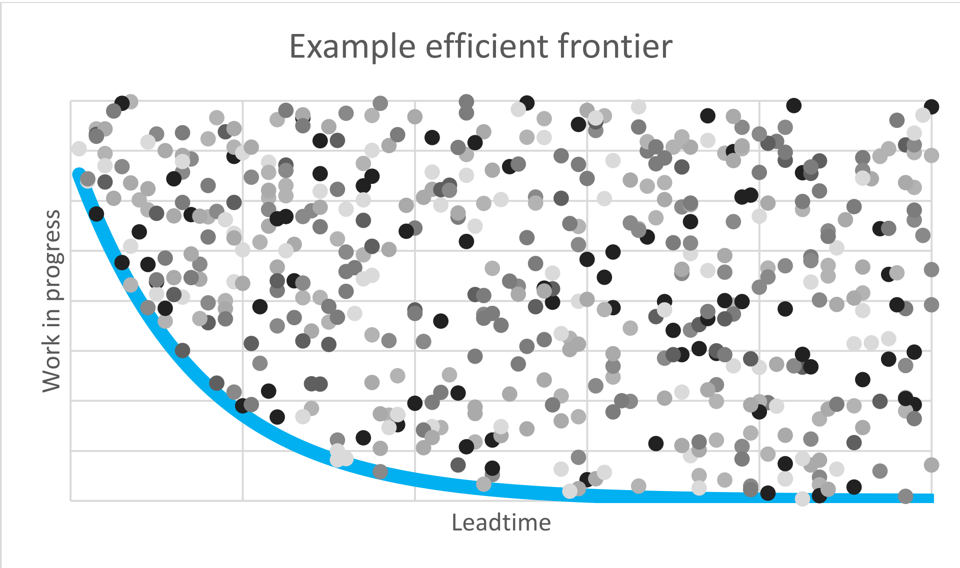

Figure 46: Example efficient frontier

However, we use a different method to distribute the weights over the four performance indicators, because calculating the efficient frontier for four performance indicators is hard to show graphically. We asked the involved employees to distribute a total weight of one hundred points over the four performance indicators, where a high weight equals an important performance criterion. After obtaining the different weights, we took the average for each performance indicator and rounded each weight. The average weights are shown in Table 6.

Performance indicator	Current
Leadtime	18
Wip	28
%Tardy	37

Tardy	17

Table 6: Weight performance indicators

The different performance indicators have various scales and therefore need to be normalized. We used a linear scoring method to determine the scores, as there is no clear preference for either low or high scores on any of the four performance indicators. Our method uses the following formula to compute the overall score.

$$Overall\ score = \sum_{i=1}^{4} Score_i * Weight_i$$

The variable i is the number of the performance indicator. By summing over all four performance indicators, we get the overall score. We analyse these scores in the next section, namely 6.2.

6.2 Analysis planning methods

In this section, we describe the results that we got from the simulation model. Table 7 shows the top thirty of all 618 experiments, using the weights that we stated in Table 6. To keep Table 7 compact, we use the following abbreviations:

- **LF** – Local Forward.
- **GF** – Global Forward.
- **LB** – Local Backwards.

We also abbreviated the sequence rules, an overview of all the abbreviations of the sequence rules is given on page 32.

Ranking	Planning	Sequence Rule	TWC Factor	Scale ATC	Leadtime	WIP	% Tardy	Tardiness	Overall score
1	LF	EDD	N/A	N/A	50.74	56.01	0.40	19.96	94.55
2	LF	EODD	N/A	N/A	50.50	56.15	0.40	19.81	94.50
3	LF	MS	N/A	N/A	50.69	56.24	0.40	20.16	94.09
4	LF	SOS	N/A	N/A	50.68	56.35	0.41	20.13	93.51
5	LF	A/OR	N/A	N/A	51.32	56.49	0.40	20.80	92.74
6	LF	S/OR	N/A	N/A	51.53	57.87	0.40	20.50	91.89
7	LF	ATC	N/A	9	50.46	57.04	0.45	21.09	88.82
8	LF	ATC	N/A	1	50.62	56.92	0.45	21.17	88.52
9	LF	ATC	N/A	10	50.57	57.26	0.45	21.16	88.49
10	LF	ATC	N/A	2	50.67	57.13	0.45	21.01	88.38
11	LF	SPT	N/A	N/A	52.32	52.18	0.37	25.72	88.32
12	LF	ATC	N/A	5	50.58	57.57	0.46	20.99	88.11
13	LF	ATC	N/A	4	50.61	57.71	0.46	20.95	88.10
14	LF	S/WR	N/A	N/A	51.39	58.34	0.45	20.83	88.05
15	LF	ATC	N/A	7	50.78	57.35	0.45	21.27	87.83
16	LF	ATC	N/A	8	50.92	57.57	0.45	21.24	87.57
17	LF	ATC	N/A	3	50.99	57.84	0.45	21.22	87.36
18	LF	FASFS	N/A	N/A	51.30	59.29	0.43	22.24	87.28
19	LF	CR	N/A	N/A	51.49	58.61	0.45	21.17	87.21

20	LF	ATC	N/A	6	51.01	57.95	0.46	21.52	86.86
21	LF	FCFS	N/A	N/A	51.03	56.79	0.44	24.04	85.03
22	GF	N/A	N/A	N/A	51.02	57.94	0.44	24.14	84.72
23	LF	MNOR	N/A	N/A	52.20	60.33	0.42	25.27	82.13
24	LF	LNOR	N/A	N/A	51.70	59.91	0.43	26.48	80.12
25	LF	Random	N/A	N/A	53.05	59.43	0.43	27.44	78.44
26	LB	SPT	7	N/A	57.02	62.46	0.41	25.16	78.29
27	LB	CR	6	N/A	56.78	60.64	0.45	23.68	77.98
28	LB	SPT	8	N/A	57.06	62.68	0.40	25.79	77.87
29	LB	SPT	4	N/A	57.31	56.62	0.45	24.93	77.74
30	LB	SPT	5	N/A	57.31	59.33	0.43	25.04	77.67

Table 7: Results top 30

The performance of the local forward planning methods is good, compared to other planning methods. It seems that planning methods with a low work in progress, such as a backwards local planning method and a low total work content factor such as one or two, do not perform well on the other three performance indicators. Therefore, they do not finish in the top thirty. The planning method that Jongbloed currently uses does not finish in the top thirty, because it does not perform that well. The difference between the current situation and the best performing production planning method is 28.5 percent. If we also compare the current production planning method to the best performing global planning method, the difference is 22 percent. The best performing overall production planning method and the best performing global planning method both show a great decrease the level of work in progress, which explains their good performance.

Every form of local planning includes automatic rescheduling, as the production orders on the production planning are only those that can actually be processed. The material is available and the previous processes have all been finished. Global planning methods do not include automatic rescheduling, as the production planning is only updated when a new project arrives. This difference explains the gap in performance between global and local planning methods. We did not include automatic rescheduling for global planning methods, because several production planning packages also do not automatically reschedule. They regard rescheduling as a planner's job, which should be done manually.

6.3 Sensitivity analysis

Giving weights to the four performance criteria is hard and we therefore like to analyse the impact of different weights and scores. Does the best performing solution change, when the weight of for example lead time changes from forty to fifty or if the score is 80 instead of 90? We do not do a sensitivity analysis for the scores, as we believe that they are given. A production planning method has certain characteristics which leads to a score. Therefore, varying the scores is not valuable. After doing the sensitivity analysis for the weights, we will evaluate different scenarios. Scenarios can be seen as all variables that cannot be influenced directly by Jongbloed, such as the interarrival time of projects. We want to investigate for which deviations the best performing planning method is still optimal.

6.3.1 Weights

Using VBA (which is a built-in programming language of Excel), we build a script that varies the weights of the four performance indicators, calculates the new score and copies the best performing planning to a worksheet of Excel. Using an accuracy of one point (with a total of one hundred points), we vary the weights of all criteria. After running the script, we got the best performing planning method for each set of weights. This enables us to determine the degree of certainty that the chosen planning method is truly the best.

We take the current solution and inspect what variations in the weights of the performance indicators are possible, without changing the optimal solution. First, we describe the optimal solution for the average weights which is the forward planning with the Earliest Due Date (EDD) sequencing rule. The forward planning in general performs well, especially in terms of the percentage of the projects that is delivered beyond the due date and the average tardiness of projects. The second best planning method is the forward planning in combination with the Earliest Operation Due Date (EODD) sequence rule. Normally, the EODD sequencing rule would outperform the EDD sequencing rule as the EODD rule is more advanced. Earlier, we stated that the EODD sequencing rule generates a due date for each operation. We believe that the estimates of the processing times are not accurate enough to provide precise operation due dates. A more general sequencing rule such as the EDD rule is more insensitive to inaccurate estimates of processing times, as the total processing time is likely to include over- and underestimates of processing times. Table 8 below shows our sensitivity analysis.

Performance indicator	Current weight	Minimum weight	Maximum weight
Leadtime	18	0	21
Wip	28	3	68
Percentage Tardy	37	35	72
Tardy	17	5	20

Table 8: Sensitivity analysis of the weights of the best performing production planning method

We now look at the impact of large changes in weights. What would happen if the weight of leadtime would go beyond 21? The best performing production planning method would then be the local forward planning rule in combination with the earliest operation due date sequencing rule. This rule performs slightly better on the leadtime performance indicator, therefore an increase in the weight of leadtime to at least twenty two would yield the local forward planning rule in combination with the earliest operation due date sequencing rule as the best performing rule.

The WIP performance indicator is relatively stable, large changes in weights do not result in a different optimal production planning rule. We therefore do not further investigate the WIP performance indicator.

The percentage tardy performance indicator is however sensitive to a small change in its weight. If it would decrease from 37 to 35, it would pick a different production planning rule namely the local forward planning rule in combination with the earliest operation due date sequencing rule. This rule performs slightly less on the percentage tardy performance indicator, therefore a decrease of weight on this performance indicator would result in the local forward planning rule in combination with the earliest operation due date sequencing rule as the best performing rule.

Currently, the performance indicator Tardy has a weight of 17. If this would increase to 20, it would again pick the local forward planning rule in combination with the earliest operation due date sequencing rule as the best performing rule. The reasoning is similar to the lead time performance indicator, as the local forward planning rule in combination with the earliest operation due date sequencing rule performs slightly better on the tardy performance indicator compared to the current best performing rule.

We deviated the performance indicator one-by-one, which means that all the weights are relative. A weight of ninety for the performance indicator Percentage Tardy results in a total weight of ten for the other three performance indicators.

A reason why the global production planning methods do not outperform the local global planning rules, is because they do not automatically reschedule when the necessary material is not available. We explicitly did not include automatic rescheduling, as scheduling software packages also do not automatically update the production planning. The planner is responsible for manually updating the production planning, when the necessary material to start a process is not available. Thus, the real world performance of global production planning rules can improve and therefore we also investigated these global production planning rules separately.

For the global production planning rules, the forward production planning rules outperforms all others. It dominates the other global production planning rules on three performance indicators, namely lead time, percentage tardy and tardy itself. However, if the weight of the performance indicator WIP is 95 or higher the best performing rule is the global backward planning method with a total work content factor of one. This is quite logical, as the performance of the global backwards planning method on the WIP performance indicator is superior compared to the global forward planning method.

The excellent performance of the global forward production planning rule on the sensitivity analysis is shown in Table 9, which includes the sensitivity analysis of all global production planning rules.

Performance indicator	Current	Minimum weight	Maximum weight
Leadtime	18	0	100
Wip	28	0	94
%Tardy	37	0	100
Tardy	17	0	100

Table 9: Sensitivity analysis global production planning rules

According to Table 9, the work in progress is allowed to increase to a weight of 95 without altering the forward global production planning rule as the best solution.

6.3.2 Scenarios

In this section, we discuss several scenarios. They are defined as environmental factors that are more difficult to influence, such as the interarrival time of new projects. We are interested in two specific scenarios, one about varying the interarrival times and one about varying the material availability. We first discuss the sensitivity analysis on interarrival times and then continue with the sensitivity analysis of material availability.

6.3.2.1 Varying Interarrival times

Currently, our model uses the interarrival times of historic data. We could change these times to investigate the impact of more/less projects. We expect that the performance deteriorates when the interarrival times increase and the performance improves when the interarrival times decrease. The question in both cases is, by what amount? Furthermore, what decrease/increase interarrival time is allowed without altering the optimal solution?

We would however like to change the interarrival times, in order to check what happens if the interarrival time increases or decreases. We could simply calculate the expected interarrival time and vary this, but this would result in a constant interarrival time. We however take a different approach, by adjusting the bounds of each bin. The number of observations in each bin stays exactly the same, but we do change the bins itself. We alter each bin, from minus five hours until plus five hours with an interval of an hour for the top ten planning methods. We select the best performing planning method for each set of bins and use that in our sensitivity analysis. The results are shown in Table 10.

Bin adjustment	Planning	Sequence rule	LT	Tardy	WIP	% Tardy	Score LT	Score Tardy	Score WIP	Score % Tardy	Overall score
-5 hours	LF	EDD	54.3	22.0	68.1	0.4	1.0	1.0	1.0	1.0	100.0
-4 hours	LF	EDD	53.6	21.0	66.0	0.4	0.6	0.9	1.0	1.0	90.5
-3 hours	LF	MS	52.5	20.7	62.6	0.4	0.9	1.0	1.0	0.9	94.0
-2 hours	LF	EODD	51.6	20.5	59.3	0.4	1.0	0.8	1.0	1.0	95.3
-1 hour	LF	S/OR	50.3	19.6	56.6	0.4	0.8	1.0	1.0	1.0	96.5
Normal situation	LF	EDD	49.5	19.2	54.7	0.4	1.0	1.0	1.0	1.0	100.0
+1 hour	LF	EDD	48.6	19.2	52.0	0.4	1.0	0.9	1.0	0.9	94.9
+2 hours	LF	EDD	48.1	19.1	51.0	0.4	1.0	1.0	1.0	1.0	99.2
+3 hours	LF	A/OR	46.9	18.4	48.6	0.3	0.9	1.0	0.8	1.0	93.9
+4 hours	LF	EODD	46.6	18.6	47.6	0.3	1.0	0.8	1.0	1.0	96.8
+5 hours	LF	A/OR	46.0	18.3	44.7	0.3	1.0	1.0	1.0	1.0	100.0

Table 10: Sensitivity analysis top ten interarrival times

Table 10 directly shows that the earliest due date sequence rule in combination with local forward planning remains the best performing if the interarrival times decreases. However, if the interarrival times increase the slack / operations remaining sequence rule outperforms the earliest due date sequence rule, both in combination with local forward planning. This means that we need to revise our best planning method, if the interarrival time of project increases. Still, the performance of all rules in Table 10 is similar. If we for instance look at a deviation of minus three hours of the bins, the difference between the worst and best performing planning method on the performance indicator leadtime is only 1.86. Still, a large increase in interarrival times again leads to the earliest due date sequence rule in combination with the local forward planning method as the best performing planning method.

The main question is: is it necessary to switch to a different planning method, if the interarrival times change? To answer this question, we use Table 11.

Bin adjustment	Planning	SR	LT	Tardy	WIP	% Tardy	Score LT	Score Tardy	Score WIP	Score % Tardy	Overall score
-3 hours	LF	MS	52.48	20.72	62.64	0.42	0.91	1.00	1.00	0.88	93.98
	LF	EDD	52.85	21.39	63.80	0.43	0.71	0.65	0.75	0.82	75.32
-2 hours	LF	EODD	51.62	20.49	59.35	0.41	0.97	0.76	1.00	1.00	95.32
	LF	EDD	52.34	20.95	60.84	0.42	0.50	0.52	0.70	0.84	68.69
-1 hour	LF	S/OR	50.31	19.57	56.57	0.39	0.81	1.00	1.00	1.00	96.52
	LF	EDD	50.48	19.78	57.08	0.39	0.70	0.88	0.83	0.92	84.81
+3 hours	LF	A/OR	46.95	18.37	48.59	0.34	0.93	1.00	0.83	1.00	93.93
	LF	EDD	47.86	18.92	49.24	0.36	0.19	0.68	0.59	0.79	60.76
+4 hours	LF	EODD	46.65	18.57	47.57	0.34	1.00	0.82	1.00	1.00	96.79
	LF	EDD	47.30	19.23	49.11	0.35	0.65	0.59	0.50	0.90	69.01
+5 hours	LF	A/OR	45.97	18.32	44.71	0.32	1.00	1.00	1.00	1.00	100.00
	LF	EDD	46.49	18.87	47.32	0.40	0.59	0.60	0.24	0.04	28.91

Table 11: Comparison sensitivity analysis

We only look at the bin adjustments where the best performing planning method for the current situation is not altered. Table 11 shows that keeping the local forward planning rule in combination with the EDD sequencing rule regardless of changes in interarrival times results in reasonable low penalties. The differences in scores are significant, but that is only because we calculate the scores based on the top ten planning methods and not all planning methods.

We now take a look at the global planning method. Again, we select top ten and evaluate these at the same interarrival times that we did for the overall top ten planning rules. The results are visible in Table 12.

Bin adjustment	Planning	Leadtime	Tardy	WIP	Percentage Tardy	Score Leadtime	Score Tardy	Score WIP	Score % Tardy	Overall score
-5 hours	GF	57.95	28.95	75.08	0.52	0.10	0.47	0.96	1.00	73.78
-4 hours	GF	55.31	27.21	69.52	0.49	0.14	1.00	1.00	1.00	84.49
-3 hours	GF	55.36	27.46	68.96	0.48	0.11	0.88	0.97	1.00	81.16
-2 hours	GF	53.39	25.60	65.31	0.47	0.13	1.00	1.00	1.00	84.40
-1 hour	GF	51.92	24.87	59.76	0.44	0.15	1.00	1.00	1.00	84.73
Normal situation	GF	51.02	24.14	57.94	0.44	0.16	1.00	1.00	1.00	84.82
+1 hour	GF	50.98	23.82	57.28	0.44	0.13	1.00	1.00	1.00	84.30
+2 hours	GF	49.21	22.65	53.26	0.41	0.17	1.00	1.00	1.00	84.98

+3 hours	GF	48.73	22.91	51.13	0.41	0.15	1.00	1.00	1.00	84.68
+4 hours	GF	48.48	22.83	51.39	0.40	0.15	1.00	1.00	1.00	84.73
+5 hours	GF	47.79	22.51	48.77	0.39	0.15	1.00	1.00	1.00	84.66

Table 12: Sensitivity analysis interarrival times global planning method

Table 12 shows us that all the global forward planning method outperforms all the other global planning method, regardless of the change in interarrival times. Therefore, the global forward planning method can be seen as a stable solution among all the global planning methods.

6.3.2.2 Material availability

In this section, we describe our sensitivity analysis on material availability. We first look at the overall top ten, and then discuss the sensitivity analysis on material availability on global planning method. Normally, the material availability is fixed at 98 percent. We vary the material availability between ninety and almost one. The results are visible in Table 13.

Material Availability	SR	LT	Tardy	Wip	% Tardy	Score LT	Score Tardy	Score WIP	Score % Tardy	Overall score
0.999	LF - S/OR	49.54	19.84	54.83	0.37	1.00	0.88	1.00	1.00	97.97
0.98	LF - EDD	50.74	19.96	56.01	0.40	0.77	0.92	1.00	0.99	94.24
0.97	LF - EDD	50.81	19.74	55.07	0.40	0.90	1.00	1.00	0.93	95.45
0.96	LF - A/OR	51.58	20.25	56.99	0.41	1.00	1.00	1.00	1.00	100.00
0.95	LF - EODD	52.18	21.02	57.88	0.42	1.00	0.81	1.00	1.00	96.79
0.94	LF - S/OR	52.82	20.77	58.27	0.43	0.81	1.00	1.00	1.00	96.67
0.93	LF - MS	53.88	21.86	60.93	0.46	0.63	0.53	1.00	0.94	82.86
0.92	LF - MS	53.99	21.07	60.88	0.46	1.00	1.00	0.89	0.92	94.00
0.91	LF - EODD	55.49	22.94	61.96	0.47	0.67	0.74	1.00	0.93	86.89
0.9	LF - A/OR	55.75	22.63	63.80	0.48	1.00	0.99	0.82	1.00	94.59

Table 13: Sensitivity analysis material availability top ten

Normally, the material availability is 98 percent. If the material availability is between 98 or 97 percent, our best performing solution does not differ. However, if the material availability is 0.999 or is lower than 0.97 than the optimal solution differs. We do the same analysis as we made for the interarrival times. What is the penalty for sticking to the current optimal production planning method, which is local forward planning rule in combination with the earliest due date sequencing rule? This is shown in Table 14.

Material Availability	SR	LT	Tardy	Wip	% Tardy	Score LT	Score Tardy	Score WIP	Score % Tardy	Overall score
0.999	LF - S/OR	49.54	19.84	54.83	0.37	1.00	0.88	1.00	1.00	97.97
	LF - EDD	50.36	20.02	55.92	0.39	0.48	0.77	0.68	0.75	68.69
0.96	LF - A/OR	51.58	20.25	56.99	0.41	1.00	1.00	1.00	1.00	100.00
	LF - EDD	51.82	20.48	58.15	0.42	0.78	0.83	0.68	0.85	78.90
0.95	LF - EODD	52.18	21.02	57.88	0.42	1.00	0.81	1.00	1.00	96.79
	LF - EDD	52.65	21.36	58.08	0.43	0.60	0.65	0.94	0.95	83.20
0.94	LF - S/OR	52.82	20.77	58.27	0.43	0.81	1.00	1.00	1.00	96.67
	LF - EDD	53.76	21.61	60.97	0.45	0.17	0.35	0.18	0.71	40.53
0.93	LF - MS	53.88	21.86	60.93	0.46	0.63	0.53	1.00	0.94	82.86
	LF - EDD	54.28	22.06	61.07	0.46	0.36	0.41	0.93	0.95	74.28
0.92	LF - MS	53.99	21.07	60.88	0.46	1.00	1.00	0.89	0.92	94.00
	LF - EDD	54.51	22.06	61.19	0.46	0.63	0.57	0.80	0.88	76.00
0.91	LF - EODD	55.49	22.94	61.96	0.47	0.67	0.74	1.00	0.93	86.89
	LF - EDD	55.70	22.57	64.10	0.48	0.54	0.99	0.53	0.74	68.60
0.9	LF - A/OR	55.75	22.63	63.80	0.48	1.00	0.99	0.82	1.00	94.59
	LF - EDD	56.29	23.03	64.30	0.49	0.46	0.70	0.64	0.83	69.07

Table 14: Comparison sensitivity analysis material availability

Similar to the comparison for the interarrival times, the difference between the current optimal production planning method and the optimal method for a specific material availability is not that large. The difference is quite large, but that is because we only use the top ten planning methods in our method to calculate the scores. We can conclude that the penalty for sticking to one production planning rule is limited. Now, we look at the global planning methods. They are shown in Table 15.

Material Availability	SR	Leadtime	Tardy	Wip	% Tardy	Score LT	Score Tardy	Score WIP	Score % Tardy	Overall score
0.999	GF	50.68	24.09	57.43	0.43	1.00	1.00	1.00	1.00	100
0.98	GF	51.02	24.14	57.94	0.44	1.00	1.00	1.00	1.00	100
0.97	GF	52.23	25.15	59.82	0.45	1.00	1.00	1.00	1.00	100
0.96	GF	52.53	25.60	60.96	0.45	1.00	1.00	1.00	1.00	100
0.95	GF	53.52	25.29	62.75	0.47	1.00	1.00	1.00	1.00	100
0.94	GF	53.09	25.14	60.85	0.47	1.00	1.00	1.00	1.00	100

0.93	GF	54.18	25.46	63.33	0.48	1.00	1.00	1.00	1.00	100
0.92	GF	54.85	25.85	63.61	0.48	1.00	1.00	1.00	1.00	100
0.91	GF	56.01	26.83	66.16	0.50	1.00	1.00	1.00	1.00	100
0.9	GF	56.91	27.43	67.22	0.50	1.00	1.00	1.00	1.00	100

Table 15: Sensitivity analysis material availability global planning

Table 15 is similar to the sensitivity analysis of the interarrival times. The global forward planning method performs the best of all global planning methods, for all material availabilities that we tested. Therefore, of all global planning methods the global forward planning method performs the best.

6.4 Conclusions

In this chapter, we answered one of the most important question for this research namely: “How do the different production planning rules perform on Jongbloed’s production?”

The performance of the production planning rules that we test greatly varies. Especially the local planning rules performed good, compared to the global planning rules. The best performing planning rule was the local forward production planning rule, with the EDD sequence rule with an overall score of 94.55. If we compared this score to the best performing global planning rule, there’s a 10.4 percent difference. A great advantage of a local planning rule was that they automatically ‘replan’, because they only include jobs that are ready for processing.

Earlier in this report, we described that Jongbloed currently ‘pushes’ their printing press orders and then schedules them according to the due date in the other departments. This causes friction, which results in a high amount of work in progress. The difference between Jongbloed’s current production planning and the local forward planning rule in combination with the EDD sequence is 28.5 percent. If we also compare Jongbloed’s current planning policy to the best performing global planning method, we note a 22 percent increase in performance in terms of scores. The forward global planning method also manages to decrease the number of work in progress production orders.

We then tested the stability of the different rules, when the interarrival times and the material availability change. We did this separately for the top ten production planning rules and the global planning rules. We concluded that the penalties are small, if we would keep the local forward planning rule in combination with the EDD sequence rule regardless of changes in the interarrival times and material availability.

7 Implementation and evaluation

In the following two sections, we discuss how we are going implement our advice and later on evaluate it. We use this chapter to two research questions, which are as follows:

- How can the best performing production planning rule be implemented?
- How can the best performing production planning rule be evaluated?

7.1 Implementing the solution

In this section, we would like to discuss the difference between the current and the future situation. A new project starts by ordering the required materials and formulating the work instructions. If the delivery date of the materials is known, the planning method can add the projects to the production schedule. Using Axapta (Jongbloed's ERP system), the corresponding production orders are transferred to the scheduling software. The production orders are added, using the precedence relations of the production orders, to the current schedule using the forward production planning algorithm that we discussed in the previous chapter. If a certain process cannot start at the earliest possible time, because the material is not available at the earliest possible time, the scheduling automatically corrects for this. In programming language, the planning rule loops over all the required processes and adds them to the first possible time slot given the material availability restriction. One exception is the scheduling of the printing presses. We noticed that the lead times, work in progress, tardy and percentage tardy performance indicators dramatically increase when we do not separately schedule the Timson 3 printing press, which has an exchangeable cylinder and folding machines. Not taking these exchangeable cylinders and folding machines into account results in high setup times, as exchanging the cylinder and/or folding machines takes a lot of time.

The difference between the current and the future situation is that the production orders are scheduled into first possible timeslot, whereas currently production orders are scheduled according to the due date. If an irregularity occurs, such as the material is not delivered on time and/or the wrong quantity is delivered, the planner manually needs to update the production planning in order to get a new feasible schedule.

We expect that the actual implementation of our solution is not very hard. In the production planning software, we need to select the correct production planning rule. Possibly, an add-on is necessary to cover the scheduling of the printing presses.

After the production order is finished, the information that is retrieved during production can be send back to Axapta such that the data is available for future use.

7.2 Evaluate the solution

After the new scheduling software is fully implemented and working, time has come to evaluate the implementation. We believe that the full implementation takes at least half a year before the new scheduling rule is fully operational. Earlier, we stated that we are able to achieve a 22 percent reduction on the four performance indicators given the weights in Table 6. The following data enables us to assess the performance of the new scheduling method:

- Edition size.
- Lead time.
- Work in progress.
- Percentage of projects that are delivered beyond the due date.
- Average number of days that the project is delivered beyond the due date, if the project is tardy.

If we retrieve this information from Jongbloed's ERP system, we can compare the new data to the historical data. The difference between these two data sets tells us whether the new scheduling method yields the promised increase in performance. We must note that the two datasets that we compare during evaluation are different. It is not possible to compare two exact same data sets, as the projects vary over time. This means that the expected difference, which we calculate in this report, can differ from the increase in performance that will be calculated during the evaluation.

7.3 Conclusions

In this chapter, we answer the two following research questions:

- How can the optimal production planning rule be implemented?
- How can the optimal production planning rule be evaluated?

Actually, we expect that implementing the solution is not very difficult. Commonly, in a production planning package different types of production planning rules can be selected. We simply need to select the global forward planning rule. As discussed earlier, an add-on might be required to schedule the printing presses.

We expect that the evaluation of the new production planning rule will be quite easy. We need to extract the performance data from the production planning software, and compare it to older data. Then, we can conclude whether the new production planning software indeed yields an overall improvement of 22 percent.

8 Conclusions and future research

In this chapter, we address our advice and future research. Our advice is at the same time the answer to our research question which we stated in section 1.3, which is as follows:

"What production planning rules should be used to automate and improve Jongbloed's production planning?"

In this thesis, we analysed several planning methods. We saw that the total difference in terms of score between the local and global production planning is approximately ten percent, given the average weights that we just stated in section 6.1. Unfortunately, we believe that a local production planning rule does not solve one of the main issues of the problem diagram which was introduced in Chapter 1 namely 'Planning perceived as wishlist'. If the production planning is local, the production is not 'pushed' to realize the production planning. A local production planning makes it impossible to check whether production orders are behind schedule, as there is no real schedule. Therefore, even given the limited performance of global production planning rules, we advise this rule. Both sensitivity analyses show that the global forward planning method is stable for all situations that we tested. However, we schedule the printing presses differently such that orders with similar characteristics are grouped. As we discussed earlier, the real performance of global production planning rule is higher than our model predicts because of the manual rescheduling. Furthermore, a global planning rule provides clarity on the shop floor by not only including the production orders waiting but also production orders that arrive in the future. One practical implication is that it is easier to respond to high workloads in near future by planning more personnel to speed up the process. Another example is that Jongbloed is capable of planning preventive maintenance on exactly the right time, when the machine has a relatively low workload. Capturing 'vague' variables such as clarity in a performance indicator is almost impossible to do, but we should definitely take these into account when picking a new production planning method.

8.1 Comparison to current situation

Finally, we would like to compare the performance of the current way of working to the 'new' way of working. The difference, in terms of score (which thus includes the weight and scores of all four performance criteria) is 22 percent. This difference is largely due to the decrease in work in progress. The hybrid global production planning immediately starts processing new production orders (like the forward global production planning), but after being processed by the printing presses the planning method looks at the due date. These different ways of working, namely first push and then pull conflict. This results in a higher work in progress. For all the reasons that we just stated, we advise the forward global production planning rule.

8.2 Future research

We think that there are several interesting topics that require further investigation. They are as follows:

- More advanced production planning rules. In this research, we specifically picked rather 'basic' production planning rules because we argue that the execution time of the rule should be small. Still, a possible future topic is to include more advanced production planning algorithms in the simulation model. The start of such a research could be our simulation model, as it only requires adding the new production planning rule to the already existing model. After analysis, the future researchers can make a trade-off between the high performance of advanced production planning rules and the run time of basic production planning rules.

- Printing press. As discussed earlier in this report, the printing presses require a lot of maintenance and often fail. Jongbloed is currently analysing the printing presses that are available on the market to replace the old ones. We believe that our simulation can be helpful in this analysis, with several tweaks. The performance of the printing press, such as the setup times, the failures and the processing times are currently hard-coded in the simulation model. It is not hard to change these characteristics, using the specifications of the new printing presses.

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10 Appendices

10.1 Appendix A – Overview of the research method

In this appendix, we give a small summary of the research method that we are using. We start with the Managerial Problem Solving Method and continue with the 'accompanying' framework which is called the methodological checklist. The MPSM consists of seven phases, which are briefly discussed below (Heerkens H. , The Managerial Problem Solving Method, 1998).

- **Identification of the problem**
    - In this chapter, we discuss the current situation. How is Jongbloed currently planning, and how do they use this planning in practice? Also, we describe the ideal situation. Furthermore, we highlight the different views of the people that are affected by the production planning. Most likely, there are different views on what people believe a production planning should include.
- **Formulation of problem-solving method**
    - Here, the planning of the solution process be described. The MPSM is quite vague in that sense, that the method does not give any guidelines how to describe such a solution process because they are too much context dependent. We describe the constraints of the project, which influences the scope of my research. Moreover, we describe the resources that are necessary to execute my research. An example is the information that is necessary to describe the current situation.
- **Problem analysis**
    - Problem analysis is an important chapter. This part is basically the translation of the first two chapters to a model, which displays the reality in a simplified version. The problems that we discussed earlier should be transferred in concrete, measurable terms named indicators. They facilitate measuring the performance of solutions that are proposed later in our research. Likewise, criteria can be derived to assess different solutions. Indicators need to be expressed as concretely as possible. Whenever this is not possible, we should find indicators that are closely related to the problem that we are trying to describe.
      The second part of problem analysis is the tracing of causes. Here, we describe the variables that influence indicators that we identified earlier. Causes can be found using interviews and observations.
      Finally, the relation between the indicators and the causes need to be established. There are a million relations that can be researched, but the most important are the relations that make an essential contribution to the solution of the problem and those that can be influenced. Relations that do not contribute to solve the problem do not need to be analysed, neither do relations that cannot be influenced. Indicators, causes and relations between indicators and causes can be combined into a model. This model is a visual representation of the reality.
- **Formulation of alternative solutions**
    - Alternative solutions should be formulated according to the different indicators that we would like to change. Implementing an alternative solution should take away the difference between the actual and desired situation. All benefits and disadvantages should be indicated per alternative solution. An overview of the different solutions and their effects in terms of advantages and disadvantages can be presented in for example a table.
- **Decision**

    - Based on an overview of all the alternative solutions and the corresponding benefits and downsides, one must ultimately pick one (or a combination) of solutions to implement. Several topics need to be taken into account when making the decision, such as the acceptance by the involved employees and the information supply in terms of the clarity of decision making procedures.
- **Implementation**
    - Again, the MPSM is quite limited in facilitating the implementation of the chose alternative. The method does however 'warn' that people are not willing to change.
- **Evaluation / feedback**
    - On this aspect, the MPSM model is more thorough. The methodology stresses several points that need to be taken care of when designing an evaluation. They are as follows:
        - Nobody should take too much time for evaluation, people do not like this.
        - Objectives of the evaluation should be clear and be able to assess the performance of the implemented solution.

We now discuss the complementary framework called the research cycle. The cycle has one phase more compared to the MPSM, namely eight (Heerkens H. , A methodological checklist for the High-tech Marketing Project, 2004). They are as follows:

- **Research goal**
    - The research goal consists of six elements, namely
        - Central aim, why do we want to know the answer to your problem?
        - Background information, which consists of information like why is the organization not yet known and who formulated the problem.
        - Required knowledge, what information is necessary to solve the problem of the MPSM.
        - Information that is already available.
        - Information that is not yet available.
        - Information that the research generate.
- **Problem statement**
    - Here we need to discuss the following items:
        - Sort of research, either descriptive, explanatory or testing
        - Variables, the relation and the research population
        - A model of the problem that we are trying to solve, by using the methodological checklist. The model consists of a visualization of the problem, using variables and relations.
        - Definitions of all the required research aspects.
        - Theoretical background. The relation of theory to the problem that we are trying to solve using the methodological checklist.
        - Constraints, which are given by the person who described the problem.
        - Limitations, which are set by the user of the framework.
- **Research questions**
    - Basically, research questions are a representation of the problem that we are trying to solve. If we answer all these questions, then we have the answer to solve the problem.
- **Research design**

- Research design is how we are going to execute the research. This section should cover the following aspects, namely:
  - Division of the measurements groups. Do we separate the population in two groups?
  - Research strategy, which consists of the parts, which are:
    - Do we manipulate the variables or are we simply observing?
    - Do we interact with the research population or not?
  - Research population, what is the population that we are investigating?
  - Research elements, which is the portion of the population that we are trying to research.
  - Observation units. Units of the research elements which are actually measured, such as just one department of an organization.
  - Way to gather data. For instance observation, survey, interviews or a content analysis.
  - Processing and analysing data. Is the data qualitative or quantitative?
  - Expected results per research question, which are described earlier.
  - Activity overview, what are we going to do and when.

- **Operationalization**
  - Variables that were described earlier need to be made measurable. They are two way to do so:
    - Make them concrete.
    - If it is not possible to make them concrete or for any other reason, decompose the variable into pieces. Each piece is covered by one indicator.
- **Measurement**
  - This is the execution of the research that was designed earlier. This phase contains a description of the process and how the measuring unit (which is the way that we are trying to retrieve the data such as an interview or an observation) was performing.
- **Processing of data**
  - After retrieving the data from the measurement phase, we analyse the data. Again, there is no standard way to do so. Everything depends on the context of the assignment.
- **Drawing of conclusions**
  - Here, we answer the research questions. It is a good practice to check whether we actually answered your research questions that we stated earlier and to check the fit between the problem that we are solving using the methodological checklist and the 'main' problem.

10.2 Appendix B – Description Data Set

In this dataset, we try to find a theoretical distribution for each process. As discussed earlier, finding a theoretical distribution is not always possible to do so. In that case, we use an empirical distribution based on the data. As discussed earlier, we use Plant Simulation to find the distributions of the setup- and the processing times. Plant Simulation tests the data against twelve theoretical distributions, which are as follows:

- Binomial.
- Geometric.
- Poisson.
- Beta.

- Erlang.
- Negexp.
- Gamma.
- Lognorm.
- Normal.
- Triangle.
- Uniform.
- Weibull.

We looked the possible applications of distributions, according to Law (Law, 2007). The twelve distributions above are the most promising (and common) to fit our processing- and setup times. We now state the theoretical distribution that we found for each process. Plant Simulation uses three tests to check the fit between the data and the theoretical distribution, namely the Chi-square, Kolmogorov-Smirnov (KS) and the Anderson-Darling (AD) test. The idea behind each test is similar, calculating the fit between a theoretical distribution and the real data. We use a level of significance of 5%, which is common in statistics.

If multiple theoretical distributions pass the tests, we pick the distribution that has the lowest value on the KS test. Typically, each dataset has less than 200 observations and the KS test is powerful in this region.

Plant Simulation states that we should have at least ten observations per data set in order to be able to calculate the KS and AD test. If the dataset has less than ten observations, we use the 'real' data. Furthermore, if a theoretical distribution does not fit the data we use an empirical distribution.

First, we tried whether using one theoretical distribution per process is possible. Unfortunately, this is not the case. This is quite logical, as a small printrun relatively takes less processing and setup time compared to a large printrun. We use the same ranges as used when estimating the costs of project. Within each bin, the projects share similar setup and processing times per book.

10.3 Appendix C – Full description simulation model

In this appendix, we first discuss all departments in detail and continue with a description of the methods on the main screen.

10.4 Departments

The departments frame contains all the different departments. All the movable units (production orders) move through the departments, using their own routing. The 'Start' department is a fictitious department, we use this department to generate orders. The buffer is used to store production orders that already have been processed at least once but did not finish yet. We use this to calculate our WIP performance indicator. We discuss the departments one-by-one from the left side of the picture to the right side, starting with the 'Start' department. This department is shown in Figure 47.

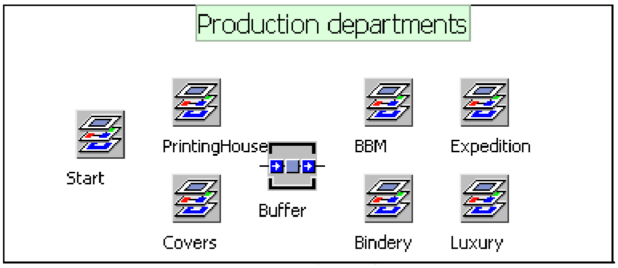

Figure 47: Overview all departments

10.4.1 Start

As discussed earlier, the Start department is non-existent on Jongbloed's shop floor. A screenshot of this 'department' is visible in Figure 48. The source is used to generate new projects, using the interarrival times of the table 'Interarrival'. Each time a new moveable unit arrives according to the interarrival time, the method CreateEdition is triggered. Using a uniform distribution, we pick a random project. Each project has several corresponding production orders, which are retrieved from the table 'DataOrder'. If a production order is generated, the method processing times is triggered. This method computes a processing time for each process that the production order needs, according to the table PTTable. This table contains all the probability density functions that we found earlier. If all the above methods are finished, the production order is added to the production planning using the 'Planning' method.

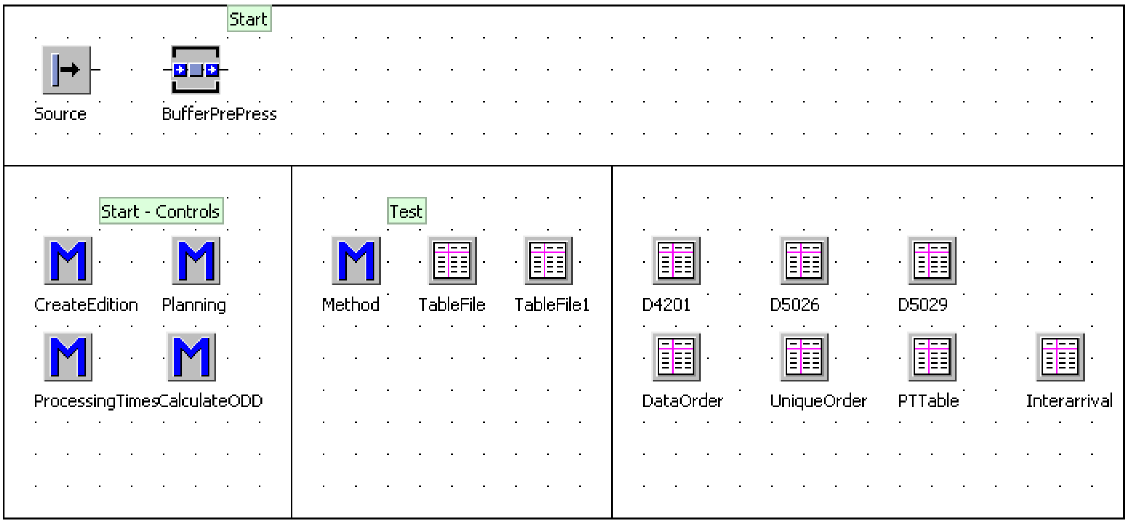

Figure 48: Start

10.4.2 Printing house

The printing house department actually covers two departments, namely both the printing house and the pre-press department. Both departments are shown in Figure 49. The pre-press department is simple, first the files are processed on 'M30021' and 'M30022' by two workers. These employees work in a day shift. Once the files are processed, they can be put on plates such that they can be used in the Printing department.

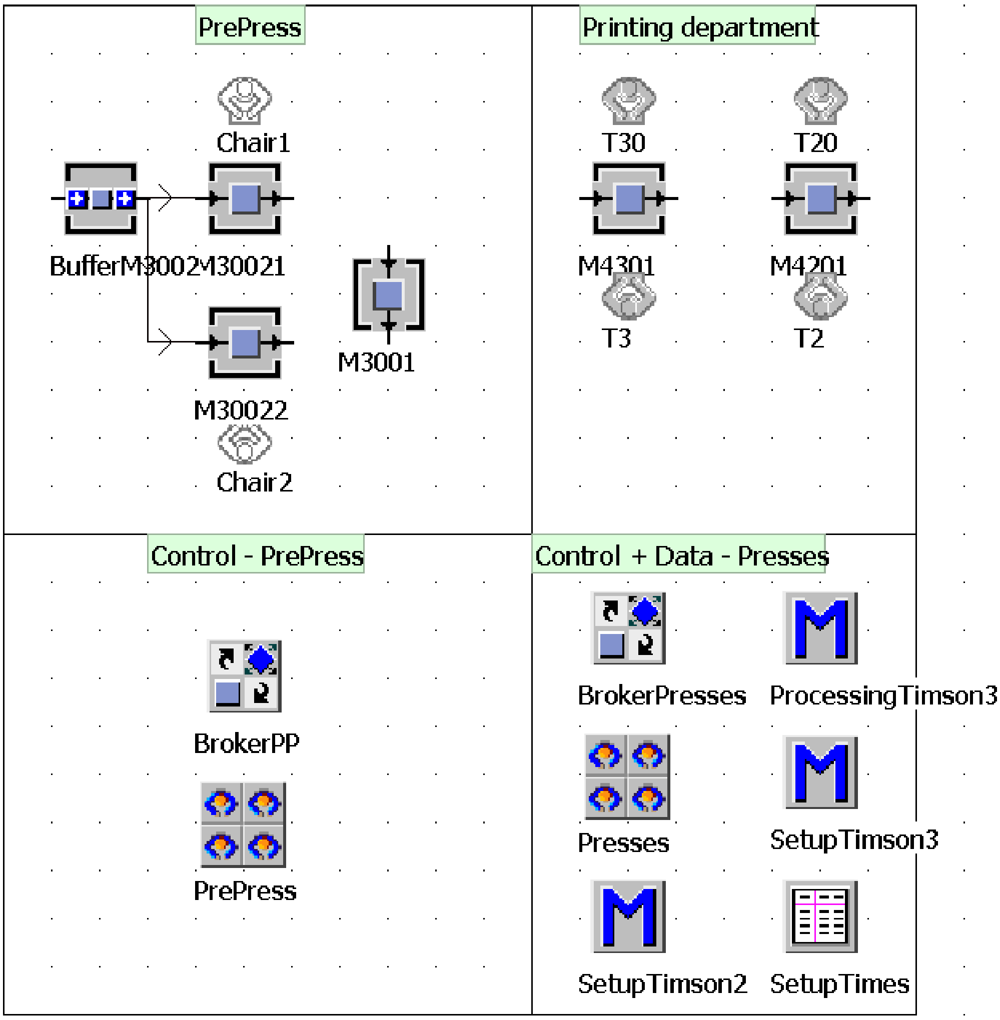

Figure 49: Printing house

The 'second' step in the Printing House department is the Printing house itself. In total, two employees are necessary in order to operate one press. These employees work in three shifts. Using the methods 'SetupTimson3' and 'SetupTimson2' and the table 'SetupTimes', the setup times are calculated.

10.4.3 BBM

The book block manufacturing department is similar to the printing house department, in the sense that it also consists of two steps. A screenshot of the book block manufacturing department is given in Figure 50. First, the books are gathered which is shown on the right side of the picture below. In total, three employees are necessary to operate the gathering machine. Normally, these three employees work in a day shift.

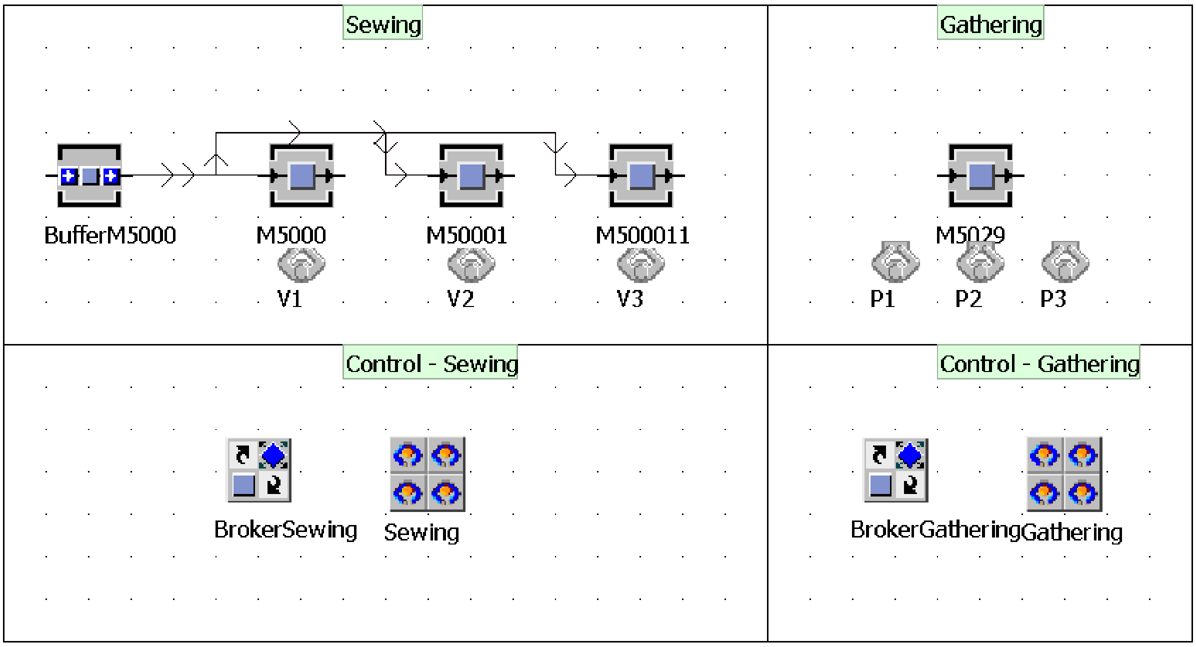

Figure 50: BBM

Once the books are gathered, often they need to be sewn. This is done on one of the three sewing machine. Each sewing machine needs one employee to operate the machine. All the employees that operate the sewing machine work in two shifts.

10.4.4 Cover department

All the cover making is done at the cover department, often at the same time when the book blocks are gathered and sewn. The cover department is shown in Figure 51. At a first glance, it looks like there are a lot of different machines but actually they are all different processes. Several processes can only be executed at one machine, and therefore cannot be executed simultaneously.

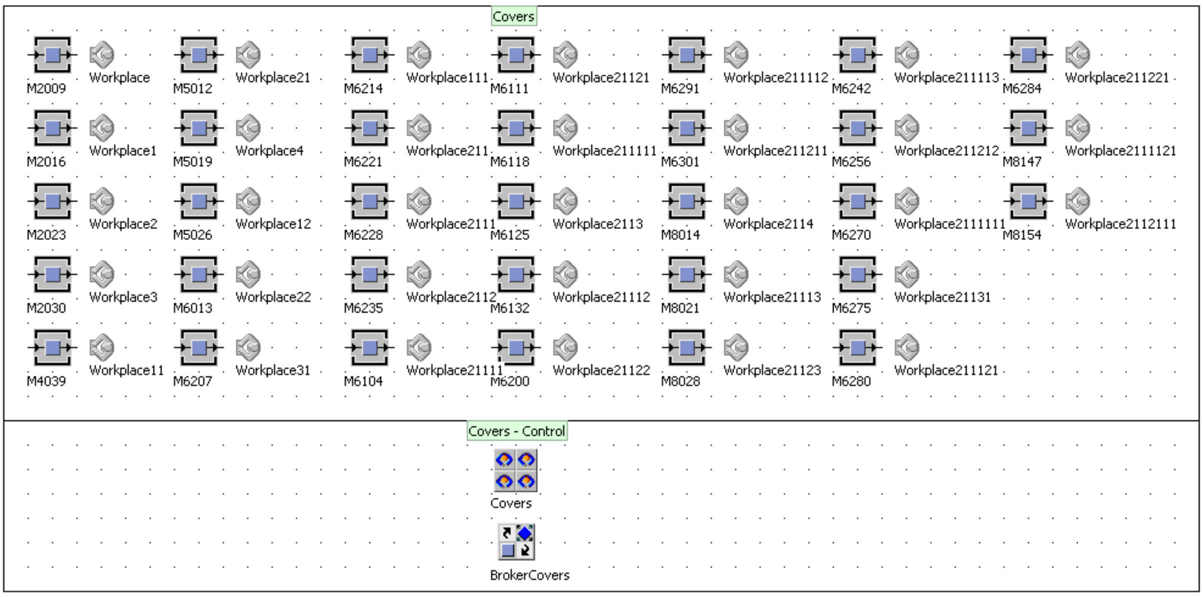

Figure 51: Cover department

In total, five employees work at the cover department. All of them work in the day shift.

10.4.5 Bindery department

The bindery department consists of two separate assembly lines, called “Bindlijnen” in Dutch. Each assembly line consists of multiple stations, which can be separately. Therefore, we modelled them as individual processes, instead of one large machine. They are shown in Figure 52.

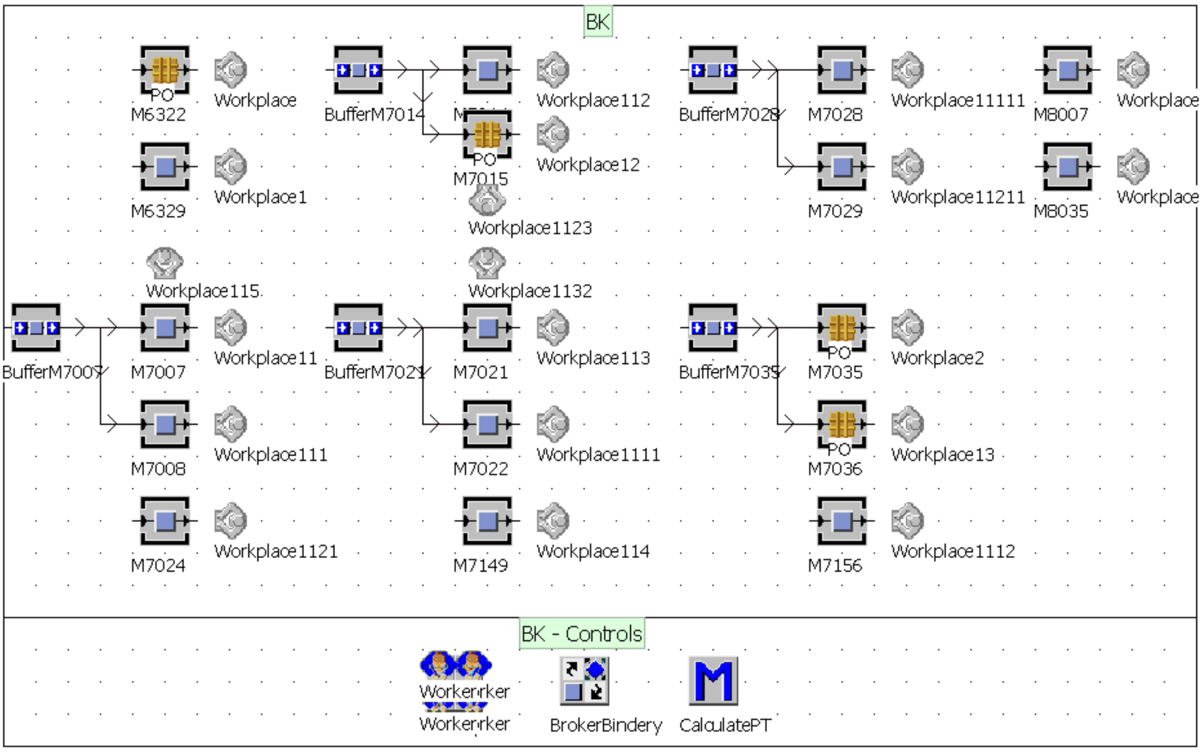

Figure 52: Bindery department

After processing the production order on the first station, the simulation model writes the last location in an attribute of the production order. The model moves the production order to the second station if necessary. Using the method ‘CalculatePT’, the method determines whether the last location is on the same assembly line. If so, the method does not compute processing time because this means that the production order is processed in line. However, if the last location is not on the same assembly line it means that the production order is not processed on the same assembly. Therefore, it needs to be processed again.

10.4.6 Luxury department

Similar to the cover, the luxury department also contains a lot of different processes. Though, machines do not limit the capacity. The capacity at the luxury department is almost always limited to the number of employees. The different processes are shown in Figure 53.

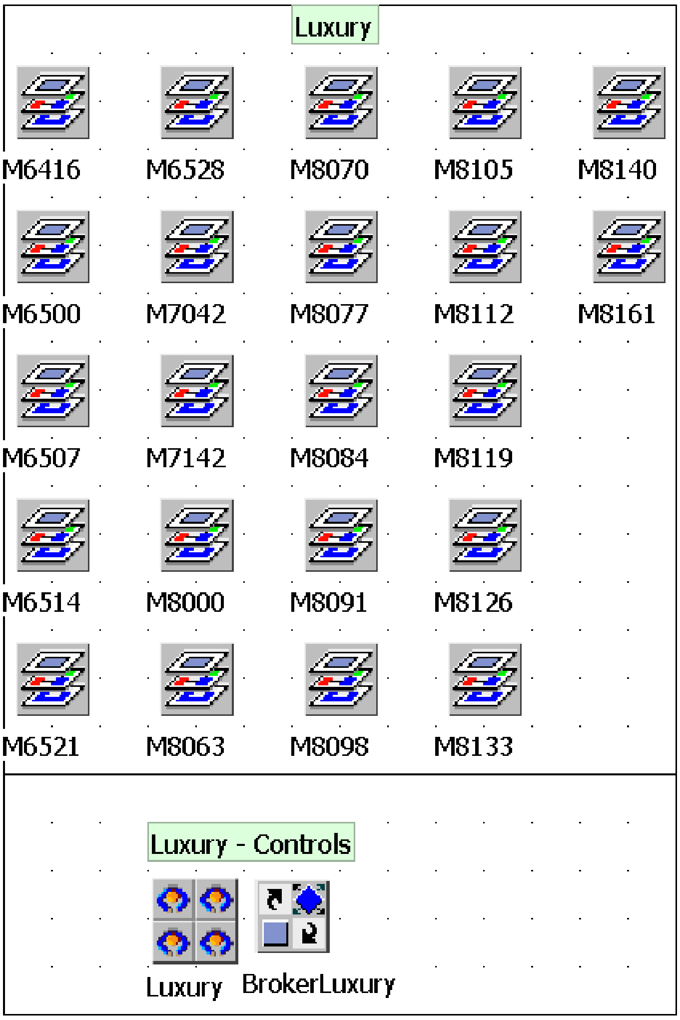

Figure 53: Luxury department

Each frame in the figure above looks is similar for each process. On average, six employees work at the luxury department per day. Therefore, we made six work centers such that all employees can work on the same production order at the same time. This is shown in Figure 54.

Figure 54: Luxury department - Process 6416

Depending on the number of employees that are available, the method 'CalculateProcessing' computes the required process time per employee using the total necessary processing time as input. All employees at the luxury department work in a day shift.

10.4.7 Expedition department

The expedition department is always the final department in the production process of Jongbloed, the frame in our model is shown in Figure 55. After arriving, the books need to be packaged, counted and the bill of lading needs to be printed. Using the methods 'CalculatePackage' and 'CalculateCount', the necessary processing times are calculated for packaging and counting the books. The processing time for printing the bill of lading is fixed, namely fifteen minutes. This seems like a lot of time to print one bill of lading, but all the required information needs to be retrieved and typed in manually.

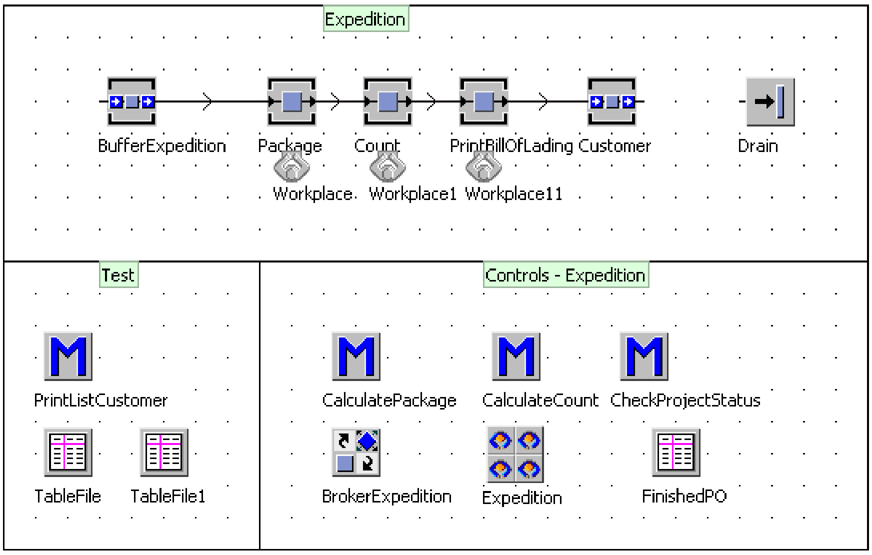

Figure 55: Expedition department

If the books are packaged, the method 'CheckProjectStatus' checks whether all editions are shipped individually or at once. If indeed all editions that belong to one single project are shipped at once, the edition is added to the table 'FinishedPO'. The method 'CheckProjectStatus' then checks if all editions already arrived at the expedition department. If this is the case then a performance method on the main screen is triggered and all the different editions are moved to the drain. The performance method registers all the performance indicators, such as lead time, tardy of early projects.

10.5 Description methods main screen

All the methods on the main screen are used to plan and move the production orders through the production facility. The main screen contains the following methods, which we describe briefly:

- **InitStatus**. In our simulation model, we normally have four production orders. However, these production orders cannot be processed simultaneously. Therefore, we need to determine the dependencies of the production orders
- **UpdateProductionPlanning.** This method is used to update the production planning, if a certain job is finished or a machine starts processing a new job. It makes sure that the production planning stays up to date.
- **Schedule.** This method is triggered when a machines' planning needs to be rescheduled. It reschedules the machine that needs replanning using the simulation models' settings.
- **InitiateProduction.** The InitiateProduction method is executed when a job starts processing on a machine. It is used to set for example the necessary processing time and status of the job.

- **FinishedMachine.** Once the job finished processing, this method is triggered to update the current production step and the status of the job. Also, it checks whether there are more production orders waiting. If so, the machine starts processing the next job.
- **PerformanceMeasurement.** If a project is finished, this method writes several performance data to a table in the simulation model so we can analyse the data later on.
- **CalculateWIP.** At midnight, the simulation model writes the current level of Work In Progress to a performance data table. This is done using the method CalculateWip.
- **SchedulePresses.** Earlier in this report, we stated that the setup times of the printing presses are long. Therefore, we would like to combine projects with similar characteristics such that we minimize the setup times. This is done in the method SchedulePresses.
- **MaterialAvailable.** Material is not always immediately available. Sometimes the quality is not alright or the supplier did not deliver the required quantity. In the method MaterialAvailable, we check whether the material of a production that wants to start processing is actually available.