MASTER

An operations planning and control system, for orders produced in a combination of a process shop and a flow shop, with uncertainty in the production process

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An Operations Planning and Control System, for orders produced in a combination of a process shop and a flow shop, with uncertainty in the production process

Master Thesis

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Abstract
This is a report of the master thesis project for Operations Management and Logistics at Eindhoven University of Technology. The organization involved is Marsna Paper, which is a paper producer that offers customizable paper with opportunities for small orders.

Marsna Paper is challenged by the problem of low delivery reliability. This project analyses and designs the integral planning of the production process of Marsna Paper. The goal of this master thesis project is to design an operations planning and control system from scratch, that meets objectives with respect to cost (labour-, holding-, start-up- and backlog cost) as well as on service level, such as delivery reliability.

Bertrand et al. (1990) presents a systematic approach for the process of designing logistic control systems based on three phases: (1) a conceptual design phase, (2) a detailed design and (3) an integrated design.

In this report, the conceptual design and the detailed design are presented. The first chapter gives information about Marsna Paper and the problem they face. The second chapter a literature review is presented. This literature review gives a summary of the existing literature on the subject and states the limitations. Furthermore chapter two describes the assignment formulation, the project approach the deliverables and the scope.

In the third chapter a detailed analysis of Marsna Paper is presented where all relevant aspects of the current situation such as the production process, demand and costs are analysed. In chapter four a scientific contribution is presented. It is discussed what type of lead time assignment rules are correct for manufacturing systems with the characteristics involved in this project. Chapter four also analyses how the conceptual- and detailed designs presented in this project could be well adapted by manufacturers with the same characteristics as Marsna Paper. In chapter five, the conceptual design is made for the case study (Marsna Paper). In the conceptual design phase the main structure of the operations planning and control system is decided. Furthermore there are in the conceptual design rough-cut calculations about the feasibility done. In chapter six, the detailed design is made for the case study. In the detailed design is the batch size, order sequence and production schedule for each production unit created. Furthermore this chapter discusses the role of the GFC control, which coordinates the production units. Chapter seven shows the differences between the current situation (of Marsna Paper) and the designed situation in this project. This chapter outlines also the steps required to implement the design at Marsna Paper. Furthermore are the conclusions and recommendations presented.

Keywords: Operations Planning and Control System, small customer orders, a combination of Process Shop and Flow Shop production process, Triple Resource Constrained System and Sequence-Dependent Setup Times.
Executive summary
This report is the result of my Master Thesis project at Marsna Paper. Marsna Paper is a company with 45 employees, which produces many different types of paper in a small batches. Marsna Paper is challenged by the problem of low delivery reliability. Besides the objective to increase the delivery reliability, the general manager has asked what is the best design for an operations planning and control system, in terms of cost and service level for Marsna Paper.

In order to investigate this problem, this project analyses and designs the integral planning of the production process of Marsna Paper. The projects objective is to design an operations planning and control system, that meets objectives with respect to cost (labour-, holding-, start-up- and backlog costs) as well as on service level, such as delivery reliability, from scratch. This project is guided by the theory of Bertrand et al. (1990) as he presents a systematic approach for the process of designing operations planning and control systems.

Marsna Papers’ characteristics
The production process consists of paper production operations and finishing operations on several workstations, all having their own restrictions and characteristics. The production departments’ capacity exceeds the finishing departments’ capacity greatly. Produced paper is wound on a tambour, a steel structure for holding paper rolls. These tambours are an essential resource and are limited in number. Paper is always delivered to the finishing department on tambours, where due to some operations on workstations, the physical format of the paper changes, whereby tambours are no longer needed.

Further relevant characteristics on the integral planning of Marsna Paper are: (1) small customer orders, (2) a combination of process shop and flow shop production processes, (3) large variety of operations, (4) triple resource constrained system (resources: staff, tambours and machine), (5) machine capacity exceeds staff capacity, (6) high start-up costs and (7) sequence-dependent setup times.

Lead time assignment rules
In the research (chapter 4) the information on Marsna Paper is generalized, in order to connect this information to similar manufacturers linked by uncertainty in production processes leading to low delivery reliability. A method to hedge against such uncertainties is formed by determine lead times. Based on interviews and existing literature on determine lead time assignment rules, it can be concluded that routing-dependent and workload-dependent as well as flexible lead times are useful for manufactures with the same characteristics as Marsna Paper. The combination of these three rules will lead to a customized lead time assignment rule: Lead time is based on the routing of a manufacturing system with a due date expressed in weeks instead of days. Once a manufacturing system has a high utilization rate, releasing longer lead times based on the workload of the plant, should be optional. This conclusion on the lead time assignment rule is used in the design of a control system for Marsna Paper.

Designed situations
At first a conceptual design is presented in which the main structure for a control system is created, based on the insights on multiple characteristics in the assignment. Marsna Papers’ design problem is decomposed into three production units (PUs) in order to simplify design issues. Furthermore, the feasibility of the objectives are being proved based on rough-cut calculations. The system has been proved feasible because (1) the demand is smaller than the capacity and (2) the throughput time (total production time of order) is shorter than the agreed lead time.
In the next, detailed design phase, functional specifications and design parameters for all three PUs are determined. More specific, for every PU batch sizes, sequence of orders and production schedule are described. Furthermore, the Goods Flow Control (GFC) is introduced, as an interface that smoothens the interdependencies between the PUs.

**Proposed improvements**
Comparing the current and newly designed situation, it is striking that the amount of Work In Progress (WIP), probably caused by the difference in capacity of the two production departments, is high thus causing a lack of tambours. Urgency of orders is at some points neglected, in order to release tambours for production. Reducing the (expensive) WIP by introducing another production schedule, would lead to an actual financial benefit, but moreover would automatically generate more available tambours. Furthermore it releases manpower as well, that subsequently can be used for more urgent tasks in increasing delivery reliability.

Besides the WIP, also variability is reduced, by using the designed lead time assignment rule and capacity extension and thus, according to Hopp (2000) and Little's law, also an production orders' throughput time is reduced.

The new production schedule that reduces the WIP, also reduces the start-up costs. Instead of being operational every week with a regular shut down on Fridays, the design chooses a production schedule in which the production department is shut down once per six weeks. Besides the paper machines, the workstation RPM is also started less frequently, in order to reduce start-up costs. A detailed calculation on the savings on start-up costs of paper production and RPM is given and a saving of €9572 per year is realised.

In the current situation, multiple paper machines are used in one week. In the design has been chosen to work with one paper machine per week. This planning rule has two advantages: (1) heating cost would only be relevant for one machine and (2) a decrease in workload and cost, created by cleaning of the machine. Relevant financials are stated.

Although one workstation has large setup times, the main planning rule for this workstation is based on the orders' urgency and minimizing the total setup times is not taken into account. The design optimizes the amount of setups, thus resulting in a reduction of the total setup time and costs, and releasing capacity.

The last proposed improvement is to use available manpower more efficiently. When the process runs, an operator at the paper production line structurally has downtime. In the design, these operators are deployed in the finishing department thus creating a substantial increase of capacity in the bottleneck of the production process.

**Implementation**
For this project, planning rules need to be adapted to implement the design. These planning rules can relatively easy be changed by the responsible managers.
Preface
This report is the result of my Master Thesis project as part of the Master Operations Management & Logistics at Eindhoven University of Technology. This project took place at Marsna Paper between February 2016 and August 2016.

First I would like to express my gratitude to dr.ir. van Ooijen, my first supervisor from Eindhoven University of Technology. His enthusiasm about the subject, and support through the project helped me. When the continuation of the process impeded, he thought me different insights. I truly appreciate his support. I also want to thank ir. dr. Flapper, my second supervisor, who was very important during my project. He provided me multiple times with valuable feedback on my report.

Next, I would like to thank Rolf Pijsel, owner and general manager of Marsna Paper and his wife Sophie Pluim. I am glad that I had the opportunity to graduate within this company. They provided me with an challenging assignment and were very supportive to me during the project. From Marsna Paper I would also like to thank Leon Wingender. He explained the complex production process of Marsna Paper in detail. Furthermore was he willing to discuss some of my ideas in order to validate if an idea was applicable. Also I would like to thank the staff of Marsna Paper for answering my questions, providing me with input and suggestions.

Last but not least, I would like to thank my girlfriend Cato, and her mother, Lilian Vrouenraets for their help on the reporting of this project.

I hope you will read my thesis with great pleasure and interest.

Denis Vaessen

Figure 1 - Denis Vaessen at Marsna Paper
1. Introduction

1.1. Marsna Paper

Marsna Paper is a company, with 45 employees, located in Meerssen, in the South of the Netherlands. Marsna Paper produces different types of high quality paper and customers use the paper for example for passe-partouts. A customer can choose between multiple paper qualities and colours. Moreover, many different finishing options are available, for example watermarks or specific paper cuts. What makes Marsna Paper unique is the fact that customers can place relatively small orders. The minimum order quantity for customers of Marsna Paper is 1000 kilogram, while competitors use a minimum order quantity of 3000 or 5000 kilograms.

Organisation and system

Figure 2 illustrates the organization chart of Marsna Paper. The organisation of Marsna Paper consists of seven departments. The production department (15 employees) is divided in pulp preparation and paper machines. The finishing department (11 employees) is also part of the production process. The maintenance department (8 employees) supports the production and finishing department. There are four staff departments (11 employees); sales, finance and administration, quality and human resources which consists of office staff.

Characteristics of Marsna Paper

The properties of the production process of Marsna Paper, while focussing on the integral planning of Marsna Paper are: (1) small customer orders, (2) a combination of process shop and flow shop production processes, (3) large variety of operations, (4) triple resource constrained system (resources: staff, machines and production resource), (5) machine capacity exceeds staff capacity, (6) high start-up costs and (7) sequence-dependent setup times. Further details of Marsna Paper are described in chapter 3: 'Detailed analysis'.

1.2. Problem description

In April 2015, Marsna Paper made a new start with 45 employees instead of 75 employees prior to this period. As a result, a capacity problem was created. There are enough machines to handle the demand, but there is relatively little staff to operate the machines (Pijsel, 2016). Orders are often delivered with delay. In 2015, 47% of all orders were not delivered on time. In 2016 till week 14, this percentage was already reduced to 39%, but this fraction is still too large according to the managing director. His goal is to improve the delivery reliability up to 95%. Failure to comply with the delivery agreement ensures lower customer satisfaction, which eventually can result in losing customers to competitors.

After the restart of Marsna Paper with less employees, processes, production schedules and planning rules were adapted, based on the opinion of experienced people. These adaptations were necessary because the previous production design of Marsna Paper – including more employees– was no longer applicable. Besides the objective to increase the delivery reliability, the general manager poses the question what is the best design for an operations planning and control system for Marsna Paper. If this design is efficient, costs are minimized while production quantity and quality remain equal.
2. Assignment

In this chapter the assignment is discussed. First a literature review is given, in which a summary of the existing literature on this subject is presented. In the second section, the assignment is formulated based on the problem statement. In the next section the project approach is discussed. Section four states the deliverables and in the final section, the scope is presented.

2.1. Literature study

In order to solve the delivery problem, as described in chapter 1, at first a literature review is done. In this chapter a literature review is given, in which a summary of the existing literature on this subject is presented. The review states the limitations on the topic, as well as a possible solution for the problem. For more details on the found literature I refer to the extended literature report.

Google scholar and Focus (TUe) were used to collect relevant literature on the topic. The following keywords were used: paper industry, textile industry (production) scheduling, (production) planning, flow shop, process shop, small batch, triple resource constrained, work force scheduling, human resource scheduling, capacity management, demand variety, throughput time (reduction), lead time (reduction), sequence-dependent setup times, energy intensive production process, production run.

In total, 61 relevant articles were selected based on title, subject and abstract. After critical analysis, 40 articles did not qualify because of their lack of relevance for the research assignment. Ultimately, 21 articles qualified, and are stated in table 1.

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Conclusion

Although a lot of literature is available about production planning and control systems, none of the articles leads to a clear solution (no article discusses all subjects) because of the complexity and unique features of Marsna Paper. It is necessary to combine insights on multiple characteristics in the assignment, as most articles review characteristics for one, mostly different model. Furthermore, the restrictions and objectives in the literature often differ from the case study, thus deviating from the model. This results in limitations concerning production planning and scheduling strategies because other restrictions and
variables need to be taken into account. Parts of literature will be used to create a model useful for Marsna Paper and manufacturers with the same characteristics as Marsna Paper. Literature which is used will be presented in the report at the relevant paragraph.

2.2. Formulation of the assignment

In chapter 1 it was shown that Marsna Paper challenges the problem of low delivery reliability. The production department and the finishing department both have their own planning policy. The planning of both departments is complex. For the production department there are a lot of important issues, such as start-up costs, sequence-dependent setup times and differences in paper machines. The finishing department produces orders in a flow shop where processes are triple resource (staff, machines and production resource) constrained. In this final master thesis project the integral planning of the production process of Marsna Paper will be analysed and designed. The goal of this master thesis project is to design an operations planning and control system from scratch, which meets objectives with respect to costs (labour-, holding-, start-up- and backlog costs) and service level, such as delivery reliability.

At this moment the planning is made manually, based on knowledge of the past and is not structured. In this assignment it is also important to develop a structured planning procedure. The assignment formulation is:

Design an operations planning and control system, for orders, produced in a combination of a process shop and a flow shop with uncertainty in the production process.

2.3. Project approach

Planning designs have infinitely large solution space which asks for a systematic approach. Bertrand (1999) presents such a systematic approach on the process of designing logistics control systems. It is chosen to follow his method in this project because Bertrand has demonstrated that with his method, a planning can be designed from scratch in a complex production environment. According to Bertrand, one can distinguish three phases while designing and implementing a complete operations planning and control system: (1) a conceptual design phase, (2) a detailed design and (3) an integrated design phase. These different phases will be explained below.

Detailed analysis

To design an operations planning and control system on the method of Bertrand, substantial information about Marsna Paper is necessary. Therefore a detailed analysis is presented first. The information of the detailed analysis is in three different ways obtained. Staff members (production staff and manager) have been interviewed, observations are done and information is gained from the information system of Marsna Paper.

The detailed analysis states the current situation of Marsna Paper. The detailed analysis states information about, customers & orders, the production process and the demand. Furthermore are processing times & setup times and the capacity determined. Finally the current production planning, relevant costs and the performance of the current manufacturing system are discussed.

Conceptual design phase

In the conceptual design phase the main structure for a control system is created. In this phase the design problem is decomposed in a number of modules (sub problems) in order to simplify design issues. Furthermore an interface between the modules is needed to define the interdependencies between the sub problems. This design achieves the level to inform you when to execute which process with which resources. In this phase objectives for the system are defined, as well as the Customer Order Decouple Point is determined.
In general, the feasibility of the objectives needs to be verified in this phase. Rough-cut calculations are used to check the feasibility of the system. The system is feasible if (1) the demand is less than the capacity and (2) the throughput time (total production time of order) is shorter than the agreed lead time.

**Detailed design**
In the next phase, the detailed design phase, for each sub problem (module), functional specifications and design parameters are determined. According to Bertrand (1999) there are three important heuristic algorithms for every module. These heuristic algorithms operate as a rule of thumb, resulting in an acceptable solution. (1) The first set of heuristics aims to determine which orders are selected for further production. Priorities are set to orders. (2) The second set of heuristics determine which operator serves which machine on which day. As Marsna Paper is triple resource constraint, both machine, human and another resources are needed for production, this information is crucial. (3) The third set of heuristics determines the sequence of orders.

**Integrated design**
The last phase in designing an operations planning and control system is the integration and implementation phase. Based on both the conceptual design, as well as the detailed design, a simulation model will be built in the integrated design. With this simulation, the design is tested. Adjustments can be made when necessary.

In this project, the simulation in the integrated design is not presented through lack of time. The last chapter of this report states the implementation plan. In the implementation plan it is stated what actions has to be done for implementation, who is responsible for the actions and what is the expected time for realization.

**Academic contribution**
As described above, this project focuses on designing an operations planning and control system for the case study of Marsna Paper in order to solve its current problems. Besides the design of an operations planning and control system for Marsna Paper, this project also aims at a scientific contribution. This project suggest how to apply these designs presented in this to manufacturers with similar characteristics as Marsna Paper. This part of the project is presented in chapter four.

2.4. **Deliverables**
Marsna Paper and Eindhoven University of Technology have expressed their expectations on the following deliverables:
- Conceptual design for Marsna Paper
- Detailed design for Marsna Paper
- A report defining the methodology and results.
- A presentation about the project, as well for the TU/e as for Marsna Paper.
- A list of recommendations for Marsna Paper.

2.5. **Scope**
As mentioned before, this project focuses on the integral planning of the production process of Marsna Paper. All processes and costs directly related to the production process are relevant and are covered by the scope of this project. More specific, these are the processes between the time an order is released for production and the time order is ready for shipment. (Due date of Marsna Paper is the moment an order is ready for shipment.) The relevant costs (given by client) for this project are labour-, holding-, start-up- and backlog costs. The scope is explained in detail in the conceptual design of Marsna Paper. Issues as maintenance, distribution, material availability, inventory control and administration are discussed.
3. Detailed analyses – Current situation

In this chapter a detailed analysis of Marsna Paper is presented, which states the companies’ current situation. First information is presented on customer orders of Marsna Paper. More specific, this section consists of information about the type of customer orders, the administration process and delivery times (3.1). Hereafter, the entire production process including restrictions and specifications is described. The production process can be divided in the paper production-, finishing- and quality department (3.2). In the next section the demand is analysed (3.3). Thereafter the processing times and setup times are stated (3.4). In the capacity calculation a distinction is made between machine capacity, paper production staff capacity and finishing staff capacity. This section also provides information about flex-workers (3.5). The following section explains how the current production is planned and by whom the planning is created (3.6). Furthermore the relevant cost are presented (3.7). Finally, the performance of the current manufacturing system of Marsna Paper is discussed (3.8).

As far as maintenance on is concerned, this item will not be taken into account in this project, because personnel maintains the machinery in periods when they are switched-off. Every workstation has non-productive periods, because there are less employees than workstations and demand varies, no workstation is always working. Thus, maintenance of machinery is of no influence on this project.

The information of the detailed analysis is obtained via three different sources: staff members (production staff and managers) have been interviewed, personal observations were used, as well as information was gained from the information system of Marsna Paper.

3.1. Customer orders

Customers deliver a mail which contains all order specifications. Size, paper thickness, quality, colour and finishing options should be stated. A customer order should have the minimal weight of 1000 kg. Orders with a smaller order quantity than 1000 kg are not accepted. When the order request is complete, Marsna Paper registers an order request in the information system by hand. Once an order is booked, it is ready for production (release moment). Orders are registered on the same day the order is received in 90% of all cases, the remaining orders on the day after the order is received.

Once a customer of Marsna Paper places an order, the delivery date is agreed upon. For Marsna Paper the agreed delivery date is the point in time when an order is ready for transport, not when the order is delivered to the customer. Delivery time is determined in weeks, and it is not relevant on what day the order is ready for transport, as long as the day fits in the week. Standard delivery periods take six weeks from the release moment. Delivery time is extended for two more weeks in case orders need to be squeezed or pasted on one side, or for three more weeks in case orders need to be squeezed on both sides. Orders are to be delivered completely (partial deliveries are not allowed based on customer wishes).

3.2. Paper production process

In this subchapter important paper production process issues are stated. First the paper production process inclusive restrictions and specifications is described. For every operation the processing time and setup time is given. Also the capacity per department and costs are stated.

Figure 3 represents an overview of the entire production process. The production process exists of paper production operations, finishing operations and quality checks, which will be explained in detail in the next sections. At the end of the production process, an order will be directly transported to customers. As can be seen in figure 3, the entire production
process of Marsna Paper is a process shop. In a process shop, all orders are produced by the all production departments with the same sequence. For Marsna Paper every order starts by the paper production department, followed by the finishing department and has some control points for quality.

Figure 3 – Overview of the production process for Marsna Paper. The production process consists of a paper production- and a finishing operations. Quality of the paper is checked at two points in the process.

The processes of Marsna Paper (paper production and finishing) are constrained by both machine and human resources. This kind of system is known as a triple resource constrained (DRC system).

3.2.1. Paper production process

Three paper production lines operate in the paper production department. A paper production line consists of pulp preparation and the operations of the paper machines. A certain quality and colour code represents a particular recipe of cellulose, fillers and dyes. The pulp preparation converts the raw materials for each order according to recipe. Water is added to the raw materials and they are mixed to pulp. Next the colour of the pulp is made by adding dyes. The mixed pulp is inserted to the paper machine. In the paper machine, water is extracted from the pulp and the rest materials–or paper–is rolled on a tambour. A tambour is a steel structure for holding paper rolls. Figure 4 shows the paper production line.

Figure 4 - A paper production line in the paper production department of Marsna Paper

Specification of the paper production process

As far as the paper production process is concerned, there are four important issues to consider:

(1) One of the important issues is the difference in paper machines. The paper production stage consists of three parallel lines (PM2, PM3 and PM4). Every machine has a different speed and is able to make different kinds of paper. The three different machines Marsna Paper is using and their specifications are listed in table 2.

Table 2 - Differences in paper machines (PMs) used by Marsna Paper

<table>
<thead>
<tr>
<th></th>
<th>PM 2</th>
<th>PM 3</th>
<th>PM 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum speed</td>
<td>210 meters/min</td>
<td>180 meters/min</td>
<td>80 meters/min</td>
</tr>
<tr>
<td>Average speed</td>
<td>195 meters/min</td>
<td>175 meters/min</td>
<td>65 meters/min</td>
</tr>
<tr>
<td>Type of orders</td>
<td>White and some</td>
<td>Coloured paper</td>
<td>Thick paper</td>
</tr>
<tr>
<td></td>
<td>colours paper</td>
<td>GT Mark</td>
<td></td>
</tr>
<tr>
<td>Watermark</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness of paper</td>
<td>≤ 200g</td>
<td>≤ 350g</td>
<td>≤ 425g</td>
</tr>
</tbody>
</table>

(2) Another issue regarding the production process is the starting process of the machines. As there is no production during the weekends, the machinery needs to be switched on- and off-weekly. Starting a machine is an expensive process, therefore accurate planning
is desirable. These high costs originate mainly from energy: a large boiler must be turned on, consuming a lot of gas for heating. In addition, maintenance personnel must prepare associated equipment 2.5 hours before production starts. The start-up costs are €953 per start-up.

3) A third notable issue in production line is the planning of a production run. A production run for Marsna Paper is mainly based on colour sequence, but other factors must be considered as well. The colour layering is most important process in the production run. The colour of the first orders in the production run is white and the production run ends with the black orders. If the colours of different products vary too much, the production line needs to be cleaned before it is possible to create paper in a new colour, resulting in start-up and other costs. So, planning a production run based on colours is very important. As indicated above, other complicating factors in planning can arise, an example of which is the customers’ wish on humidity of paper. If the paper is ordered to be dry, a paper machine needs to be very hot. If the next production order desires more humidified paper, the machine must be cooled, again losing a lot of energy and indirectly money before regular production can be continued. Furthermore, as Marsna Paper has high quality measures, solid quality checks are implemented in planning process. See chapter 3.2.4.

(4) The last significant issue in production process is the number of tambours. As explained before, a tambour is a steel structure for creating paper rolls. Paper is wound up on a tambour after production. Marsna Paper has 106 tambours. The number of tambours can restrict the production process. In the finishing department the paper is operated by multiple workstations. When the paper is operated by workstations “Bob2”, “Bob3”, or “RS10”, the paper is no longer on the tambour and the tambour can go back to the production department, where the tambour can be used for new production. When the WIP in the finishing department on tambours is very high, which means that all 106 tambours are in use, it is not possible to produce paper, because tambours are indispensable in the paper production process.

3.2.2. Finishing

After leaving the production department, the paper is further processed in the finishing department. The process in the finishing department varies with customers’ requests. In the finishing department eight different finishing operations are available, performed by thirteen different workstations. In the finishing department, orders are produced in a flow shop process. The characteristic of a flow shop process is that each job enables an appropriate sequencing for the process, but not every job will go through every process step. Figure 5 shows the flow shop process with all finishing operations for Marsna Paper.

![Flow shop process of finishing department](image)

The coloured lines are examples of various orders for Marsna Paper. An order undergoes some finishing operations. For example, the red line is an order which only needs to go to the satin and bobine workstations within the finishing department.
The abbreviations of the workstations are explained in appendix B. Table 3 explains the operations of the workstations in the finishing department. Furthermore shows table 3 the physical input- and output of the paper. The paper production delivers paper on tambours (large paper rolls) for the finishing department. The output of workstation X needs to be equal to the input of workstation X+1. Therefore some routings are standard and necessary.

Table 3 - Workstations in the finishing department

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Input</th>
<th>Operation</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kal7</td>
<td>Large roll (on tambour)</td>
<td>Satine. Satined paper has some sheen to it.</td>
<td>Large roll (on tambour)</td>
</tr>
<tr>
<td>BOB2</td>
<td>Large roll (on tambour)</td>
<td>Cutting rolls</td>
<td>Small roll</td>
</tr>
<tr>
<td>BOB3</td>
<td>Large roll (on tambour)</td>
<td>Cutting rolls</td>
<td>Small roll</td>
</tr>
<tr>
<td>PK2</td>
<td>Small roll</td>
<td>Squeezing</td>
<td>Small roll</td>
</tr>
<tr>
<td>PK4</td>
<td>Small roll</td>
<td>Squeezing</td>
<td>Small roll</td>
</tr>
<tr>
<td>RPM</td>
<td>Small roll</td>
<td>Paste multiple rolls into one roll and cut the roll into sheets</td>
<td>Sheets</td>
</tr>
<tr>
<td>RS07</td>
<td>Small roll</td>
<td>Cutting</td>
<td>Sheets</td>
</tr>
<tr>
<td>RS09</td>
<td>Small roll</td>
<td>Cutting rolls with watermark</td>
<td>Sheets</td>
</tr>
<tr>
<td>RS10</td>
<td>Large roll (on tambour)</td>
<td>Cutting</td>
<td>Sheets</td>
</tr>
<tr>
<td>Polar</td>
<td>Sheets</td>
<td>Split sheets</td>
<td>Sheets</td>
</tr>
<tr>
<td>GRM</td>
<td>Sheets</td>
<td>Wrapping multiple sheets in packaging paper</td>
<td>Packs</td>
</tr>
<tr>
<td>LAMB</td>
<td>Sheets</td>
<td>Wrapping multiple sheets in packaging paper (smaller format)</td>
<td>Packs</td>
</tr>
<tr>
<td>Packing</td>
<td>Pallet</td>
<td>Pallet packing with foil</td>
<td>Pallet</td>
</tr>
</tbody>
</table>

Although no standard routings are to be found, Marsna Paper’s orders have two main routings in the finishing department. (Figure 6) Approximate, 70% of all orders is processed via one of these two routings. This conclusion is drawn based on the demand between May 2015 and May 2016.

**Squeeze workstations**

Marsna Paper has two workstations (PK2 and PK4) to squeeze orders, which both operate different squeeze possibilities. PK4 has 7 different squeeze possibilities and PK2 has 20 different squeeze possibilities. In the last year customers ordered all these 27 different squeeze possibilities.
There are two types of squeezing. (1) Wild squeezing and (2) report squeezing. (1) Wild squeezing is a type of squeeze where paper goes through one unique (unique for squeeze possibilities) figure roll and one smooth (not unique) roll. (2) Report squeezing is a type of squeeze where paper goes through two unique figure rolls. Table 4 summarizes squeezing options, the possibilities per workstation and the types of squeezing.

<table>
<thead>
<tr>
<th>Total squeeze possibilities</th>
<th>Per workstation</th>
<th>Type per workstation</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 squeeze possibilities</td>
<td>20 squeeze possibilities PK2</td>
<td>14 squeeze possibilities are always wild squeezing</td>
</tr>
<tr>
<td></td>
<td>7 squeeze possibilities PK4</td>
<td>1 squeeze possibility is always report squeezing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 squeeze possibilities could be as well wild as report squeezing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All (7) squeeze options are wild squeezing</td>
</tr>
</tbody>
</table>

**Start-up costs RPM**

Starting the paste machine (RPM) costs approximately €150 euro (time and energy) because this machines must be warmed before production. Furthermore an operator is up busy half an hour to start this machine. The start-up costs for the other machines are negligible. Start-up times for other machine are around the 10 minutes.

### 3.2.3. Quality

Because Marsna Paper produces high-quality paper, quality is an important issue. Products can be rejected both internally (by the quality department) and externally (by customer). Paper can be rejected based on colour, paper characteristics or wrong production. Because each order is unique, every decision for rejection must be investigated case by case. If the quality department and the customer agree that an order must be rejected, the order will be produced again. Table 5 states the percentages of the rejected orders both internally and externally.

<table>
<thead>
<tr>
<th>Year</th>
<th>% rejected internally (rejected kilos / bruto production)</th>
<th>% rejected externally (amount of credit notas / total invoiced)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>1.64%</td>
<td>1.30%</td>
</tr>
<tr>
<td>2016</td>
<td>1.63%</td>
<td>1.29%</td>
</tr>
</tbody>
</table>

In the production process of Marsna Paper, two employees are responsible for the quality of the paper. (1) One employee is responsible for the quality of the colour and (2) the other employee is responsible for the overall quality of the paper. There are two control points for quality in the production process of Marsna Paper. (1) The first control point is after the paper production and (2) the second control point is at the end of the finishing department. Every order is checked for its quality, both colour and overall quality are evaluated. The colour of paper is only checked after the paper production, because the operations at the finishing department have no influence on the colour. The overall quality is checked at both control points. Quality control takes around ten minutes and is always carried out within a day. The quality control happens parallel with the production process. An order is not processed by the next workstation within a day and an order is transported two days after an order is ready for transport. Therefore, there is no effort made for an order that is rejected internally.

### 3.3. Demand (from customer)

There are no contracts with customers for the demand (future demand unknown). To analyse the demand, all orders after the restart (from 17 April 2015 till 29 April 2016) are
viewed and categorised based on order quantity and processing steps, because the order quantity and the routing are important issues for the production planning.

In figure 7, the order entry quantity (demand in tons of paper) per week is stated for the period between the restart (April 17, 2015) and May 6, 2016. Figure 7 shows that the order entry fluctuates a lot every week.

![Order entry](image)

**Figure 7 - Order entry in tons per week of Marsna Paper from the restart till May 6, 2016.**

Because there is only data of one year known, it is not possible to determine seasonality the data. Data before the restart is not reliable because Marsna Paper had 75 employees instead of 45 employees, so the plant had more capacity and thus needed more demand. From an interview with the sales manager, who has been working for more than 25 years for Marsna Paper, it appears that besides Christmas (when demand is low) there is no pattern in demand.

The quality and colour of the paper makes no difference for the process of paper making. For example, when an order is red instead of yellow, other dyes need to be added. However, adding these other dyes does not change the process. For the process and demand it does matter which finishing operations are requested by the customer, because the processing time varies when the finishing operations are not the same. For example, an order which is squeezed, pasted and cut has a longer total processing time than an order which only has to be cut. On average 89.65 tons of paper per week was ordered last year and had a standard deviation of 36.36 tons. The average order quantity was 1670 kg. Table 6 gives the probability of the order quantity in KG paper. In total 2369 orders (orders of the previous year) were analysed to determine this conclusion.

**Table 6 - Probability of order quantity**

<table>
<thead>
<tr>
<th>Interval (KG)</th>
<th># orders</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000-1050</td>
<td>1126</td>
<td>0.475306</td>
</tr>
<tr>
<td>1050-1250</td>
<td>249</td>
<td>0.105108</td>
</tr>
<tr>
<td>1250-1450</td>
<td>111</td>
<td>0.046855</td>
</tr>
<tr>
<td>1450-2000</td>
<td>194</td>
<td>0.081891</td>
</tr>
<tr>
<td>2000-3000</td>
<td>462</td>
<td>0.195019</td>
</tr>
<tr>
<td>3000-4000</td>
<td>89</td>
<td>0.037569</td>
</tr>
<tr>
<td>4000-6000</td>
<td>83</td>
<td>0.035036</td>
</tr>
<tr>
<td>6000-10000</td>
<td>34</td>
<td>0.014352</td>
</tr>
</tbody>
</table>
Regarding the demand it should be considered how many orders should be produced by which paper machine. As stated in the restrictions every paper machine is unique and can produce certain orders. Table 7 shows how much percent of the orders needed to be produced per paper machine.

**Table 7 - Percentage of orders produced at a certain paper machine**

<table>
<thead>
<tr>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM2</td>
</tr>
<tr>
<td>PM3</td>
</tr>
<tr>
<td>PM4</td>
</tr>
</tbody>
</table>

Table 8 shows the percentage of the orders that went to the different workstations in the finishing department. For example, 20.4% of all orders went to workstation ‘Kal7’. An order may be processed by multiple workstations and therefore the sum of the percentages is more than 100%. The total sum of 346.1 percent means that an average order is operated by 3.46 workstations.

**Table 8 - Percentage of orders processed per workstation in the finishing department**

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Demand / week</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kal7</td>
<td>18.28</td>
<td>20.4%</td>
</tr>
<tr>
<td>Bob2</td>
<td>40.74</td>
<td>45.4%</td>
</tr>
<tr>
<td>Bob3</td>
<td>10.57</td>
<td>11.8%</td>
</tr>
<tr>
<td>PK2</td>
<td>19.39</td>
<td>21.6%</td>
</tr>
<tr>
<td>PK4</td>
<td>3.63</td>
<td>4.0%</td>
</tr>
<tr>
<td>RPM</td>
<td>7.45</td>
<td>8.3%</td>
</tr>
<tr>
<td>RS10</td>
<td>40.25</td>
<td>44.9%</td>
</tr>
<tr>
<td>RS7</td>
<td>17.13</td>
<td>19.1%</td>
</tr>
<tr>
<td>RS9</td>
<td>1.86</td>
<td>2.1%</td>
</tr>
<tr>
<td>Polar</td>
<td>26.11</td>
<td>29.1%</td>
</tr>
<tr>
<td>GRM</td>
<td>38.31</td>
<td>42.7%</td>
</tr>
<tr>
<td>LAMB</td>
<td>1.39</td>
<td>1.5%</td>
</tr>
<tr>
<td>Packing</td>
<td>85.17</td>
<td>95%</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>346.1%</td>
</tr>
</tbody>
</table>

### 3.4. Production rates

In this section the production rates on the several operations are defined. Section 1 and 2 outline the production rates of the paper production- and finishing operations. As can be read in the conclusion to both descriptions, it is not possible to calculate the total production rates with this method. In section 3 an estimation of the production rates for the paper production department is presented. In section 4, work reports are introduced in order to determine the production rates of the finishing department.

#### 3.4.1. Production rates of the paper production operations

The production rate of the paper production line is specified in production rate of the paper machine, setup time, exchange time for a unit (time to switch tambours) and time needed for internal transport to the next workstation.

As can be seen in figure 4, a paper production line exists of four operations. It has to be noticed, that the operations at the paper machine has the lowest production rate and thus represents the bottleneck in the paper production line. The other operations can easily
maintain this production rate. As a result, it can be concluded that the production rate of the paper machines is equal to the production rate of the paper production line.

Production rate of the paper machines:
As discussed earlier, the average paper machine speed is 195 meters/min for PM2, 175 meters/min for PM3 and 65 meters/min for PM4.

Setup times:
The setup times during the production of paper are sequence-dependent, based on colour. If the colours of different products vary too much, the production line needs to be cleaned before it is possible to create paper in a new colour. The setup time varies, related to the deviation between colours. If a colour resembles the previous colour, the setup time is up to half an hour; If the colour differs significant, the setup time increases to one hour.

Exchange time:
Once a tambour reaches its maximum capacity, it must be replaced by an empty one. The exchange time does not affect the processing time, because the switch of tambours happens parallel to the production of paper. During the replacement of a tambour, the paper machine keeps producing. Replacing a tambour takes about 5 minutes and is done by a paper production operator.

Internal transportation time:
Internal transportation time in paper production presents itself when moving an order from the paper production- to the finishing department. As noticed in the exchange time, this operation happens parallel to the production of paper and therefore has no influence on the processing time.

Total production rate:
The values given above, lead to the conclusion that it is not possible to calculate an exact standard production rate for the paper production line, because of the quantity of variables. The speed of the paper machine are average speeds, so the speed of an order is different for each situation. When for example, a customer orders dry paper, the production rate of the paper machine is lower, because of the heating of the paper machine. Furthermore, the order sizes is of influence on the production rate: if the order sizes are large, the number of setups are relatively small. Likewise, the colour of an order in combination with the colour of the previous order, influences setup times and thus the total production rate.

3.4.2. Production rate of the finishing operations
The production rate of the workstations in the finishing department exist of production rate of the workstation, setup time for a machine, exchange time for a unit (time to switch paper rolls or sheets), internal transportation time and other actions of operators of the finishing.

Production rate of the workstation:
Table 9 states the production rates of the workstations in the finishing department.

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Production rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kal7</td>
<td>200 meters/min</td>
</tr>
<tr>
<td>BOB2</td>
<td>300 meters/min</td>
</tr>
<tr>
<td>BOB3</td>
<td>300 meters/min</td>
</tr>
<tr>
<td>PK2</td>
<td>250 meters/min</td>
</tr>
<tr>
<td>PK4</td>
<td>250 meters/min</td>
</tr>
<tr>
<td>RS7</td>
<td>200 meters/min</td>
</tr>
<tr>
<td>RS9</td>
<td>200 meters/min</td>
</tr>
<tr>
<td>RS10</td>
<td>200 meters/min</td>
</tr>
<tr>
<td>RPM</td>
<td>35 meters/min</td>
</tr>
<tr>
<td>-----------</td>
<td>---------------</td>
</tr>
<tr>
<td>Polar</td>
<td>950 KG/hour</td>
</tr>
<tr>
<td>GRM</td>
<td>1000 belts/min</td>
</tr>
<tr>
<td>LAMB</td>
<td>800 belts/min</td>
</tr>
<tr>
<td>Packing</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Setup times:**
Every workstation, with the exception of the workstation PK2, has a small setup time. Workstations need be set for every order and this takes between five and ten minutes.

In the chapter 3.2.2. the various types of squeezing paper were specified. For PK2, setup times between the two types of squeezing differ much. Table 10 states the setup times per squeezing type for PK2. Column one indicates the starting position, whilst column two and three give the type of squeeze after the setup. You will notice that set up time from wild squeezing to report squeezing, takes 3 hours. Please note that these are sequence-dependent setup times.

<table>
<thead>
<tr>
<th>from\ to</th>
<th>Wild squeezing</th>
<th>Report squeezing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild squeezing</td>
<td>1 h (replace figure roll)</td>
<td>3 h (replace the figure and smooth roll for two figure rolls, 2h. Washing the rolls, 1h)</td>
</tr>
<tr>
<td>Report squeezing</td>
<td>2 h (replace 2 unique figure rolls for one unique and one smooth roll)</td>
<td>3 h (replace the two figure rolls for two figure rolls, 2h. Washing the rolls, 1h)</td>
</tr>
</tbody>
</table>

The setup times for PK4 are relatively small because this machine already has multiple figure rolls built in, so it can change easier from one roll to another. Setup times for this working station take 5 minutes.

**Exchange time:**
Although exchange time differs by each workstation or unit, it is stated that it takes approximately 5 to 15 minutes.

**Internal transportation time:**
Internal transportation time for units and workstations does not differ much and takes approximately 5 minutes.

**Other tasks (not related to production):**
In addition to the processing times as described above, operators have other tasks not related to production. There is no information available to indicate how long an operator is busy with other tasks. It is also impossible to make a reliable estimation of these tasks. Other tasks which are not related to production are:
- Treatment of residual paper;
- Recycling residual paper;
- Cleaning of machines;
- Work meetings.

**Total production rate:**
Although the production rates of the workstations are constant, the setup times and exchange times are very dependent on the type of orders and thus, it is not possible to calculate an exact reliable total production rate based on the data above. Furthermore, it is not possible to quantify how much time an operator spends on other not-production related activities.
3.4.3. Production rates of paper production department

As discussed in section 3.4.1, it is not possible to calculate an exact standard production rate for the paper production line, because there are a lot of variables. In order to estimate the production rates, calculations are done, based on work reports of the paper production operators. In these work reports, a team states how many kilograms of paper they produced within a shift. Table 11 states the production rates and standard deviations based on the work reports per paper production line.

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Sample size (# days data)</th>
<th>Production rate (KG/h)</th>
<th>Standard deviation (KG/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM2</td>
<td>150</td>
<td>1125</td>
<td>348</td>
</tr>
<tr>
<td>PM3</td>
<td>150</td>
<td>1000</td>
<td>332</td>
</tr>
<tr>
<td>PM4</td>
<td>150</td>
<td>1250</td>
<td>370</td>
</tr>
</tbody>
</table>

As can be seen in table 11, the production rates are not very reliable because standard deviation is very high, as the production rate is dependent on paper thickness and possible errors in the paper production process.

To gain more accurate and reliable total production rates, the total production rate is split into the production rates for paper being operated on a paper machine and production rates for setup times.

The production rates for paper machines are given in kilograms per time unit. These values vary enormously as they are dependent on for instance the papers’ thickness. If thin paper is being produced, the average production rate (in kg/time unit) will be much higher than the actual production rate (in kg/time unit), whereas it is the other way around if thick paper is being produced. The speed of the paper machines (expressed in meters per time unit) are almost fixed values for all machines. The number of meters that can be produced per time unit is almost constant because the machine speed is hardly varies. Includes means capacity can almost precisely be expressed in meters per time unit. A customers order doesn’t state the required meters of paper, but this value can be calculated, reckoning the papers’ thickness, its order quantity (in kg), and format size.

The setup times are sequence dependent. Based on data of the information system it can be concluded that the average setup time takes 35 minutes for all paper production lines. The setup time is varies between the 15 and 55 minutes.

3.4.4. Production rates of finishing department based on work reports

As can be read in section 3.4.2., the information that is available on production rates in the finishing department, is insufficient in order to calculate reliable production rates, because the information is either order or sequence-dependent. On top of this, information that is available, cannot be quantified. For example it is impossible to determine what time an operator spends on other activities, not related to production tasks.

Therefore, an estimation of the production rates for the operations of the workstations in the finishing department has been calculated based on work reports. Work reports are completed by the operators and indicate the production rate in kilograms per workstation per time unit. During this project a lot of work reports have been analysed, categorized and used to determine the production rates. Therefore the estimation of the production rates is reliable. Appendix H shows an example of a work report for the finishing department.

Another benefit of using the work reports to calculate the production rates is that in these reports production rates are converted from meters/minute into KG/minutes. As stated in the chapter 3.3., the customers demand is expressed in weight (tons of KG). So, in order
to answer the most important question of this thesis, how to improve Marsna Paper’s delivery status, figures that can be compared to the customer’s demand are indispensable. Every machine in the finishing department operates at its own speed, regardless of the order. But, for some machines their capacity is expressed in meters/minute, whereas other machine capacities are expressed in KG/minutes. Due to lack of information it is not possible to convert the demand and other variables to production rates in meters/min. Furthermore, by using these figures from the work reports, insight is given into the indeterminable time for staff activities that are not related to production indeed: as they represent experience based figures, they are included in the results of the work reports. Thus, production rates in meters per minute that are converted into production rates in kilogram per minute advance the solution of the thesis’ subject.

All values of the work reports have been categorized and thus an average production rate per workstation has been calculated. Furthermore the standard deviation calculated and the sample size is showed. Table 12 shows the results.

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Sample size (# days data)</th>
<th>Production rate (KG/h)</th>
<th>Standard deviation (KG/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kal7</td>
<td>63</td>
<td>1147</td>
<td>333</td>
</tr>
<tr>
<td>BOB2</td>
<td>104</td>
<td>1433</td>
<td>401</td>
</tr>
<tr>
<td>BOB3</td>
<td>93</td>
<td>623</td>
<td>255</td>
</tr>
<tr>
<td>PK2</td>
<td>106</td>
<td>548</td>
<td>221</td>
</tr>
<tr>
<td>PK4</td>
<td>60</td>
<td>488</td>
<td>148</td>
</tr>
<tr>
<td>RS7</td>
<td>84</td>
<td>611</td>
<td>147</td>
</tr>
<tr>
<td>RS9</td>
<td>14</td>
<td>377</td>
<td>81</td>
</tr>
<tr>
<td>RS10</td>
<td>112</td>
<td>944</td>
<td>472</td>
</tr>
<tr>
<td>RPM</td>
<td>69</td>
<td>355</td>
<td>127</td>
</tr>
<tr>
<td>Polar</td>
<td>116</td>
<td>783</td>
<td>240</td>
</tr>
<tr>
<td>GRM</td>
<td>106</td>
<td>1531</td>
<td>725</td>
</tr>
<tr>
<td>LAMB</td>
<td>4</td>
<td>272</td>
<td>80</td>
</tr>
<tr>
<td>Packing</td>
<td>127</td>
<td>1894</td>
<td>575</td>
</tr>
</tbody>
</table>

The production rate per workstation based on the work reports, includes setup time, exchange time, production time of the machine, internal transportation time and other, non-productive tasks of the operators.

These values are reliable because of the sample size of the work reports. Standard deviation is high, which should be taken into account during calculations. The reason for these high standard deviations lie in the variable options of an order. The thickness of the paper for example, is a crucial factor. A machine’s velocity does not change by the thickness of paper, as the results (customers demand) are measured in kilograms, an order’s goal is reached earlier when the paper is thicker. Furthermore squeezing of paper on one or at both sides, doubles the processing time. Similar deviation arises for the pasting process, when for example 2 or 3 layers is ordered.

The calculations made above, are based on the assumption that the work reports and the data in the information systems are correct.

### 3.5. Capacity

In this subchapter the capacity of Marsna Paper is discussed. First the staff capacity of the paper production department is calculated. In the second section the staff capacity of the finishing department is determined. Besides the staff capacity, also the workstation capacity needs to be analysed. The capacity of the workstations is calculated in section 3.
**Staff capacity of the paper production department**

The manpower in paper production department is closely related to the paper production process. The paper production department has three paper production lines which are 24 hours a day, 5 days per week available for production. A paper production line is energy intensive, and therefore the start-up costs of a paper production line is high (€953 per start-up). For this reason, a production line is active 24 hours/day. It takes 5 employees to operate the paper production line: two employees for the pulp preparation and three employees to operate the paper machine. There are 15 employees working in this department. A shift works 8 hours a day. With this amount of paper production employees, it is not possible to produce more than one line at the same time (if the paper production line operates 24 hours a day), because to operate a line, three shifts of 8 hours are needed to minimize the total start-up costs.

There are two vacation shutdowns of two weeks, in Summer and at Christmas. Each employee is entitled to 200 hours holidays a year and is on average absent for 20 hours a year, due to illness. With these numbers it can be concluded that the production line runs 46.5 weeks a year (=52 weeks – 5 weeks’ vacation shutdowns – 0.5 weeks illness). Staff works 5 days a week, 8 hours a day.

A shift exists of 8 hours working and there are 15 shifts a week. On a yearly basis this results in 697.5 shifts (46.5 weeks/ year * 15 shifts/ week) and thus 5580 production hours (697.5 shifts p. year * 8 hours p. shift). There is a maximum of three hours overtime per week per line. The potential capacity of overtime is relatively small, because 5 employees need to do overtime at the same time to operate one production line. Illness of an employee is covered by overtime of other employees of other shifts.

**Staff capacity of the finishing department**

As far as manpower in finishing department is concerned, the following issues should be considered. The finishing department works with two shifts. In total there are 11 operators working in the finishing department who work 40 hours a week (2 shifts of 5 operators and 1 operator doesn’t work with shifts). Operators switch between workstations to process all orders divided over multiple workstations. Of the thirteen workstations, an employee can work with on average 5.1 workstations. Appendix D states the skills matrix (which employee can operate which machine) of the employees. Some employees of the production department can operate some machines of the finishing department. Staff of the finishing department cannot work in the production department.

Similar to the production staff, these employees get 200 hours vacation and are on an average basis sick for 20 hours on yearly basis. Therefore the capacity of an employee is 1860 hours a year ((40 hours per week * 52 weeks per year) – 200 hours vacation – 20 hours illness). The total capacity of the finishing department is therefore 20460 hours a year (1860 hours p. employee p. year * 11 employees). Because every employee works individually, it is easier to work hours overtime. The maximum amount of overtime in the finishing department is 8 hours a week per operator. This gives a maximum total of overtime of 4136 hours a year (11 employees* 8 hours * (52 weeks - 5 weeks’ vacation shutdowns – 0.5 weeks illness)).

**Machine capacity**

Because the finishing department works in two shifts, the workstations are 16 hours a day, 5 days a week available for production. The paper production department works with 3 shifts and are therefore 24 hours a day, 5 days a week available. Table 13 gives the workstation capacity for the paper production- and finishing department.

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Workstation capacity 16h production</th>
<th>Workstation</th>
<th>Workstation capacity 24h production</th>
</tr>
</thead>
</table>

*Table 13 - Workstation capacity*
### 3.6. Current planning

Planning can be divided into two parts: (1) production planning and (2) finishing planning. The production planning is done by the production manager and the finishing planning by the finishing manager.

**Production Planning**

Production planning deals with the moment an order is booked (release moment) till the moment that an order is ready for the finishing department. There are a lot of restrictions to keep in mind during the production planning. Not all orders can be produced on every machine, one must deal with start-up costs of a paper machine, batches are created based on colour sequence. Because of the occupation of operators, it is not possible to operate on more than one machine at the same time. Furthermore, the production run is based on sequence of colour, in order to minimize the cost. Up to now, planning is done manually by the production manager. Every Thursday, the planning for the next week is made. The production manager creates a production run for a paper machine. Orders with an early due date and orders which fit in the production run based on colours are selected for the production run. The size of the production run differs every week based on the type of orders which need to be produced. The production manager tries to operate one paper machine per week (to minimize start-up and cleaning cost). In practice, often more than one paper machine operates in a week in order to meet the due date. (Orders with an early due date are spread over different paper machines).

When there is over capacity at the production department, the paper machine is switched off the last day of the week and the staff of the production department helps within the finishing department.

**Finishing Planning**

The second part of the planning is the planning of the finishing department. As described above, most orders require more than one finishing step. In practice, the most important factor for the weekly planning of the finishing process is the delivery date. Orders are produced on Earliest Due Date (EDD) for every machine. The finishing manager let the workstations “RS10” and “Bob2” work as much as possible (even if EDD is not followed), because with these operations, tambours are created for the production. (Explained in 3.1.1.) The other workstations work according EDD. The squeeze machines have long setup times and therefore all the orders with the same type of squeeze and with the same EDD, are produced in batches in order to keep the setup time small.

During a shift in the finishing department 5 operators are working, while 13 workstations are available for production. The choice which workstation operates is based on the
priority of an order. If for instance, demand is high and more than 5 workstations need to produce, the choice which workstations will operate, is based on the highest utilization of the workstation.

3.7. Cost

Table 14 gives all relevant cost for this project. The client of this project determined which cost are relevant for this project.

<table>
<thead>
<tr>
<th>Cost driver:</th>
<th>Description:</th>
<th>Costs:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy &amp; staff</td>
<td>Start-up cost WKC</td>
<td>€802.72 / start-up (Gas, water, energy and chemicals) €150 / start-up (staff costs (5 hours))</td>
</tr>
<tr>
<td></td>
<td>Start-up cost RPM</td>
<td>€150 / start-up (energy and staff)</td>
</tr>
<tr>
<td>Staff</td>
<td>Production staff</td>
<td>€22,36 / hour (incl. 3 shift bonus)</td>
</tr>
<tr>
<td></td>
<td>Finishing staff</td>
<td>€18,36 / hour (incl. 2 shift bonus)</td>
</tr>
<tr>
<td></td>
<td>Overtime cost</td>
<td>Regular hour * 1,4</td>
</tr>
<tr>
<td>General</td>
<td>Holding cost of WIP</td>
<td>1% of cost price</td>
</tr>
<tr>
<td></td>
<td>Raw material price (on average)</td>
<td>€856 / ton</td>
</tr>
<tr>
<td></td>
<td>Cost price of paper (on average)</td>
<td>90% of selling price = €1820,7 / ton</td>
</tr>
<tr>
<td></td>
<td>Selling price (on average)</td>
<td>€2023 / ton</td>
</tr>
</tbody>
</table>

3.8. Performance

In this subchapter the current performance of Marsna Paper is examined. All performance results are based on the production year from May 2015 till May 2016.

**Throughput time**

The throughput time is defined as the average (actual) time from release of a job at the beginning of the routing until it reaches an inventory point at the end of the routing. The throughput time of Marsna Paper is on average 5.7 weeks. Figure 8 shows the average throughput time and time in production for orders of Marsna Paper. As can be seen, the production of an average order starts at 2.9 weeks after the release moment, because a batch and a production run is created. The average time between the start of the production and the end of the production is 2.8 weeks. More than 90% of the complete throughput time consists of waiting time, compared to the relative small fraction of processing time.

![Figure 8 - Throughput time Marsna Paper](image)

**Delivery performance**

Orders are often delivered with delay. In 2015, 47% of all orders were not delivered on time. In 2016 till week 14, this percentage was reduced to 39%. 75% of the orders which are delivered too late are only a few workdays late. Some orders are delivered much too late (2 or 3 weeks). Mostly, these are orders that have been rejected on quality and are being re-produced. The average tardiness is 5 workdays.
**Work In Progress (WIP)**

WIP is defined as inventory consisting of products that are in semi-finished state. WIP of Marsna Paper are the orders which are produced by the paper production department, but which are not ready for transport. All stock before a workstation in the finishing department can be considered as WIP. The average WIP of Marsna Paper of last year contains 178 ton of paper.

**Throughput**

Throughput is defined as the production rate of a process or activity measured in units or flow per unit time. For Marsna Paper the throughput is the average amount of orders which are ready for transport per week. The throughput of Marsna Paper contains 94 ton of paper per week.
4. General design for manufacturers with the same characteristics as Marsna Paper

This project focuses on the design of an operations planning and control system for Marsna Paper in order to solve its current problems. Besides the design of an operations planning and control system for Marsna Paper, this project has also a scientific contribution. This project suggest how the designs presented in this project (case study of Marsna Paper) could be adapted for manufacturers with the same characteristics as Marsna Paper.

In the first sub chapter lead time assignment rules are discussed. These lead time assignment rules are later on used to set the functional requirements of Marsna Paper. In the second section the role of the batch size is discussed and finally the sequence of orders for manufacturers with the characteristics of Marsna Paper is investigated.

4.1. Lead time assignment rules

This assignment focusses on increasing delivery reliability for Marsna Paper. This chapter generalises this process, in order to translate higher delivery reliability to other manufacturers with the same characteristics as Marsna Paper. As described earlier in this paper, this includes manufacturers with certain characteristics: (1) small customer orders, (2) process and flow shop production processes, (3) large variety of operations, (4) a triple resource constrained system (resources: staff and machine), (5) demand uncertainty, (6) high start-up costs, (7) sequence-dependent setup times and (8) make to order.

Delivery reliability is influenced by many variables, such as demand uncertainty, available capacity or variability. (Hopp, 2000) Most manufacturers with uncertainties keep inventory to hedge against random fluctuations (Suri, 1998). Another method to hedge against random fluctuations of demand is modifying lead time (Suri, 1998). This sub chapter will describe lead time and lead time assignment rules (in Dutch: leverdatumafgifteregels) combined with its application for other manufacturers with the same characteristics as Marsna Paper, based on a literature search and interviews with experts.

Lead time is widely used in manufacturing. There are different types of lead time as can be seen in figure 9. For example delivery lead time describes the time from a finished product till delivery to the customer. Order lead time describes a broader process which starts when the customer places an order and ends when the customer receives the produced product. This papers’ focus will be on order lead time, which will be referred to as ‘lead time’.

A literature study was done on lead time combined with manufacturers’ characteristics as described above. It is striking that there is no article which combined lead time with all relevant characteristics. Therefore articles and interviews with experts were combined to discuss what lead time assignment rules are good for manufacturers with these specific characteristics.

Lead time assignment rules can be used in order to increase the delivery reliability in a process with a lot of uncertainties. There are multiple possibilities for determine lead time assignment rules, which will be explained in this subchapter.
First it is important to understand why it is important to determine lead-time assignment rules. Having some sort of flexibility in lead times is a very commonly utilized method of managing uncertainty in a production process (Muharremoglu, 2003). While searching for literature multiple possibilities for determine lead time dynamically are found. Possible lead-time assignment rules are:

- fixed lead time
- flexible lead time
- order quantity-dependent lead time
- routing-dependent lead time
- workload-dependent lead time.

These lead-time assignment rules can be combined to set the lead time of a manufacturing system. For example it is possible to have a flexible, order quantity-dependent and workload-dependent lead time.

In order to discuss lead time assignment rules 13 articles were analyse (summarised in appendix E) and 15 interviews were conducted with both a customers and producers’ view (appendix E).

4.1.1. Fixed lead times
The most straightforward type of lead time is the fixed lead time. This lead time assignment rule is independent of order quantity, routing and available capacity. Every order always has the same lead time. With this lead time assignment rule, the producer captures the flexibility of for example demand or routing.

The interviews revealed that fixed lead time as a lead time assignment rule is most favourable for customers, because this provides the most guarantees or certainties. On the other hand, fixed lead time is not easily implied in production systems with the previous described characteristics. Small customer orders, flow shop production process, large operation variety, demand uncertainties and sequence-dependent setup times result in a large variability and uncertainty for the manufacturer. These thoughts are confirmed in literature: Muharremoglu (2003), Pahl (2007), Bjork (2006) and Zijm (1996) all concluded that fixed lead times are not beneficial when the production process requires flexibility. Therefore -based on literature and interviews- fixed lead times will not be applied, because of the impossibility to imply fixed lead time in a highly variable production process.

4.1.2. Flexible lead time
Flexible lead time gives an indication of the lead time, because the due date is not fixed. The producer can deliver products earlier or later than the delivery date. There are boundaries given by the flexibility agreement.

Flexible lead times are not favourable for customers, because it creates uncertainties for the order delivery. Experts stated that flexible lead times can result in early deliveries as well, which would be favourable for customers. However, orders delivered too late are a problem, because this can jeopardize the production process of a manufacturer.

Based on the interviews with producers it can be concluded that flexibility in the lead times is desired. In practice there is a lot of uncertainty and variability in a manufacturing system with these characters. This uncertainty implies that it is very difficult to estimate exactly when an order is ready. Flexible lead time rules gives a manufacturer the opportunity to tackle uncertainty and variability on a certain level.

Flexible lead times are also discussed in the literature. Bjork (2007) discussed the effect of flexible lead times on a paper producer. In the paper two models to investigate the effect were presented. One model with fixed lead times and one model with flexible lead times. According to this paper, flexible lead times are beneficial for the entire production process. This because producers suffer from extensive production setup costs. Bjork (2007) also
quantified the possible savings and concluded that the savings where approximately 24% when the producer was given a flexibility range of only one day in each direction. When uncertainty occurs in the manufacturing system (for example demand uncertainty), it is expected that the savings are larger, because it is more difficult to deliver at a fixed delivery date when uncertainty occurs. Zijm (1996) also confirms that flexible lead times are useful, especially when uncertainty occurs in a manufacturing system.

As described, flexible lead time are not favourable for customers. For manufacturers with the characteristics of Marsna Paper, flexible lead times are very beneficial. The advantage of flexible lead times for manufacturers in this situation arises because it is very difficult to deliver at an exact due date when a manufacturing system has a lot of uncertainty. For manufacturers with the characteristics of Marsna Paper is chosen to express a due date in weeks, instead of days. Then, the order needs to be delivered somewhere during the selected week. Customers can use the latest date as due date (Friday), where an early delivery might be considered as ‘an extra’. With a due date expressed in weeks, the customer has a semi concrete delivery moment and the producer has flexible lead times.

4.1.3. Order quantity-dependent lead time
Order quantity-dependent lead times are dependent on order size. The lead time increases when the order quantity is bigger. Most customers explained during the interview that fixed lead times are ideal, but order quantity-dependent lead time is also favourable, due to consequent lead times. As an example: two orders with the same order quantity, ordered on two different moments, have the same lead time. This is experienced positive by customers because the lead time is known –based on lead times in the past– before they place an order.

Based on interview with producers, experts have different opinions about this lead time assignment rule. If the opinions are summarized, it can be concluded that experts think that order size has an impact on the lead times, but this impact is not extreme. The experts state that processing time is a small fraction of the total lead time. Waiting time, setup times, and such are the largest fraction of the total lead time. Suri (1998) confirms that the actual processing times on the workstation exists of less than 5% of the total lead time. When the order size increases, the processing times on workstations increases mainly linear. But other times, such as setup times, will not increase when the order size increases, because setup occurs independent of the order quantity. Therefore multiple experts believe that the order size has only a small impact on the lead time, especially when setup times are relatively large compared to processing times.

There is not much relevant literature about the relation between order size and lead times. Nielsen (2016) made a data analysis from a Danish company which reveals the relationship between lead time and order size. It was concluded that this relationship is not simple. He stated that the relation between order size and lead time is not linear, but the lead time grows when the order size grows.

Based on the interviews and limited available literature, it can be concluded that order quantity has little influence on the lead times, and customers do not prefer this lead time assignment rule. It is chosen to make a little distinction for lead times for orders based on the order size. If an order size is significantly bigger (compared with a standard order size), the released lead time will be larger, because the processing times of an orders takes longer.

4.1.4. Routing-dependent lead time
A routing-dependent lead time is a lead time that is dependent on the routing of an order. So, the number of operations and type of operations are relevant to set a lead time for an order by routing-dependent lead times.
The interviews showed that customers understand the fact that certain orders with a particular routine take longer compared to orders with a simpler routing. The customers’ most important feedback was that the lead time is set when an order is placed and this is experienced favourable.

Based on the interviews with the producers it can be concluded that producers prefer routing-dependent lead times. Orders which have many complex operations need longer lead times to make a suitable planning. Also, the experts explained that a long lead time for certain routings can reduce costs. For example, when a workstation has long setup time, it is beneficial to have a long lead time in order to maximize the batch size and minimize the setup time. Besides setup time, there are multiple variables in routings which influence the lead time, such as workstations with long processing times or bottleneck workstations. At such workstations it is beneficial for the production planning and costs to have a long lead time.

The existing literature indicates that it is beneficial to have long lead times when there is a complex routing. Conway (1967) has created a model where the number of processing steps varied between 1 and 39, while the same lead time is set for all orders. Conway concluded that the deadline is too tight for orders with many operations, while the delivery period is quite spacious for the orders with a few processing steps. This has a negative effect on the delivery reliability because the variability in order delivery is too big. Routing-dependent lead times have therefore a positive effect on the delivery reliability, because the number of processing steps are taken into account. Van Ooijen et al (2012) indicate that different throughput times occur through the impact of the dynamic behaviour of the queues. Therefore it is beneficial to release lead times, depending on the routing.

Based on the conducted interviews and existing literature is concluded that routings have a high impact on the lead time of orders. There is a positive effect between routing-dependent lead times and a high delivery reliability. Therefore routing-dependent lead times will be applied.

4.1.5. Workload-dependent lead time

Workload-dependent lead times are lead times where available capacity is taken into account. When the demand in a certain period is high, the lead time increases, compared to a situation in which the demand is low.

Based on interviews with customers, it can be concluded that workload-dependent lead time is not favourable for customers. This because when workload-dependent lead time is applied, the delivery time is uncertain for customers. As an example: two equal orders, ordered on two different moments, can have different lead times. Producers on the other hand prefer workload-dependent lead times, because of the easier control of production. Thereby workload-dependent lead time ensures order delivery almost always on time because the capacity is always larger than the workload.

Literature confirms the experts’ statement. There are many ways to deal with uncertainty. For example overtime or temporary workers can be used to capture peak periods. But the best solution can be found in workload-dependent lead time because this is an unlimited solution. According to Pahl (2007) lead time increases exponential in the relation with the utilization. Das (2003) confirms this statement and has evidence that this is a result of dynamic behaviour of queues when the utilization of workstations increase. This non-linear relation between lead time and utilization of workstations may lead to significant differences in planned and realized lead time if fixed lead time assignment rules are used. According to van Ooijen (2012), applying workload-dependent lead time can detect potential over- and underutilization. This can be solved by re-planning orders and slide orders forward and backward in production planning. Aouam (2015) discussed the
relationship between demand uncertainty and workload-dependent lead times and concluded that when demand uncertainty is present, workload-dependent lead times are more preferable. Dobson (2011) researched a broader relation between uncertainty and workload-dependent lead time. Dobson underlines the importance of workload-dependent lead time and concludes that workload-dependent lead time increases the system performance when any uncertainty is present in a manufacturing system.

Based on the interviews, it can be concluded that there is a difference between the ideal situation for customers and producers. Customers prefer lead times which are as standard as possible. Producers prefer workload-dependent lead times, because in this situation the workload of manufacturing systems can stay equal.

As described above, customers do not prefer workload-dependent lead times, while producers prefer this lead time assignment rule. Because of this contradiction, partial workload-dependent lead time for manufacturers is chosen. This means that basically a standard lead time is used. If the demand exceeds the capacity, workload-dependent lead times are used. Then is the lead time longer than the standard lead time.

4.1.6. Conclusion

Every lead time assignment rule has pros and cons for both the manufacturer and the customer. Table 15 gives an overview of different lead time assignment rules and their gradation according to manufacturers and customers.

Table 15 - Conclusions about lead time assignment rules based on interviews and literature

<table>
<thead>
<tr>
<th>Lead time assignment rule</th>
<th>Manufacturers</th>
<th>Customers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed</td>
<td>___</td>
<td>+++</td>
</tr>
<tr>
<td>Flexible</td>
<td>++</td>
<td>--</td>
</tr>
<tr>
<td>Order quantity-dependent</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Routing-dependent</td>
<td>+++</td>
<td>-</td>
</tr>
<tr>
<td>Workload-dependent</td>
<td>+++</td>
<td>___</td>
</tr>
</tbody>
</table>

Legend
+++ = very positive
+ = positive
- = negative
___ = very negative

Based on interviews and existing literature a conclusion can be drawn: fixed lead times are not useful for manufacturers with the characteristics of Marsna Paper. As described in the previous sections routing-dependent, workload-dependent and flexible lead times are useful for manufactures described in this paper. These lead time assignment rules should be combined, in order to create a customized lead time assignment rule. Because of the usage of workload-dependent lead time, the order size is considered because more capacity is reserved when the order quantity is larger.

Combining the three most important lead time assignment rules results in the following lead time assignment rule. Based on the routing of a manufacturing system a lead time is given. It is chosen to express the due date in weeks, instead of days. Then, the order needs to be delivered somewhere during the selected week (note that this is a flexible lead time). Besides these lead time assignment rules, has the manufacturer the possibility to assign longer lead times based on the workload of the plant. This should only happen if the manufacturing system has a high utilization rate.

With this method to assign a lead time, the manufacturers have lead times that deal with the uncertainty of the process and the customer is provided with some guarantees and certainties.
4.2. Batch size
Because manufacturers with the characteristics of Marsna Paper have small customer orders, batch size is often very relevant. The batch size is highly dependent on the start-up costs, setup times and the demand. A large batch size keeps the total start-up costs low and total setup time short. A disadvantage of a large batch size is the production flexibility. With a large batch size, it is not possible to produce a particular order any time. Below, the effect of the start-up costs, setup times and demand on the batch size is shown.

Start-up costs
This project investigates companies with an energy intensive production process. If a production process is energy intensive, in most cases a workstation must be heated. This means that start-up costs occurs. If a machine has start-up costs, it is important to make a large batch size, because the start-up cost per order is then relatively low.

\[
\text{Startup costs per product} = \frac{\text{Total startup costs}}{\text{Batch size}}
\]

As can be seen in above formula, the start-up costs per order reduce as the batch size increases.

Setup times
This project investigates companies with small batches and diverse orders. Small batches and diverse orders indicate setup times on regular basis. The reasoning presented in the previous section (start-up costs) can also be done in this section. The larger the batch size, the shorter the setup time per order (See formula below).

\[
\text{Setuptime per product} = \frac{\text{Total setuptime}}{\text{Batch size}}
\]

Demand
This project investigates companies that produce diverse orders. Production of diverse orders means that a company has a lot of different workstations and that a lot of setups are done. For flexibility it is good to minimize the batch size, so that demand can be selected on every criteria. For example, it would be fine to produce orders based on earliest due date. This may be in conflict with a batch size based on minimizing the total setup time.

Conclusion
Depending on the setup times, start-up costs and customer demand the batch size is being determined. Table 16 states the batch size under various circumstances.

<table>
<thead>
<tr>
<th>Circumstances:</th>
<th>Batch size:</th>
</tr>
</thead>
<tbody>
<tr>
<td>High start-up costs</td>
<td>Large</td>
</tr>
<tr>
<td>Low start-up costs</td>
<td>Small</td>
</tr>
<tr>
<td>Long setup times</td>
<td>Large</td>
</tr>
<tr>
<td>Low setup times</td>
<td>Small</td>
</tr>
<tr>
<td>Varied demand</td>
<td>Small</td>
</tr>
<tr>
<td>Standard demand</td>
<td>Large</td>
</tr>
</tbody>
</table>

4.3. Sequence of orders
In this subchapter, the sequence of orders during production is discussed. The problem statement in this project is a low delivery reliability because many orders are delivered too late. Baker (2002) stated that earliest due date (EDD) is an effective rule to minimize tardiness. Therefore the main rule in deciding the sequence of orders is EDD. If several orders have the same due date, other criteria can be included (Differs for each workstation).
**Sequence-dependent setup times.**

In this project, companies with sequence-dependent setup times are investigated. For workstations where sequence-dependent setup times are relevant, a combination of EDD and minimize the setup time needs to be used. First, the functional requirements must be met. The functional requirements specify in what time frame an order should be made. So, the batch size is made as large as possible (in order to minimize the setup time) as long as the functional requirements are met.

**Employees can operate multiple workstations**

Small companies with small customer orders have often employees who can operate multiple workstations. It can be a challenging problem to allocate the resources (staff) for processes. It is important to provide rules for allocation of staff to workstations. First it is important to recognize the workstation which is the bottleneck. This workstation needs to produce always. The second planning rule is based on the location of the workstation in the production process. Daniels (1994) states that the allocation of workers for flow shop problems is based on the position of the workstation in the production process. When the workload of the workstations is equal, workstations early in the production process (upstream) have priority (for allocation of workers), compared with workstations later in the production process (downstream).
5. Conceptual Design: Marsna Paper

In this chapter, the conceptual design for Marsna Paper is presented. This chapter will describe a conceptual design focused on the single case of Marsna Paper, resulting in a more specific and practical conceptual design. For constructing the conceptual design, the values resulting for the detailed analysis in chapter three will be used. This conceptual design is made during this project and is not the same as the current situation. In the first part of this chapter the scope for the conceptual design will be described. In the second section the feasibility of the system will be checked. In this section are rough cut calculations presented to determine if (1) the production hours needed to produce the demand is smaller than the available capacity and (2) the throughput time (total production time of order) is shorter than the agreed lead time. The functional requirements will be stated in the third section. The fourth part of this chapter will described where the system is decoupled and which production units are created. Thereafter it will be explained how the production unit will work together through the GFC. Because all production units need to operate independently, functional requirements per production unit are stated in the next section. Finally the difference between the current situation of Marsna Paper and the design situation during this project is given.

5.1. Scope

Because this project investigates the delivery reliability of a manufacturer, concerns the scope of this project the moment an order is received by Marsna Paper (release moment) till the moment an order is ready for transport (transport itself fall outside the scope). The agreed delivery date of Marsna Paper with a customer is the moment an order is ready for transport. (Not when the order is delivered at the customer.) For the capacity calculations, it should be taken into account that a truck must be loaded by the employees of Marsna Paper (loading the truck falls within the scope).

For the design, there is the assumption that all the raw materials are always available. This assumption is realistic because in the previous year, there was no production stop because of a lack of raw material (Wingender, 2016). If there is always raw material available, the buying and inventory policy of raw material has no influence on the throughput time (and delivery reliability), because production can start when an order is released. For this reason the buying and inventory policy of raw material fall outside the scope.

When a new colour is requested by a customer of Marsna Paper, this colour creation process falls outside the scope, because the delivery date is determined when the colour creation procedure is finished. When an order request is received (final), then the order is released for production.

Because there are less employees than machines and demand varies, machines are often switched-off (not any machine is always working). Preventive maintenance occurs when an machine is switched-off. If corrective maintenance is necessary, the defect machine is switched-off (and maintenance occurs) and another machine is switched-on. Therefore, maintenance doesn’t affect the delivery reliability and for this reason is maintenance irrelevant for this project in the case study of Marsna Paper.

Order acceptance falls outside the scope of this project. The production manager determines if an order can be produced by Marsna Paper and the sales manager decides if the price is acceptable. For this project it is assumed that all orders, which are accepted by the production- and sales manager, need to be produced.

5.2. Feasibility

A major concern for this project is the feasibility of the objectives for the system. The problem of this project (low delivery reliability) can be a result of low capacity or
unrealistic agreements with customers about the lead-time. In this subchapter the rough-cut feasibility of the system is calculated. The system is feasible if (1) the production hours needed to produce the demand is smaller than the available capacity and (2) the throughput time (total production time of order) is smaller than the agreed lead time.

The demand in the future is uncertain. To forecast the demand, the demand of last year is used. The demand of last year is analysed in the detailed analyses. There is a risk because the orders of last years do not guarantee the quantity and type of orders for next year. To minimize the risk, two interviews with the general manager and the sales manager have been conducted. Conclusion of these interviews is that Marsna Paper expectations for next year are roughly equal to the demand of last year and thus the demand of last year is useful to estimate the demand for next year.

5.2.1. Stability
To analyse if the entire system is stable, the total demand should be compared to the total available capacity. Because workstations are multiple resource constrained (machines and staff), the stability for both machines and staff is checked. The system is stable if:

- Staff capacity of each PU > Staff capacity needed to produce the demand per PU
- Staff capacity entire system > Staff capacity needed to produce the demand for the entire system
- Machine capacity of each PU > Machine capacity needed to produce the demand per PU
- Machine capacity entire system > Machine capacity needed to produce the demand for the entire system
- Combination of machine and staff capacity > Machine and staff capacity needed to produce the demand

**Machine stability**
First the machine capacity (capacity of a workstation) needs to be compared with the demand per machine. Table 17 compares the demand per workstation with the machine capacity. As described in the detailed analysis, the paper production occurs 24 hours a day and the finishing department works 16 hours a day. The occupation rate states the percentage that a workstation on average operates to produce the demand. The conclusion can be drawn that there is more capacity than demand at each workstation.

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Demand</th>
<th>Max machine capacity 16h production</th>
<th>Max machine capacity 24h production</th>
<th>Occupation rate based on max capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM2</td>
<td>51.1 ton / week</td>
<td>129 ton / week</td>
<td>39.6%</td>
<td></td>
</tr>
<tr>
<td>PM3</td>
<td>24.2 ton / week</td>
<td>115 ton / week</td>
<td>21.0%</td>
<td></td>
</tr>
<tr>
<td>PM4</td>
<td>14.3 ton / week</td>
<td>144 ton / week</td>
<td>9.9%</td>
<td></td>
</tr>
<tr>
<td>Kal7</td>
<td>18.28 ton / week</td>
<td>88 ton / week</td>
<td>20.7%</td>
<td></td>
</tr>
<tr>
<td>Bob2</td>
<td>40.74 ton / week</td>
<td>110 ton / week</td>
<td>37.0%</td>
<td></td>
</tr>
<tr>
<td>Bob3</td>
<td>10.57 ton / week</td>
<td>48 ton / week</td>
<td>22.0%</td>
<td></td>
</tr>
<tr>
<td>PK2</td>
<td>19.39 ton / week</td>
<td>42 ton / week</td>
<td>46.2%</td>
<td></td>
</tr>
<tr>
<td>PK4</td>
<td>3.63 ton / week</td>
<td>37 ton / week</td>
<td>9.0%</td>
<td></td>
</tr>
<tr>
<td>RPM</td>
<td>7.45 ton / week</td>
<td>27 ton / week</td>
<td>27.6%</td>
<td></td>
</tr>
<tr>
<td>RS10</td>
<td>40.25 ton / week</td>
<td>69 ton / week</td>
<td>58.0%</td>
<td></td>
</tr>
<tr>
<td>RS7</td>
<td>17.13 ton / week</td>
<td>47 ton / week</td>
<td>36.4%</td>
<td></td>
</tr>
<tr>
<td>RS9</td>
<td>1.86 ton / week</td>
<td>29 ton / week</td>
<td>6.0%</td>
<td></td>
</tr>
<tr>
<td>Polar</td>
<td>26.11 ton / week</td>
<td>60 ton / week</td>
<td>43.5%</td>
<td></td>
</tr>
</tbody>
</table>
### Staff stability

Besides the machine stability also the staff stability needs to be analysed. To analyse if the entire system is stable, the overall hours needed to produce the demand should be compared to the total available capacity. For the staff a distinction should be made between the (1) production and (2) finishing department, because those departments work separately.

Marsna Paper made the assumption that no staff can be fired. Furthermore it is not possible to change the percentage shift work. Concretely, this means that the employees of the production department will work in three shifts and the finishing department in two shifts.

1. **Production department:**
   
   In the detailed analyses (subchapter demand and production rates) it has been stated what the average demand for Marsna Paper is and what the production rates per workstation are. Based on this information it is calculated how many production hours (on average) are needed to produce the demand in the production department per year.

   **Table 18 - Production hours needed to produce the demand in the production department (Excl. start-up time and cleaning time)**

<table>
<thead>
<tr>
<th>Workstation</th>
<th>% orders per workstation</th>
<th>Orders (tons / year)</th>
<th>Production rate (kg / h)</th>
<th>Production hours needed to produce demand (h/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM2</td>
<td>57%</td>
<td>2657.2</td>
<td>1125</td>
<td>2361.9</td>
</tr>
<tr>
<td>PM3</td>
<td>27%</td>
<td>1258.7</td>
<td>1000</td>
<td>1258.7</td>
</tr>
<tr>
<td>PM4</td>
<td>16%</td>
<td>745.9</td>
<td>1250</td>
<td>596.7</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>4661.8</td>
<td></td>
<td>4217.4</td>
</tr>
</tbody>
</table>

   Besides the production hours, there are 5 hours needed to start a machine and to clean a machine every week.

   As explained in the detailed design (subchapter capacity), the total staff capacity for the production department is 5580 hours a year. Total capacity needed is 4217.4 (production hours) + 235 (Start-up and cleaning hours for 47 weeks) = 4452.4 hours a year.

   Production department is stable because: 5580 > 4452.4

2. **Finishing department:**
   
   Also the finishing department is stable if the capacity is larger than the needed production hours. Table 19 shows how many hour are needed to produce the demand for the finishing department. Again, the demand and processing times are analysed in the detailed analyses (subchapters demand and processing times).

   **Table 19 - Production hours needed to produce the demand in the finishing department per year**

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Demand (Tons / year)</th>
<th>Production rate (kg / hour) (incl. setup and move time)</th>
<th>Hours needed to produce demand</th>
<th>Production to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kal7</td>
<td>951</td>
<td>1147</td>
<td>829.1</td>
<td></td>
</tr>
<tr>
<td>Bob2</td>
<td>2116</td>
<td>1433</td>
<td>1476.9</td>
<td></td>
</tr>
<tr>
<td>Bob3</td>
<td>550</td>
<td>623</td>
<td>883.0</td>
<td></td>
</tr>
<tr>
<td>PK2</td>
<td>1007</td>
<td>548</td>
<td>1837.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PK4</td>
<td>RPM</td>
<td>RS10</td>
<td>RS7</td>
</tr>
<tr>
<td>---</td>
<td>-----</td>
<td>-----</td>
<td>------</td>
<td>-----</td>
</tr>
<tr>
<td></td>
<td>186</td>
<td>387</td>
<td>2093</td>
<td>890</td>
</tr>
<tr>
<td>RPM</td>
<td>488</td>
<td>611</td>
<td>890</td>
<td>944</td>
</tr>
<tr>
<td>RS10</td>
<td></td>
<td></td>
<td>2351.9</td>
<td></td>
</tr>
<tr>
<td>RS7</td>
<td></td>
<td></td>
<td>943.2</td>
<td></td>
</tr>
<tr>
<td>RS9</td>
<td></td>
<td></td>
<td>275.8</td>
<td></td>
</tr>
<tr>
<td>Polar</td>
<td></td>
<td></td>
<td>1732.5</td>
<td></td>
</tr>
<tr>
<td>GRM</td>
<td></td>
<td></td>
<td>1300.2</td>
<td></td>
</tr>
<tr>
<td>LAMB</td>
<td></td>
<td></td>
<td>771.3</td>
<td></td>
</tr>
<tr>
<td>Packing</td>
<td></td>
<td></td>
<td>2338.3</td>
<td></td>
</tr>
<tr>
<td>Transport</td>
<td></td>
<td></td>
<td>1560.0</td>
<td>(6,5 h/day)</td>
</tr>
</tbody>
</table>

An employee is required to operate a workstation. Only for the LAMB, three employees are required to process the paper. Furthermore, the employees’ task is to load the transport when the truck has arrived. This costs approximately 6.5 hours a day.

As explained in the detailed design (subchapter capacity) an employee is available for 1860 hours a year. With 11 staff members, the total capacity for the finishing department is 20460 hours a year.

*Finishing department is stable because: 20460 > 17315.1*

**Conclusion stability for entire system**

As well for the production as the finishing department is the capacity greater than the hours needed to produce the demand. Also the workstation capacity is greater than the needed workstation capacity. It is also important to analyse the combination of the staff- and workstation capacity, because in some triple resource constrained systems, there is sufficient staff- and workstation capacity, but the combination of the staff and workstation allocation is a problem.

The combination of staff- and workstation capacity in the paper production department is feasible, because the different teams can operate each paper production line. With this staff capacity one paper production line can be operated, while there are three paper production lines. Therefore there isn’t a problem for the combination of staff- and machine capacity in the paper production department.

In the finishing department there are 13 workstations and 11 employees. As described above, the maximum workstation utilization is 59%. In addition, an operator can work with on average 5.1 workstations. Since the utilization of workstations is low and employees can work at many different workstations, it can be concluded that the combination of staff- and workstation capacity is feasible.

So, the entire system of Marsna Paper is stable.

**5.2.2. Feasible lead times**

The next thing to analyse is the rough-cut throughput time (the average (actual) time from release of a job at the beginning of the routing until it reaches an inventory point at the end of the routing) of the production units, because to determine if the delivery agreement can be realised, the throughput time of the orders needs to be evaluated and compared to the agreed lead times (time that is required to fill an order or meet customer demand).

The time required for production is known, but the waiting time which will increase the throughput time is not known yet. The throughput time of a workstation exists out of processing time and waiting time.
According to Hopp (2000), the waiting time is dependent on the utilization, variability and processing times.

The utilization need to be calculated for the paper production department and the finishing department because both departments have their own staff resources. Using the values calculated in the previous section the utilization for every department is calculated.

\[
Utalization\ Production = \frac{\text{production hours needed}}{\text{capacity production personel}} = \frac{4217.4}{5640} = 0.7478
\]

\[
Utalization\ Finishing = \frac{\text{finishing hours needed}}{\text{capacity production personel}} = \frac{17315}{20460} = 0.8463
\]

Variability is expressed in a coefficient of variation. The coefficient of variation needs to be considered for the arrival rate and the production rate. The coefficient of variation calculates the ratio of standard deviation compared with the arrival- or production rate. Based on the detailed design it can be estimated that the:

- Coefficient of arrival variation for the paper production is ± 0.165
- Coefficient of variation for the paper production line is ± 0.075
- Coefficient of arrival variation for the finishing department is ± 0.115
- Coefficient of variation for the workstations in de finishing department are between ± 0.058 and 0.583.

The last variable, the processing times is dependent on the routing of an order but are ± 2 hours.

The total throughput time of an order is always different because the order quantity and the routing of the order differs per order. The utilization is far from the 100%, the variability is medium and the processing time is small. Based on the utilization, variability and processing times it can be concluded that the total throughput time is around the week. Therefore it is possible to produce all orders within the assigned lead times. The calculations to estimate the throughput time can be found in appendix F.

To gain more efficiency, some orders are produced in batches. This affects the throughput time, because creating a batch, increases the waiting time for production for orders. In the detailed design, the batch size per workstation will be calculated and then a new throughput time can be calculated.

5.2.3. **Conclusion feasibility**

With the rough-cut feasibility calculations it can be concluded that the system is feasible if (1) the production hours needed to produce the demand is smaller than the available capacity and (2) the throughput time (total production time of order) is shorter than the agreed lead time.

(1) As well for the production as the finishing department the capacity is larger than the hours needed to produce the demand. The workstation capacity is also larger than the needed machine capacity. Also the combination of the staff- and workstation capacity is feasible. Therefore it can be concluded that the entire system is stable.

(2) As well for the production as the finishing department the throughput time is shorter than the agreed lead time, so the system is also feasible for the lead times.

5.3. **Functional Requirements (FRs)**

In this subchapter the FRs of the logistics control system of a manufacturer are set. The FRs for the entire system are important because these are the objectives that a system needs to achieve. If the FRs are met, the design is approved. Bertrand et al. (1990) states that “the Functional Requirements regarding the performance of the Logistics Control
System can be expressed in variables, such as the delivery performance relative to demand for end-items and total logistics related costs”.

As described in chapter four, routing-dependent, workload-dependent and flexible lead times are useful for manufacturers like Marsna Paper. Concretely lead times are assigned, based on the routing of a manufacturing system. Furthermore a due date is expressed in weeks, which states that an order can be delivered any time in a certain week (note that this is a flexible lead time). Besides these lead time assignment rules, the manufacturer has the possibility to assign longer lead times based on the workload of the plant. In practice the release moment of an order (for production) is postponed when the workload is too high, and therefore the functional requirements are not changed. This should only happen if the manufacturing system has a high utilization rate. Based on the interviews with customers it can be concluded that customers only have understanding for workload-dependent lead times if this type of lead time does not appear structurally. Because the capacity of Marsna Paper exceeds the demand, it can be concluded that workload-dependent lead times are used not structurally.

The Functional Requirements for the logistics operation planning and control system for Marsna Paper are set as follows:

- \( P\{\text{throughput time} \leq \text{lead time}\} \geq 0.95 \): 95% of the total number of accepted orders should be delivered within agreed time. Partial deliveries are not allowed, because of agreements with the customer and higher transport costs.
- 5% of the total number of orders should be delivered with a maximum lateness of 1.5 months.
- All orders (with the exception of the below-described orders) released in week X need to be ready for transport in week X+6. Exceptions: Orders which need to be squeezed at one side or paste, and are released in week X need to be ready for transport in week X+8. Orders which need to be squeezed at both sides need to be ready for transport in week X+9.
- The client of this project states a budget for the costs relevant for this project. These costs should not be exceeded.
  - Employment costs: €1117708.8 per year. (15 paper production operators and 11 finishing operators)
  - Holding costs: €3239.6 per year. (1% holding costs * 1820.6 (cost price) * 178 (average WIP))
  - Start-up costs: €52930.56 per year. (48 start-ups a year for WKC and RPM)
  - Backlog costs: €15625 per year. (3125 orders per year * 5% orders to late * 100 euro penalty costs)
- The client of this project wants to maximize the throughput of the entire system.

The FRs decided regular delivery times of six, eight or nine weeks. When an order is ready before the due date, the order could be stored at Marsna Paper or send earlier than agreed. Therefore it is not a problem if orders are produced earlier than planned.

It is not realistic to demand a delivery reliability of 100%. Even if the operations planning and control system is perfect, an order can be delivered too late due to a production error or technical problem in the process. Therefore, a maximum of 5% of all orders can be delivered late.
5.4. Customer Order Decoupling Point (CODP)

In this subchapter the placement of the CODP for Marsna Paper will be discussed and determined. All orders till the CODP are make-to-stock and all orders from this point are made-to-order.

The CODP differs for every manufacturer and depends on the production process. It is beneficial to position the CODP as early as possible in the complete process (most upstream). This is preferred because production can be based on actual demand. The advantage is that orders are known and with this information the stock and processing time can be minimized and the service level be maximized.

It is in most cases not possible to place the CODP at the start of the process because the order lead time will be shorter than the production throughput time. For this reason the CODP is forced later in the process (more downstream). The disadvantage of this position of the CODP is that production is based on estimated demand which doesn’t necessarily match the actual demand. To meet the service levels in this case, a manufacturer (especially manufacturers with diverse orders) must have a lot of (safety) stocks, which costs money.

The conclusion can be drawn that the CODP must be located as early as possible in the process, with the requirement that the production lead time is shorter than the order lead time.

Customers of Marsna Paper can choose between 1200 various quality substances and 8000 different colours. Besides these options, even a new colour can be requested. Production starts only once an order is received from a customer, because make-to-stock for all these possibilities is very expensive. Furthermore is it not certain that an order produced based on make-to-stock will be sold in the future.

The lead time of the procurement of raw materials such as cellulose and dyes amounts between the four and six weeks. The agreed lead time for some orders is six weeks. So the agreed lead time is in some cases not feasible when the raw materials are ordered when an order is received. To make all possible combinations, 10 different types of cellulose and 45 different dyes are necessary. So a relatively small stock of raw materials can make all combinations of orders. On average the raw material costs 856,05 euro per ton of paper. For these two reasons the raw materials will be bought on stock.

As explained in chapter 5.2.2. the throughput time of the entire production process is shorter than the agreed lead time and for this reason the CODP can be placed at the start of the production process. Figure 10 shows where the CODP is located in the production process of Marsna Paper. Before the CODP, raw materials will be bought on stock and thereafter the CODP orders will be produced after an order is received.

![Figure 10 - Customer Order Decoupling Point. The raw material are bought on stock, but the production only starts once an order is received from a customer.]

Because the CODP is located at the start of the production process, the manufacturing system can be classified as a pull system.
5.5. Production Units

On the one hand it is difficult to take the production process as a whole, by making an integral planning, and on the other hand it is also not useful to look at each process separately because one has to keep an overview. A solution for this problem is found in decoupling processes and split them in production units (PUs). By defining PUs it is important, to make sure that PUs can be controlled independently from each other, but work together to achieve the overall functional requirements. Thus, complex planning problems are easier to deal with. PUs should work independently and should therefore be realizing their own functional requirements without any information on the other modules’ functional requirements’ realization. As stated by Bertrand et al. (1990), the introduction of PUs reduce the complexity of decision problems and increase stability, which as such may lead to improved models.

5.5.1. Decoupling points in literature

According to Bertrand et al. (1990) four reasons give rise to decouple processes:

- If two successive processes are not synchronized in either speed, uncertainty or setup: If two processes are not synchronized, there will either be a uncontrolled increasing buffer or a shortage at the beginning of the follow-up process. To tackle this problem, two not synchronized processes should be decoupled so the controlled stock point that arises between the two decoupled processes prevents buffer instabilities.

- In case resources are exchangeable in the processes: If the resources of two processes can be exchanged, these processes can be combined in the same PU, because the processes can be synchronized by exchanging resources. If this is not the case it is wise to decouple the processes.

- If differences in commonality appear: When a product changes due to the process its physical size is different from the physical size in the subsequent process, the processes need to be decoupled, because the input of an order at workstation X is different compared with the input of workstation X+1 and therefore variables such as speed or uncertainty can be different.

- At times relevant information on the process changes. According to Bertrand, new information that arises during the process and that influences the process, for example a new forecast for the demand, leads to decoupling at points where this information is of interest. As we have seen in the former paragraph, Marsna Papers’ CODP is located at the beginning of the production process. Therefore all required order information is available once the production starts, and so this indicator on decoupling processes is not relevant for Marsna Paper.

5.5.2. Decoupling points at Marsna Paper

With the information that is available for Marsna Paper and the indicators given by Bertrand, it is decided to decouple the production process of Marsna Paper in two separate PU’s. An explanation for the choices will be given in next paragraphs. A systematic overview on the PUs is given in Figure 11. Abbrevations can be found in appendix C.
Decoupling between PU1 and PU2

As it shows in figure 11, PU1 consists of the paper production department, while PU2 exits of the workstations of the finishing department. A decoupling between PU1 and PU2 has been made at this point for the following reasons:

1. Difference in speed between the PUs.
   As described in the detailed analysis (chapter 3), the production department has a larger capacity than the finishing department. If both departments produces at maximum capacity, this results in increasing WIP causing unnecessary costs. Thus, a controlled stock point is needed. By introducing this controlled stock point, the processes can be synchronized, because the goods flow control can release orders and allocate capacity. (Information about the goods flow control is given in the next section.)

2. Difference in the opportunity to vary resources.
   The absence of options on exchanging resources should be considered as being an important indicator for decoupling processes. Because the production- and the finishing department have different resources (staff and workstations), resources cannot be exchanged, so PU1 and PU2 should be decoupled.

3. Difference in order sequence:
   A production run in PU1 is based on the colours of the ordered paper (as explained in chapter 3, detailed analysis) This fact leads to a sequence of orders which is completely different from sequence used in PU2. In this PU, colour sequence has no importance, as the process here has been organized by the Earliest Due Date (EDD). This difference in order sequence is an reason to decouple PU1 and PU2.

4. Lack of synchronisation on energy costs
   Furthermore, starting a machine in the production department is an expensive operation on energy costs, because a large boiler, consuming a lot of gas for heating has be turned on. Customers demand and energy efficiency rules cause a regular on- and off-switch of these machines. In PU2 no such problems arise, as this finishing process is no high energy consuming processes.

No decoupling for other processes

The other processes can be combined in the same PU, because the processes are synchronized. Although there are difference between the workstations in PU2, these processes can be synchronized by implementing planning rules per workstation. Furthermore, resources (staff capacity) can easily be exchanged in the finishing department, because an employee on average, is able to work with 5.1 different workstations and workstation can easily be switched on and off.
There are two issues within PU2 which could indicate to split PU2. Below, these issues are discussed and is explained why PU2 isn’t decoupled.

(1) PU2 consists of squeezing machines, the most prominent of which is named PK2. As we have seen in previous chapters, PK2 has long setup times, namely between one and three hours per setup. A controlled stock point could change the PK2 sequence and thus diminish its total setup time. In this design it is chosen to work with batching- and sequence rules per workstation in order to reduce the total setup time, in order to keep the PU in one part.

(2) Another reason to consider decoupling within PU2 is related to tambours. As explained in the detailed analysis tambours are an indispensable resource for paper production. There are 106 tambours available and –as occurs regularly- when the WIP before the ‘RS10’, ‘BOB2’ and ‘BOB3’ consists of 106 tambours, the paper production is lacking tambours. For some workstations in PU2 the paper is delivered on a tambour, whereas other workstations in PU2 uses smaller rolls or even sheets. It could be a reason to decouple PU2 in two parts, where the first part is responsible for the inventory of tambours as the second part obviously is not. It is not preferable to decouple the process and post this responsibility in an individual PU because with this decoupling, some difficulties arise. PU2 consists of all workstations in the finishing department. All staff resources can be used within PU2. When PU2 is decoupled, the staff resources needs to be splits. By splitting the resources, the flexibility decreases. Another disadvantage of decoupling PU2 is extra coordination of these PUs. With one PU for the finishing department, one employee can manage all workstations and processes.

5.6. Goods Flow Control (GFC)

According to Bertrand et al. (1990) the GFC determines and controls the relationship between different PUs. The GFC accomplishes this by releasing work orders to individual PUs. The GFC is concerned with the coordination of:

- Production levels, which results in required capacity levels and capacity-use of the production units,
- Materials supply to the various stock points at the start of the production and between the manufacturing phases.

On the short term, GFC controls the stock level for Marsna Paper in the stock points through the release of work orders to the production units (detailed planning). On a somewhat longer term it also controls the capacity and production levels (aggregate planning). GFC uses control variables for making this planning.

The entire process is controlled by the GFC, as is represented in figure 11. Order retrieval and transport to the customer are no PUs. These are controlled by the GFC, but because those processes fall outside the scope, and the delivery agreement is applicable from the release moment till the moment an order is ready for transport, is this not taken into account.

At the decoupling point before the first production unit, it is important to provide enough raw material to PU1. The capacity of raw material has to be controlled so that PU1 can produce all orders. As stated earlier, the assumption is made that all the raw materials are available and can be ordered with no lead time. Therefore the stock level of the raw inventory is not controlled by the GFC in this design. Furthermore this decouple point is important, because here the CODP is positioned (Explained in chapter 5.4.).

When the finishing is done, the GFC needs to communicate with the conveyor. Again, this falls outside the scope, because the assignment focuses on the moment until an order is ready for transport.
The GFC does not decide which workstation needs to produce which orders in which sequence on what time. The PUs determine the batch size, the sequence of orders, the capacity allocation and the production schedule.

Operators enter information about the executed orders per workstation. The information system processes this information and keeps track on the progress of an order. Based on this data, the release moments are determined. It is possible to create a list of orders that have yet to be produced in the paper production- and the finishing department.

Other GFC related subjects, such as order acceptance, are described in chapter 6.3. where the GFC is discussed in detail.

### 5.7. Functional Requirements (FR) per PU

Besides the FRs for the entire system, they also need to be defined for the individual PUs. Now the analyses is done, the FRs per PU can be set. If the FR of the individual PUs is met, the FRs of the entire system should also be met.

For PU1 till PM9:

- Capacity > demand

Based on the lead time of an order, a FR is presented for every PU:

- For all customer orders:
  - PU1, Paper production: Produce every order in 4 weeks with 98% certainty
  - PU2, Finishing: Produce every order before the due date, with 98% certainty

The lead time of PU1 (paper production) is 4 weeks, because this PU has three main restrictions. (1) There are high start-up costs because of the energy intensive production process. (2) A production run based on colour sequence is necessary to minimize the setup costs. (3) Furthermore are there three paper machines which all produce different kind of orders.

Note that the product of the certainty percentages needs be equal or higher than 95% to meet the functional requirements of the entire system.

### 5.8. Difference between current- and designed situation

Table 20 shows a briefly compare between the current- and designed situation. Chapter seven discusses the differences more detailed.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Current situation</th>
<th>Design presented in this project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functional Requirements</td>
<td>Flexible and</td>
<td>Flexible, routing-dependent and</td>
</tr>
<tr>
<td></td>
<td>routing-dependent</td>
<td>workload-dependent</td>
</tr>
<tr>
<td>CODP</td>
<td>Equal</td>
<td></td>
</tr>
<tr>
<td>Production Units</td>
<td>Equal</td>
<td></td>
</tr>
<tr>
<td>GFC</td>
<td>By information</td>
<td>By information system</td>
</tr>
<tr>
<td></td>
<td>system</td>
<td></td>
</tr>
<tr>
<td>Functional Requirements per PU</td>
<td>Doesn’t exist</td>
<td>Are available</td>
</tr>
</tbody>
</table>
6. Detailed Design: Marsna Paper

Extending on the conceptual design, described in chapter 5, this chapter will describe the detailed design. The conceptual design will be functioning as a framework for the detailed design. As explained in the conceptual design, the PUs are designed and decoupled in order to operate independently. In the detailed design every production unit makes rules to meet their own functional requirements. It is important to choose the right rules that meet the functional requirements, because the entire system needs to stay feasible. The rules have to be based on information which is only locally available, because the PUs need to work independently of each other.

The paper production department has a higher production rate than the finishing department and therefore, section one discusses the balancing of the capacity. The second section of the detailed design is about the paper production department (PU1). This PU is complex because of start-up costs, sequence-dependent setup times and capacity constraints. In this section four issues are discussed: (1) number of paper machines, (2) size of the production run, (3) production schedule, (4) sequence of orders and (5) overtime management. The next section is about PU2. In this PU some workstations have start-up costs or long setup times. This PU has also a third resource which should be taken into account, namely tambours. In this section the batch size, sequence of orders, role of tambours and allocations of the staff are discussed. In the fourth section, about the GFC, several aspects such as the order acceptance function are discussed. Section five determines how much WIP is needed in the system. Finally the difference between the current situation of Marsna Paper and the design situation during this project is given.

6.1. Balancing of capacity of the PUs

An important aspect to consider is the balancing of the capacity of PU1 and PU2. The capacity is balanced if production rates of each department are equal over the long term. For balancing capacity it is important to match the production rates of the workstations with the throughput (output rate).

There are multiple benefits of balanced capacity of the PUs. (1) Waste of overproduction is eliminated. (2) Inventory is kept relatively low. (3) The maximum throughput is gain (Because the bottleneck is optimized). These benefits results in producing more orders with the same resources which will reduce the cost, because for example less overtime is needed. The throughput time of the entire system will also increase by balancing the capacity of the PUs.

Balancing capacity is relevant for Marsna Paper because the operations of both departments have different production rates. As explained in chapter three, the paper production department has a higher production rate (on average ±122 ton per week) than the finishing department (on average ± 96 ton per week). Applying balanced capacity to Marsna Paper would result in equal production capacity in all departments - in the long term- hereby maximizing the total capacity. So the production process of Marsna Paper would be balanced once the production rate of both the production and finishing department were equal. The production speeds can be equalized by creating a stop in the paper production at a selected point of time. If the paper production department produced five weeks and would stop producing during the sixth week, the production rates (for a cycle of six weeks) would be almost equal. Due to this stop in week six, it should be noted that this would include unemployment for the staff of the paper production department for one week. However, this problem resolves itself because Marsna Paper works with flexible workers, and moreover, the paper production staff is also employable in the finishing department. Although it should be noted that the employees of the production department did not hardly work as fast as the experienced finishing departments’
employees. The productivity of production staff in the finishing department was four times less than an finishing department operators productivity.

In the following calculation, the capacity of the different departments are:

*Paper production rate 5 weeks* = 5 * 122 (tons per week) = 610 tons.
*Paper production rate when there is no production (1 week)* = 1 * 0 (ton per week) = 0 ton
*Total paper production rate 6 weeks* = 610 + 0 = 610.

*Finishing rate (finishing staff) 6 weeks* = 6 * 96 (tons per week) = 576 tons
*Finishing rate (paper production staff) 1 week* = 1 * 0.25 (productivity of production staff in finishing department) * 96/11 (tons per week/number of employees in finishing department) * 15 (paper production staff) = 32.7 tons per week
*Total finishing rate 6 weeks* = 576 + 32.7 = 607.7 tons

As calculated above, a paper production stop for one week roughly equalised the capacity of the paper production- and finishing department (610 to 608 ton per six weeks). In addition, a paper production stop for one week also has another advantage in decreased costs: as no start-up costs were made during the sixth week. There were 48 production weeks in total and therefore eight cycles of six weeks. Decreasing the annual production with eight weeks would result in a saving of €952.72 (per start-up) *8= 7621.76 euros/year.

### 6.2. Production Unit 1: Paper production

This subchapter describes the detailed design of production unit 1 (PU1): paper production. PU1 consists of the paper production line. The functional requirement for PU1 –determined in the conceptual design– is: *produce every order in 4 weeks with 98% certainty*. PU1 is complex because of start-up costs, sequence-dependent setup times and capacity constraints.

#### 6.2.1. Determine the number of operating paper machines per week

In the current situation, Marsna Paper produces from Monday till Friday. There is no production during weekends (This cannot be changed). One or several paper machine(s) are started on Monday, depending on the demand. After five days of production, all used machine(s) will be switched off and the machine(s) will be cleaned. An advantage of producing with more than one paper machine per week is that the production of the paper machines can perfectly anticipate on the weekly demand, because mostly the weekly demand exists of orders for all three paper production lines.

As stated in the FRs per PU, all orders should be produced by the paper production department within 4 weeks. There are 3 paper machines, and when once per week is switched between the paper machines, the weekly demand can be produced and the FRs will be met.

On the other hand, major disadvantages are (1) start-up energy/costs for several paper machines, (2) cleaning of these machines after one week of production and (3) bigger setup times and worse quality of the paper.

1. In an ideal situation only one paper machine is started on Monday and switched off on Friday. Then there would only be heating (and heating costs) for one machine. Resulting in less energy consumption, compared with a situation in which two or three machines needed to be started. The initial costs for starting a paper machine were 150 euros.

2. Another advantage of producing paper with one paper machine per week is the decrease in workload and costs, created by cleaning of the machine. After one week of production, two or three machines needed to be cleaned in the situation where multiple paper machines produce in one week. Reducing the number of active paper machines to one per week, results in less cleaning procedures. The average time required for starting and cleaning one paper machine is ten hours per week. A more efficient schedule of
production on paper machines would decrease the number of hours needed for start-up and cleaning of the machine, which also reduces the costs.

(3) The last but no least advantage of producing with one paper machine per week is related to the size of the production run. When one paper machine operates, one production run is selected. When multiple paper machines operate, multiple production runs need to be created, because every machine needs a production run. The size of the production run for one week is larger if only one paper production machine operates per week. Therefore the colours of the orders differs less when one paper machine works per week. As discussed in the detailed analysis, this results in smaller setup times and better quality of the paper.

Evaluating the pros and cons the best decision to made is, to work with one paper machine per week, because (1) the weekly demand can be produced with a switch in paper machine every week and (2) the starting- and cleaning costs are minimized when one paper machine per week is active and (3) this results in smaller setup times and better quality of the paper.

6.2.2. Determine the size of the production run

A production run is used in manufacturing to bundle production orders in series during production. The benefit of a production run is reducing the costs of a unit by reducing the total setup cost. A large size of the production run keeps the total start-up cost and total setup time short. A disadvantage of a large size of the production run is the production flexibility. With a large size of the production run, it is not possible to produce a particular order at any time, because a strict production schedule is used.

By determining the size of a production run, several aspects need to be considered. (1) As discussed in the detailed analysis, every paper machine has a different paper machine speed. For calculating the capacity of each paper machine, the average machine speed was used. The standard deviation is relative small for the paper machine speed. (2) Another aspect which should be considered for determining the production rate is the staff. As discussed previously, only two teams are able to work with paper machine 4 (PM4). This results in a maximum production time of 16 hours per day for PM4, while the other remaining hours PM2 or PM3 need to produce.

As discussed in the previous section, it is chosen to start one paper machine per week, which indicates that the size of the production run is based on the amount of orders which can be produced in one week per paper machine. As described in the detailed analysis, an accurate and reliable estimation of the production rate of the paper machines can be calculated when the total production rate is split up in machine time and setup time. In order to make an accurate prediction, the capacity of the paper machines is expressed in meters per time unit.

The number of production orders which can be produced in one production run is based on the amount of production orders and the order quantity expressed in meters. Note that the amount of meters of paper can be calculated when the order size (in KG), paper thickness and format is known. The total capacity expressed in minutes is 7200 minutes a week (60 minutes * 24 hours * 5 days). The total capacity expressed in meters per week depends on the paper machine because every paper machine has its different machine speed.

The total capacity available for production per week is the total capacity per week minus weekly start-up and cleaning time, thus being 6900 minutes (7200 minutes per week – 300 minutes for the start-up and cleaning per week). To calculate the amount of orders which can be produced in one production run, the order quantity and amount of production orders are relevant. As discussed earlier, the average setup time is 35 minutes per production
order and for example the PM2 speed is 195 meters per min. Thus the capacity of the production run is equal to the amount of setup ups times 35 min plus the amount of meters times the average paper machine speed in meters / minute.

\[
\text{For PM2: } 6900 \geq \# \text{ setups} \times 35 + \frac{\# \text{ meters of production orders}}{195 \text{ meters/min}}
\]

\[
\text{For PM3: } 6900 \geq \# \text{ setups} \times 35 + \frac{\# \text{ meters of production orders}}{175 \text{ meters/min}}
\]

\[
\text{For PM4: } 6900 \geq \# \text{ setups} \times 35 + \frac{\# \text{ meters of production orders}}{65 \text{ meters/min}}
\]

An accurate and reliable planning can be made, because the size of the production run is expressed in meters / minute. Still, there is some variability in the production processes because of sequence dependent setup times (which can vary between 15 and 55 minutes) and errors in the process (e.g. tearing of paper during production). Section 6.2.4. (sequencing rules) explains that there are orders with and without priority. The orders without priority can in- or decrease the size of the production run at any time based on the variability.

An example: Figure 12 is an example of a production run which is produced by PM2. Red parts are orders with urgency while green parts are orders without urgency. PM2 operates in week 1, and the size of the selected production run is 129 tons per week. After four days of production, it is noted that the production is delayed due to production errors. According to the planning, 4/5th of 129 tons of paper (103.2 ton) should be produced at that specific moment, while in reality only 90 tons were produced. In this case orders without priority (green) were left out for the paper production on Friday. The total size of the production run for week 1 should be narrowed without affecting the orders with priority. All orders what are left out for paper production will be produced in the next production run on PM2.

Figure 12 - An example of a production run

6.2.3. Paper production schedule

A third important aspect in the detailed design of the paper production is the paper production schedule. A production schedule states which workstations will operate at which moment. As described in the previous section it is chosen to work with one paper machine per week. It was also highlighted that paper machine 4 (PM4) could produce only for 16 hours per day. During the remaining hours PM2 or PM3 would produce. In the subchapter ‘balancing the capacity of PU1 and PU2’ (6.1.) the idea for a six week cycle production, including one stop week was suggested. On top of this Marsna Paper indicated that PM4 must produce at least once per four weeks. In order to determine the production schedule, these findings have to be combined.

Table 21 shows the demand per paper machine per week and when the six week cycle is applied.

<table>
<thead>
<tr>
<th>Paper Machine</th>
<th>Demand / week</th>
<th>Demand / 6 weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM2</td>
<td>51.1 ton / week</td>
<td>306.6 ton / 6 weeks</td>
</tr>
<tr>
<td>PM3</td>
<td>24.2 ton / week</td>
<td>145.2 ton / 6 weeks</td>
</tr>
</tbody>
</table>
Secondly, applying balancing of the capacity for a cycle of six weeks results in the following production schedule per paper machine:

- PM2 produces 2.5 weeks
- PM3 produces 1.25 weeks
- PM4 produces 1.25 weeks (16/24% per day) so effective production is 5/6e week
- PM2 or PM3 produces 1.25 weeks (8/24% per day) so effective production of 5/12e week
- One week no paper production

By combining these results, the average production capacity per six weeks can be calculated for the above production schedule (table 22).

*Table 22 – Capacity per paper machine, during six weeks cycle*

<table>
<thead>
<tr>
<th>Paper Machine</th>
<th>Capacity per 6 weeks (per cycle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM2</td>
<td>2.5 of the 6 weeks production</td>
</tr>
<tr>
<td></td>
<td>production rate = 1125 kg/h =</td>
</tr>
<tr>
<td></td>
<td>123.8 tons/week</td>
</tr>
<tr>
<td></td>
<td>= 2.5 * 123.8 = 309.5 tons / 6 weeks</td>
</tr>
<tr>
<td>PM3</td>
<td>1.25 of the 6 weeks production</td>
</tr>
<tr>
<td></td>
<td>production rate = 1000 kg/h =</td>
</tr>
<tr>
<td></td>
<td>110 tons/week</td>
</tr>
<tr>
<td></td>
<td>= 1.25 * 110 = 137.5 tons / 6 weeks</td>
</tr>
<tr>
<td>PM4</td>
<td>5/6e of the 6 weeks production</td>
</tr>
<tr>
<td></td>
<td>production rate = 1250 kg/h =</td>
</tr>
<tr>
<td></td>
<td>137.5 tons/week</td>
</tr>
<tr>
<td></td>
<td>= 5/6 * 137.5 = 114.6 tons / 6 weeks</td>
</tr>
<tr>
<td>PM2 or PM3</td>
<td>5/12e of the 6 weeks production</td>
</tr>
<tr>
<td></td>
<td>OR: = 5/12 * 123.8 = 51.6 tons / 6 weeks</td>
</tr>
<tr>
<td></td>
<td>OR: = 5/12 * 110 = 45.8 tons / 6 weeks</td>
</tr>
</tbody>
</table>

If the demand (based on demand of last year) is compared with the capacity as calculated in table 22, it can be concluded that the total demand can be produced. Appendix G provides an overview of a production schedule for 52 weeks, based on the production schedule as proposed above, based on the demand of last year.

As can be seen in appendix G, there is no production once every six weeks. Furthermore PM4 produced once every four weeks. In addition, PM2 produces on average once every two weeks.

In weeks where PM4 operates 16 hours a day and another PM works the other 8 hours a day, a lot of energy is used. It is expensive to switch the paper machines on and off on a daily basis and therefore the paper machines remain on –even if there is no production– which results in energy loss. It would be more beneficial to use a production schedule where one operator works ten hours a day, four days a week. This is beneficial because the paper machines has less hours to stay on, resulting in less energy consumption and thus reduction of costs. The second reason why the proposed production schedule would be beneficial is because the boiler specifications change when using paper machines separately or combined. This can be explained by the boiler load: if two paper machines operate, the total energy consumption

![Figure 12 – Boiler specifications (energy) with multiple active paper machines](image_url)
will not double. As shown in figure 13, 160% energy is consumed when two paper machines operate at the same time. If one paper machine operates it will use 100% energy.

Note that with the suggested production schedule two paper machines will operate at the same time for 24 hours per week (6 hours a day, 4 days a week). A disadvantage of this production schedule is that the personnel costs will rise, due to longer working hours. However, the costs saved by a redistribution of energy usage will outweigh the additional costs for personnel. Therefore the production schedule with ten production hours a day for four days a week will be chosen.

### 6.2.4. Sequence rules

The final step in the detailed design for the production of paper, is determining the sequence and priority of orders. In this section, the above findings regarding size of the production run, balancing capacity and production schedule are applied.

**Priority orders**

Determining the priority of an order is based on the due date. When an order is received, the production schedule should be used to sort orders by priority. The FRs for individual PUs need to be met. According to the functional requirements every order needs to be produced by the paper production line within 4 weeks. If a production run starts and there is later on no other production run which can ensure that the FRs will be achieved, orders have priority.

*An example: PM3 would be used to produce an order. PM3 is able to produce in week 7, then again only in week 11. All orders which were placed in week 4, 5 or 6 cannot be produces directly, but remain for the next production run in week 7. When PM3 produced in week 7, all order from week 4, 5 and 6 should be prioritized for PM3 in week 7, because the next time PM3 operates is in week 11 and then the FRs cannot be met.*

As described above, the due date is the most important criteria to determine priority. If a large group of orders has no priority, other criteria are applied to determine if an order is selected for a batch. The first selection criteria is the earliest due date. When orders have the same due date, another criteria are applied. The second criteria is the number of workstations an order has to go through. Orders who need to go through more workstations it is desirable to start early.

**Colour sequence**

As described above, all orders with priority should be included in the production run, otherwise the due dates would not be met. Orders without priority might be included in the production run if permitted by the total capacity of the paper machine. But an important aspect that also should be taken into account is the colour sequence. The production run for Marsna Paper is based on colour sequence, because if a colour differs too much for the previous produced colour the production line should be cleaned. This results in money loss via less production and increasing costs for cleaning. Therefore it is desirable to produce more similar colours in one production run. Then it still might be possible that the colour differs too much from the desired colour and the order might be rejected, both internally or externally by the customer. Therefore it is very important to consider the quality aspect at all times during the paper production process and sequencing orders based on colour, to provide the best guarantee to avoid colour differences.

### 6.2.5. Overtime

As described in chapter 3.2., the possible amount of overtime for PU1 is relatively small (3 hours per week per operator), because 5 operators need to make overtime at the same time to operate one production line. PU1 has a larger capacity than PU2 and therefore
overtime is less necessary. Nevertheless, within this production unit overtime can be useful because of restrictions of the process.

For example: If the production time of a production run (for one week) based on colour is more than the available capacity in this week, there are two options available: (1) One could choose to carry out this production run and create more capacity by overtime. (2) Or, one could choose to split the production run in two parts. As, the paper machine must be turned on twice within option two, option 1 is less expensive than option 2.

6.3. Production Unit 2: Finishing

In PU2, the several workstations do have start-up costs or long setup times. In this production unit another issue should also be taken into account, namely the limited number of tambours that are available. In this section the batch sizes, sequence of orders, the role of tambours and the allocation of staff are discussed.

6.3.1. Batch size

As discussed earlier, the batch size depends on the setup time and start-up cost. A large batch size is preferable when the setup time is long or start-up costs is high. If setup times are short and start-up costs are low, a small batch size is preferable in order to maximize the flexibility.

**Batch size of PK2**

The setup time of PK2 is long, namely between 1 and 3 hours per setup. Therefore the main goal for workstation PK2 is to minimize the number of setups. This can be achieved by maximizing the batch sizes. So all orders with the same type of squeeze and which are released to be produced by PK2, are selected for one batch. The due date is irrelevant in selecting the batch. Table 23 shows an example of the batch size selection for PK2. Each colour illustrates a batch.

*Table 23 - Example for selecting the batch size for PK2. An colour illustrates a batch.*

<table>
<thead>
<tr>
<th>Squeeze option</th>
<th>Due date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In 2 weeks</td>
</tr>
<tr>
<td>1</td>
<td>10 tons</td>
</tr>
<tr>
<td>2</td>
<td>8 tons</td>
</tr>
<tr>
<td>3</td>
<td>5 tons</td>
</tr>
</tbody>
</table>

**Batch size and production schedule of the RPM**

The start-up costs of the RPM are relatively high, namely 150 euro per start-up. Thus, it is important to minimize the number of start-ups in order to keep the costs low. As described earlier, using large batch size keeps the start-up costs low.

The functional requirements for an individual PU state, that orders that need to be operated by workstation RPM, need to be produced within 3 or 4 weeks (dependent on the lead time of an order). So it is not necessary to switch on the RPM every week. The RPM could switched on only once per two weeks because the functional requirements can easily be met on this frequency. In this production schedule, the start-up cost for the RPM are also kept low. Once he RPM is switched on, all orders that are due for transport within three weeks, could be selected for the batch.

The average demand for the RPM is 22.3 tons per 3 weeks and has a standard deviation of 4.8 tons. A one week production on the RPM results in a throughput of 28.4 tons. These facts show that demand is significantly lower than the throughput, so these planning rules are feasible.
**Batch size other workstations**

All other workstations of PU2 barely have start-up costs and they all have small, sequence independent setup-times. Except from PK2, for each order, it takes a 5 minutes setup time. For this reason batch sizes do not have a positive effect on these workstations; all orders can be produced individually (job production).

### 6.3.2. Sequence orders

In this section, the sequence of orders for workstations PU2 is discussed. Low delivery reliability is the problem statement in this project, because many orders are delivered to late. Lateness and tardiness are both relevant performance indicators for projects where the delivery reliability is investigated (Hopp, 2000). Lateness can be calculated by subtracting the deadline time from the completion time. Positive lateness is called tardiness, while negative lateness is called earliness. In this project tardiness is the relevant performance indicator, as delivery reliability is low. In this case it is irrelevant whether (and how much) an order is ready earlier than agreed, therefore it is better to consider tardiness compared with lateness.

Baker (2002) stated that earliest due date (EDD) is an effective rule to minimize tardiness. The EDD is defined by counting the arrival time and the agreed lead time. But, EDD does not take potential differences of processing times into account. In order to find the best way to minimize the maximum tardiness, the EDD needs to be adjusted with the differences in processing times at Marsna Paper. The Earliest Adjusted Due Date (EADD) is calculated by subtracting the expected process time of the order from the EDD.

*For example, an order with 5 production steps, each taking one day for production, enters the production system on day X. The agreed lead time of the order is 6 weeks. The EDD for this order is day X + 6 weeks. The EADD for this order is the EDD minus the expected process time (five days), so the EADD is day X + 6 weeks – 5 days.*

So the sequence of orders for workstations in PU2, is based on EADD, because this starting point aims at minimizing tardiness. Within orders having the same EADD, orders with a routing that includes PK2, have priority because of its long setup times.

**Sequence order of PK2**

For the workstation PK2 the sequence of orders is not based on EADD. As described in the detailed analysis, the workstation PK2 has 20 different squeezing possibilities. There are two types of squeezing: (1) wild squeezing and (2) report squeezing. (1) As explained in the detailed analysis, there is a large difference in setup times between the two types of squeezing. Table 24 states the setup times dependent per setup type. To minimize the setup times it is necessary to switch as little as possible between wild and report squeezes. As it shows that a setup change between the two types of squeezing varies a lot, the sequence of setups is important to minimize the total setup time To determine the optimal sequence of orders for workstation PK2, table 24 is used.

<table>
<thead>
<tr>
<th>Table 24 - Setup times PK2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before \ After setup</td>
</tr>
<tr>
<td>Wild squeezing</td>
</tr>
<tr>
<td>Report squeezing</td>
</tr>
</tbody>
</table>

To illustrate this, an example is given. In this example four different wild squeeze and three different report squeeze setups need to be executed. Best case and worst case
scenario for total setup time is calculated:

**Best case:**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+1</td>
<td>+1</td>
<td>+3</td>
<td>+3</td>
<td>+3</td>
<td>+3 = 12 h</td>
</tr>
</tbody>
</table>

**Worst case:**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>+2</td>
<td>+3</td>
<td>+2</td>
<td>+3</td>
<td>+2</td>
<td>+2 = 15 h</td>
</tr>
</tbody>
</table>

*Figure 14 - Best and worst case situation for total setup time for an example*

As shown in the example (figure 14) the sequence of setups is relevant for the total setup time.

Concretely, the sequence of orders is based on the sequences of batches. First all wild squeezing batches are produced, followed by the report squeezing batches. More detailed, within all wild squeezing batches, the batch with the most orders with the EADD is chosen to start.

### 6.3.3. Tambours

As mentioned before, the number of tambours available is an important issue in paper productions. A tambour is needed to wind up the paper that has been produced. Marso Paper has 106 tambours available and the client of this project made the assumption that it is not possible to buy tambours, because these are expensive. On average a tambour holds 760 KG of paper. In the finishing department the paper is operated by multiple workstations. When the paper has been operated by workstations “Bob2”, “Bob3”, or “RS10”, the paper output is on smaller rolls and thus these tambours are cleared for the paper production department. When the WIP on tambours is very high, which means when more than 106 tambours are in use, no further paper production is possible. It costs a lot of money when production is unexpectedly stopped by lack of tambours, as employees can’t operate the machines and energy is wasted. On average, 12 tambours are needed for production of one shift. A shift has a standard deviation of 3 tambours. Safety stock counts the average amount of tambours per shift (because production operates in 3 shifts and the finishing in 2 shifts) plus the standard deviation of tambours, in order to eliminate production stops by lack of tambours. As long as the amount of tambours being unused, is higher than 15 tambours, the allocation of operators doesn’t change and orders are produced on EADD. If the amount of tambours available for paper production, is equal or smaller than 15 tambours, Bob2, Bob3, or RS10 are going to produce orders and EADD, as a planning rule, is no longer applicable.

### 6.3.4. Allocation of operators in PU2

The complete staff of the finishing department consists 11 employees in. One employee can work with on average 5.1 of the 13 workstations. Every working day, there are two shifts: the first between 6:00 and 14:00 hours and the second one between 14:00 and 22:00 hours. The allocation of the operators is based on GFC rules.

Employees of the finishing department are being distributed in proportion to the required production time. If a workstation has on average 1/11e of its time occupied, on average 1 employee is allocated to this workstation.

As described in this chapter, orders are produced based on EADD. If all workstations have to deal with orders that are due at the same EADD, a priority list based on the GFC principles determines which employee operates which workstation first. The list is as follows:

The first three workstations on this priority list owe their entry to the list to the high utilization of the machine. These workstations are occupied 58%, 58% and 46% of their time. The other workstations owe their ranking on the location of the workstation in the production process. Workstation Kal7 for example, is the most upstream workstation and is therefore given the fourth place. This sequence of priority is chosen because otherwise workstations more downstream cannot start their production if orders haven’t yet undergone the other workstations.

6.3.5. Overtime
As the options for managing overtime at PU2 are concerned, it has to be stated that at PU2, overtime can be used in two different ways. (1) Planned overtime, i.e. overtime planned two weeks before overtime occurs, for example when demand exceeds the available capacity. Planned overtime is used to extent capacity on the short term. (2) Corrective overtime, which is an ad-hoc type of overtime that copes with setbacks in production. In the finishing department, the variability of processing time is high, therefore lowering of the production rate could occur. In that case, corrective overtime is useful, in order to finish all planned orders.

6.4. Goods Flow Control
As explained in the chapter 5.6, the Goods Flow Control (GFC) determines and controls the relationship between different PUs, by releasing work orders to individual PUs and by coordinating the PUs.

Inventory control
The GFC of Marsna Paper does not take the inventory control into account. At the first controlled stock point (raw materials), the assumption is made that raw material always is available. So, production can always start once an order is released. As we saw in chapter 5.4 the CODP is placed at the start of the production process, all orders are made based on make-to-order. All finished production orders are ready for transport and therefore no stock policy is needed.

Order acceptance and release
As far as order acceptance is concerned, the process of accepting an order falls outside the scope of this project. The production manager determines if an order can be produced by Marsna Paper and the sales manager decides if the price is acceptable. This project is based on the assumption that all orders that are accepted by the production- and sales manager, have need to be produced.

Once an order is accepted, it is processed in the information system by hand. Once an order is processed, it is ready for production (release moment). In 90% of all cases, orders are processed at the same day as the day on which the order has been received. In the remaining 10%, an order is processed the day after the order has been received.

As explained in the section on functional requirements, orders can be released later if the utilization of the production is too high. As the production rate of the finishing department is the lowest of all departments, the available capacity of Marsna Paper is based on the available capacity for the finishing department. By using the production rates calculated in the detailed analysis (chapter 3), the number of orders producible per time unit, can be determined, thus calculating the amount of available capacity for the finishing department. If an order cannot be produced within the standard lead time, the release moment of an order is postponed until capacity is available again. Using this method, the functional requirements still have the same lead times. Figure 15 shows the procedure for order releases for Marsna Paper.
For example: an order is placed by a customer in week X and the lead time is 6 weeks. The finishing departments capacity is fully used until week 6. In week 7 the earliest capacity space is available for the finishing department. These facts lead to the postponement of the orders release moment. The customer is informed that the order has an lead time of 7 weeks and the order is released for production in week X plus 1. Thus, the lead time for the production remains 6 weeks.

The orders that are finished in PU1 are immediately released to PU2.

**Allocation of operators from PU1 to PU2**

Three employees are needed to operate the paper machine in PU1 itself. Once the settings and setups are done and the paper machine runs, the operators only need to monitor the paper production process. The monitoring requires only two employees. This means that one of the employees has no tasks during this period. For an order with the order size of 1000 kg, this time amounts to 20 minutes. For an order with the order size of 2000 kg, this lost time doubles to 40 minutes. This time could easily be used to perform other tasks, for example to perform tasks at the PK2. Because the paper machines in PU1 are located closely to the workstation PK2, the paper production operators could switch rapidly. They could, for example, make a setup for the PK2, thus providing an extension of the capacity in the finishing department.

### 6.5. Work in Progress (WIP)

With the help of the Little Law the average amount of WIP in order to be able to produce without interruptions can be calculated:

\[
\text{WorkInProgress} = \text{Throughput} \times \text{Throughput Time} \ (\text{Little, 2011})
\]

WIP costs money because of holding costs and for this reason the goal is to minimize the WIP. On the other hand, WIP is important for the continuity of the production process so the workstation X+1 will not have to wait for orders from workstation X.

In section 6.1, the average throughput is calculated on 101 ton per week. The average throughput time is 1.45 weeks, so:

\[
\text{Necessary Work In Progress} = 101 \times 1.45 = 146.5 \text{ ton}
\]

The necessary WIP based on the throughput and throughput time amounts to 146.5 tons of paper.

### 6.6. Difference between current- and designed situation

Table 25 shows a summary of the differences between the current- and designed situation. The different subjects of the current situation are explained in the chapter six on the detailed design. In chapter eight, the improvements based on the design presented in this project, are stated.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Current situation</th>
<th>Design presented in this project</th>
</tr>
</thead>
<tbody>
<tr>
<td>PU1</td>
<td>Every week production</td>
<td>Production free weeks</td>
</tr>
<tr>
<td></td>
<td>Multiple lines per week</td>
<td>One line per week</td>
</tr>
</tbody>
</table>
| PU2   | Workstations which create tambours operates always if possible. | Focus only on workstations which create tambours when there is a lack of tambours.  
|       | EDD                                                            | EADD                                             
|       | 1,5 of 2 weeks production at RPM                              | Optimize setups PK2  
|       |                                                                | 1 of 2 weeks production at RPM                  |
| WIP   | 178 ton                                                        | 146.5 ton                                        |
7. Conclusions, implementation and recommendations

This chapter starts with a comparison between the current- and designed situation and states the improvements. In the next section is the implementation of the design discussed. In section three the conclusion on the findings is made. Finally the recommendations for Marsna Paper are discussed.

7.1. Comparison and improvements

In this chapter the differences between the current situation and the designed situation of Marsna Paper, created during this project, are explained. More specific, the benefits of the new design are being described. Most savings are estimated or calculated exactly. For some improvements it is impossible to estimate the saving due to lack of information.

**Increasing delivery reliability**

Marsna Paper faces the problem of low delivery reliability. The goal of this project is to increase the delivery reliability.

The current planning of the finishing department is based on two rules: (1) Orders are produced based on EDD. (2) Orders to be handled by workstations RS10, BOB2 and BOB3 are always given priority, because of the limited number of tambours. Once an order is operated by workstation RS10, BOB2 or BOB3, the tambour is available for paper production for a new order. This leads to the conclusion that orders to be handled by BOB2, BOB3 and RS10, are taken into production regardless of the orders urgency.

The WIP of Marsna Paper is high (an average of 178.7 tons of paper) and, as calculated in section 6.4, it is unnecessarily high. The average required WIP to operate without interruptions is 145.5 ton of paper. If WIP is high, many tambours are in use for orders which are stocked between processes. If it would be possible to reduce the average WIP, this would lead to an actual financial benefit. WIP is expensive, but moreover it would automatically generate more available tambours. As a result, the second planning rule – on which non-urgent operations are always taken care of – would lose its significance. Staff capacity which is thus released, could be committed to urgent orders. Consequently, this new capacity allocation increases the delivery reliability.

Exact information on time spend on non-urgent orders by operators is lacking. With help of the manager of the finishing department it is estimated that operators of the RS10, BOB2 and BOB3 spend 80% of their time on non-urgent orders. Therefore it is to be expected that the delivery reliability increases with the new design rules.

**Reducing WIP and throughput time**

As described in the previous section, it is chosen to focus on reducing the WIP compared with the current situation. Little’s law (throughput time = WIP / throughput) implies that the throughput time and the WIP decrease are equivalent, provided that throughput time remains the same. However, the variability buffering law implies that reducing WIP, will cause decreasing of the throughput if the variability remains constant. (Hopp, 2000) Therefore variability reduction is an important component if the WIP is reduced. As described earlier the design allows workload-dependent lead times and an extension of capacity by working more efficient which both reduce variability. Thus, by implementing the design, both the variability and the WIP will be reduced and therefore the average throughput time of an order also decreases. A reduction in throughput time leads to a higher throughput, faster deliveries, a better cash flow and a reduction in costs (Suri R., 1998).

**Reducing the start-up costs of the paper production and workstation RPM**

In the current situation, the paper production is operational every week (except during vacation shutdowns). Because the paper production department has a larger capacity than the finishing department, the production department is regularly shut down on Friday.

50
As proposed in the chapter 6.1. on balancing the capacity, a whole week paper production (from Monday – Friday) and a paper production free week once every six weeks is preferable compared to every week production and regular shutdowns on Fridays. During such a production free week, no start-up costs are made. The start-up costs of the paper production amount up to €952.72 per start-up. As there are 48 paper production weeks per year, a paper production free week once per six weeks, leads to 8 paper production free weeks on yearly basis. In comparison with the current situation, a savings of €7,621.76 per year (8 times €952.72) can be achieved once these design rules have been implemented.

Another plan to reduce start-up costs is to switch on the RPM machine in the finishing department only once per two weeks (as described in chapter 6.3.1.) rather than 3 times per 4 weeks as occurs to be the current situation. On annual basis when the RPM has been started 13 times less compared to the current situation, an economisation of €1950 per year (13 times €150) could be realised.

**One paper production line per week**

In the current situation, multiple paper machines are used in one week. In the design has been chosen to work with one paper machine per week. This planning rule has two advantages. (1) There only would be heating (and heating costs) for one machine, resulting in less energy consumption, compared with a situation in which two or three machines needed to be started. The initial costs for starting a paper machine are 150 euros. (2) Another advantage of producing paper with one paper machine per week is the decrease in workload and costs, created by cleaning of the machine. After one week of production, two or three machines needed to be cleaned in the current situation where multiple paper machines produces in one week. Reducing the number of active paper machines to one per week, will be resulting in less cleaning procedures. The average time required for starting and cleaning one paper machine is ten hours per week. A more efficient production schedule of the paper machines as described in the design, would decrease the number of hours needed for start-up and cleaning of the machine, which also reduced the costs.

In the current situation (based on 2016) on average 1.73 paper machine work per week. In the designed situation, on average 1.25 paper machines work per week. (Once per 4 weeks, works PM4 and then 2 paper machines are work with). The saved start-up costs per machine occurs on yearly basis €3456. ((1.73-1.25) * €150 per machine start-up * 48 production weeks. Furthermore are 230 cleaning hours saved ((1.73-1.25) * 10 cleaning hours per week * 48 production weeks) if the design would be implemented.

**Reducing the PK2’s setup time**

In the current situation the main planning rule for workstation PK2 is based on the urgency of these orders (orders which need to be delivered in the current week are taken care of first): regardless of the fact whether any orders with the same type of squeeze are in stock, ready for production on the PK2. For all orders which are ready to be produced by PK2, only those who are to be delivered in the same week are relevant. The batches are created, consisting of all type of orders with the same type of squeeze, which should be ready in the current week. Similar orders, to be delivered in the following weeks, will not be included in the current batch. Thus, setup times take twice or even more time in order to produce these orders.

Moreover, switches between wild- and report squeezes are being made randomly and regularly. As explained in section 6.3.2. the setup times will be reduced when as few as possible switches between wild- and report squeezes are made.

As the setup times for the PK2 are long (between 1 and 3 hours), the target at the PK2 for the design is obviously to minimize its total setup time. In the detailed design has been chosen to maximize the batch size for PK2 by taking all the orders with the same type of
squeeze in a batch regardless of the due date. Furthermore is it important to switch as little as possible between wild- and report squeezes.

On average, setup for PK2 occurs 3.8 times per week. The adaption of these planning will cause a reduction in the total setup time. Savings of the total setup time leads to more capacity (thus cost reduction) in the finishing department. This extension of capacity increases the delivery reliability over the long term, because an operator has more time available to work on urgent orders.

**Using manpower more efficiently**

As described in chapter 6.4., during paper production runs, an employee at the paper production line, often has no tasks. This excessive time could be used to perform other tasks in the finishing department. A paper production operator could for example setup a workstation, recycle wasted paper or assist another operator of the finishing department, thus extending the finishing department’s capacity.

On average an employee has 2 hours downtime per shift. On a yearly basis there would be 1440 hours downtime available for other tasks once this capacity has been deployed. Not the whole of this time can be deployed, because downtime cannot be planned, and there will not always be tasks available which these operators could carry out.

**Developed structural method to plan (Assignment from Marsna Paper)**

As described in the detailed analysis, two experienced managers take care of the planning of the paper production and the finishing operations. Their planning is based on their experience and knowledge of the past. In the current situation, there is no structure or procedure on this item. The client in this project has, as an additional goal, requested for a structured planning procedure.

In the designs a planning procedure is presented which can be used to plan in a structured way. Chapter 6 described in detail for every production unit and workstation what planning rules are used.

**Conclusion**

Although figures are not always available, on the proposals mentioned above, the conclusion that the design improves the delivery reliability and reduces costs, is legitimated.

### 7.2. Implementation of the design

The previous chapter explained the differences between the current situation and the designed situation for Marsna Paper. In this chapter the implementation of the design, as well as the realisation of the benefits of the design are described. The main goal is a successful long-term implementation. In this chapter is stated what has to be changed, on which terms and who is responsible for the implementation. Furthermore the risks of the plan will be described, as well as a manner to minimize the risks.

A distinction will be made between the implementation for the paper production (subchapter 9.1) and for the finishing department (subchapter 9.2).

#### 7.2.1. Implementation paper production department

As described in the previous chapter, there is a difference between the current and designed planning rules of the paper production. The differences between the designed situation compared to the current situation are (1) paper production free weeks, (2) using one paper production machine per week, and (3) that down time at the paper production operators will be used to help the finishing department. Because of his responsibilities for the current planning rules, the manager of the paper production department will also be responsible for the implementation.
**Paper production free week**

While implementing a paper production free week, two issues need to be considered.

1. The first subject to discuss in the context of the implementation of a paper production free week, is the allocation of the paper production operators. In the finishing department there are 13 workstations, and mostly 5 workstations are occupied by the finishing operators for 16 hours a day. Furthermore, there is a chance that some workstations have no orders to produce. When there is a paper production free week, 15 operators will not have work in the paper production department and need to help the finishing department. If these 15 operators are spread over two shifts, there are many operators in comparison to the number of available workstations. As indicated in appendix D there are some paper production operators which can operate independently in the finishing department. Since the paper production free week occurs once every six weeks, a team always has the same shift in those weeks (team X: week 1 morning, week 2 afternoon, week 3 night, week 4 morning, week 5 afternoon, week 6 night). It is chosen that paper production operators who can work independently in the finishing department, have to work the night shift during the paper production free weeks. This leads to operators that can work the night shift in the finishing department, without the help of the finishing operators. With this allocation of the paper production operators, there are enough workstations in the finishing department.

2. If there is no paper production, there is a large capacity difference between the paper production- and finishing department. This has a big influence on the WIP. The additional capacity for the finishing department during these weeks accomplishes that the WIP will reduce quickly. Because there is no paper production, the WIP cannot increase. Therefore it is important that there is enough WIP before the paper production free week starts. As discussed in the detailed design, it is expected that 129 tons of paper are finished in a paper production free week. The variability of the production rate is high and the consequences are big as the WIP is empty, because production is not possible without WIP. Therefore an additional safety stock of 50 ton of paper is maintained. Therefore, the paper production free weeks can only continue if the WIP is greater than 179 ton of paper. Once these rules are maintained, it is hardly likely that the WIP should get empty, so the risks are minimized.

**One paper machine per week**

The transition from multiple PMs per week to one PM per week, creates the risk that orders are not produced on time. Once the implementation of one PM per week occurs, there is one PM which produces for the first time over three weeks. If some orders are released much earlier, there is a realistic chance that the functional requirements are not met. Therefore it is important to pay extra attention to meet the functional requirements for all orders during the transition from multiple- to one PM per week.

**Down time paper production operators**

It is not complex to make down time of paper production operators useful as production time in the finishing department and this process can start immediately. When down time occurs, the paper production manager sends a paper production operator to the finishing department for a period of time. The manager of the finishing department is responsible for tasks of the paper production operators in the finishing department.

**7.2.2. Change planning rules finishing department**

As described in the previous chapter there is a difference in planning rules of the finishing department between the current- and the designed situation. In the designed situation the RPM is less frequently started, the batch size for the PK2 is larger and orders which are not urgent are not processed. To implement the design, a different way for planning is maintained. This is not complex to implement, because there are almost no consequences for the changes. The manager of the finishing department is responsible for the planning.
of the finishing department and therefore also responsible for the implementation of the new planning rules. This implementation can be started as soon as the WIP is reduced. When the first production free week occurs, the WIP is low and the new planning rules can be used without any trouble, because there are enough tambours available for production. There are no significant risks associated with this implementation.

7.2.3. Change of the information system

The current information system does not have to be changed enormously when the design is implemented. In order to simplify the planning for the manager of the finishing department, only one module of the information system needs adjustment. Currently in the planning list of orders for the finishing department no workstations or routing are mentioned. The adjustment of the information system aims to give insight on the routing as well as at its progress. Figure 16 shows the current and desired information system module. The IT manager is responsible for this implementation and it is expected that this adjustment will be completed within three months.

Current information system module

<table>
<thead>
<tr>
<th>Order name</th>
<th>Due Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order X</td>
<td>Week 40</td>
</tr>
<tr>
<td>Order Y</td>
<td>Week 41</td>
</tr>
<tr>
<td>Order Z</td>
<td>Week 42</td>
</tr>
</tbody>
</table>

Desired information system module

<table>
<thead>
<tr>
<th>Order name</th>
<th>Due Date</th>
<th>Routing</th>
<th>Current position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order X</td>
<td>Week 40</td>
<td>BOB2 &gt; PK2 &gt; RS7 &gt; Packing</td>
<td>Finished by PK2</td>
</tr>
<tr>
<td>Order Y</td>
<td>Week 41</td>
<td>RS10 &gt; Packing</td>
<td>Finished by Packing</td>
</tr>
<tr>
<td>Order Z</td>
<td>Week 42</td>
<td>RS10 &gt; GRM &gt; Packing</td>
<td>Not produced yet</td>
</tr>
</tbody>
</table>

Figure 16 - Current- and desired information system module

7.3. Conclusions and recommendations

The assignment of this project was to design an operations planning and control system for Marsna Paper. This assignment is chosen in order to improve three problems of Marsna Paper. (1) Low delivery reliability, (2) inefficient production methods, and (3) using a manual, not structured planning.

Based on the comparison between the current and the designed situation and the improvements that can be made (see section 7.1), the concluded that all three problems of Marsna Paper could be solved, is legitimated. In the design is demonstrated that 95% of all production orders can be produced before the due date, thus indicating a high delivery reliability.

The production processes of Marsna Paper could be more efficient by changing planning rules which result in financial savings. In the designs for Marsna Paper a planning procedure is presented which can be used to plan in a structured way.

The management has accepted the design and is willing to implement the changes needed. Besides the design, I would like to make another recommendation for Marsna Paper. I think that it is important to create a better understanding of the total processing times of an production order in the finishing department. If the total processing time of an production order is better understood, the planning could be more accurate and reliable. Thus, customers can be informed earlier, production runs can be chosen better and the capacity control can be optimized.

As has become clear in this project, the production process of Marsna Paper faces many uncertainties. This is the reason for the employees of Marsna Paper to use estimations and no exact planning is made in advance. In practice the operators starts with the most
urgent orders and see later on how many orders may be produced. The employees indicate that it is impossible to predict the processing times because of the uncertainties and variables.

At present, the production rates of the finishing department are provided in kilograms per time unit. As discussed earlier, the value varies enormously because it depends on for example the paper thickness. The speed of a machine (in meters per time unit) in the finishing department is constant for all machines. The number of meters that can be produced per time unit is almost constant because the machine speed hardly varies. For example, it can be determined how many orders fits a production run based on meters per time unit. This means that capacity can almost precisely be expressed in meters per time unit, so I would therefore recommend a change in reproduction the production rate from kilograms into meters per time unit in order to create an accurate and reliable planning.

It should be noted that the implementation will be complex, because the employees information system and method must be adjusted significantly as they are designed to operate based on kilograms per time unit.
References


Appendix A: Assumptions

- Staff cannot be fired.
- Shift work can only be upgraded, not downgraded (for example it is possible to change 2 shifts into 3 shifts, but it is not possible to change 3 shifts into 2 shifts). Production works in 3 shifts, finishing with 2 shifts.
- Preventive maintenance is done when a machine is not working.
- If corrective maintenance is necessary, the defect workstation is switched-off (and maintenance occurs) and another workstation is switched-on. This is an realistic assumption because the utilization of the workstations are low.
- All manually packing is outsourced.
- All the accepted customers demand needs to be fulfilled.
- All raw material is always available.
- Demand of previous year is equal to the demand of the next year.
- Weekend is free. Only production from Monday till Friday.
- Each order needs to be produced via a certain routing, which cannot be changed.
- The data of the week reports is correct.
- The data of the information system is correct.
- It is not possible to buy extra tambours or machines.
- It is not possible to outsource (partially) orders.
- Temporary workers cannot be hired.
Appendix B: Glossary

Backlog: The amount of actual demand, orders or contracts that are in the pipeline for future sales.

Batch: A group of production orders which can be produced with one setup.

Bottleneck: The workstation with the lowest production rate.

Buffers: Inventory between processing or activity units.

Capacity: For a process or activity the maximum throughput that can be sustained.

Coefficients of variation: The ratio of a standard deviation to the mean for statistical demands & processes.

Corrective maintenance: Maintenance task or operation done in order to identify, isolate or separate and rectify a particular fault.

Throughput time (Also called average throughput time, flow time, throughput time and sojourn time): The average (actual) time from release of a job at the beginning of the routing until it reaches an inventory point at the end of the routing.

Customer satisfaction: A term in Total Quality Management that implies the degree to which customers are pleased with a product or service.

Days: Calendar days.

Demand: (Customer demand) Customer requirements measured in production or sales per unit time.

Decoupling: Implies that through buffers and inventory, processes in a product line can operate relatively independently of each other.

Delivery date: is the date an order should be delivered according to the agreement with the customer.

Downtime: Downtime explained as the time that is non value added.

Triple resource constrained: A process is triple resource constrained when both machine, operator and a third resource are needed to produce an order.

Effective: Adjective denoting real capacity of a processing unit is fully utilized when it was available.

Efficiency: Measure of total processing cost of an activity or process.

Exchange time: is the time used to switch a physical unit. For example the time to switch a tambour with paper.

Fill Rate: Fraction of total demand satisfied by inventory on hand.

Finished goods: Goods that have been completed and are awaiting sale.

Fixed lead time: is independent of order quantity, routing and available capacity. Every order always has the same lead time.

Flexible lead time: gives an indication of the lead time, because the due date is not fixed. The producer can deliver products earlier or later than the delivery date.

Flow Shop: An operation that produces products at volume in a continuous flow or a well-defined, connected sequence of activities or processes.

Idle time: A period when system is not in used but is available.

Inventory: Goods and products held by a company in the product value stream that are eventually intended for sale to customers on their own or as part of a product system.

Labour: The workforce in a plant, the people activity that produces value in a product.

Lead time: Time that is required to fill an order or meet customer demand.
Little’s law: The equation relating Throughput, Inventory and Throughput time for a process.

Make-to-order: Operations that make products or deliver services only to customers order. No finished good inventory.

Make-to-stock: Operations that make products to inventory in anticipation of customer demand.

Operations: Any activity that transforms and adds value to an input stream.

Order entry: A measurement for placed orders by the customers.

Order quantity-dependent lead times: are dependent on order size. The lead time increases when the order quantity is bigger.

Overhead: All manufacturing costs, other than direct material and direct labor.

Overtime: Work beyond the federally mandated work period.

Preventive maintenance: Systematic inspection and correction of incipient failures, before they become actual or major failures.

Process shop: all orders are produced by the all production operations with the same sequence.

Production run: A group of similar goods that is produced at once. Marsna Paper has a production run based on colour sequence.

Productivity: Defined as ratio of output over input. Productivity depends on several factors such as workers skills, jobs method and machine used.

Queuing: Formation of a line. Queuing theory is the study of the formation and variation of queues.

Routings: Routings are the sequence of steps that a product follows through a manufacturing plant as it moves from machine to machine.

Routing-dependent lead time: is dependent on the routing of an order. So, the number of operations and type of operations are relevant to set a lead time for an order by routing-dependent lead times.

Schedule: Ordering of production to meet forecasted or actual customer demand.

Setup: Denotes the process of changing or fitting tools on general-purpose equipment to produce a particular product.

Setup time Efficiency: The ratio of the setup time to the process flow time.

Shift work: An employment practice designed to make use of more than the regular 8 work hours a day.

Stable system: A system where the capacity is larger than the demand.

Start-up costs: Cost which are made by switching an machine on.

Throughput: The production rate of a process or activity measured in units or flow per unit time.

Utilization: The average fraction of the capacity of a process or activity that is utilized during an operation.

Variability: The variations in any portion of an operation – demand, processes, activities, quality etc.

Variance: That deviation from the standard cost for a product or process in production.

Due date expressed in weeks: states that an order can be delivered any moment in a certain week (note that this is a flexible lead time).

Work in Progress (WIP): Inventory consisting of products that are in semi-finished state.
Workload-dependent lead times: are lead times where available capacity is taken into account. When the demand in a certain period is high, the lead time increases, compared to a situation in which the demand is low.

Workstation: A physical area where a worker with tools / one or more machines or unattended machines such as robot perform specific task in a production line.
Appendix C: Abbreviations

Bob2 – Bobine 2: Name of workstation in finishing department which split a large roll into smaller rolls.

Bob3 – Bobine 3: Name of workstation in finishing department which split a large roll into smaller rolls.

GRM – Semi automatic Strap machine: Name of Workstation in finishing department which split a large roll into smaller rolls.

Kal7 – Kalander 7: Name of workstation in finishing department which satin rolls of paper.

PK2 – Squeeze Kalander 2: Name of workstation in finishing department which squeeze rolls of paper.

PK4 – Squeeze Kalander 4: Name of workstation in finishing department which squeeze rolls of paper.


RS7 – Roll Cut machine 7: Name of workstation in finishing department which cut rolls into sheets.

RS9 – Roll Cut machine 9: Name of workstation in finishing department which cut rolls into sheets.

RS10 – Roll Cut machine 10: Name of workstation in finishing department which cut rolls into sheets.

RPM – Roll Paste machine: Name of workstation in finishing department which paste multiple rolls into one roll or sheets.

WIP – work in progress

WKC – Water Kracht Centrale: Large boiler makes steam for the PMs and water is pumped.
Appendix D: Skill Matrix

In table 26 an overview is given which states which employees of the finishing department can operate which workstations. Table 27 states which employees of the paper production department can operate which workstations of the finishing department. An “x” in the table shows that an operator can operate a workstation.

Table 26 - Employees of finishing department can operate multiple workstations

<table>
<thead>
<tr>
<th>Employee</th>
<th>PK 2</th>
<th>PK 4</th>
<th>Kal.7</th>
<th>BOB 2</th>
<th>BOB 3</th>
<th>RS 7</th>
<th>RS 9</th>
<th>RS 10</th>
<th>RPM</th>
<th>Polar</th>
<th>GRM</th>
<th>IPS</th>
<th>Expeditie</th>
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</table>

Table 27 - Employees of paper production department can operate some workstations of the finishing department

<table>
<thead>
<tr>
<th>Employee</th>
<th>PK 2</th>
<th>PK 4</th>
<th>Kal.7</th>
<th>BOB 2</th>
<th>BOB 3</th>
<th>RS 7</th>
<th>RS 9</th>
<th>RS 10</th>
<th>RPM</th>
<th>Polar</th>
<th>GRM</th>
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Appendix E: Interviews and literature on lead time assignment rules

In chapter four, information is given about lead time assignment rules. Information is gained by conducting interviews. Interviews can be divided in two groups, because some interviews were conducted with the view of both the customer and the producer on lead times. Interviewed persons were all experienced in the topic. Besides the interviews, literature is used to made arguments about lead time assignment rules. This appendix states which articles are used and which interviews are conducted. Also the questions used in the interviews are stated.

**Literature**

In total, 32 relevant articles were selected based on title, subject and abstract. After critical analyses, 19 articles did not qualify because of their lack of relevance for the present research assignment. Ultimately, 13 articles qualified. Table 28 gives an overview where for all relevant articles the subjects are stated.

<table>
<thead>
<tr>
<th>Article (Year)</th>
<th>Demand uncertainty</th>
<th>Workload dependent</th>
<th>routing in routing</th>
<th>Flexible lead times</th>
<th>Payer producer</th>
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**Interviews with customers**
Table 29 shows which experts have been interviewed to gain the view of customers on lead time assignment rules.

<table>
<thead>
<tr>
<th>Company</th>
<th>Expert &amp; function</th>
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<tbody>
<tr>
<td>DS Metaal</td>
<td>Harold Kostons, General manager</td>
</tr>
<tr>
<td>Sotec</td>
<td>Ed Schoens, General manager</td>
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<tr>
<td>Marsna Paper</td>
<td>Jan Berbers, Purchasing manager</td>
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<tr>
<td>Deben Techniek</td>
<td>Jack Deben, Owner and general manager</td>
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<td>De Smid</td>
<td>Paul Weynheymer, Owner and general manager</td>
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<tr>
<td>Kivit Staalbouw</td>
<td>Jasper Quirijnen, Purchasing manager</td>
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</table>

**Interview schedule (customers)**

What is a customers' view about fixed lead times?
What is a customers' view about flexible dependent lead times?
What is a customers' view about order quantity dependent lead times?
What is a customers' view about routing-dependent lead times?
What is a customers' view about workload-dependent lead times?
**Interviews with producers**

Table 30 shows which experts have been interviewed to gain a view of producers on lead time assignment rules.

*Table 30 - Interviews with experts on lead time assignment rules based on the view of a producers*

<table>
<thead>
<tr>
<th>Company</th>
<th>Expert &amp; function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hilton Engineering</td>
<td>Eggie Prick, Production manager</td>
</tr>
<tr>
<td>Facade</td>
<td>Jan Machausen, Production manager</td>
</tr>
<tr>
<td>Marsna Paper</td>
<td>Leon Wingeer, Production manager</td>
</tr>
<tr>
<td>Makura</td>
<td>Roel Prick, Owner and general manager</td>
</tr>
<tr>
<td>Unipor Coriso</td>
<td>Math vd Boorn, Production manager</td>
</tr>
<tr>
<td>AGC</td>
<td>Mitch Odekerken, Production manager</td>
</tr>
<tr>
<td>Koninkijke Mosa</td>
<td>Floortje Gerits, Production manager</td>
</tr>
<tr>
<td>Tata Steel</td>
<td>Dennis Kurvers, Production manager</td>
</tr>
<tr>
<td>Marsna Paper</td>
<td>Ron Janssen, Production manager</td>
</tr>
</tbody>
</table>

Interview schedule (producers)

What is a producers’ view about fixed lead times?
What is a producers’ view about flexible dependent lead times?
What is a producers’ view about order quantity dependent lead times?
What is a producers’ view about routing-dependent lead times?
What is a producers’ view about workload-dependent lead times?
Appendix F: Rough cut throughput time calculations

In chapter 5.2.2, it is discussed how the throughput time is shorter than the lead time. In this appendix, the calculation behind the conclusions are presented.

To analyse the rough cut throughput time (the average (actual) from release of a job at the beginning of the routing until it reaches an inventory point at the end of the routing) of the production units because to determine (indication) if the delivery agreement can be realised, the throughput time of the orders needs to be calculated and compared to the agreed lead times (time that is required to fill an order or meet customer demand).

The time required for production is known, but the waiting time that will increase the throughput time is not known yet. As explained in chapter 2.2.2, the throughput time of a workstation can be calculated as follows:

\[ TT = TT_q + t_e \]  
\( TT = \text{Throughput Time}, TT_q = \text{Throughput Time in queue and } t_e = \text{processing time} \)

The throughput time in the queue can be calculated using the following formula:

\[ TT_q = \left( \frac{c_a^2 + c_e^2}{2} \right) \times \left( \frac{u}{1-u} \right) \times t_e \]

\( c_a \) and \( c_e \) can be calculated using the following formula:

\[ c^2 = \frac{\sigma^2}{t^2} \]

**Throughput time for the production unit: Paper production**

\[ c_a^2 = \frac{\sigma_a^2}{t_a^2} = \frac{36.36^2}{89.65^2} = 0.165 \]

\( t_e \) (average) = fraction PM2 * processing time PM2 + fraction PM3 * processing time PM3 + fraction PM4 * processing time PM4

\[ = 0.57 \times 0.889 + 0.27 \times 1 + 0.16 \times 0.8 = 0.905 \text{ hour/ton} \]

\( \sigma_e \) (average) = \( \sqrt{\text{fraction PM2} \times \text{standard deviation PM2}^2 + \text{fraction PM3} \times \text{standard deviation PM3}^2 + \text{fraction PM4} \times \text{standard deviation PM4}^2} \)

\[ = \sqrt{(0.57 \times 0.248^2 + 0.27 \times 0.232^2 + 0.16 \times 0.270^2)} = 0.247 \text{ ton} \]

\[ c_e^2 = \frac{\sigma_e^2}{t_e^2} = \frac{0.247^2}{0.905^2} = 0.075 \]

The \( u \) in the equation stands for the utilization of the production units. The utilization for the paper production module is:

\[ U_{utilization \ Production} = \frac{\text{production hours needed}}{\text{capacity production personel}} = \frac{4217.4}{5640} = 0.7478 \]

\[ TT_q = \left( \frac{c_a^2 + c_e^2}{2} \right) \times \left( \frac{u}{1-u} \right) \times t_e = \frac{0.165 + 0.075}{2} \times \frac{0.7478}{1 - 0.7478} \times 0.905 = 0.322 \text{ hours} \]

\[ TT = TT_q + t_e = 0.322 + 0.905 = 1.227 \text{ hours} \]

**Throughput time for the finishing department**

As explained in the detailed analyses, there is no standard routing in the finishing department. The coefficient of variation of arrival for each workstation depends on the
Because the previous workstation differs for every order (because of the flowshop), the coefficient of variation is differs for every order. During this calculations the assumption is made that an order processed by a workstation in the finishing department has the departure coefficient of variation of the production process. This assumption is not realistic, but has a small influence on the calculations. Because this are rough-cut calculations, this small influence is acceptable.

Figure 17 - Relation between coefficient of variation of workstations. Hopp (2008)

\[
C_a^2\text{(production)} = C_a^2\text{(finishing)} = u^2C_e^2 + (1 - u^2)C_a^2 = 0.7478^2 \times 0.075 + (1 - 0.7478^2) \times 0.165 = 0.115
\]

Table 31 - Throughput times for the workstations in the finishing department

<table>
<thead>
<tr>
<th>u</th>
<th>ca</th>
<th>te (h/ton)</th>
<th>σ (h/ton)</th>
<th>ce</th>
<th>CTq (days)</th>
<th>CT (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kal7</td>
<td>84.63%</td>
<td>0.115</td>
<td>0.963</td>
<td>0.330</td>
<td>0.117</td>
<td>0.072</td>
</tr>
<tr>
<td>BOB2</td>
<td>84.63%</td>
<td>0.115</td>
<td>0.800</td>
<td>0.365</td>
<td>0.208</td>
<td>0.125</td>
</tr>
<tr>
<td>BOB3</td>
<td>84.63%</td>
<td>0.115</td>
<td>2.000</td>
<td>1.527</td>
<td>0.583</td>
<td>1.944</td>
</tr>
<tr>
<td>PK2</td>
<td>84.63%</td>
<td>0.115</td>
<td>2.424</td>
<td>1.455</td>
<td>0.360</td>
<td>0.954</td>
</tr>
<tr>
<td>PK4</td>
<td>84.63%</td>
<td>0.115</td>
<td>2.200</td>
<td>0.676</td>
<td>0.094</td>
<td>0.134</td>
</tr>
<tr>
<td>RS7</td>
<td>84.63%</td>
<td>0.115</td>
<td>1.800</td>
<td>0.589</td>
<td>0.107</td>
<td>0.122</td>
</tr>
<tr>
<td>RS9</td>
<td>84.63%</td>
<td>0.115</td>
<td>2.800</td>
<td>0.675</td>
<td>0.058</td>
<td>0.128</td>
</tr>
<tr>
<td>RS10</td>
<td>84.63%</td>
<td>0.115</td>
<td>1.190</td>
<td>0.300</td>
<td>0.064</td>
<td>0.057</td>
</tr>
<tr>
<td>RPM</td>
<td>84.63%</td>
<td>0.115</td>
<td>3.200</td>
<td>1.197</td>
<td>0.140</td>
<td>0.289</td>
</tr>
<tr>
<td>Polar</td>
<td>84.63%</td>
<td>0.115</td>
<td>1.400</td>
<td>0.490</td>
<td>0.123</td>
<td>0.109</td>
</tr>
<tr>
<td>GRM</td>
<td>84.63%</td>
<td>0.115</td>
<td>0.700</td>
<td>0.230</td>
<td>0.108</td>
<td>0.048</td>
</tr>
<tr>
<td>LAMB</td>
<td>84.63%</td>
<td>0.115</td>
<td>4.000</td>
<td>1.027</td>
<td>0.066</td>
<td>0.193</td>
</tr>
<tr>
<td>Packing</td>
<td>84.63%</td>
<td>0.115</td>
<td>0.700</td>
<td>0.657</td>
<td>0.881</td>
<td>1.521</td>
</tr>
</tbody>
</table>

When an order is operated by multiple workstations, the total throughput time of the order is the sum of the throughput times per workstation, because the workstations operate independent of each other. The total throughput time of an order is always different because the order quantity and the routing of the order differs per order. Without batching and with a standard order size, the total throughput time is around the week.

To gain more efficiency some orders are produced in batches. This effects the throughput time, because creating a batch, increases the waiting time for production for orders. In the detailed design, the batch size per workstation will be calculated and then a new throughput time can be calculated.
Appendix G: Production schedule (example)

Table 32 gives an example of the production schedule for one year, as suggested by the new design, based on the demand of last year (May 2015 till May 2016).

Table 32 - Production schedule of demand is as previous year.

<table>
<thead>
<tr>
<th>Week</th>
<th>PM</th>
<th>Week</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PM3</td>
<td>27</td>
<td>PM4 &amp; PM2/3</td>
</tr>
<tr>
<td>2</td>
<td>PM2</td>
<td>28</td>
<td>PM2</td>
</tr>
<tr>
<td>3</td>
<td>PM4 &amp; PM2/3</td>
<td>29</td>
<td>PM3</td>
</tr>
<tr>
<td>4</td>
<td>PM2</td>
<td>30</td>
<td>Vacation shutdowns</td>
</tr>
<tr>
<td>5</td>
<td>PM3</td>
<td>31</td>
<td>Vacation shutdowns</td>
</tr>
<tr>
<td>6</td>
<td>No production</td>
<td>32</td>
<td>PM2</td>
</tr>
<tr>
<td>7</td>
<td>PM4 &amp; PM2</td>
<td>33</td>
<td>PM4 &amp; PM2/3</td>
</tr>
<tr>
<td>8</td>
<td>PM2</td>
<td>34</td>
<td>PM2</td>
</tr>
<tr>
<td>9</td>
<td>PM3</td>
<td>35</td>
<td>PM3</td>
</tr>
<tr>
<td>10</td>
<td>PM2</td>
<td>36</td>
<td>PM2</td>
</tr>
<tr>
<td>11</td>
<td>PM4 &amp; PM3</td>
<td>37</td>
<td>PM4 &amp; PM3</td>
</tr>
<tr>
<td>12</td>
<td>No production</td>
<td>38</td>
<td>No production</td>
</tr>
<tr>
<td>13</td>
<td>PM2</td>
<td>39</td>
<td>PM2</td>
</tr>
<tr>
<td>14</td>
<td>PM3</td>
<td>40</td>
<td>PM3</td>
</tr>
<tr>
<td>15</td>
<td>PM4 &amp; PM2</td>
<td>41</td>
<td>PM4 &amp; PM2/3</td>
</tr>
<tr>
<td>16</td>
<td>PM2</td>
<td>42</td>
<td>PM2</td>
</tr>
<tr>
<td>17</td>
<td>PM3</td>
<td>43</td>
<td>PM3</td>
</tr>
<tr>
<td>18</td>
<td>No production</td>
<td>44</td>
<td>No production</td>
</tr>
<tr>
<td>19</td>
<td>PM4 &amp; PM2</td>
<td>45</td>
<td>PM4 &amp; PM2/3</td>
</tr>
<tr>
<td>20</td>
<td>PM2</td>
<td>46</td>
<td>PM2</td>
</tr>
<tr>
<td>21</td>
<td>PM3</td>
<td>47</td>
<td>PM3</td>
</tr>
<tr>
<td>22</td>
<td>PM2</td>
<td>48</td>
<td>PM2</td>
</tr>
<tr>
<td>23</td>
<td>PM4 &amp; PM2/3</td>
<td>49</td>
<td>PM4 &amp; PM2/3</td>
</tr>
<tr>
<td>24</td>
<td>No production</td>
<td>50</td>
<td>PM2</td>
</tr>
<tr>
<td>25</td>
<td>PM3</td>
<td>51</td>
<td>Vacation shutdowns</td>
</tr>
<tr>
<td>26</td>
<td>PM2</td>
<td>52</td>
<td>Vacation shutdowns</td>
</tr>
</tbody>
</table>
Appendix H: Example of a work report

Table 33 shows an example of a work report of the finishing department which are used in the current situation.

Table 33 - Example of a work report of the finishing department

<table>
<thead>
<tr>
<th>Datum</th>
<th>Ochtenddienst</th>
<th>Middagdienst</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>KG</td>
<td>meters</td>
</tr>
<tr>
<td>10-5-2016</td>
<td></td>
<td></td>
</tr>
<tr>
<td>kalander 7</td>
<td>7131</td>
<td>8</td>
</tr>
<tr>
<td>bob 2 splits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bob 2 bobi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bob 3 splits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bob 3 bobi</td>
<td>3351</td>
<td>8</td>
</tr>
<tr>
<td>PK 2</td>
<td></td>
<td>2485</td>
</tr>
<tr>
<td>PK 4</td>
<td></td>
<td>511</td>
</tr>
<tr>
<td>PK 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RS 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RS 9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RS 10</td>
<td>8667</td>
<td>8</td>
</tr>
<tr>
<td>RPM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polar</td>
<td>8553</td>
<td>8</td>
</tr>
<tr>
<td>GRM KG</td>
<td></td>
<td>10270</td>
</tr>
<tr>
<td>GRM riem</td>
<td></td>
<td>567</td>
</tr>
<tr>
<td>LAMB KG</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LAMB riem</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oningeriemd</td>
<td></td>
<td>6070</td>
</tr>
<tr>
<td>Inpakstraat</td>
<td></td>
<td>13386</td>
</tr>
<tr>
<td>Dozen A4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>totaal MA ult</td>
<td>12018</td>
<td>0</td>
</tr>
<tr>
<td>Totaal Inpak</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>