Improved performance by integrated corrugator and convertor scheduling

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MANAGEMENT SUMMARY

This research is as part of the Master Industrial Engineering and Management at the University of Twente. The aim of this project is to deliver a solution that models the tasks of the production planners at DS Smith Packaging B.V. located in Eerbeek, The Netherlands. This model gives valuable insights for improving production planning and scheduling. This solution decreases the tardiness of orders from *confidential* to 7.04% and even to 2.76% if we correct for orders that are only 4 hours tardy.

PROBLEM IDENTIFICATION

Currently DS Smith is using an ERP system that separately solves the cutting stock problem and scheduling problems. Production planners build and change production schedules based on intuition and experience. However, the complexity is high, so it is hard to keep track of the performance of a schedule while making the schedules separately. This results in schedules that cause disruptions in the production process. We use the following main research question for this research:

"How should DS Smith Packaging B.V. solve the cutting stock problem and generate production schedules in order to find a good balance between minimizing waste, minimizing idle times of machines, and maximizing the on time delivery performance of orders?"

THE GENERAL MODEL

In order to model the different tasks of the production planners, we use a modular approach. Each module performs a task of the production planners. We have to deal with NP-hard problems. Therefore we decide that we are modeling the different tasks in modules that solve the problems separately instead of solving the whole problem at once. The solution consists of five modules: an order selection module, a cutting stock problem module, a corrugator scheduling module, a converting scheduling module, and a Pentek (buffer zone) module.

The order selection module selects the orders that enter the cutting stock problem module. Deckle solutions are generated in the cutting stock problem module. A deckle solution is the set of Corrugator Instruction (CI) jobs of a certain board grade. These deckle solutions are scheduled in the corrugator scheduling module with the objective to minimize setups of the corrugator machine and tardiness of the corrugator jobs. The converting scheduling module schedules the converting jobs based on the FIFO principle by using the first available production time. After that, a load balancing procedure is used to check if alternative machine routings may improve the solution. The Pentek module uses the starting and finishing times of the corrugator and converting jobs to calculate the fill rate of the Pentek. This module may be used for timely identifying problems caused by the Pentek and make important (re)scheduling decisions.

ALTERNATIVES

We formulate alternative objective functions for solving the cutting stock problem. Currently, trim loss minimization is used as objective function. We formulate objective functions that minimize the needed total run length of the corrugator machine and an alternative that minimizes production costs of the corrugator machine. For solving the corrugator scheduling problem we formulate three alternative approaches. The first approach uses a 1-Opt heuristic. This heuristic selects a random deckle solution and inserts it at another place. The second is a

heuristic based on simulating annealing (SA) and the third heuristic is based on the adaptive search (AS). After each approach, we use an integrated corrugator and converting scheduling heuristic. We also formulated an alternative where we only use the integrated heuristic. This results in eight alternative solutions that we test with a simulation for weeks 14 and 15 in 2014.

Results

The alternative minimum run length and minimum cost objective function show significant differences on total run length, trim loss, and number of paper width changes with the trim loss objective function. We propose the cost objective function with production costs of *confidential* per hour as best solution. Even if the production cost per hour ranges between €600 and €1600, the maximum cost deviation is at most 0.07%.

We evaluate the eight model alternatives based on eight criteria: tardiness, earliness, output of the corrugator machine, trim loss, waiting time, waiting on corrugator (WOC) idle time, fill rate of the Pentek, and simplicity of the alternative (see Table 0.1 for the overview of the evaluation). We propose alternative 5 as best solution. This alternative uses the 1-Opt heuristic and the cost objective for the cutting stock problem. It performs best on tardiness (2.76% corrected tardy orders). This is a large improvement compared to the current situation where *confidential* of the orders are tardy. Next to this, it also performs well on the output of the corrugator, WOC idle time, fill rate of the Pentek, and on simplicity. Alternatives 3, 4, 7, and 8 are not interesting because they score low on tardiness, earliness, output of the corrugator machine, or fill rate of the Pentek.

Alternative	Tardiness	Earliness	Output	Trim loss	Waiting time	WOC idle time	Fill rate	Simplicity
1 (1-Opt – trim)	+	+/-	+/-	-	+/-	+	+/-	+
2 (SA – trim)	++	+/-	+/-	-	+/-	+/-	+/-	-
3 (AS – trim)	--	-	+/-	-	+/-	+/-	--	-
4 (Int – trim)	+/-	+	-	-	+	-	-	+
5 (1-Opt – cost)	**++**	**+/-**	**+**	**-**	**-**	**+**	**+**	**+**
6 (SA – cost)	+	+/-	+/-	-	+/-	+/-	+	-
7 (AS – cost)	--	-	+	-	-	+	--	-
8 (Int – cost)	+/-	+	-	-	+	-	+/-	+

Table 0.1 Final results: the trim loss results of all alternatives are worse than the current situation and comparable to each other. Therefore, all get the score -. In bold the alternative we propose.

Conclusions

The Pentek module gives a good insight in the future fill rate of the Pentek and helps in making timely (re)scheduling decisions. Moreover, we recommend implementing the cost minimization objective for the cutting stock problem. Another important recommendation is the use of performance measurements for scheduling. Currently the production planners do not have insight in the performance of the generated schedules. Finally, implementing the method for coping with uncertainty improves the robustness and reliability of production scheduling. Overall, this research has provided valuable insights that help DS Smith in improving their production planning and scheduling. This may lead to a decrease in waste and idle time of machines, and an increase in the on time delivery performance. This helps DS Smith in being more competitive in the market and to meet customer demands.

PREFACE

This thesis is the result of my graduation project at DS Smith Packaging B.V., located in Eerbeek. The aim of this project was to deliver a solution that models the different tasks of the production planners. This was a very challenging goal; the situation at DS Smith is complex with many restrictions and limitations that need to be considered. I am happy that after seven months I completed the project with the expected result.

I thank DS Smith for giving me the opportunity to perform this graduation project. I really enjoyed my time in Eerbeek and learned a lot during the project about business specific processes and working in a professional environment. I thank my colleagues Evert Berends and Riny Wiggers for their help with understanding the whole planning and scheduling process. I also thank Edwin Mulder, my external supervisor, for his support during the project. Next to them, I thank Marco Schutten and Peter Schuur, my supervisors from the University of Twente, for giving me valuable feedback for writing this thesis. This thesis would have been of less quality without their feedback.

Finally, I thank my family and friends for their unconditional support during my study and graduation. Their support, encouragement, and belief have been of great help for successfully ending my study.

Jeroen Kars

Eerbeek, September 2014

GLOSSARY AND LIST OF ABBREVIATIONS

AS: *Adaptive Search, construction algorithm for solving combinatorial optimization problems*

Board grade: *The paper quality measured in grams per square meter*

CI job: *Corrugator Instruction job*

Converting machines: *The machines that convert the corrugated board sheets into boxes*

Corrugating Instruction (CI) job: *A corrugator job consisting of one or two orders* of a certain board grade for a certain run length

Corrugator machine: *The machine that makes the corrugated board sheets*

Corrugator roll: *Part of the corrugator machine that makes the flutes of the cardboard*

Creases: *A line made on the corrugated board to ease folding*

CSP: *Cutting stock problem*

Die Cutter: *Converting machine that has a high die cutting capability and no ability to fold boxes*

Deckle solution (ds): *Combination of jobs for the corrugator machine in order to reduce waste*

Flute: *The wavy paper in the middle of corrugated board*

FFG: *Flexo Folder Gluer, a converting machine with a small die cutting capability and the ability to fold boxes*

1-Opt: *Greedy Insertion heuristic*

IF: *In Full delivery, order is delivered between the minimum and maximum order size*

ILP: *Integer Linear Programming*

MILP: *Mixed Integer Linear Programming*

OT: *On Time delivery of an order*

OTIF: *On Time and In Full delivery of an order*

Pentek: *This is the automated WIP buffer between the corrugator machine and the converting machines*

RCCP: *Rough Cut Capacity Planning*

SA: *Simulated Annealing, local search algorithm for solving combinatorial optimization problems*

Trim loss: *Waste of the corrugator machine at the sides*

TS: *Tabu Search, local search algorithm for solving combinatorial optimization problems*

WIP: *Work in Process*

WOC: *Waiting on Corrugator*

WOP: *Waiting On Pentek*

TABLE OF CONTENTS

1. INTRODUCTION

This thesis is part of a master graduation project for the master Industrial Engineering and Management at the University of Twente. This project is performed at DS Smith Packaging B.V., located in Eerbeek, The Netherlands. Currently the production schedules at DS Smith result in problems in the production process. This was the reason to start this research graduation project about production scheduling at DS Smith Packaging. Section 1.1 provides a description of the company and a brief overview of the production process at DS Smith. Section 1.2 provides a description of the main problems and Section 1.3 formulates the main research question and its sub questions.

1.1. COMPANY DESCRIPTION

DS Smith is one of the market leaders in the packaging industry in the world. It is capable of designing, producing, supplying, and recycling packaging. This means that they can supply all solutions for packaging. DS Smith has four divisions: Paper, Packaging, Plastics, and Recycling. The plant in Eerbeek is specialized in the production of corrugated board packaging with its main focus on carton boxes. That is why the plant in Eerbeek is called a box plant. DS Smith Packaging has around 500 employees working in the Benelux, 190 of them are working in Eerbeek.

The production departments work in three shifts per day, five days a week. The first shift works from 06:00 until 14:00, the second shift works from 14:00 until 22:00, and the third shift works from 22:00 until 6:00. The production capacity is around 130 million square meters of corrugated board per year. On average 1750 pallets with products are produced each day. 98% of the customers of DS Smith Eerbeek are located in The Netherlands and the other 2% are customers located in Germany, Belgium, France, and Denmark. We now give a brief explanation of the production process. Figure 1.1 provides a graphical representation of the production process and Figure 1.2 provides an overview of the production plant.

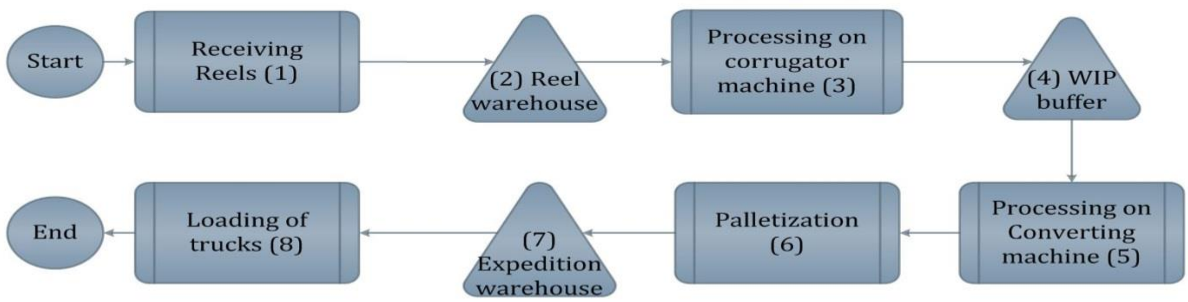


Figure 1.1 The production process at DS Smith Packaging B.V.

The first step in the production process is receiving reels (1). These reels are placed in the reel warehouse (2). Reels are big rolls of paper that are material input for the production process. About 70 kinds of reels are in stock in the reel warehouse. They are different in width, color, and paper quality (measured in grams per square meter). The reels are input for the corrugator machine that makes sheets of corrugated board (3). After processing on the corrugator machine, the sheets of corrugated board are transported to the WIP buffer (4). The next processing step is done at a converting machine. A converting machine converts the sheets of corrugated board into carton boxes (5). Carton boxes are stacked on each other at the end of the machines. The stacks are then transported to the palletizing area where the stacks are put on pallets, pressed, banded, and sealed in plastic for secure transportation (6). The pallets with products are then stored in the expedition warehouse (7). Within a few days the pallets are loaded into trucks that transport the pallets to customers or to an external warehouse (8).

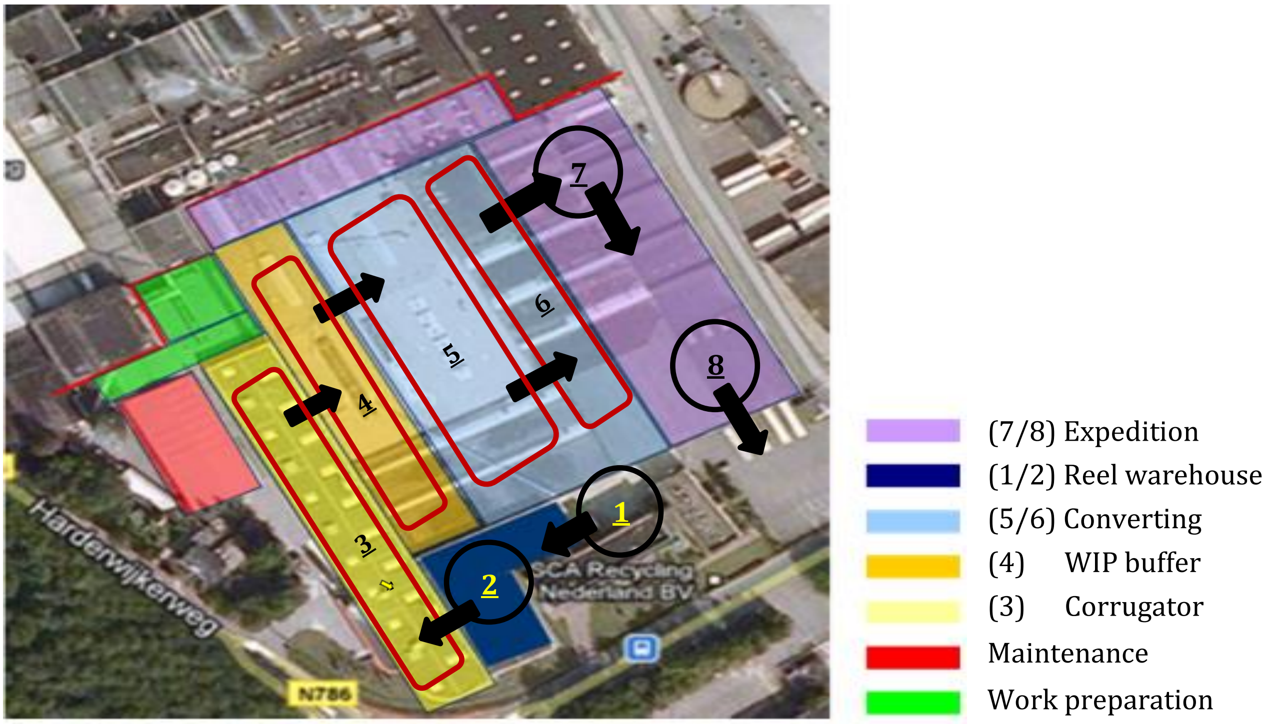


Figure 1.2 Overview of the production plant of DS Smith Packaging B.V.

1.2. PROBLEM DESCRIPTION

There are several steps in the production process that need to be scheduled for a smooth and balanced production. The ERP system that DS Smith uses has a build-in production scheduling module. However, this module schedules the production processes per machine. Separately scheduling results in schedules that are not adapted to each other. Because of this, the production planners are changing these schedules based on experience and intuition. Planning and scheduling is a complex task, since there is a large order mix. The effects of a scheduling decision are hard to keep track of during scheduling. So there is a high chance that there are better schedules than the current found schedules. These schedules may cause problems in the production process. Better schedules produce less waste, less idle time of machines, and/or have a better on time delivery percentage.

One of the problems with the current schedules is that they may cause stoppages and disruptions in the production process. In the current situation, one cause of stoppages and disruptions is that the capacity and flows through the WIP buffer are not taken into account, i.e., in some situations the fill rate of the WIP buffer becomes too high. Another important cause is that the machines are scheduled separately. This may result in idle time of machines due to precedence relations. An important aspect of scheduling is that orders need to be combined to minimize waste. This can be formulated as the cutting stock problem (CSP). This problem occurs when stock material needs to be cut to produce smaller pieces of material for different customers with different order quantities and dimensions. The side waste (called trim loss) of material is dependent on the made combinations of orders. The solutions for the CSP are called deckle solutions and consist of one or more Corrugator Instruction (CI) jobs.

These deckle solutions minimize waste. However, they also cause a decrease in flexibility for scheduling. The choice for a certain deckle solution has a large impact on the schedules and the production process. Currently the impact of deckle solutions is not taken into account. We define the problem that lead to this research in the following way:

"The current approach for production scheduling results in non-optimal schedules that cause stoppages and disruptions in the production process. This affects the degree in which DS Smith can meet customer demands and be competitive in the market. "

1.3. RESEARCH QUESTIONS

To conduct proper research, a main research question and sub questions need to be formulated. This enables us to solve the problem formulated in Section 1.2. Figure 1.3 gives a graphical representation of the research approach and outline of this thesis.

MAIN RESEARCH QUESTION

The main research question for this research is:

"How should DS Smith Packaging B.V. solve the cutting stock problem and generate production schedules in order to find a good balance between minimizing waste, minimizing idle times of machines, and maximizing the on time delivery performance of orders?"

SUB RESEARCH QUESTIONS AND OUTLINE OF THE THESIS

Chapter 2 describes the current production processes and schedules. Chapter 2 also elaborates on the evaluation and performance of the current schedules. We also discuss the problems related to the current approach for scheduling and define the scope of our research. To get a good understanding of the current situation, we work together with team leaders of production and the planning employees. We also do an analysis of the performance in 2013. We analyze the current performance based on data about the down- and idle-times of machines, and based on the produced waste in 2013. Chapter 2 answers the following sub question:

<u>Q1. What is the current situation at DS Smith?</u>

- *a) What are the different production processes?*
- *b) What production processes need to be scheduled and how are these schedules related to each other?*
- *c) How does DS Smith solve the cutting stock problem?*
- *d) How does DS Smith evaluate its current production scheduling?*
- *e) What is the current performance of production scheduling at DS Smith?*
- *f) What are the problems involving production scheduling at DS Smith?*

Chapter 3 provides a description of the used literature and how this literature supports our research. We elaborate on existing literature about performance measurement for scheduling, the CSP, classifications of scheduling, algorithms for combinatorial optimization problems, coping with uncertainty, and about production scheduling in combination with the CSP. We describe the approach and the structure of the literature research in Appendix A. Chapter 3 answers the following sub question:

<u>Q2. What literature supports our research at DS Smith?</u>

- *a) How is production scheduling measured and evaluated in literature?*
- *b) What solutions for the cutting stock problem are available in literature?*

c) *What approaches for scheduling are available in literature?*
d) *How can scheduling and the cutting stock problem be combined?*
e) *What methods for coping with uncertainty in production scheduling are used in literature?*

Chapter 4 formulates the general model and alternative solutions. We use the gathered information of the literature research for the development of alternatives. Chapter 4 answers the following sub question:

Q3. What are alternatives for the cutting stock problem and production scheduling at DS Smith?

Chapter 5 provides an evaluation of the alternatives and makes a choice for the best alternative for DS Smith. Chapter 5 answers the following sub question:

Q4. What is the best alternative for the cutting stock and scheduling problem at DS Smith?

Chapter 6 gives some implementation issues of the proposed alternative. This chapter also elaborates on parts of the proposed alternative that can be implemented. We also formulate an evaluation framework for production scheduling. Chapter 6 answers the following the sub question:

Q5. What are the implementation issues of the proposed alternative?

Finally, Chapter 7 answers the main research question and gives final conclusions and recommendations.

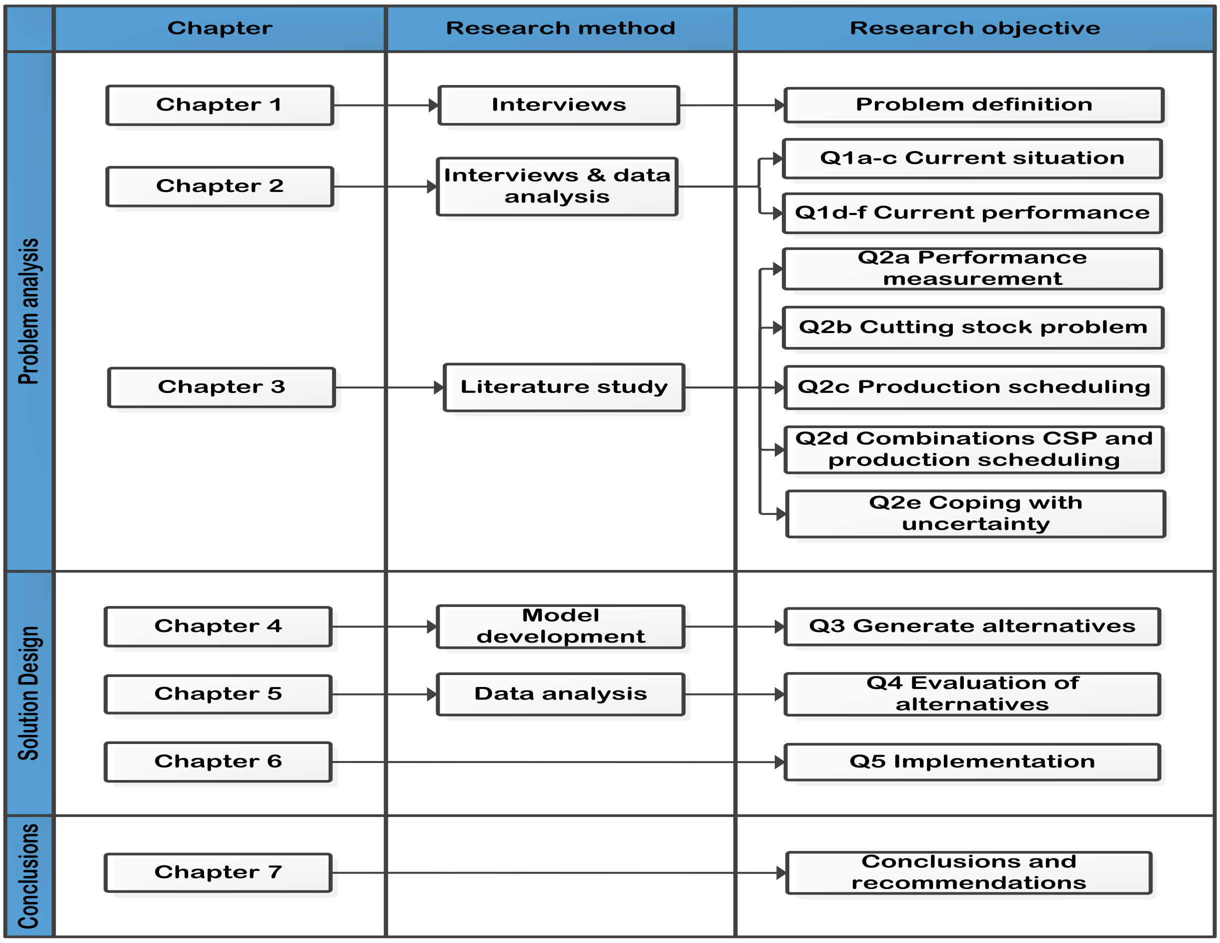


Figure 1.3 Research approach

2. CURRENT SITUATION

This chapter answers the first research question: *"What is the current situation at DS Smith?"* In Section 2.1 we describe the general process from order acceptance until shipment of orders to customers. Section 2.2 describes the corrugator machine and Section 2.3 describes the WIP buffer (called the Pentek). Section 2.4 describes the converting and expedition department. Section 2.5 describes the planning department with its scheduling processes and their approach in solving the CSP. Section 2.6 provides the current performance of scheduling. In Section 2.7 we elaborate on the problems regarding scheduling of production processes and we define the scope of this research. Finally, Section 2.8 provides conclusions.

2.1. THE GENERAL PROCESS AT DS SMITH

In this section, we describe the process of a customer placing an order until the shipment of the order to the customer. For a graphical representation of this process, see Figure 2.1. The first step in the process is an order request of a customer. The sales department checks the Rough Cut Capacity Planning (RCCP) whether there is enough capacity in the factory for the period that the customer requested the order. If there is enough capacity, a delivery date is communicated with the customer. The sales department accepts and releases the order for production. If there is not enough capacity, the order should be booked in another time period. However, most of the time the sales employees discuss with the planning employees to look for any opportunity to produce the order in the requested time period. The sales department also determines the initial machines on which the orders are produced.

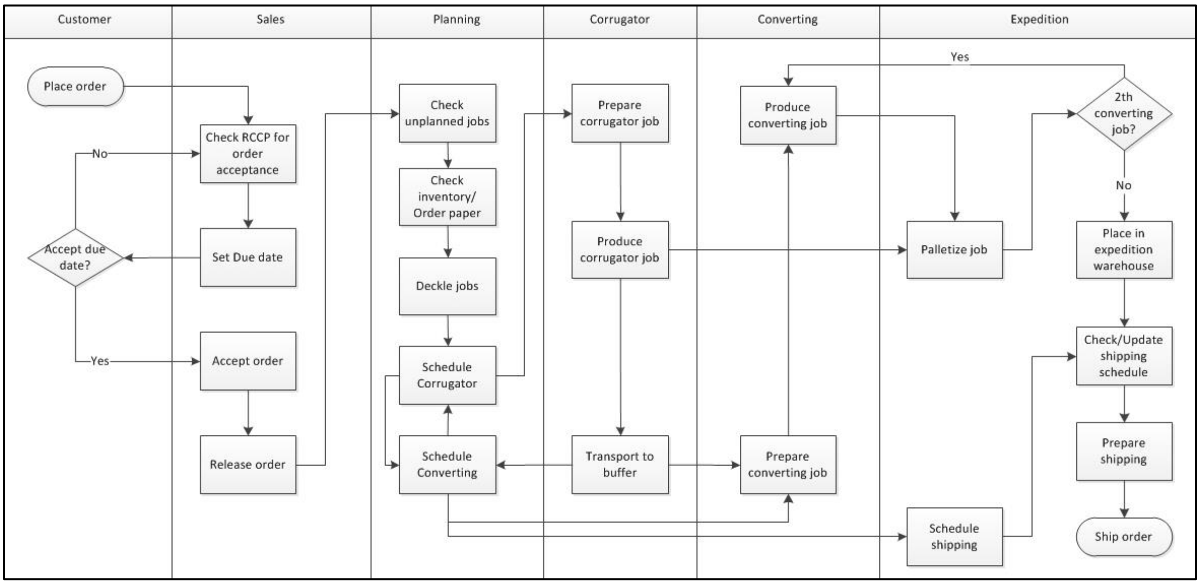


Figure 2.1 Graphical representation of the general process

The planning department can start scheduling when the order is released for production. An order can be split up in more than one job to minimize waste. We define a job by a task for production employees to produce a certain amount of an order at a specific time. The planning employees are responsible for checking the inventory of paper reels (big rolls of paper), ordering paper reels, making *deckle solutions*, scheduling CI jobs, and scheduling converting jobs. In Section 2.5 we elaborate on the tasks of the planning employees.

The first production step is processing jobs on the corrugator machine (see Figure 2.2). Briefly described, this machine makes corrugated board sheets. Material input for this machine are paper reels. Some preparation is needed before the jobs can be processed. One of the preparation tasks is making sure that the right paper reels are in place. Section 2.2 elaborates on the production process of the corrugator machine.

Figure 2.2 The corrugator machine

Stacks of corrugated board come out the corrugator machine and are transported with conveyors and an Automated Guided Vehicle (AGV) to the Pentek (the WIP buffer). The Pentek itself also consists of conveyors. Section 2.3 describes the Pentek in detail.

The converting step depends on the route of an order; see Figure 2.3 for the different routes. Corrugated board needs to be produced for every order. The corrugator machine is the first processing machine in every route. Palletizing is the last step for every route. We divide the converting machines in two groups. The die cutter machines (Dutch: stans machine) are the first group and the Flexo Folder Gluers (FFGs) are the second group. The FFGs have a small die cutting capability and their main function is to fold and glue boxes. The die cutter machines have a high capability for die cutting and no capability to fold and glue. For boxes that require a high die cutting capability and need to be glued, the route is according to option A. There are also boxes that do not need to be glued, but require die cutting. These orders are only processed on a die cutter (option B). Boxes that only require a small die cutting capability and need to be glued are processed directly on a FFG machine (option C). A small amount of the orders consist of “sheet” work. This means that a customer only ordered corrugated board sheets. These orders only require a corrugator step and a palletizing step (option D).

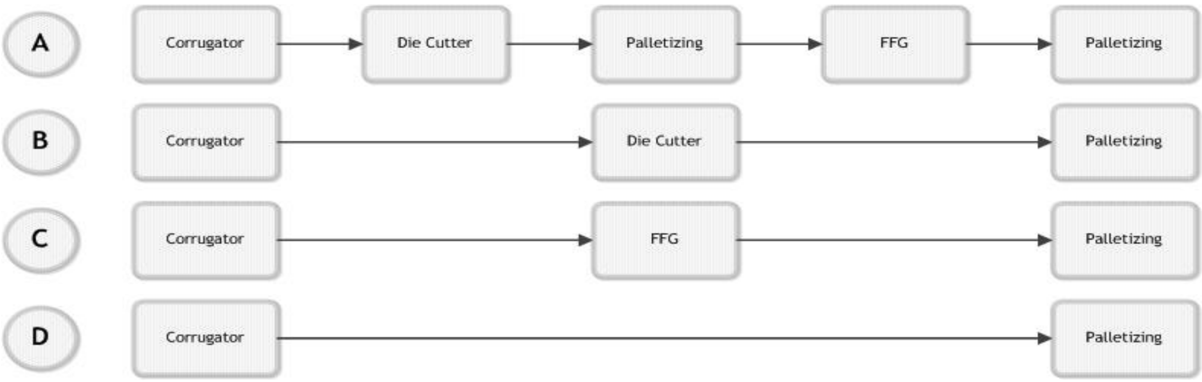


Figure 2.3 The different product routes

The products are stacked on each other at both the die cutters and the FFGs. These stacks are transported via conveyors to the palletizing system that is part of the expedition department. If an order requires a second converting step (option A), the pallets are transported back to the Pentek at the moment that this job is scheduled. Otherwise the pallets are placed in the expedition warehouse. The pallets are then loaded into trucks and within a few days they are shipped to the customer or to the external warehouse.

2.2. Corrugator machine

The corrugator machine makes sheets of corrugated board. Corrugated board consists of different layers of paper. DS Smith is capable of producing single wall and double wall corrugated board. Single wall corrugated board consists of three layers of paper: a bottom layer, a flute layer, and a top layer (see Figure 2.4). Double wall corrugated board has two flute layers (see Figure 2.5).

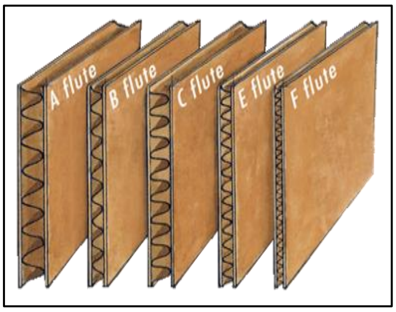


Figure 2.4 Single wall corrugated board

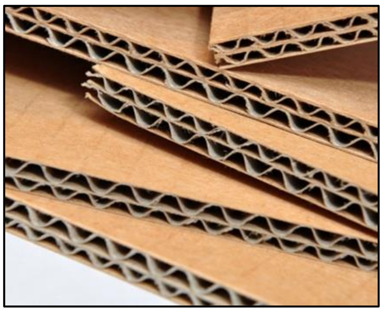


Figure 2.5 Double wall corrugated board

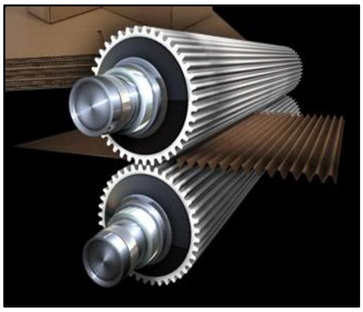


Figure 2.6 Corrugating rolls

For each flute different kinds of corrugating rolls are needed. The corrugating rolls make the shape of the flute (see Figure 2.6). The first part of the machine makes corrugated board. The machine is capable of making eight different kinds of corrugated board. Four single wall with a B-, C-, E-, or R-flute and four double wall with flute combinations B-E, E-B, B-C, or E-E. Moreover, there are also quality differences because of different kinds of paper. The quality of the corrugated board is called the board grade.

The next part of the machine makes the creases and cuts the corrugated board in width and length. Up to seven sheets can be cut next to each other. Two jobs can be produced next to each other that are of the same board grade. This is an important feature of the machine that enables minimizing waste of corrugated board. See Figure 2.7 for a simplified representation of the different stages of the corrugator machine.

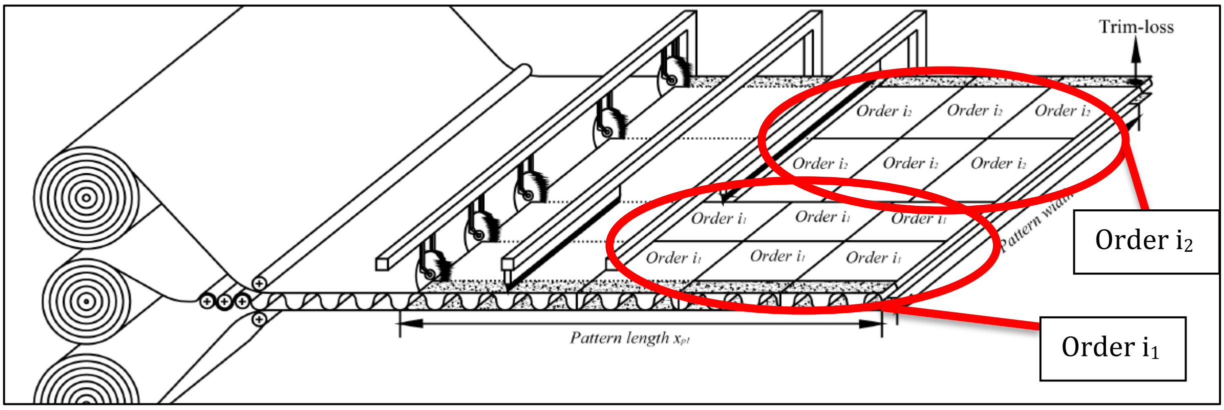


Figure 2.7 Stages of the corrugating process (Rodriguez & Vecchietti, 2013). In this example of a CI job where two sheets of order i_1 and two sheets of order i_2 are produced next to each other.

The possibility to combine orders makes scheduling more complex. Making the combinations of orders for the corrugator machine is called making a deckle solution. In Section 2.4 we explain how these deckle solutions are made and evaluated. The corrugator machine automatically stacks the corrugated board sheets and finally these stacks are transported to the Pentek (Figure 2.8).

ISSUES

There are several issues regarding the corrugator machine.

- Waste: The planning department makes schedules that ensure producing minimal waste. This can result in a deckle solution and corrugator schedule that has a lot of changeovers and require more time for production.
- Down/Idle time: Changeovers result in set-up time in the case of a corrugator roll change. Also just before and after the change, the speed of the machine is less. Effective production time and speed is lost when doing changeovers. Moreover, it is easier to maintain the right quality when producing large runs of the same quality. The corrugator machine is the bottleneck machine. So down/idle time of this machine results in a reduction of throughput of the whole factory.
- Workload: Having a lot of changeovers result in a higher workload for the lift truck driver, who needs to get the reels out of the reel warehouse for every changeover. Left over reels must be transported back to the reel warehouse.

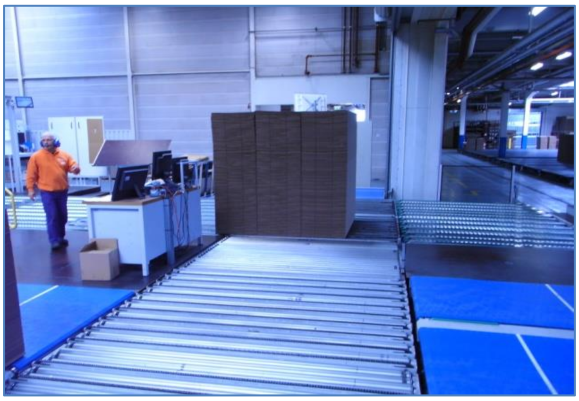


Figure 2.8 Transporting stacks to the Pentek

Figure 2.9 Conveyors of the Pentek

2.3. THE PENTEK (WIP BUFFER)

The WIP buffer, from now on called the Pentek, has an important role in the production process. After the production at the corrugator machine, the stacks of corrugated board sheets are transported to the Pentek with an AGV (AGV1). The Pentek is used as a buffer to enable a smooth production process, but is also used as drying area. Some board grades require a certain drying time before it can be processed on a converting machine. The stacks are transported with a second AGV (AGV2) to the converting machines. The Pentek consists of 31 automated conveyors each with a length of 16.5 meter (see Figure 2.9). When the utility of the Pentek is higher than 75% the corrugator machine is shut down. High utilization of the Pentek results in disruptions and stoppages in the whole production process.

Figure 2.10 gives an overview of how the Pentek is connected with the machines. The large blue block on the left is the corrugator machine. There are four output conveyors next to the corrugator machine. All the yellow/orange blocks are automated conveyors, the two AGVs can only travel vertically between the arrows, and the green blocks are the converting machines.

AGV1 picks up stacks from the output conveyors of the corrugator machine and places the stacks on one of the conveyors of the Pentek. AGV2 picks up the stacks from the conveyors and transports them to the input conveyors of the converting machines. The sequence in which the stacks are placed on the conveyors are of great importance. Once a stack is placed on a conveyor, the stacks are handled according to the FIFO rule. There is a possibility to shuffle the stacks. However, this costs capacity of AGV2 that transports the stacks to the machines. So shuffling of stacks can result in congestion in the Pentek due to unavailability of AGV2. Another drawback of shuffling is that the Pentek can become a “big mess”. There is a chance that stacks of the same order are placed all over the Pentek. This can result in further shuffling of stacks in the Pentek.

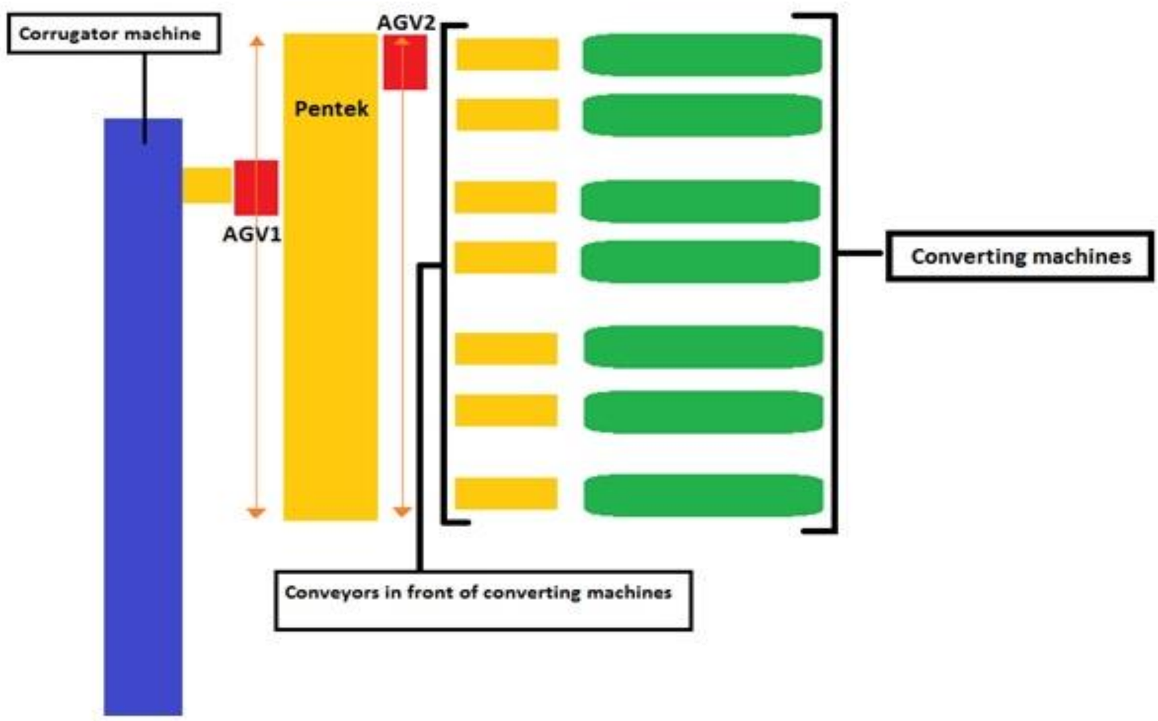


Figure 2.10 Overview of the Pentek

ALLOCATION OF THE STACKS TO A CONVEYOR

For monitoring and controlling the AGVs and the Pentek itself, the company uses a separate IT system. Once the stacks of corrugated board sheets are leaving the corrugator machine, the stacks enter the Pentek system and are linked to a Production Order number (PO number). Via this PO number the stacks are linked to a machine on which they need to be processed.

On entrance, the stacks are allocated to a certain conveyor number. This is done based on the width of the stacks, because the conveyors have different widths. Also the system tries to place stacks of the same order on the same conveyor.

TRANSPORTING STACKS FROM THE CONVEYOR TO THE MACHINES

AGV2 is controlled based on the fill rates of the conveyors that are placed in front of the machines. On each conveyor there are sensors that measure the fill rate. AGV2 first picks up stacks for machines that have the lowest fill rate. When a conveyor is full, the AGV cannot transport stacks to that conveyor. If there are no possibilities for the AGV to transport any stacks from the Pentek to the machines, it looks for shuffling tasks. This can be done by using a retrieving conveyor. One conveyor in the Pentek is used for retrieving. This conveyor transports the stacks back into the direction of the corrugator machine. These stacks are then picked up with AGV1. This AGV brings the stacks to another conveyor.

ISSUES

One important issue with the Pentek is that it uses a separate IT system. At this moment there is no possibility to allocate the stacks based on the schedule of the corrugator machine and/or the converting machines. The positioning of the operational control policy of the Pentek, based on the framework of Landeweerd & Mantel (1995), is a separated, centralized, no think ahead, pull policy (see Figure 2.11). The AGVs and conveyors are controlled centrally in the separated IT system. It is reacting only on events that are happening right now and is not looking ahead how future orders affect the utilization and allocation of stacks in the Pentek. It is controlled according to the pull strategy since it is triggered when stacks need to be transported to another conveyor and it is looking at the fill rates of the conveyors to prevent dead locks.

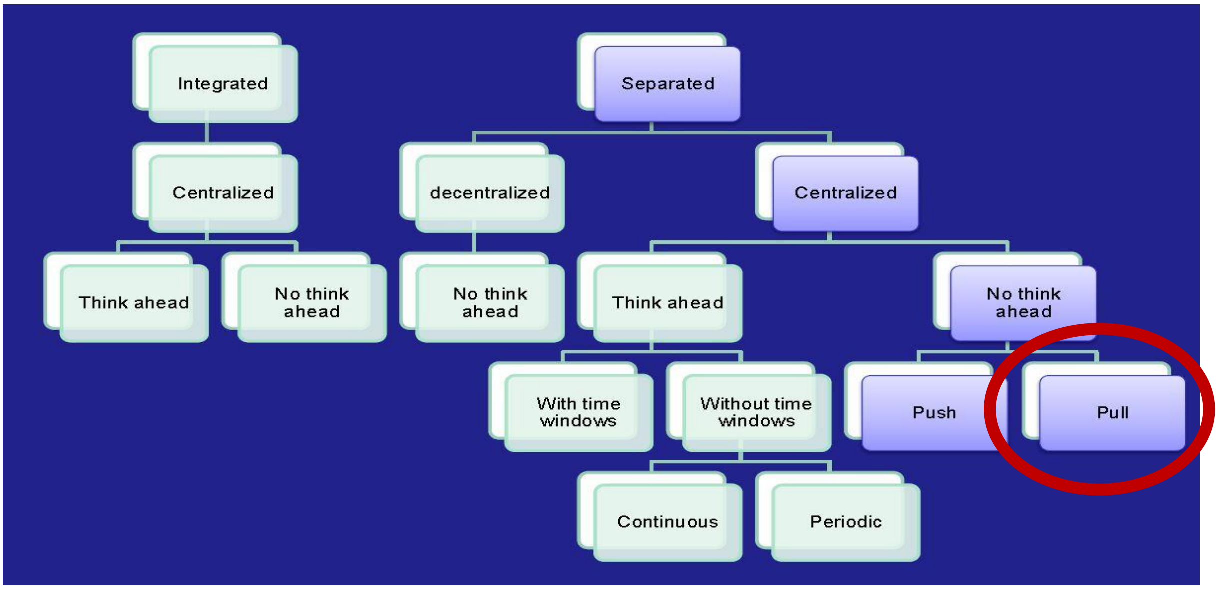


Figure 2.11 AGV operational control policies (Landeweerd & Mantel, 1995)

Another issue is that the AGVs are sometimes manually controlled. This is done when stacks are placed on the Pentek that need a second converting job. This cannot be done automatically at the moment. Also, when there are changes in the schedule and automatically shuffling of stacks takes too much time then production employees take over the AGV. The problem with this is that the fill rates of the other machines are not taken into account. This may lead to empty conveyors in front of the other machines, which leads to idle time due to Waiting on Pentek (WOP).

2.4. CONVERTING AND EXPEDITION DEPARTMENT

This section describes the converting and expedition department.

2.4.1. CONVERTING DEPARTMENT

The converting department consists of seven machines. Three belong to the die cutter group and four belong to the Flexo Folder Gluer group. Some machines have the same characteristics and can process the same orders. On the converting machines, sheets of corrugated board are printed with ink. Then the shape of the carton box is cut out of the corrugated board. If the job is

Figure 2.12 Stacks of finished products

processed on one of the FFGs, then the boxes are also folded and glued. At the end of each machine the carton boxes are stacked on each other. The stacks are transported to a palletizing area via automated conveyors (see Figure 2.12).

The characteristics of the machines are summarized in Table 2.1. We do not give a detailed description of the different types of machines. This is not relevant for our research and understanding of the process.

Machine number	Supplier	Number of colors	Type
728			
729			
735			
419		*confidential*	
425			
426			
436			

Table 2.1 Converting machines

The number of colors that a job requires determines to what degree the machines are interchangeable. If an order needs a converting step on a FFG and has three colors it can be produced on three machines (425, 426, and 436). If it has four colors it can only be produced by the 425. The dimensions of the corrugated board also determine what machine can be used. The machines have different production speeds. The speed of a machine depends on several aspects: sheet dimensions, number of colors, and cardboard quality. The ERP-system keeps track of the historical production speeds per order. The average of these speeds is used to determine the production time of an order.

Issues

One issue related to scheduling is that the production department has different objectives than the planning employees. The production employees want to produce in such way that set-ups are the easiest. So they want schedules that take into account sheet dimensions, colors, and also which dies are used. However, the planning employees do not take this into account. Delivery dates and a smooth and balanced production process are their objectives. In some situations this results in changes of the converting schedule, e.g., a certain change in schedule results in less or easier set-up for production and cause no problems in the process. However, not all effects of scheduling changes are known and visible.

2.4.2. Expedition department

The expedition department is responsible for palletizing the finished and semi-finished products. This is done automatically with machines that press the products on pallets, banding the pallets, and if necessary sealing the pallets in plastic. If a second converting job is needed, the pallets are transported back to the Pentek or stored for a short time in the warehouse. Transporting pallets back into the Pentek is done by pushing the semi-finished products from the pallets on a conveyor. The conveyor used for this is not an automated conveyor. Therefore, AGV2 needs to be controlled manually to place the semi-finished products on another conveyor of the Pentek or in front of the right machine.

ISSUES

The expedition department is not taken into account with scheduling. However, the expedition department may become a bottleneck when all the seven converting machine are producing on full speed. When one of the machines of the expedition department is down, the whole expedition department is down since the machines are serially positioned. This does not happen frequently, so this is not an issue that we need to take into account.

2.5. PLANNING DEPARTMENT

In this section we describe the tasks of the planning employees. The tasks are split up in making deckle solutions, CI job scheduling, converting scheduling, expedition scheduling, and monitoring and controlling the schedules and Pentek. The schedules are made for 20-30 hours in advance.

2.5.1. *MAKING DECKLE SOLUTIONS / CSP*

Making a deckle solution is the process of combining corrugator jobs in order to minimize waste. As mentioned earlier, this can be formulated as the CSP. The CSP is applicable in many industries. Also the literature about the CSP is extensive; Sweeney and Paternoster (1991) have identified more than 500 papers about the CSP.

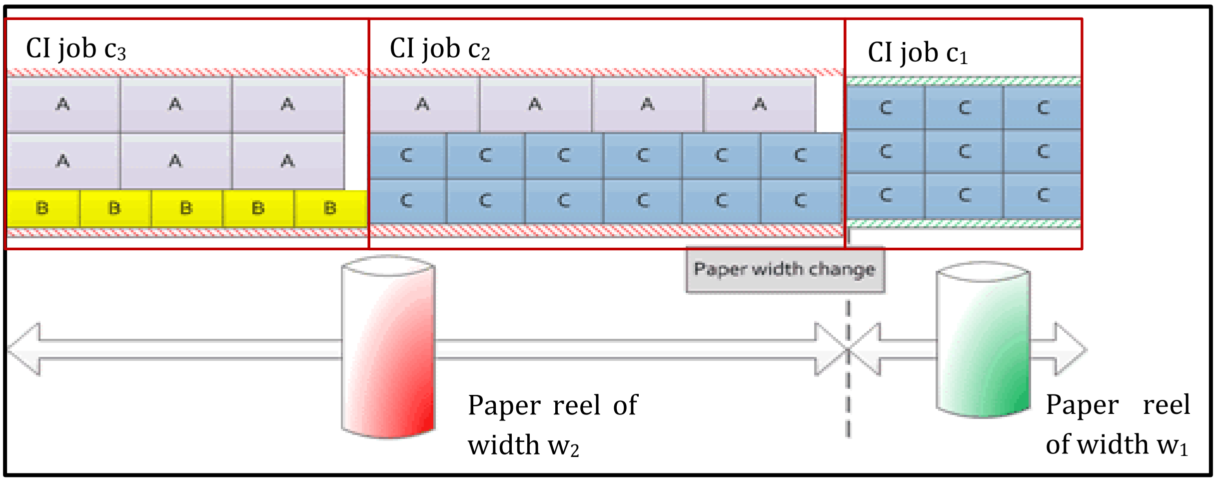


Figure 2.13 Example of a deckle solution that consist of three CI jobs (c_1, c_2, and c_3), uses two paper widths (w_1 and w_2), and produces sheets for three orders (A, B, and C). The red and green shaded areas are trim loss.

See Figure 2.13 for an example of a deckle solution. This deckle solution consists of three CI jobs (in literature called cutting patterns or patterns). The first CI job (c_1) produces three sheets next to each other of the same order (C-C-C) with a paper reel of width w_1, the second (A-C-C) and third (A-A-B) CI job (c_2 and c_3) produce sheets of two different orders with a paper reel of width w_2. The red and green shaded areas are the trim loss waste of corrugated board of the Deckle solution. These deckle solutions are generated via a built-in Integer Linear Program (ILP). Before running the ILP, parameters and constraints need to be filled in about paper dimensions, minimum trim los, maximum trim loss, minimum *CI job run length*, minimum *run length per paper width*, and the minimum and maximum *order quantity* that may be delivered to the customer. The program shows several feasible solutions. The planning employee chooses a solution that fits best the preferences of the production employees and that also has a low trim loss.

See Figure 2.14 for a graphical representation of the process of making deckle solutions. The first step is checking for urgency jobs. If there are urgency jobs, the planning employee checks if there are any deckle solutions that have the same board grade. If it is feasible to add this urgency job to this deckle solution, the job is added and the schedule for the corrugator is updated. Otherwise a new deckle solution is made with not yet deckled orders that are in certain due date ranges. If there are no feasible solutions, the due date range is updated and new deckle solutions are made. The best solution is selected and the new deckle solution is added to the schedule.

Making deckle solutions of non-urgency jobs is almost the same. The difference is that the workload and finishing times of the converting machines are taken into account. A board grade is selected for which there are the most jobs for the machine with the lowest workload/finishing time. After that, the due date range is determined and jobs are selected. There is a possibility to upgrade an order. This means that another board grade is used that uses paper with more grams per square meter. Company rules dictate that upgrading is only allowed when the trim loss of a deckle solution is above 5-6%.

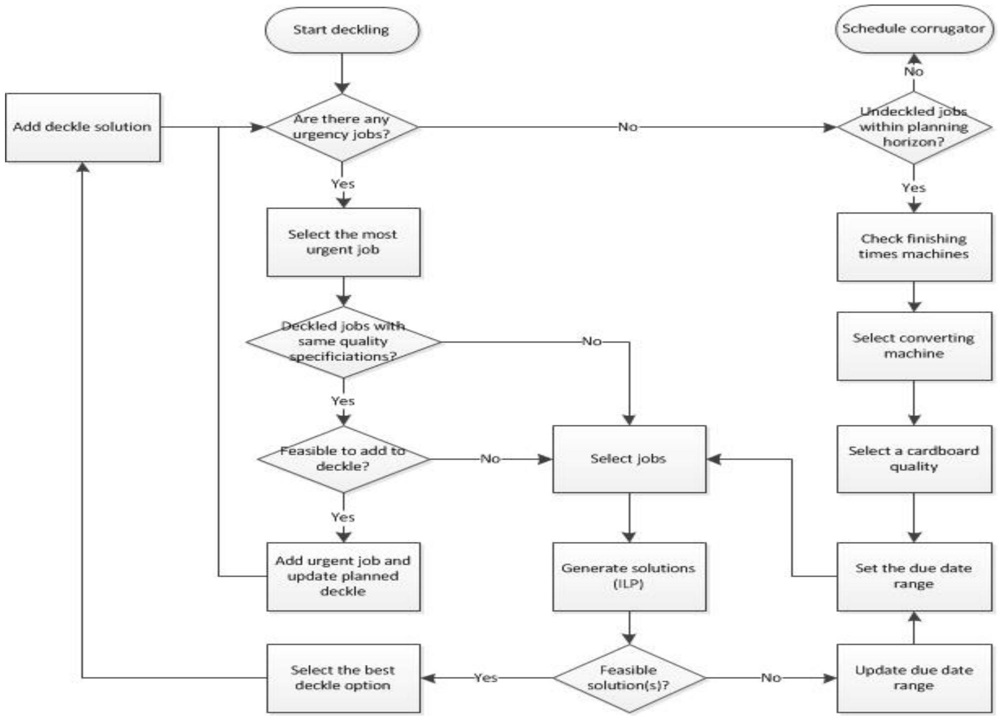


Figure 2.14 Graphical representation of the deckling process

2.5.2. *CORRUGATOR SCHEDULING*

The CI jobs that come out of the deckle solutions need to be scheduled on the corrugator machine. These jobs are scheduled based on several directives. The first directive is about how to schedule the change in flutes. The directive dictates the following sequence: B-C-CB-B-E-EB-EE-BE-B. The R-flute can be planned after and before a single job, so before and after a B, C, or E flute. This directive is made because some changeovers require a change of corrugating rolls. This may result in downtime of about 25 minutes, plus a loss of speed just before and after the changeover.

After that, the planner checks if the schedule of the corrugator causes idle time for converting machines. If it does, the schedule of the corrugator machine is reconsidered to minimize the idle time. When it is not possible to prevent idle time, the machines that have large idle times are taken out of the schedule for production.

The second directive dictates that jobs with the same flute and board grade are scheduled in descending order based on trim loss. This is done because jobs with small trim loss require a higher accuracy. Scheduling them in the beginning can cause problems since the first job of a certain quality requires some fine tuning. The third directive dictates that large jobs are planned first and the fourth directive is about the paper width. The corrugator jobs with the largest paper width should be produced first within a deckle solution.

2.5.3. *Converting scheduling*

After the CI jobs are scheduled, the estimated arrival times at the Pentek are known and the converting jobs are scheduled. The jobs are first planned based on the FIFO rule. After that, the workloads and finishing times of converting machines are checked. If the workload of a machine is too high, jobs of that machine are scheduled on an interchangeable machine. The initial machine is determined by the sales department as mentioned in Section 2.1. If the workload is too low, this machine probably becomes idle. Jobs on interchangeable machines are then scheduled on this idle machine. If this is not possible or insufficient, the schedule of the corrugator machine can be changed to balance the workload. This can be done by changing the sequence of the deckle solutions.

The directives for converting scheduling are different from the directives of corrugating scheduling. The most important directive is that due dates are met (Directive 1). So if the FIFO rule results in jobs that are not finished before the due date, the schedule needs to be changed.

The second directive is about job characteristics. If there are jobs with the same characteristics, then these jobs are scheduled after each other to minimize set up times. The third directive dictates that jobs of the same board grade should be scheduled after each other.

Scheduling of converting jobs is done after making deckle solutions and scheduling of the CI jobs. However, the workload of converting machines is already taken into account when making deckle solutions and scheduling the CI jobs to prevent many changes afterwards.

2.5.4. *Expedition scheduling*

The expedition schedule is made one day ahead. Orders are combined to optimize truck utilization and transportation costs. The expedition department benefits from reliable production schedules. If there are changes in production schedules, then there is a possibility that the schedule of expedition also changes. If this is not communicated or is done at the last moment, trucks need to wait or are not full. This results in higher costs of transportation and the on time delivery decreases.

2.5.5. *Monitoring and controlling the current schedules and Pentek*

Since there is uncertainty, it is necessary to monitor and control the schedules. A small change in one schedule may cause other schedules to change as well. These changes may be a cause of downtime, idle time, maintenance, unavailability of workforce, unavailability of dies, etcetera. In order to keep a balanced and smooth production, these changes need to be evaluated and rescheduling may be needed. Utilization of the Pentek also needs to be monitored since this can cause both the corrugator and converting machines to become idle. Another reason for monitoring and controlling the Pentek is that it gives a good picture of the workload for the converting machines for the coming hours.

2.6. CURRENT EVALUATION AND PERFORMANCE OF SCHEDULING

The performance of production is currently evaluated based on several performance indicators. Some of these indicators can also be used for the evaluation of the performance of scheduling since they are directly a result of the schedules.

TRIM LOSS

This is the performance indicator that measures the quality of the deckle solutions. Trim loss is waste of corrugated board at the corrugator machine at both sides of the paper, measured in percentage of the total width of the paper. The total trim loss was *confidential* in 2013 (the target trim loss is 3.6%). We conclude that the performance of the deckle solutions is on target. However, when we take into account the waste of a *side job*, the total waste was *confidential* in 2013. A side job is trim loss that cannot be drained by the corrugator machine. A new corrugator job is created to transport the waste (the side job) to the Pentek.

IN FULL (IF)

Each order has minimum and maximum quantities. The standard tolerances in the packaging industry are -10% and +10% of the ordered quantity. The In Full indicator measures how many orders are delivered within these minimum and maximum order quantities. In 2013 the In Full percentage was *confidential* while the target was 90%. It is hard to predict the amount of waste produced for a specific order. Also there are company directives that dictate that the planned quantity must be between 104% and 106% of the ordered quantity.

ON TIME DELIVERY (OT)

This indicator measures how many orders are delivered on time. Orders that are not delivered In Full but are on time are also counted as delivered on time. In 2013 the On Time Delivery percentage was *confidential* where the target was 96%.

ON TIME IN FULL DELIVERY (OTIF)

This indicator measures how many orders are both In Full and On Time delivered. The target for this indicator is 85% while in 2013 only *confidential* is reached. This indicator is not an indicator that stands for itself. It is a combination of the On Time Delivery and the In Full delivery.

WAITING ON PENTEK (WOP)

This is the performance indicator that measures how much time a converting machine was idle because it needed to wait on sheets. This is a result of the Pentek that could not deliver sheets in time. In 2013, the converting machines needed to wait in total *confidential* days on the Pentek.

WAITING ON CORRUGATOR (WOC)

Waiting on corrugator is the indicator of idle time of the converting machines, because the corrugator machine could not make sheets in time for the converting machines. The total idle time of the converting machines because of waiting on corrugator was *confidential* days in 2013.

IDLE TIME OF CORRUGATOR CAUSED BY A FULL PENTEK

This indicator is based on the total registered idle time caused by a full Pentek for the corrugator machine as percentage of the total available time of the machine. The total idle time at the corrugator machine caused by a full Pentek in 2013 was *confidential* days. Per idle time occasion, the average idle time was around two hours. The available production time in 2013 was *confidential* days. So the corrugator machine was *confidential* of the time idle due to a full Pentek.

2.7. PROBLEM IDENTIFICATION

In this section we identify the problems that are related to scheduling. There are three main problems that have the highest impact on the production process. These are idle/down times of the corrugator machine and converting machines and the high utilization of the Pentek. The problems are shown in a problem tree (see Figure 2.15).

A: DOWN/IDLE TIME OF THE CORRUGATOR MACHINE

Down or idle time of the corrugator machine can be caused by different situations. However, only two of the causes are related to scheduling. The first one is that there is a schedule that needs changeovers that are not according to the directives of corrugator scheduling. These changeovers cause the corrugator machine to have downtime. Another cause of idle/down time is that the utilization of the Pentek is above 75%. If the Pentek is utilized above 75% it is not working properly and the corrugator machine is shut down. Since the corrugator machine is the bottleneck of the company, downtime or idle time results in an overall lower throughput.

B: HIGH UTILIZATION OF THE PENTEK (>75%)

A high utilization of the Pentek has several causes. The first cause is that the corrugator machine is producing more than the converting machines. A bad allocation of the stacks in the Pentek may be a cause for the low output of the converting machines. This causes the AGVs to travel long distances and also results in shuffling of stacks.

With the current way of scheduling the limitations of the Pentek are not taken into account. This causes a high variability in utilization level of the Pentek. If the Pentek has a low utilization, converting machines may become idle due to waiting on corrugator. A high utilization of the Pentek may result in downtime of the corrugator machine. Other reasons are changes in the converting schedules and manually controlling the AGVs.

C: DOWN/ IDLE TIME OF THE CONVERTING MACHINE

The reduced throughput of the Pentek may result in idle/down time of the converting machines. Low throughput causes machines to wait on sheets, i.e., the AGVs cannot supply the machines in time. Another possible cause for idle time is that there are no sheets in the Pentek. This may be a result of downtime at the corrugator machine or a “bad” schedule.

Another cause of the downtime at the converting machine may be that a second processing job for converting is needed. Time is needed to get the stacks in the Pentek and also the AGVs need to be controlled manually. People are needed for this and if there are none available the operators need to do it themselves. This causes the converting machine to become idle.

MAIN CAUSES

The main causes of the problems are that corrugator and converting scheduling is not integrated (1). Next to this, DS Smith is using an objective function for solving the CSP that only takes into account trim loss(2). The last main cause is that the utilization of the Pentek is not taken into account (3). This results in schedules that are not robust and not reliable.

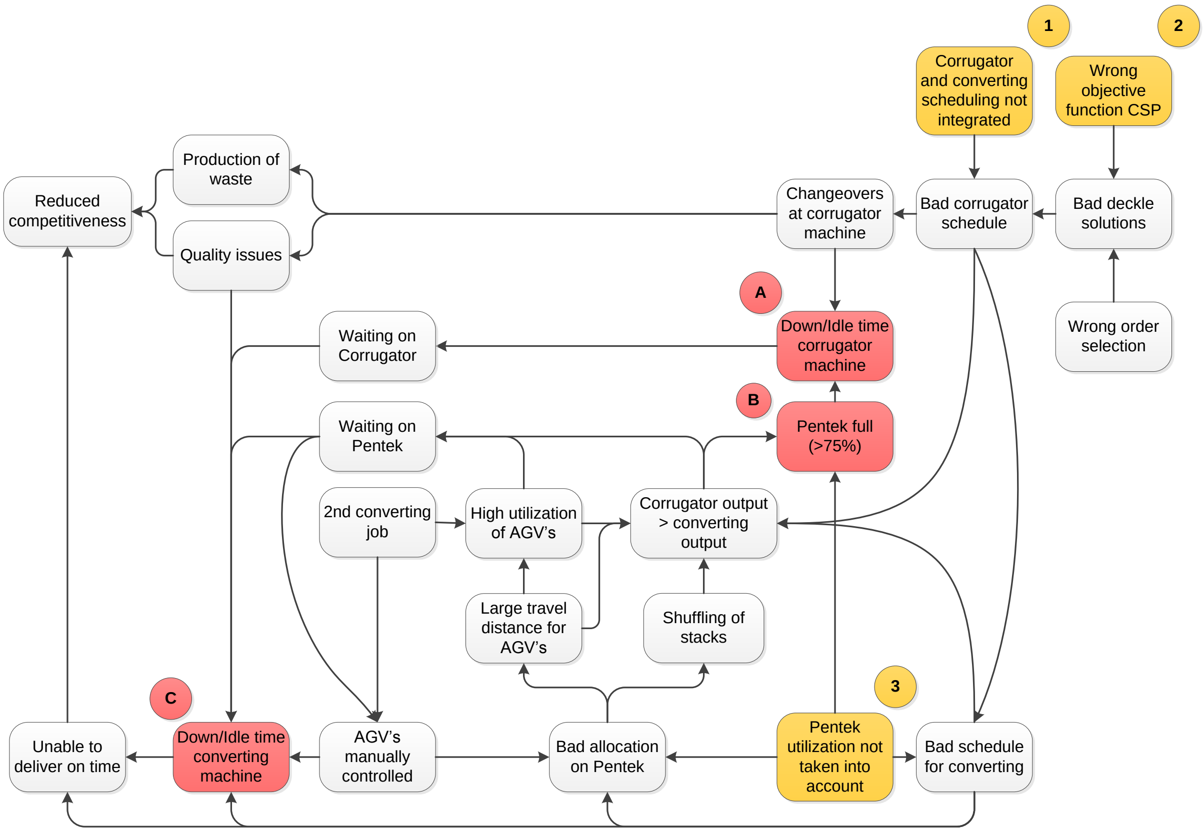


Figure 2.15 Problem tree

SCOPE

The scope of this research is on the area of resource capacity planning on an operational level. See Figure 2.16 for the graphical positioning of this research based on the hierarchical framework of Hans *et al.* (2007).

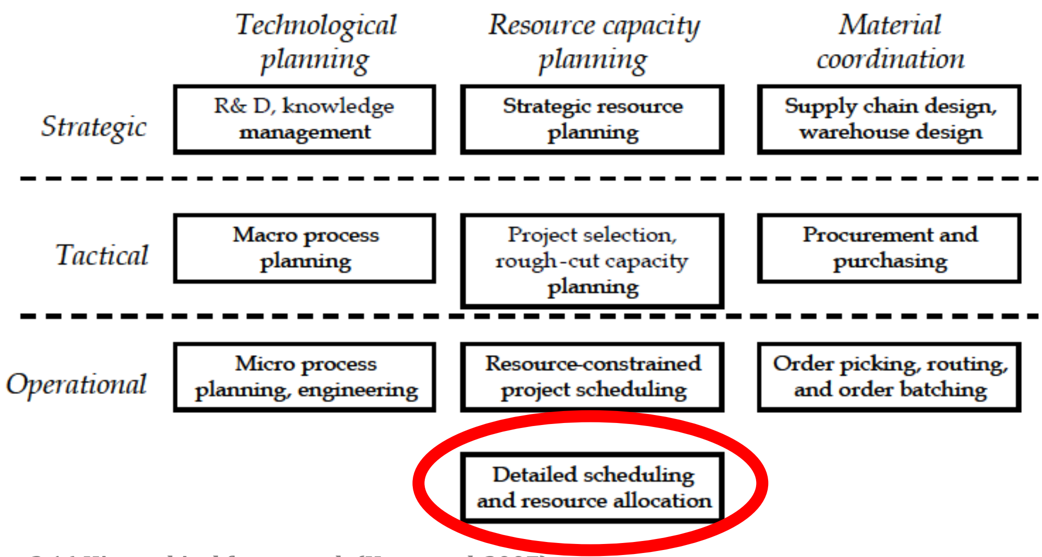


Figure 2.16 Hierarchical framework (Hans *et al.* 2007)

The scope of this research is to find a way to integrate corrugator and converting scheduling and to find an objective function for the CSP that takes into account the preferences for production. The Pentek is also in the scope of this research. Expedition planning is out of our scope since production scheduling only affects expedition scheduling and not vice versa. RCCP and order acceptance are on a tactical level and not on an operational level. Although both affect production scheduling, we exclude it from the scope. If we would include it in the scope, the problem would become more complex. We decided to exclude RCCP and order acceptance to keep the research manageable. Upgrading of board grades of orders is also excluded from the scope of this research. Upgrading is a last resort if the trim loss is too large and is not preferred because the customer ordered a different board grade, i.e., the demands of the customer are not met if a board grade is upgraded.

DELIVERABLES

The deliverable of this research is a solution that supports the tasks of the production planners. We need to model the process of order selection, solving the CSP, scheduling the corrugator machine, scheduling the converting machines, and monitoring and controlling the Pentek. The different tasks are first modelled as separate modules. Alternative solutions are developed where modules are integrated or closely linked. The aim is not to implement this solution. The outcomes of this research are used to give new insights in the planning and scheduling processes at DS Smith. These insights may be used to implement parts of the solution in the current ERP system of DS Smith to improve planning and scheduling.

2.8. CONCLUSIONS

In this chapter we described the current situation at DS Smith. First jobs are processed on the corrugator machine and then transported to the Pentek. After that, one or two converting jobs are performed. Finally, the pallets with the finished products are palletized and transported to customers or to the external warehouse.

Orders need to be combined for the corrugator machine. This is called making deckle solutions and can be formulated as the cutting stock problem (CSP). The choice for a deckle solution has a high impact on the schedules of the corrugator machine and the converting machines. Currently, the preferences of production are only taken into account for a small amount when making and selecting the deckle solutions. This results in problems in the production process. Another cause for problems in the production process is that corrugator and convertor scheduling is not integrated. Finally, the Pentek with its limitations is also not taken into account.

The scope of this research is to find a way to integrate corrugator and convertor scheduling and to find an objective function for the CSP that takes into account preferences of production. This research needs to deliver a solution that supports the tasks of the production planners in different modules. Alternative solutions are developed where these modules are integrated or closely linked. To model the tasks of the production planners in the best way, we do a literature review on the CSP, performance measurement, and scheduling techniques in Chapter 3.

3. THEORETICAL FRAMEWORK

In Chapter 2 we elaborated on the current situation at DS Smith and defined the main problems, the scope, and the deliverables of this research. In this chapter we outline the theoretical framework for this research by answering the second research question: "*What literature supports our research at DS Smith?*"

First we describe literature about performance measurement for production scheduling in Section 3.1. Second, Section 3.2 describes the CSP and the solutions for it in the corrugated board industry. In Section 3.3 we elaborate on different classifications for production scheduling and what classification is applicable for DS Smith. Section 3.4 provides algorithms that are capable of solving hard combinatorial optimization problems. Section 3.5 describes combinations of the CSP with production scheduling. Section 3.6 describes approaches for coping with uncertainty. Finally, Section 3.7 provides conclusions.

3.1. PERFORMANCE MEASUREMENT

We need to know how we can evaluate and measure the performance of a schedule in order to determine which scheduling approach or algorithm is the best for DS Smith. A performance measure can be defined as "a metric used to quantify the efficiency and/or effectiveness of an action" (Neely *et al.*, 2005). In our case we want to quantify the effectiveness of a production schedule. Kempf *et al.* (2000) mention the importance of quality measurement of a schedule. They state that a clear understanding of the quality of a schedule is essential for a successful implementation of a scheduling system.

3.1.1. PERFORMANCE INDICATORS

We need to define performance indicators of a production schedule in order to assess the quality of a certain schedule. Hoogeveen (2005) state that if only one indicator is used, the schedule is likely to be unbalanced, no matter what indicator is considered. The following performance indicators are widely used in literature (Hsu, 2006; Hoogeveen, 2005; De Snoo *et al*., 2011; Bandinelli *et al*., 2005):

- Maximum completion time
- Total completion time
- Maximum lateness
- Average lateness
- Total flow time/cycle time
- Maximum tardiness
- Average tardiness
- Total tardiness
- Maximum cost
- Maximum earliness
- Total earliness
- Total number of tardy jobs
- Total waiting time

Indicators that can directly be calculated from scheduling objects (set of jobs, time assignments and machines) are called atomic metrics (Kempf *et al*., 2000). These atomic metrics quantify how much time each scheduling object is in each possible state. Examples of states of a machine are: busy, setup, maintenance, idle, and down. Examples of states of a job are: in process, in transport, on hold or idle. These atomic metrics can also be used as performance indicators. For example, the percentage of time a machine is idle and/or down.

3.1.2. MULTI-CRITERIA SCHEDULING

Only using one of the many performance indicators is not sufficient for evaluating a schedule. So we need a way to evaluate a schedule based on multiple criteria. Hoogeveen (2005) mentions two approaches to deal with multiple criteria. The first one is the hierarchical or lexicographical optimization approach. This approach selects one performance criteria, say f, which is the most important. A set of optimal schedules based on f is generated. From this set of optimum schedules, the schedule is selected that has the best performance on the other criteria.

The second approach is simultaneous optimization, where the performance criteria are evaluated simultaneously. Simultaneous optimization is divided in three different approaches: a priori optimization, interactive optimization, and a posteriori optimization (Fry *et al.*, 1989; Evans, 1984).

- A priori optimization: With this approach all the criteria are taken together in one objective function. This function can be linear, but also quadratic, or any other form. A drawback of this approach is that it is hard to define the parameters of the objective function. Another drawback is that minimizing the objective function is most of the time NP-hard for scheduling problems.
- Interactive optimization: This approach uses the expertise of the decision maker. One or more schedules are already generated and the decision maker must select the one that is preferable and in which direction the search should continue.
- A posteriori optimization: This last approach is used when the objective function is not known. A set of feasible solutions is presented to the decision maker and he/she must choose the one that is the best according to him/her.

A problem with using multiple criteria is that they can be related to each other (Kempf *et al.*, 2000). For example: Maximizing machine utilization may result in an increase in WIP, while minimizing WIP is another objective. Another problem with using multiple criteria is that it results in an increase in complexity of the scheduling problem.

3.1.3. EVALUATION FRAMEWORK

Bandinelli *et al.* (2005) propose a framework for the evaluation and comparison of production schedules. The framework is based on three layers: The effectiveness domain, the robustness domain, and the flexibility domain.

- Effectiveness domain: This domain evaluates the effectiveness of the company according to the control of a scheduling solution. It describes how the whole manufacturing system works and not just the efficiency of machines and workforce.
- Robustness domain: This domain consists of indicators that measure the robustness level of scheduling solutions. Robustness is defined as the ability of a scheduling system to perform with graceful degradation of the performance in the face of external or internal disruptions.
- Flexibility domain: This domain measures how easy a scheduling system can be implemented in a different production environment or when the environment changes.

De Snoo *et al.* (2011) distinct between product and process related performance. Product performance is about how well internal and external constraints are fulfilled and process performance is about the reliability, flexibility, response speed, and communication and harmonization capabilities of the schedulers. De Snoo *et al.* (2011) propose a new scheduling performance measurement framework that consists of four parts, see Figure 3.1. The first part consists of criteria focused on the scheduling product. The second part consists of criteria focused on the scheduling process. The third part consists of indirect scheduling performance criteria and the last part consists of influencing factors.

The framework of Bandinelli *et al.* (2005) made a clear distinction between different domains of scheduling. Besides measuring the performance of a schedule they also evaluate how the schedule or scheduling method performs when disruptions occur and if it could be implemented in another environment. De Snoo *et al.* (2011) are more focused on scheduling performance in a certain company/organization. They do not measure how flexible the scheduling is and the robustness is only incorporated in one performance indicator (6).

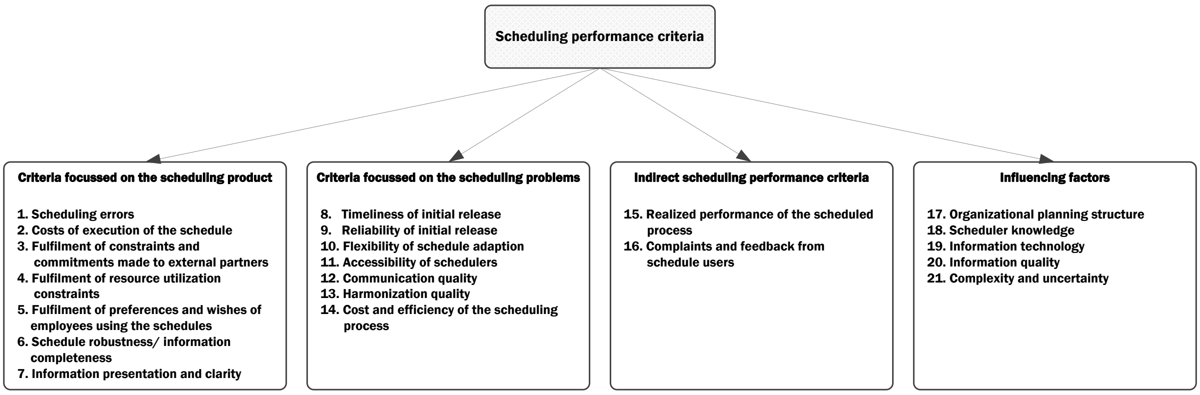


Figure 3.1 Scheduling performance measurement framework (De Snoo *et al.,* 2011)

3.1.4. *DIFFICULTIES WITH PERFORMANCE MEASUREMENT OF SCHEDULING*

Measuring the performance of a schedule is not easy. One difficulty with scheduling is how to cope with uncertainty. Aytug *et al.* (2005) address that it is unlikely, in any environment other than a tightly integrated automated situation, that a predictive schedule is executed exactly as planned. A schedule developed under certain assumptions (such as no disruptions will occur) is called a predictive schedule. The schedule may be changed when disruptions occur. This is referred to as reactive scheduling or rescheduling.

Aytug *et al*. (2005) identify three dimensions of uncertainty: cause, context, and impact. Cause can be seen as an object, for example: material, process, resource, tooling or personnel. An object is in a certain state, for example: ready, not ready, high quality, low quality, damaged, healthy, etcetera. The context is about how the environmental situation is at the time of the scheduled event. A situation can be either context-free or context-sensitive. A context-free situation does not need any additional information on the situation (the situation is always the same) and a context-sensitive situation does need additional information for decision making (the situation changes). The result of uncertainty, for example disruptions in the production process, is referred to as the impact of uncertainty. Impact can be categorized as time, material, quality, independent or dependent, and context-free or context-sensitive. The impact of uncertainty on other jobs and activities is referred to as dependent or independent. So if uncertainty of one job has an impact on other jobs it is dependent. Inclusion is an additional dimension of uncertainty and it is about how to cope with uncertainty, in a predictive or in a reactive way.

Another difficulty is that most performance measures only consider all the jobs at once. They do not consider the individual needs of a specific job, while customers may have different requirements for their orders (Hsu, 2006) .

3.2. CUTTING STOCK PROBLEM

The CSP is a widely researched problem, with many applications. In this section we give solutions that are available in the literature for the corrugated board industry.

3.2.1. TYPOLOGY OF THE CUTTING STOCK PROBLEM

Dyckhoff (1990) proposes a typology for cutting and packing problems. Dyckhoff (1990) distinguishes between the dimensionality, kind of assignment, assortment of large objects, and assortment of small items. We underline the typology that is applicable for the situation at DS Smith.

DIMENSIONALITY

Dimensionality is the most important characteristic of the typology. It refers to the number of dimensions necessary to describe the geometry of the patterns. The elementary types are:

- <u>(1) One-dimensional: only the width of patterns is considered.</u>
- (2) Two-dimensional: both the width and length in patterns are considered.
- (3) Three-dimensional: the width, length, and height of patterns are considered (applicable for packing problems).
- (N) Multi-dimensional: this is a three dimensional problem with time as fourth dimension.

This research only consists of one-dimensional problems, since trim loss minimization only takes into account the width of cutting patterns.

KIND OF ASSIGNMENT

For the classification it is important to know what kind of assignment is needed. Two possible kinds of assignments are possible. The first assignment is a selection of items (orders) that need to be assigned to all the available large objects (paper reels). This is the case when there are limited raw materials and jobs need to be selected for production. The second assigns all items to a selection of large objects. In the situation of DS Smith there are sufficient raw materials and the raw materials to use need to be selected. So, the second kind of assignment is applicable for the trim loss optimization at DS Smith.

- (B) All objects and a selection of items
- <u>(V) A selection of objects and all items</u>

ASSORTMENT OF LARGE OBJECTS

The assortment of large objects means in our case the assortment of the paper reels. Three types of assortments are distinguished: one object, identical figure, and different figures. With one object is meant that the small items (orders) need to be cut out of one large object (paper reel). With identical figure is meant that the small items need to be cut out of multiple large objects and these objects are identical. In the case of DS Smith we deal with different figures, i.e., the orders need to be cut out of multiple paper reels that are of different paper qualities and different widths.

- (O) One object
- (I) Identical figure
- <u>(D) Different figure</u>

ASSORTMENT OF SMALL ITEMS

The assortment of small items (orders) is the output of the process. So the pieces that come out of the large input objects that need to be cut. Four types of assortments are possible for the small items:

- (F) Few items
- (M) Many items of different figures
- <u>(R) Many items of relatively few different figures (non-congruent)</u>
- (C) Congruent figures

With this research we cope with many orders and the figures are always rectangles but not congruent in most cases. So we deal with many items of relatively few different figures. With congruent figures is meant that the figures all have corresponding sides and angles. We conclude that our CSP can be formulated as a 1/V/D/R CSP.

3.2.2. SOLUTION APPROACHES FOR THE CUTTING STOCK PROBLEM

The work of Gilmore & Gomory (1961; 1963) was the first significant work on the area of solving the one-dimensional CSP. They solved the CSP by solving a knapsack problem to determine the next pattern to enter the Linear Program (LP) basis. In this way not all possible patterns need to be considered. However, in most practical situations we need an Integer Linear Program (ILP) instead of an LP. The number of products cut out must be an integer number or we need auxiliary integer/binary variables when including constraints. Haessler and Sweeney (1991) formulated the following ILP model for a one-dimensional CSP (1/V/I/R). With this model, rl_i is the lower bound of the order requirement and ru_i is the upper bound of the order requirement. UW is the width of a paper reel. $a_{i,j}$ is the number of sheets to be cut next to each other of width w_i from cutting pattern j. X_j is the total run length of cutting pattern j. The objective function is to minimize the total trim loss.

$$Min \text{ z: } \sum_j t_j * X_j \qquad (3.1)$$

Subject to:

$$rl_i \leq \sum_j a_{i,j} * X_j \qquad \forall \text{ i} \qquad (3.2)$$

$$ru_i \geq \sum_j a_{i,j} * X_j \qquad \forall \text{ i} \qquad (3.3)$$

$$\sum_i a_{i,j} * w_i \leq uw \qquad \forall \text{ j} \qquad (3.4)$$

$$t_j = uw - \sum_i a_{i,j} * w_i \qquad \forall \text{ j} \qquad (3.5)$$

$$X_j \geq 0 \quad \text{and integer}$$

<u>Indices:</u>
i = order number
j = pattern number

<u>Parameters:</u>
$a_{i,j}$ = # sheets of order i in pattern j
rl_i = minimum order quantity
ru_i = maximum order quantity
t_j = Total trim loss of pattern j
uw = Width of the paper reel
w_i = sheet width of order i

<u>Variable:</u>
X_j = Runlength of pattern j

This formulation only takes into account the trim loss. However, in most situations other factors need to be considered as well. Moreover, this formulation only takes into account one paper width, while in many situations multiple paper widths are available. To be applicable for our research we must formulate the ILP model for a 1/V/D/R model instead of the 1/V/I/R model proposed by Haessler and Sweeney (1991).

Limitation on the number of patterns

Goulimis (1990) addressed the limitation of pattern changes and how to cope with it. When there is a limitation on the number of patterns appearing in the solution, we can add an additional binary variable, say Y_j. Y_j is zero if X_j is zero and one if X_j is greater than zero. The additional constraint states that the sum of the Y_i is smaller or equal to the maximum number of CI jobs in a solution. This can be modelled by adding constraints 3.6 and 3.7 to the first model. M is a number greater or equal to the maximum run length of a pattern.

$$Y_j * M \geq X_j \qquad \forall\ j \qquad (3.6)$$

$$\sum_j Y_j \leq MaxNrChanges \qquad (3.7)$$

$$Y_j \in \{0,1\}$$

Using multiple widths of paper reels

Using multiple widths of paper reels is not a problem for the model when $a_{i,j}$ and t_j are parameters. Using multiple widths only result in an increase in number of feasible cutting patterns. However, this increase in number of feasible patterns makes the problem harder to solve and requires more computational time.

Limitation on the minimum run length

The corrugator machine of DS Smith has a limitation on the minimum run length of a CI job. The Y_j variable can also be used for this minimum run length restriction. MP is the minimum run length for a pattern.

$$Y_j * MP \leq X_j \qquad \forall\ j \qquad (3.8)$$

Generating the cutting patterns

The following two constraints are used by Goulimis (1990) for generating feasible cutting patterns: (1) Limitation on the minimum utilized pattern width (there is a limit on the width of the trim). (2) Limitations of the number of sheets that can be cut next to each other (the corrugator machine has a limited number of cutting knives).

Other solution approaches

For most CSPs in practice ILPs are hard to solve to optimality because the number of patterns can easily become more than one million (Pierce, 1964). This means having too many cutting patterns causes problems when solving the ILP. Literature subscribes heuristics, for these kinds of problems. However, these heuristics are not interesting for our research. Our problem instance has a limited number of feasible cutting patterns, due to the limitation on the minimum trim loss and the number of orders that need to be combined (for most instances less than 20).

3.3. Classifications of production scheduling

In this section we describe the most important aspects for the classification of production scheduling at DS Smith. Pinto & Grossman (1998) propose a roadmap for scheduling problems. Méndez *et al.* (2006) propose a roadmap for batch plants only. Their proposed roadmap consists of thirteen categories where the roadmap of Pinto & Grossman (1998) only consists of seven. For the classification of production scheduling at DS Smith we use both roadmaps in order to come up with the best possible classification.

Plant typology
Two types of plant typology exist, a serial and a network typology. If products follow the same production path its typology is serial. It is a network plant if products follow different production paths. We define the plant of DS Smith in Eerbeek as a network plant, i.e., there exist different production routes (see Figure 2.3).

Mass Balances
The second aspect for the classification is how *mass balances* are taken into account. With mass balances is meant how the products are produced. If there is a need to produce the same products after each other, then it is batch based production. Otherwise it is based on flexible production of products. The scheduling at DS Smith is batch based. Méndez *et al.* (2006) also made a distinction between fixed or variable batch sizes and a distinction between fixed or variable batch processing times. If the batch processing time is fixed it can either be unit dependent or independent. At DS Smith the batches have a fixed size and a fixed processing time that is unit dependent.

Time representation
The most important aspect of the classification is the time representation. The different time representations are discrete fixed time slots, continuous time slots associated with units, or continuous time slots based on events. Currently DS Smith uses continuous time slots based on the events.

Transfer policy
The degree in which storage is taken into account is also important for the classification. Four policies exist: unlimited intermediate storage (UIS), no intermediate storage (NIS), zero-wait storage (ZW), and finite intermediate storage (FIS) (Ku *et al.;* 1987). Currently DS Smith is not taking into account the limitations of the Pentek, so the unlimited intermediate storage (UIS) is currently used.

Resource constraints
The different processing tasks require utilities and manpower that are limited. These limitations may be taken into account while generating a schedule. Resource constraints may be taken into account in a discrete or continuous way. There are also situations where no resource constraints need to be taken into account. This research only takes into account machine availability that is time constrained.

Time constraints
Production scheduling may also be time constrained. The possible time constraints are caused by non-working periods, maintenance, and availability of shift personnel.

Demand pattern
The demand pattern can either be variable or at a fixed rate. With a variable demand rate, scheduling is most of the time done for the short term and for individual customer orders with individual due dates. For a fixed rate demand pattern, the demand rates are constant. This enables a cyclic production schedule that is often for a longer period than scheduling for variable demand patterns. At DS Smith the demand pattern is variable where each order has its own due date.

CHANGEOVERS

How and if changeovers are modelled are also important for the classification of scheduling. Machines may have different changeover times, i.e., no changeovers, unit dependent, family dependent, time dependent, or frequency dependent changeovers. Changeovers of the corrugator machine are family dependent and the changeovers of the converting machines are unit dependent.

COSTS

Certain scheduling decisions may have a high impact on the costs. Therefore it is important to classify the scheduling also based on the costs. This may be equipment, utilities, inventory, and changeover costs. This research takes into account costs for solving the CSP.

DEGREE OF UNCERTAINTY

The degree in which uncertainty is taken into account is also important for the classification. Uncertainty can be modelled as deterministic or as stochastic. The longer the planning horizon the more important taking into account uncertainty becomes. This research does take into account uncertainty; see Section 3.6 for a literature review on uncertainty.

3.4. ALGORITHMS FOR PRODUCTION SCHEDULING

In this section we provide algorithms that can be used for production scheduling. The scheduling problem at DS Smith is an NP-hard problem, i.e., multiple machine, stage, and criteria scheduling problem. Solving NP-hard problems with exact methods is not possible in most cases. Therefore we only provide heuristic algorithms that are capable of solving difficult combinatorial optimization problems.

3.4.1. SIMULATED ANNEALING

Simulated annealing (SA) is a popular local search technique. The origin of this technique lies in the field of simulating the annealing of solids (Metropolis *et al.*, 1953). Kirkpatrick *et al.* (1983) and Cerny (1985) were the first to adapt this technique to solve combinatorial optimization problems. Since then it has been a popular technique for solving combinatorial optimization problems, scheduling is one of them. It is popular, because of its ease of implementation, convergence properties, and capability to escape from local optima.

At each iteration of the SA algorithm two solutions are compared, the current solution, with f(i) as objective value, and a neighbor solution, with f(j) as objective value. In minimization problems, if $f(j) \leq f(i)$, then the neighbor solution is always accepted as the new current solution. If $f(j) > f(i)$, then the neighbor solution is accepted with a certain probability. This probability depends on the temperature parameter, which is non-increasing in each iteration and also depends on the difference in objective function between f(j) and f(i). The algorithm is capable of escaping from local optima because worse solutions can also be accepted.

SA in pseudo code as outlined by Eglese (1990):

- Select an initial state $i \in S$; (S is the finite solution space)
- Select an initial temperature $T>0$; (starting temperature)
- Set the temperature change counter $t = 0$;
- *Repeat*
    - *Set repetition counter n=0;*
    - *Repeat*

        - *Generate state j, a neighbor of i;*
        - *Calculate δ=f(j)-f(i);*
        - *If δ<0 then i=j;*
        - *Else if random(0,1) < Exp(-δ/T) then i=j;*
        - *n=n+1;*
    - *Until n=N(t)*
- *t= t+1*
- *T=T(t)*
- *Until stopping criterion true (most of the time a stopping temperature)*

The quality of the final solution generated by SA depends on the starting temperature, stopping temperature, cool-down scheme N(t), and the possible neighbor solutions. The Boltzman probability, P{Neighbor i accepted} = *Exp(-δ/T),* (Aarts & Korst, 1989) is most used in literature for the acceptance probability.

3.4.2. TABU SEARCH

Tabu search (TS), developed by Glover (1989;1990), is a local search technique that makes use of neighborhood solutions. Tabu search stores a certain number of solutions. These solutions are eliminated from the set of neighborhood solutions to escape from local optima, i.e., these solutions are tabu. Tabu search moves from a solution ω to a neighbor solution ω'. Where ω' is the neighbor with the best objective value and is non-tabu. After each iteration the available set of neighborhood solutions N(ω) is updated. The algorithm runs until some stopping criterion is met. Examples of stopping criteria are: total running time, running time since last improvement, and no neighborhood solutions left.

3.4.3. ADAPTIVE SEARCH

Kolisch and Drexl (1996) proposed the adaptive search (AS) method for solving hard resource constrained project scheduling problems. AS is a randomized construction heuristic that uses a priority rule. For scheduling problems, the jobs are the construction blocks. If for example the due date is used as a priority, the job with the earliest due date has the highest probability to be chosen. Given a set of jobs j (j=1,2,…n), we can calculate its priority V_j . From these priorities we calculate the regret factor R_j, see Equation 3.9. This regret factor is the non-negative difference between the priority V_j and the minimum of all priorities.

$$R_j = V_j - \min\{V_1, V_2, \ldots V_n\} \qquad (3.9)$$

The higher R_j, the more regret if this job is not selected. Based on R_j, the probability P_j can be calculated by the following formula, where α is the bias factor (α≥0):

$$P_j = \frac{(r_j+1)^{\propto}}{\sum_i (r_i+1)^{\propto}} \qquad (3.10)$$

Each job j has probability P_j to be selected as the next job in the schedule, see Equation 3.10. After a job is selected that job is added to the schedule and deleted from the set of jobs that need to be scheduled. Also new regret factors and probabilities are calculated. The performance of the schedule is evaluated when all construction blocks are scheduled. If the performance of the current schedule better than the best schedule, the current schedule is set as the best schedule. After that, a new iteration of the AS algorithm is started.

3.5. COMBINING THE CUTTING STOCK PROBLEM AND PRODUCTION SCHEDULING

Both the CSP and production scheduling are discussed extensively in literature. However, only a few authors address the problem of integrating the CSP and production scheduling. In most industries the CSP is performed in the planning stage and there is no need to combine both problems. However, in the corrugated box industry the CSP is an essential part of scheduling.

Bookbinder & Higginson (1986) address the problem of solely using trim loss as objective function. Customer service is highly affected by the decision to optimize only on trim loss. They conclude that is would be more appropriate that trim loss should be a constraint instead of being in the objective function. Also breaking up orders to produce minimal waste is done frequently, which results in breaking up a large number of orders that may result in less customer service. Bookbinder & Higginson (1986) therefore mention that the set of orders should be split in two sets. One set that needs to be processed in the current planning horizon and a set that can be produced in a later stage. Orders of the second set can be added to the first set to minimize waste if capacity is available.

Bolat (2000) proposes a binary linear program (BLP) to maximize the total length of converted corrugated board and minimize the trim loss in one shift. This BLP takes into account the CSP, buffer utilization, and machine loading problems. The work of Bolat (2000) is an addition to the work of Savsar and Cogun (1994). Savsar and Cogun (1994) only take into account the WIP buffer as one big area instead of separate (roller) conveyors of different widths. Another improvement of Bolat (2000) is that multiple setups are taken into account, where Savsar and Cogun (1994) only take into account one setup per shift.

Rodriquez & Vecchietti (2013) propose a model that integrates the CSP with the scheduling of the corrugator machine that takes into account due dates of jobs. They also take into account setup time of the corrugator machine. They first formulated the problem as a mixed-integer non-linear program (MINLP) and then transformed this problem to a mixed-integer linear program (MILP) in order to solve it via linear optimization.

Arbib *et al.* (2012) use a LP-based tabu search method for combining batch scheduling and the CSP with finite buffers. Although this research is not directly applicable for the situation at DS Smith it is an interesting research. Their method of combining the CSP with scheduling gives some input for the development of our model.

3.6. COPING WITH UNCERTAINTY

As mentioned earlier, it is very unlikely that a predictive schedule is executed exactly as planned (Aytug *et al.* 2005). Uncertainty may be caused by activities that take less or more time than estimated, resources that become unavailable, orders may be added or cancelled, and delay of arrival of materials (Leon, Wu, & Storer, 1994; Herroelen & Leus, 2005; Al-Fawzan & Haouari, 2005; Vonder, Demeulemeester, & Herroelen, 2008). Because of this, the validity of static deterministic scheduling has been questioned and criticized (Goldratt, 1997). Herroelen & Leas (2005) distinguish between five approaches for dealing with uncertainty in scheduling; (1) reactive scheduling, (2) stochastic scheduling, (3) scheduling under fuzziness, (4) proactive (robust) scheduling, and (5) sensitivity analysis.

REACTIVE SCHEDULING

Reactive scheduling does not cope with uncertainty when constructing the predictive schedule. The effort is put in repairing the schedules when unexpected events occur. This approach is currently used at DS Smith for coping with uncertainty.

STOCHASTIC SCHEDULING

Stochastic scheduling takes into account the stochastic nature of processing times and occurrence and duration of resource unavailability. However, the probability distributions need to be known in order to perform stochastic scheduling. There is no information about the probability distributions and they are hard to define given the limited data and the validity of this data at DS Smith. Therefore, we do not elaborate further on stochastic scheduling.

SCHEDULING UNDER FUZZINESS

Scheduling under fuzziness uses fuzzy numbers for modeling activity durations, instead of stochastic variables. Fuzzy optimization uses the knowledge and experience of people in case of imprecise information. Fuzzy optimization is not preferable since we need to incorporate the experience and knowledge of the production planners in the optimization model. The production planner should give input about pessimistic and optimistic processing/setup times for every job. This is not a preferred option given the large number of jobs that are processed every day.

PROACTIVE ROBUST SCHEDULING

Proactive robust scheduling takes into account uncertainty by minimizing the effects of disruptions on the performance measures. Gao (1995) proposes to use temporal protection, that extends the duration of activities that use a breakable resource. Breakable resources are resources that have non-zero probability of a breakdown. The duration of the activities is extended based on the expected breakdowns and their durations (mean time to failure, mean time to repair). Davenport *et al.* (2001) propose an improvement of this technique by using time window slack and focused time window slack approached. The slack time needed is dependent on the activity and time window in which the activity is performed. Another approach is to insert idle time into the schedule. This is proposed by Mehta & Uzsoy (1998; 1999) in order to buffer for any machine breakdowns. This approach is interesting for DS Smith. It is a simple approach where adaptions in the duration of activities are creating buffers for uncertainy.

SENSITITIVY ANALYSIS

The last approach, sensitivity analysis, is used to evaluate the performance of schedules under certain parameter changes. This is interesting when some parameters in the model may change over time. For the situation at DS Smith it can be interesting what the effect of paratmeter settings is on the performance of the generated schedules.

3.7. CONCLUSIONS

In this chapter we answered the second sub question. We provided several performance measurement indicators and discussed different approaches of how to use multiple indicators for scheduling. We also discussed two frameworks for the evaluation of production schedules. We addressed difficulties of performance measurement of scheduling. The different indicators, frameworks, and the addressed difficulties provided us a good insight in performance measurement of production scheduling.

Based on the typology of Dyckhoff (1990) we positioned the CSP at DS Smith as 1/V/D/R. We formulated the CSP as an Integer Linear Program. We also elaborated on how to include several constraints. For the classification of scheduling we combined the roadmaps of Pinto & Grossman (1998) and Méndez *et al.* (2006). We can classify the plant of DS Smith in Eerbeek as a network plant that produces fixed batches that have unit dependent processing times. Currently the unlimited intermediate storage (UIS) policy is applied. Changeovers are family dependent for the corrugator machine and unit dependent for the converting machines. Several classification aspects depend on the model that is used, such as time representation, resource constraints, time constraints, and the degree of uncertainty that is taken into account.

In Section 3.4 we described two local search methods, simulated annealing and tabu search. Both methods are often used in practice because of their capability to escape from local optima, and their ease of implementation. Next to the two local search methods we also described adaptive search which is a constructive heuristic that is proven to be a powerful construction heuristic. Although the CSP is extensively discussed in literature, there are only a few articles that address the combined cutting stock and scheduling problem. The articles that address this combination use BILP and MILP formulations for solving the combined problem. However, the problem instances at DS Smith are more complex than the ones in the articles.

Uncertainty has a large effect on the "real" performance of a schedule. Herroelen & Leus (2005) identified five approaches for coping with uncertainty; (1) reactive scheduling, (2) stochastic scheduling, (3) scheduling under fuzziness, (4) proactive (robust) scheduling, and (5) sensitivity analysis. Stochastic and fuzzy scheduling are difficult approaches for the situation at DS Smith. With stochastic scheduling you need information about the probability functions and fuzzy scheduling requires a lot of input from the production planners. Reactive scheduling is currently the way of coping with uncertainty. Proactive (robust) scheduling copes with uncertainty by minimizing the effects of disruptions. This can be done by increasing the processing times (Davenport, Gefflot, & Beck, 2001; Gao, 1995) or inserting idle time between jobs (Mehta & Uzsoy, 1998; Mehta & Uzsoy, 1999).

Within DS Smith there is a need to develop a new model that is capable of solving the cutting stock problem and corrugator and convertor scheduling at DS Smith. We propose a model specially developed for DS Smith in Chapter 4. In Chapter 5 we evaluate the different alternatives and select the best alternative. First, we describe and explain the general model and the alternatives in Chapter 4.

4. MODEL DEVELOPMENT

In Chapter 1 we stated that the current approach for production scheduling results in non-optimal schedules. From Chapter 2 we learned that this results in problems in the production process, such as corrugator and converting idle time. Also the on time delivery and in full percentages are below target. In Chapter 3 we outlined important literature related to this research. This gave us insight for the model that this chapter formulates. This chapter answers the third research question: "*What are alternatives for the integrated production scheduling and cutting stock problem at DS Smith?*"

First, Section 4.1 describes the basic characteristics of the general model. After that, Section 4.2 describes the solution method we use. Section 4.3 describes the general model that is split up in five modules: an order selection module, a cutting stock problem module, a corrugator scheduling module, a converting scheduling module, and a Pentek module. Section 4.4 describes the alternatives. Finally, in Section 4.5 we provide conclusions.

4.1. BASIC CHARACTERISTICS

Before we describe the general model we elaborate on the different tasks to model, assumptions made, and statements of DS Smith that we use.

TASKS TO MODEL

In Chapter 2 we elaborated on the different tasks of the production planners. We explained the current way of solving the CSP, corrugator scheduling, converting scheduling, and monitoring and controlling the Pentek. In order to solve the CSP we need to have a set of orders that need to be scheduled. These orders are currently selected based on due dates, the make span of converting machines, and experience of the production planner. We model this order selection process in a separate module (see Section 4.2 for an elaboration on the modeling method).

After that, the output of the order selection module (the selected set of orders) enters the cutting stock problem module. This module solves the CSP and generates deckle solutions. Within the corrugator scheduling module the deckle solutions are scheduled. After that, the CI jobs are scheduled based on the company directives.

The converting scheduling module schedules the converting jobs on the converting machines. The converting jobs are scheduled based on the FIFO principle. A heuristic is used to check if an alternative routing would improve the solution. Finally, we also make a module for monitoring and controlling the Pentek. This module estimates the fill rates of the different conveyors and the overall fill rate of the Pentek.

ASSUMPTIONS

For this research we make the following assumptions:

- The AGVs capacity is unlimited and always available.
- Palletizing capacity is unlimited and always available. Most of the time, the palletizing system has enough capacity and is reliable.
- Inventory of paper reels is always available for the given reel widths and board grades.
- Preferences for trial orders are not taken into account. Trial orders are orders that have some new features. This can be new composition of paper, new dies, new ink, change in

machine settings, etcetera. These trial orders need to be produced between 08:00 and 17:00, because this is the time that non-production employees are present at DS Smith.

- Conveyors of the Pentek of the same width are modelled as one conveyor, with its length equal to the cumulative length. This assumption leads to a decrease in complexity of the model. Precise handling of the order to the Pentek is not in the scope of this project. Moreover, handling is done via a separated IT-system. The Pentek should only be modelled in order to give an estimation of the fill rate. The fill rate the Pentek may be taken into account in (re)scheduling decisions by the production planners.
- The capacity of loading and unloading of conveyors is dependent on the AGVs capacity. We use the assumption that the AGVs capacity is unlimited and always available. Therefore, also the capacity of loading and unloading of conveyors is unlimited.
- Machine availability is known one week in advance. It is necessary to know the availability of the machines before scheduling is done. Machines can become unavailable due to a limited workforce, breaks, and preventive maintenance.
- Processing speeds are known for every order on each converting machine.
- Corrugator speeds are dependent on the board grade, run length of the CI job, and sheet width.

Statements of DS Smith

Next to the assumptions, we also use some statements of DS Smith that we use as given information for our model.

- A second converting job is transported directly to the machine where it needs to be processed at the scheduled time. Moreover, only a small percentage of the orders require a second converting job. This means that we do not have to take into account second converting jobs in the calculation of the fill rate of the Pentek.
- Reshuffling of stacks in the Pentek is not preferred. There is a high probability that something goes wrong when stacks are shuffled in the Pentek. This may be strange allocations of the stacks among the conveyors or stacks may fall because they are handled too often. Therefore we only schedule the converting machines based on the FIFO rule.
- Orders with a latest production time for the corrugator machine less than 48 hours from now must be selected for the next scheduling period.

4.2. Solution method

In Chapter 3 we discussed classification frameworks for scheduling at DS Smith. In this section we elaborate on some important classification decisions, the method used for modeling the different processes, and the problem solving methods.

Time representation

Time representation is an important classification category. This highly determines how scheduling is performed and also determines the accuracy of the schedule. DS Smith is currently using continuous time slots based on events. We are also using continuous time slots based on events. This is the most commonly used time representation for production scheduling. Start and end times of jobs can accurately be determined.

Scheduling horizon

The planning department works in two shifts per day. So per day there are two scheduling instances. Therefore, we use a rolling horizon with a periodic scheduling of 12 hours. The scheduling horizon is 36 hours (1.5 days). We choose 36 hours because this is the preferred scheduling horizon by DS Smith. Rescheduling is done when large disruptions occur, i.e., machine failure, high utilization of the Pentek, and unexpected unavailability of machines. In case of a large disruption rescheduling is necessary because the schedules do not reflect the reality anymore. Moreover, the finishing times of jobs are not reliable. This has a large impact on the expedition schedule. So it is important to reschedule for both the performance of the production and expedition schedule. Rescheduling is done for the remaining time in the scheduling horizon and only requires changing the corrugator and/or the converting schedule.

Transfer policy

Although the storage of the Pentek is finite, we model it as unlimited intermediate storage (UIS). The fill rate is only important in specific situations and requires difficult decision making that may be different in each situation. Therefore, we calculate the fill rate of the Pentek afterwards and we are not using the fill rate as a decision variable.

Time and resource constraints

Time constraints are taken into account in the machine availability. These time constraints can be non-working days, breaks, and meetings for production employees. Also resource constraints are taken into account in the machine availability. Machines may be unavailable because preventive maintenance is carried out or not enough production employees are available.

Setups

We have to do with two kinds of setups at DS Smith. The first setup is at the corrugator machine. This setup time is sequence dependent, i.e., dependent on the flute combination of a board grade (family dependent setups). The second setups that we take into account with scheduling are the setups of the converting machines. These setups are unit and sequence dependent, e.g., tools that need to be used for production that are unit specific. However, we model the setups of the converting machines as sequence independent. For sequence dependent setups we need to incorporate all the information of the tools in our model, while the differences would only be small.

Problem solving method

Literature proposes different methods for solving the CSP. Although the CSP is a NP-hard problem, the CSP at DS Smith can be solved to optimality using an ILP in relatively small computation time. This is possible due to the limited number of orders that need to be combined, this results in only a relatively small number of feasible cutting patterns. Solving the order selection problem is solved using a heuristic. Moreover, the order selection is not the focus in this project. Therefore we use a simple heuristic method to select a set of orders that need to be scheduled. The scheduling problems are known as hard problems which are often solved using heuristics, based on local search methods. These local search methods explore many solutions.

MODELING METHOD

In order to model the different tasks of the production planners we split the model in modules. Each module performs a task of the production planners. We have to deal with NP-hard problems. This makes it already difficult to find "good" solutions for the modules in a reasonable amount of time. Therefore we decided that we are modeling the different tasks in modules that solve the problems separately instead of solving the whole problem at once. This would become too complex, given that the single problems are already hard to solve. See Figure 4.1 for an overview of the general model.

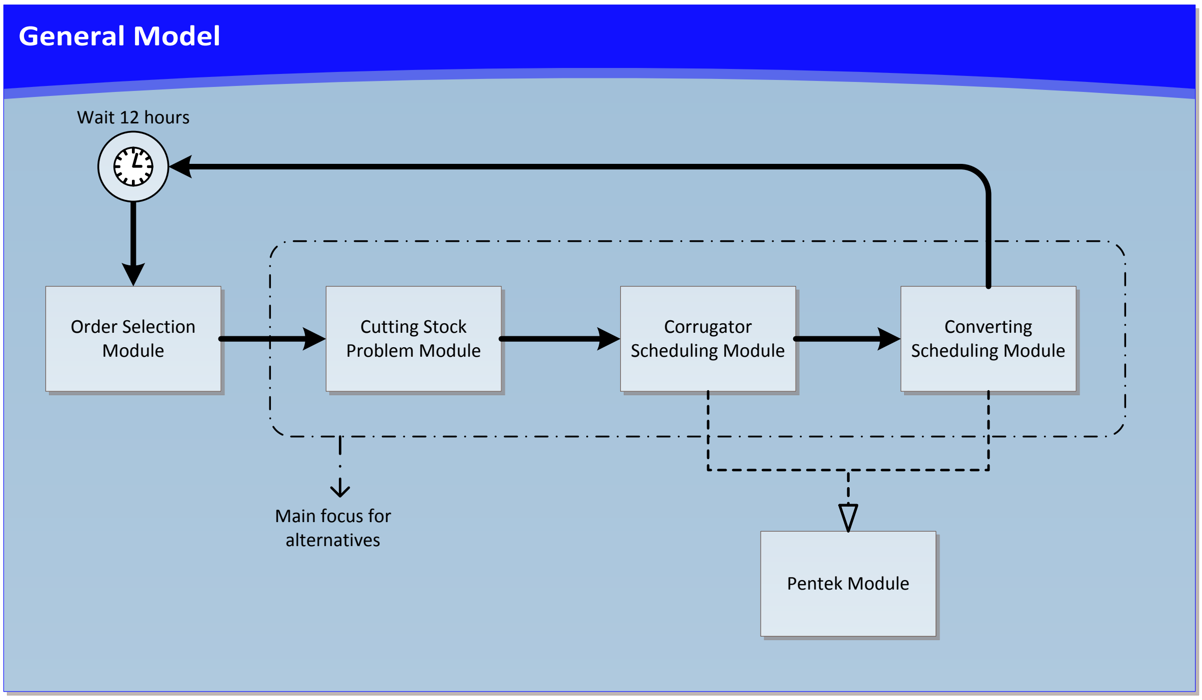


Figure 4.1 Overview of the general model

The model runs each 12 hours, because of the rolling horizon. We run the four modules sequentially, these four modules are necessary for a feasible production schedule. The Pentek module uses information of the corrugator and the converting schedule to calculate the fill rate of the conveyors and the overall Pentek. The Pentek module is not necessary for a feasible production schedule and is strictly used for monitoring and controlling the Pentek. This general model is only formulated in order to find feasible production schedules. Therefore, we run the modules sequentially and do not include any feedback loops. In Section 4.4.4 we introduce a feedback loop from the converting scheduling module to the corrugator scheduling module.

4.3. GENERAL MODEL

A general model needs to be formulated in order to test several alternative solutions and to define the differences between these solutions. In Section 4.3.1 we elaborate on the order selection module. In Section 4.3.2 we formulate the strategy for solving the CSP in the cutting stock problem module. Deckle solutions are the result of the CSP. These deckle solutions need to be scheduled on the corrugator machine. In Section 4.3.3 we elaborate on the corrugator scheduling process in the corrugator scheduling module. Section 4.3.4 describes the converting scheduling module. Finally, in Section 4.3.5 we describe the Pentek module.

4.3.1. ORDER SELECTION MODULE

The function of the order selection module is to select orders that enter the cutting stock problem module. Selecting the right orders is important because it has a direct impact on the feasibility of the corrugator schedule, on time delivery performance, and the workload of the converting machines. When the workload of the converting machines is not taken into account, a schedule may arise with a high workload for one machine and other machines with a low workload. This results in lost production time of the converting machines. In this order selection module we take into account these three important factors (feasibility of the corrugator schedule, on time delivery performance, and workload of converting machines). For a graphical representation of the order selection module see Figure 4.2.

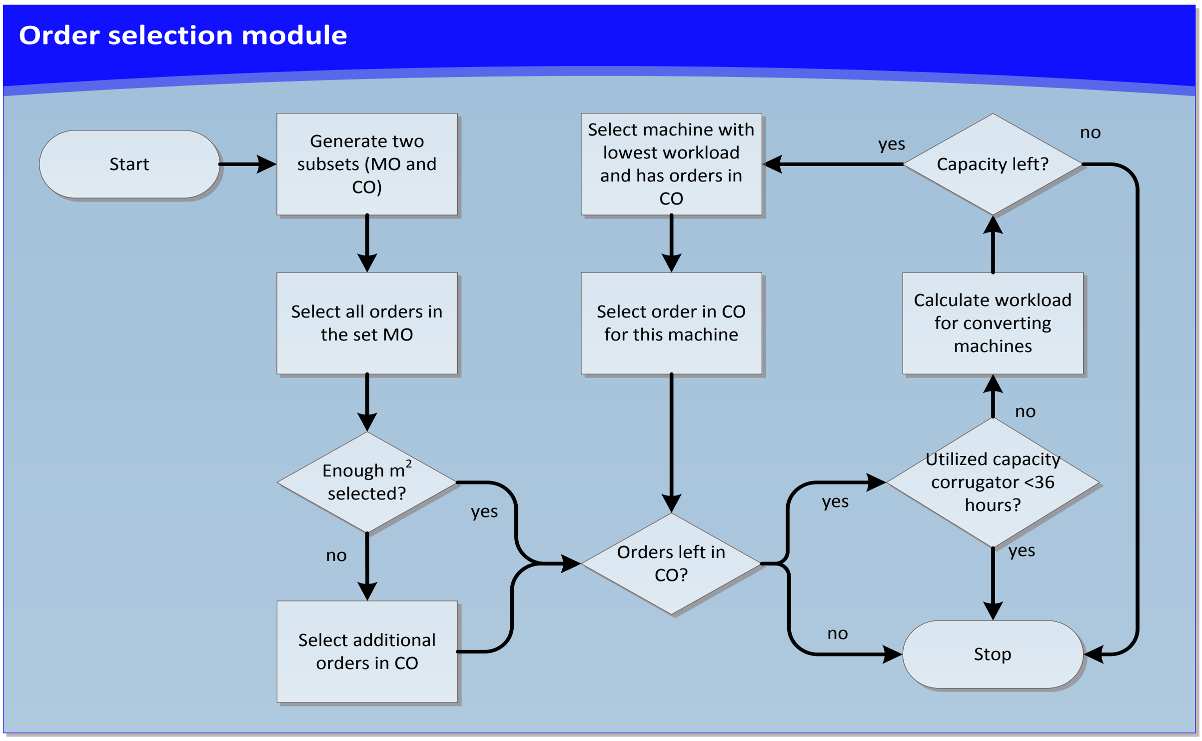


Figure 4.2 The order selection module (orders selected in previous periods are included in the workload of the corrugator and converting machines).

We generate two subsets of orders that make sure that the on time delivery target is met. Given the set of all booked and not scheduled orders O we generate a subset MO ($MO \subseteq O$). Orders are included in MO if the latest production time for the corrugator machine ($LSTCor_o$) is within 48 hours. MO is the set of orders that must be produced within the planning horizon. Another subset CO is generated for orders that can be selected. Orders are included in CO when the latest production time for the corrugator machine is more than 48 hours from now, but within 7 days ($o \in CO$ and $o \notin MO$).

To make sure that the cutting stock problem module generates deckle solutions for the corrugator machine that are feasible, the total squared meters of corrugated board sheet selected per board grade must be greater than 4900 m². Otherwise, deckle solutions are generated that do not meet the minimum run length restriction per paper width. We first select all the orders in the set MO. If this results in a selection of orders for a certain board grade that does not have 4900 m² of board sheet, we select orders in set CO of that board grade until 4900 m² is reached. When there are no orders of that board grade in CO, the orders enter the cutting stock problem module with a violation for the corrugator machine. This means that the minimum run length restriction per paper width cannot be met and needs to be decreased in order to find feasible deckle solutions.

Processing speeds for converting machines are known in advance. From this we calculate the workload of an order for each converting machine (the workload is the sum of total processing time and setup time). In order to make a schedule that results in a smooth and balanced production process we need to balance the workload of the converting machines. We also have information about the availability of a machine. This is measured in the total available days in the planning horizon. We include the jobs that are accepted previous periods in the workload of the converting machines. After that, we calculate the available time left for production for each converting machine.

When enough m^2 of corrugated board sheet is selected, we select the converting machine that has the most available time left. For this selected machine we look for orders in the set *CO* that may be processed on this machine and have a board grade that is already selected. The first order based on latest production time for the corrugator machine is selected. The new availability of the machines is calculated. Selecting orders is repeated until there are no orders left, the corrugator machine is planned full for the next 36 hours, or all converting machines are planned full for the next 36 hours.

4.3.2. *Cutting Stock Problem Module*

The cutting stock problem module is used to generate cutting patterns and solving the CSP in order to generate deckle solutions. See Figure 4.3 for the graphical representation of the cutting stock module. As mentioned in Chapter 3 we are dealing with a 1/V/D/R CSP. Upgrading of board grades is not included in our model.

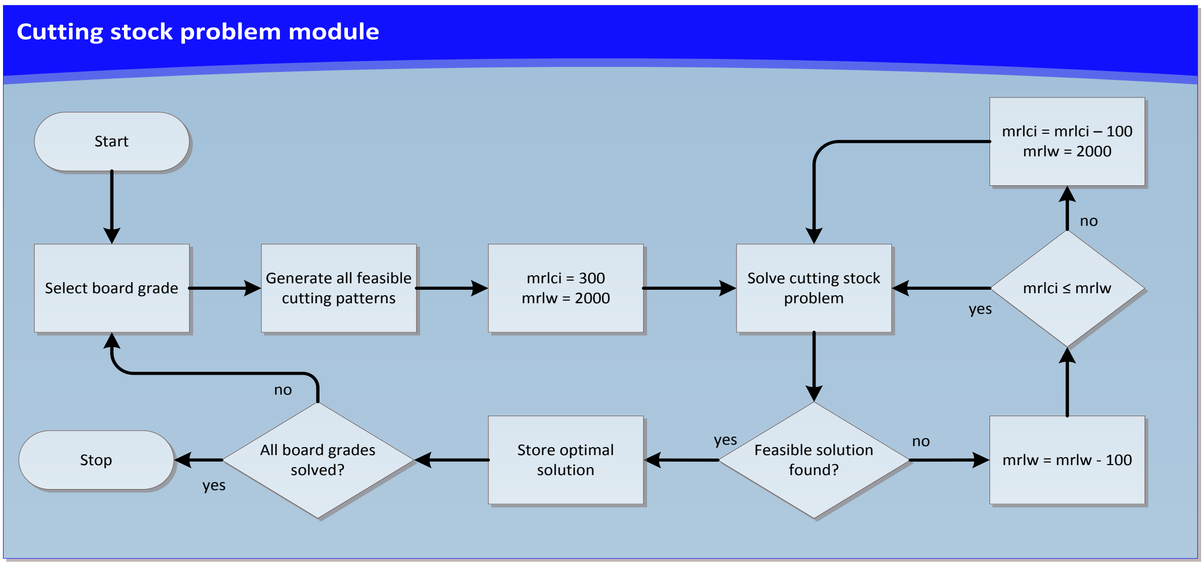


Figure 4.3 The cutting stock problem module. (mrlci = minimum run length per CI job, mrlw = minimum run length per paper width, both measured in meters)

It is preferable that each order is produced in the ordered board grade. Therefore, we solve the CSP for each board grade separately, i.e., combining orders of different board grades is not possible. We first select a board grade. Next, we generate all feasible cutting patterns for the orders of the selected board grade. We initialize the minimum run length per CI job restriction (mrlci) and the minimum run length per paper width restriction (mrlw). After that, we use the generated cutting patterns as parameters in the ILP model (see Appendix C for the complete ILP model and pseudo code for generating the cutting patterns). If feasible solutions are found we store the optimal one and select a new board grade. If all board grades are solved we stop the cutting stock module. If no feasible solutions exist we decrease mrlw by 100 meters. If mrlw ≥ mrlci, we solve the ILP model. Otherwise the mrlci is decreased by 100 and mrlw is set to the initial value. This means that we first look if no feasible solutions can be found due to the paper width restriction. If this is not the case, we decrease the minimum run length per CI job restriction.

GENERATING CUTTING PATTERNS

In order to solve the ILP model we first need to generate the cutting patterns that are input parameters for the model. We need to generate all feasible cutting patterns. A cutting pattern is feasible when the trim loss is greater than or equal to the minimum trim loss. The minimum trim loss constrained is used because the corrugated board on the sides is not of the right quality and needs to be cut off. Moreover, the minimum trim loss is also needed because there are tolerances on the paper reels and on the tool positioning that cut the corrugated board sheets. There is a possibility to model the pattern generation in such way that we do not need the minimum trim loss restriction. However, this is not preferred because the minimum trim loss depends on the tolerances of the paper widths and on the accuracy of tool positioning. This means that the minimum trim loss may vary for different board grades and may change if the accuracy of the tool positioning improves. The model can be updated/ adapted easier when we keep the minimum trim loss restriction in the model.

Another restriction is that the trim loss of the pattern must be smaller than or equal to the maximum trim loss when two orders are in the cutting pattern. The maximum trim loss constrained is needed because the waste retrieving system on the corrugator machine can only handle trim waste up to the maximum trim loss. When one order is selected a side job can be created. This means that the waste is not handled by the waste retrieving system of the corrugator. Another important constraint is that the paper width that is used for the pattern must be available for the given board grade. See Appendix B for the pseudo code of the procedure that generates the cutting patterns. To generate all feasible cutting patterns we use complete enumeration.

OBJECTIVE FUNCTION

The objective function calculates the total trim loss produced in squared meters. This can be calculated by multiplying the run length of pattern p (RLP_p) with the trim loss of pattern p (tl_p). Using this objective function means that we find a deckle solution that minimizes the total squared meters trim loss produced.

$$\text{Min Z } = \sum_{p} RLP_p * tl_p \tag{4.1}$$

ADDITIONAL CONSTRAINTS

The corrugator machine has some limitations. One of the limitations is that the run length of a CI job must be at least 300 meters (mrlci). In order to incorporate this limitation we set up constraint 4.2. For this we need an auxiliary binary variable, AP_p, which indicates if pattern p is active {0 if inactive, 1 if active}, a pattern is active if it is used in a deckle solution (an active pattern becomes a CI job). We need this variable because not all cutting patterns are active when solving the CSP. If we would exclude the variable then all cutting patterns would become active because the run length must be at least 300 meters. Now only the active cutting patterns must have a run length of at least 300 meters. When using such an auxiliary variable one must also incorporate a restriction that states if a cutting pattern is not active the run length should be zero. This is done with constraint 4.3 that uses a BigM parameter. The maximum run length of a pattern should be smaller or equal to this BigM parameter.

$$RLP_p \geq mrlci * AP_p \qquad \forall \text{ p} \qquad (4.2)$$

$$RLP_p \leq BigM * AP_p \qquad \forall \text{ p} \qquad (4.3)$$

$$\sum_p RLP_p * pwp_{p,w} \geq mrlw * APW_w \qquad \forall \text{ w} \qquad (4.4)$$

$$\sum_p RLP_p * pwp_{p,w} \leq BigM * APW_w \qquad \forall \text{ w} \qquad (4.5)$$

Another limitation is for the run length of a certain paper width (mrlw). This run length must be greater or equal to 2000 meters. If the run length of a paper width is below these 2000 meters the operators do not have enough time to change the paper reels and the corrugator machine is shut down until the right paper reels are in place. For this limitation we also use an auxiliary binary variable, APW_w, which indicates if a paper width w is active {0 if inactive, 1 if active}. For the auxiliary binary variable APW_w holds the same as for AP_p. For this we use the same BigM parameter. The parameter $pwp_{p,w}$ indicates if pattern p is of width w {0 if pattern is not of width w, 1 if pattern is of width w}.

4.3.3. *Corrugator scheduling module*

The functionality of the corrugator scheduling module is to schedule the deckle solutions and schedule the CI jobs within the deckle solutions. For the graphical representation of the corrugator scheduling module see Figure 4.4. The module first calculates the weighted tardiness ($WTarDS_{ds}$), see Equation 4.6. The deckle solutions are than scheduled based on this weighted tardiness, which uses the latest start time of the corrugator machine ($LSTCor_o$) for each order in the deckle solution ($OinDS_{o,ds}$=1 means that order o is in deckle solution ds).

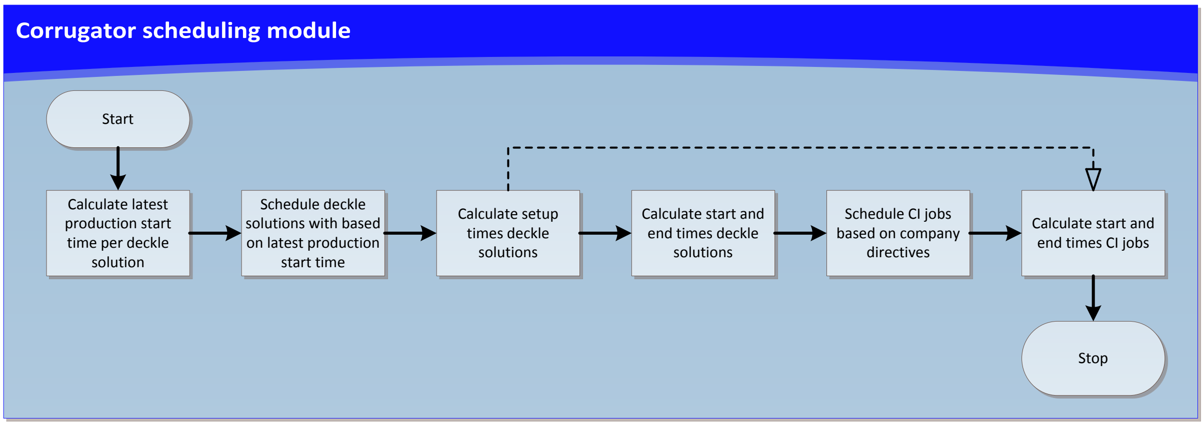


Figure 4.4 The corrugator scheduling module

From this schedule we can calculate the setup times for each deckle solution. Once this is done, we can calculate the start and end times for the deckle solutions. We take into account the unavailability of the corrugator when calculating the start and end times. The CI jobs are then scheduled based on the company directives (see Section 2.5.2). When this schedule is also determined we calculate the start and end times of the CI jobs, the setup times of the deckle solutions are also used for the first CI job in a deckle solution. For an overview of the corrugator scheduling module, see Appendix I.

$$WTarDS_{ds} = \sum_{o|OinDs_{o,ds}=1} LSTCor_o - (CurrentTime + PlanningHorizon) \qquad \forall \text{ ds} \tag{4.6}$$

CORRUGATOR SPEED

In order to calculate the processing times of the CI jobs we need to know the speed of the corrugator for a CI job. Currently the ERP system of DS Smith calculates the speed as follows: for each board grade Table 4.1 is filled in. The average speed of a CI job is then determined by linear interpolation. For example: if the run length of a CI job is 700 meters, then the average speed of the corrugator is: 150 + (250-150)*(700-500)/500 = 190 meters per minute. In this way the average speed of the corrugator becomes dependent on the run length ($RLCI_{ci}$). Instead of the linear interpolation method DS Smith is currently using, we propose to estimate the average speed by using the cumulative exponential distribution (equation 4.7 and 4.8). According to the production planners, the cumulative exponential distribution gives a better estimation of the average corrugator speed ($SCor_{ci,\,bg}$) and requires less parameters. The cumulative exponential distribution requires only the lambda (λ_{bg}) and the maximum speed ($MaxSC_{bg}$) that are dependent on the board grade (bg). The minimum speed (MinSC) is equal for all board grades. See Figure 4.5 for an example of the average corrugator speed.

Run length	Average speed (m/min)
0	60
500	150
1000	250
2000	300

Table 4.1 Example run speed corrugator machine

$$SCor_{ci,bg} = F\left(\lambda_{bg}, RLCI_{ci}\right) * \left(MaxSC_{bg} - MinSC\right) + MinSC \tag{4.7}$$

$$F\left(bg, ci\right) = 1 - e^{-\lambda_{bg} * RLCI_{ci}} \tag{4.8}$$

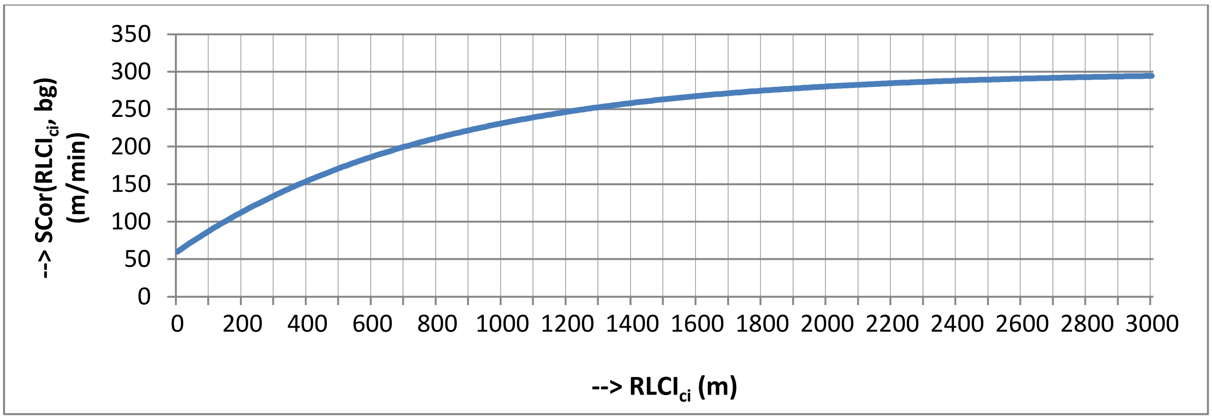


Figure 4.5 Example average corrugator speed ($MaxSC_{bg}$=300 ; λ_{bg}=0.00125)

Together with the production planners we decided that the lambda is equal for all board grades and is estimated to be 0.00125. When necessary the lambda can be changed for each board grades. The maximum speeds of all board grades are known and do not need to be evaluated. Another variable to determine the speed is the length of each sheet within a CI job. The cutting tools have a variable maximum speed, depending on the sheet length. The shorter the sheet length, the lower the maximum speed of the cutting tools. The maximum speed of the cutting tools ($MaxTS_{ci}$) is currently estimated by linear interpolation if the sheet length of an order that is in the CI job ($OinCI_{o,ci}$=1 means that order o is in CI job ci) is between the minimum sheet length (480 mm) and the sheet length for which the maximum speed is reached (1200 mm). The speed is equal to the maximum speed if the sheet length is equal or greater than 1200 millimeters. Producing sheets that are shorter than 480 mm is not possible. We choose to estimate the maximum speed of the cutting tools the same as DS Smith. The minimum sheet length is equal to 480 millimeters and the highest possible maximum speed is 300 meters per minute. For the graphical representation of the maximum speed of the cutting tools see Figure 4.6 and for the calculation see Equation 4.9. To calculate the final estimated average speed ($ASC_{ci,bg}$) we take the minimum of $MaxTS_{ci}$ and $SCor_{ci,bg}$ (See Equation 4.10).

$$MaxTS_{ci} = min\left\{300\ ;\ 100 + 200 * \frac{\min\limits_{o|OinCI(ci,o)=1} \{sl_o\}}{1200}\right\} \tag{4.9}$$

$$ASC_{ci,bg} = \min\left\{SCor_{ci,bg}\ ; MaxTS_{ci}\right\} \tag{4.10}$$

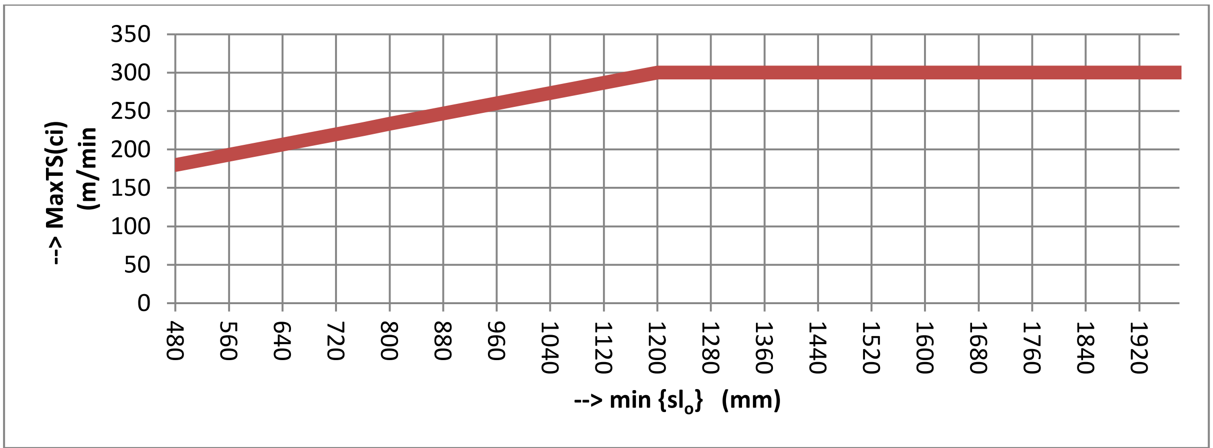


Figure 4.6 Example maximum speed cutting tools

SETUP TIMES CORRUGATOR

Setup times are an important decision variable for the corrugator scheduling because the corrugator machine is the bottleneck of the plant in Eerbeek. Setup times occur when there is a board grade change on the corrugator machine. We determined the setup times together with the operators of the corrugator machines. In most cases, the setup time is caused by a corrugator roll change. For the different setup times dependent on the flute combination, see Appendix E.

4.3.4. CONVERTING SCHEDULING MODULE

The converting scheduling module constructs the schedule for the converting machines and performs a load balancing procedure to improve the performance of the converting schedule. The first step is to calculate the release time of each order for converting. This is determined by the corrugator schedule, i.e., the time that stacks of order o are in the Pentek. After that the first possible starting time for each job is determined based on the release time and in case of a second converting job based on the finish time of precedence job. Also transportation and drying time are taken into account in the first possible starting time calculation. The jobs are scheduled based on this first possible starting time. After that, the performance of the schedule is determined (tardiness of orders, waiting time of orders, and waiting on corrugator idle time).

We use a load balancing heuristic to check if alternative converting machine routing would improve the solution. For each job with waiting time alternative converting machine routes are considered. The routing of these jobs is changed and the performance of the schedule is evaluated. If the performance improves we accept the rerouting of the job. Otherwise the rerouting is rejected. See Figure 4.7 for the graphical representation of the converting scheduling module. We now elaborate on the transportation and drying time, precedence relations, processing times, setup times, and the performance criteria.

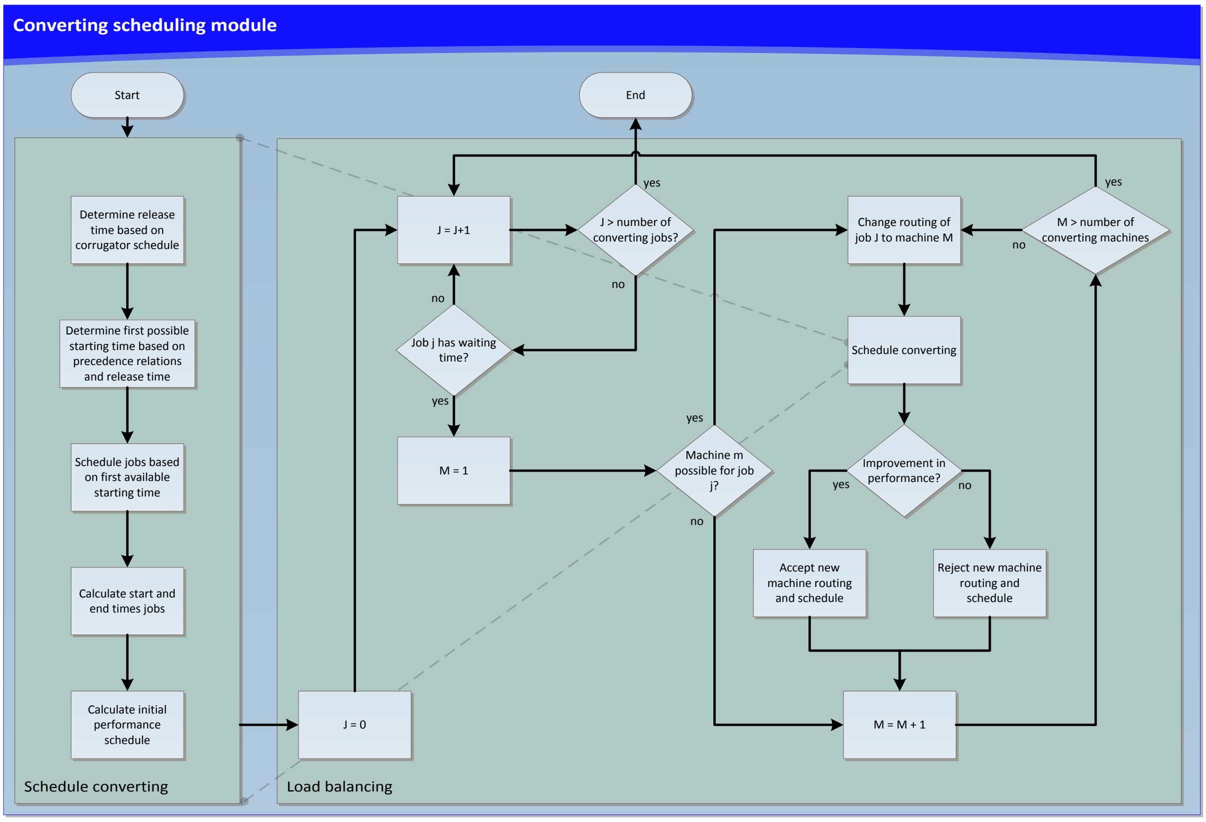


Figure 4.7 The converting scheduling module consisting of two main parts: scheduling of converting jobs and the load balancing procedure.

Transportation and drying time

It is important to take the transportation into account when calculating the first possible starting time. Otherwise the starting times do not reflect the real situation. The transportation times can be found in Appendix F. However, for some board grades the sheets of corrugated board need to dry before the converting machines can process these sheets. This is required because of quality issues. In case of drying time, not the transportation time but the total drying time is taken into account for the first possible starting time, i.e., delay = max {transportation time, drying time}.

Precedence relations

Precedence relations exist for both a first and second converting job. The precedence relation dictates that the first possible starting time of a converting job must be after the start of the first CI job plus the delay, e.g., sheets for a converting job may be produced by multiple CI jobs. The precedence relation for the second converting job is almost the same. The second job cannot start before the start of the first converting job plus the transportation time.

PROCESSING AND SETUP TIME

Within the ERP system of DS Smith the historical machine processing speed per hour per order is registered. This data is used to determine the processing speed per machine per order. This data in combination with the planned quantity is used to calculate the total processing time. The setup times for the converting jobs on each machine can be retrieved by the ERP system of DS Smith. This data is used as input in our model.

PERFORMANCE CRITERIA

In order to evaluate the performance of a schedule we need to calculate the performance criteria. Important performance criteria for converting scheduling are the tardiness of orders, waiting on corrugator (WOC) idle time and the waiting time of jobs. Tardiness is an important criterion because there is a direct link with customer satisfaction. The other two performance criteria are more internal criteria that have to do with efficiency.

4.3.5. PENTEK MODULE

The Pentek module is a supporting module. The general model does not use the Pentek module for (re)scheduling decisions. It is purely developed for the support of the production planners. The Pentek consists of conveyors of seven different widths. We choose to model each width as one long conveyor. So if there are ten conveyors with a width of two meters and length of twenty meters we model it as one long conveyor of length 200 meters. We also modelled the conveyors in front of the machines. The width of these conveyors is sufficient so we do not need to take the width into account for these conveyors.

STACKS

In order to calculate the fill rate of the conveyors we need to know how many stacks each CI job produces per order ($StaCI_{o,ci}$). The corrugated board sheets have a certain thickness (Th_o) that is determined by the board grade. We also need to know the stack height of each order (SH_o). This stack height is dependent on the sheet width. The smaller the sheet width, the lower the stack height. The maximum stack height is 1800 mm when the width is equal or greater than 480 mm. The minimum stack height is 750 mm when the width is equal to 260 mm (this is the minimum sheet width). The stack height is determined by Equation 4.11. The number of stacks that each CI job produces for an order is estimated by Equation 4.12 ($NOinCI_{o,ci}$ indicates how many times order o is in CI job ci). From this we calculate the occupied meters in the Pentek by each CI job (Equation 4.13) and by each order (Equation 4.14).

$$SH_o = 1800 - 1050 * \frac{\max\{0; 480 - \min\{480; sw_o\}\}}{260} \tag{4.11}$$

$$StaCI_{o,ci} = \left\lceil \frac{RLCI_{ci} * NOinCI_{o,ci} * Th_o}{sl_o * SH_o} \right\rceil \tag{4.12}$$

$$MCI_{o,ci} = StaCI_{o,ci} * \mathrm{sl}_o \tag{4.13}$$

$$TMO_o = \sum_{ci} MCI_{o,ci} \tag{4.14}$$

FILL RATE

For the estimation of the fill rate of the Pentek we use fixed time intervals. We do this because this simplifies the calculation and only has a limited effect on the reliability. To estimate the fill rate of the Pentek we look at the number of stacks on each conveyor at each point in time. We take a time interval of a quarter of an hour. This gives a reasonable estimation of the average fill rate of each conveyor. This is reasonable because processing times plus setup times are in general longer than a quarter of an hour. So no “big” changes occur within fifteen minutes.

The fill rate is determined by the number of stacks that are on the conveyors. For the determination of the total meters produced by CI jobs and the determination of how many stacks are already processed by the first converting job we use a linear relation. For example: if a CI job starts at time t=0 and ends at t=10 then the total estimated stacks of that CI job at time t=5 is $MCI_{o,ci}$ /(10/5), i.e., only the half of the total meters is produced. Equation 4.15 calculates the meters produced by the CI jobs of a specific order. Equation 4.16 calculates the current occupation in meters of order o at time t ($CMO_{o,t}$).

$$\mathrm{MP}_{o,t} = \sum_{ci|OinCI_{o,ci}=1} \left(\frac{\mathrm{MCI}_{\mathrm{o,ci}}}{\max\left\{1;\ \frac{\mathrm{TPTCI}_{ci}}{\min\left\{\mathrm{TPTCI}_{ci}\ ;\ \mathrm{t}-\ \mathrm{STCI}_{ci}\right\}}\right\}} \right) \tag{4.15}$$

$$\mathrm{CMO}_{o,t} = \mathrm{MP}_{o,t} * \left(1 - \max\left\{ 0\ ; \frac{\min\limits_{m|Route_{o,1}=m} \left\{ TPTJ_{o,m}\ ; t - STJ_{o,m} \right\}}{\frac{MP_{o,t}}{TMO_o} * TPTJ_{o,m}} \right\} \right) \tag{4.16}$$

$$FP_t = \frac{\sum_c MCon_{c,t}}{\sum_c cl_c} \tag{4.17}$$

However, not all stacks of $CMO_{o,t}$ are in the Pentek. If the order is currently processed by a converting machine, then stacks are on the conveyors in front of the converting machine. These conveyors are not included in the Pentek. The conveyor allocation is estimated in the following way: first all the stacks that are in the Pentek are allocated to the smallest conveyor on which the stacks fit. If the total occupation of a conveyor is more than the length of the conveyor, then the surplus length is added to the next conveyor that is wider. This is done for every conveyor. The total fill rate of the Pentek is calculated by Equation 4.17. $MCon_{c,t}$ is the total meters that are occupied of conveyor c at time *t*. For an overview of the Pentek module see Appendix H.

4.4. ALTERNATIVE SOLUTIONS

In this section we formulate alternative solutions. These alternatives are based on different solution approaches for solving the sub problems in the modules. First we formulate alternative objective functions for solving the CSP in Section 4.4.1. In Section 4.4.2 we describe different heuristics for solving the corrugator scheduling problem. Section 4.4.3 describes a heuristic for the corrugator schedule that uses feedback from the converting schedule. In this way we try to integrate the corrugator and the converting schedule. Section 4.4.4 elaborates on a way to cope with uncertainty. Finally, Section 4.4.5 gives an overview of the alternative solutions.

4.4.1. CUTTING STOCK PROBLEM ALTERNATIVES

As stated by Bookbinder & Higginson (1986) solving the CSP solely by minimizing trim loss is not the best choice. Minimizing on trim loss has become an important objective because this is a large cost factor in the corrugated board and paper industry. However, solely minimizing on the trim loss is a remarkable choice. Trim loss is not the only cost factor that is influenced by the

CSP. Therefore we formulate three alternatives for solving the CSP. The first alternative uses minimizing the total run length as objective. The second minimizes on production and trim loss costs and the third alternative also takes into account costs associated with paper width and CI job changes.

RUN LENGTH OBJECTIVE

In the current situation the corrugator machine is the bottleneck of the plant in Eerbeek. The machine is in production 24 hours a day, 5 days per week. This means that DS Smith uses the full capacity of the corrugator machine. Since the total run length needed for a given set of orders is dependent on the solution of the CSP, we can take this total run length into account. Reducing the run length of a deckle solution means that we need to use less capacity of the corrugator machine measured in meters. This results in a reduction of overtime needed or an increase in available capacity for additional orders.

$$\text{Min Z } = \sum_p RLP_p * \left(1 + \frac{tl_p}{100}\right) \tag{4.18}$$

We are not only using the run length in the objective function (see Equation 4.18). Only using the run length could result in a deckle solution that has a minimum run length, but another solution could exist with a minimum run length and also have a lower trim loss. We divide the trim loss of a pattern by 100 in order to make the trim loss only important when the run length of a solution is the same or very close to each other. The factor of 100 is a sufficient choice. The trim loss of a pattern is between 32 and 200 mm (0.032 and 0.2 meter), so dividing it by 100 makes the run length be multiplied by a factor between 1.00032 and 1.002. The average run length of a pattern is 2850 meters, so even if the trim loss is 200 mm the extra run length accounted for is only 5.7 meters, which takes 1.7 seconds more production time. This is a negligible difference.

COSTS MINIMIZATION

Production cost of the corrugator machine (cc) is the other important cost factor in the corrugated board industry. This can be expressed in cost per hour production. The baseline costs are the personnel costs and the energy/utility costs. We can estimate the time needed to produce a certain deckle solution with the average speed of the corrugator (asc). The average speed of the corrugator is around 200 meters per minute. So if for example the run length for a deckle solution is 10000 meters, the estimated production time is 50 minutes. We cannot use the run length dependent average speeds. The objective function would not be linear anymore and solving the CSP becomes a problem.

The exact cost for producing one hour on the corrugator machine is hard to define. Besides the cost of energy and personnel, there are also depreciation costs of the machine, building, and other fixed costs. Another cost factor that is open for debate is the cost of lost sales or opportunity cost. When a deckle solution is chosen that has a long run length, there is no capacity left to produce additional orders. This means that an opportunity is lost to make more revenue and profit by producing additional orders. There is no data available about lost sales and the profit margin, therefore it is debatable if we should take into account these cost. See Equation 4.19 for the alternative objective function (cbg_{bg} are the cost per m^2 of corrugated board of board grade bg).

$$\text{Min Z } = \sum_{p} RLP_p * \left(\frac{cc}{asc} + tl_p * cbg_{bg} \right) \quad (4.19)$$

COSTS MINIMIZATION: CI WASTE/TIME LOSS, PAPER WIDTH WASTE/TIME LOSS

Trim loss is not the only factor in the CSP solution that results in waste. Also a CI job change and a paper width change result in waste of corrugated board. On average, each CI job change results in three meters waste of corrugated board. The total m^2 of waste produced is dependent on the gross width of the pattern (gw_p). The average waste of corrugated board for a paper width change is seven meters and the m^2 of waste is dependent on the used paper width (w). A CI job change results on average in a half minute of lost production time (twp) and a paper width change results on average in five minutes of lost production time (tww). The objective function becomes as stated by Equation 4.20

$$\text{Min Z } = \left(\sum_{p} \left(\frac{RLP_p}{asc} + AP_p * twp \right) + \sum_{w} \left(APW_w * tww \right) \right) * cc + \left(\sum_{p} \left(RLP_p * tl_p + 3gw_p * AP_p \right) + \sum_{w} \left(APW_w * 7w \right) \right) * cbg_{bg} \quad (4.20)$$

4.4.2. HEURISTICS FOR CORRUGATOR SCHEDULING

In the general model we schedule the deckle solutions based on the latest start time of a deckle solution. However, this does not result in a schedule that is preferable. These schedules have much setup time and also have a bad performance based on tardiness. Therefore we formulate three alternative heuristics. The first alternative is based on a 1-Opt heuristic, the second uses the SA local search heuristic, and the third uses the AS construction heuristic. These heuristics are based on a simultaneous optimization technique that uses a priori optimization. This means that we formulate an objective function that takes into account two or more criteria.

OBJECTIVE FUNCTION CORRUGATOR SCHEDULING

In order to evaluate the performance of a corrugator schedule we need to define the objective function that is used by the different scheduling heuristics. The two important indicators are tardiness of orders and the setup time of orders. At this stage we look at the tardiness of the deckle solutions. Each order has a latest production time for the corrugator machine ($LFTCor_o$) and a deckle solution has a finishing time ($FTDS_{ds}$). The tardiness of a deckle solution is the weighted sum of the tardiness of the orders within that deckle solution. Each customer has a customer importance weight ($CusIm_o$). If it is a strategic customer, the weight is two, otherwise the weight is one. See Equation 4.21 for the calculation of the total tardiness of the deckle solutions (TTarDS).

$$TTarDS = \sum_{ds} \sum_{o|OinDS_{o,ds}=1} \left(LFTCor_o - FTDS_{ds} \right) * CusIm_o \quad (4.21)$$

$$Min\ Z = TTarDS + 50 * \sum_{ds} SetDS_{ds} \quad (4.22)$$

It may seem redundant to use both tardiness and setup time. If setup time is decreased, less time is needed for production and thus also tardiness is decreased and also vice versa. However, there are situations where a schedule with more setup time may have a lower total tardiness. Therefore we used both the tardiness and setup time for the objective function. The objective function becomes as stated by Equation 4.22. Together with the production management at DS Smith we set the importance of the setup time equal to 50 times the tardiness of the deckle solutions. This means that reducing the setup time around 30 minutes is equal to reducing the tardiness of the deckle solutions with one day. This gives an indication how important the tardiness is compared to the setup time.

1-OPT HEURISTIC

The 1-Opt heuristic is a local search heuristic that uses as starting point the schedule of the previous period. The deckle solutions that are added in the current period are added sequentially to the schedule. Then the start time is set. The first step of the heuristic is to select a random deckle solution. This deckle solution is moved to another random place in the schedule. This new schedule is evaluated based on the defined objective function. If the new schedule improves the objective function then the new schedule is accepted. Otherwise the new schedule is rejected. This is done until the elapsed time is greater or equal to the maximum time that is available for the heuristic. See Figure 4.8 for the graphical representation of this heuristic.

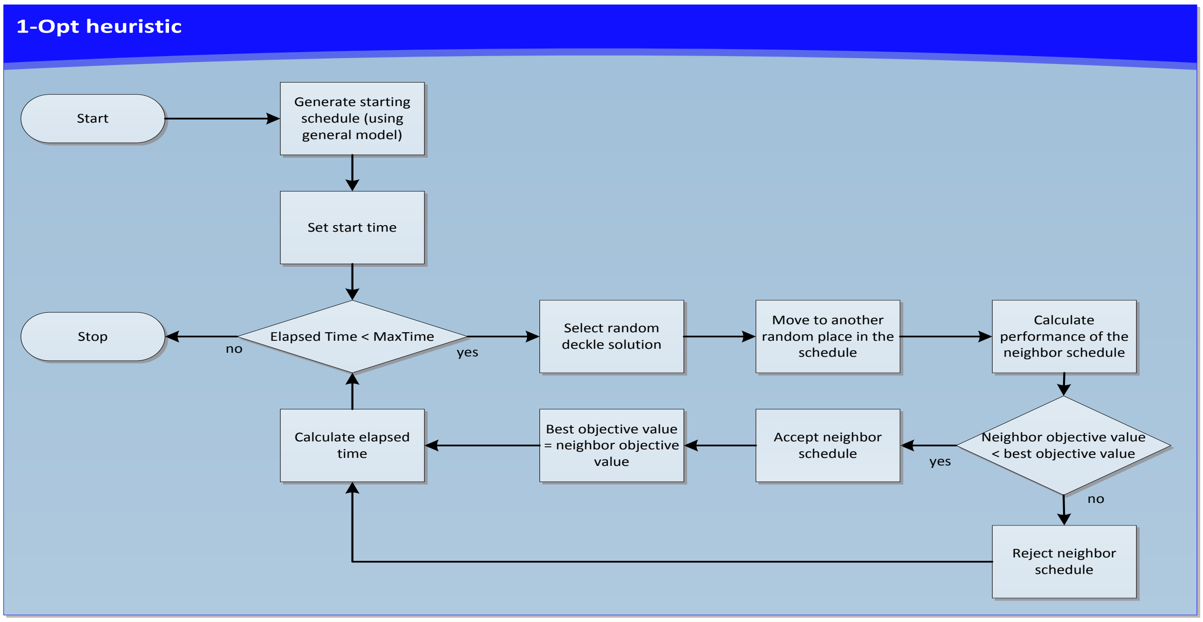


Figure 4.8 Algorithm structure of the 1-Opt heuristic

SIMULATED ANNEALING (SA) HEURISTIC

The SA algorithm is also a local search heuristic and starts with a corrugator schedule from the previous period plus the new generated deckle solutions. The maximum time available for the algorithm is converted to a start temperature, stopping temperature, interval temperature, and max N (number of iterations per temperature). Then the current temperature is set to the start temperature and n is set to zero.

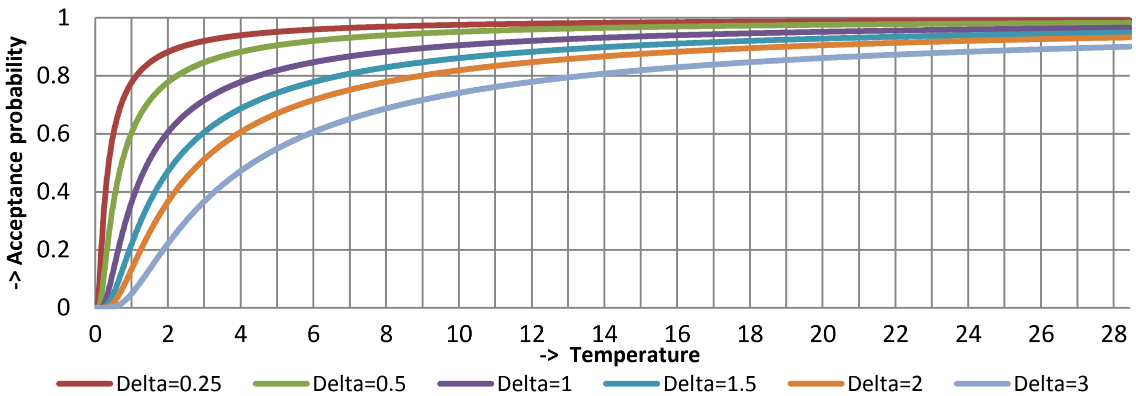


Figure 4.9 Graph of the acceptance probability tested for different delta

There are four parameters that need to be determined: the starting temperature, the stopping temperature, max N, and the interval temperature. We can determine the starting and stopping temperature by using Figure 4.9. This shows the acceptance probability of a solution as a function of the temperature. It is also dependent on the found delta (difference between current and previous solution). The delta is on average between 0.5 and 1.5. We chose to start with a temperature of four. The acceptance probability at the start is then between 90% and 70%. The stopping temperature we have chosen is 0.1. With this stopping temperature the acceptance probability is between 0.67% and 0.00%.

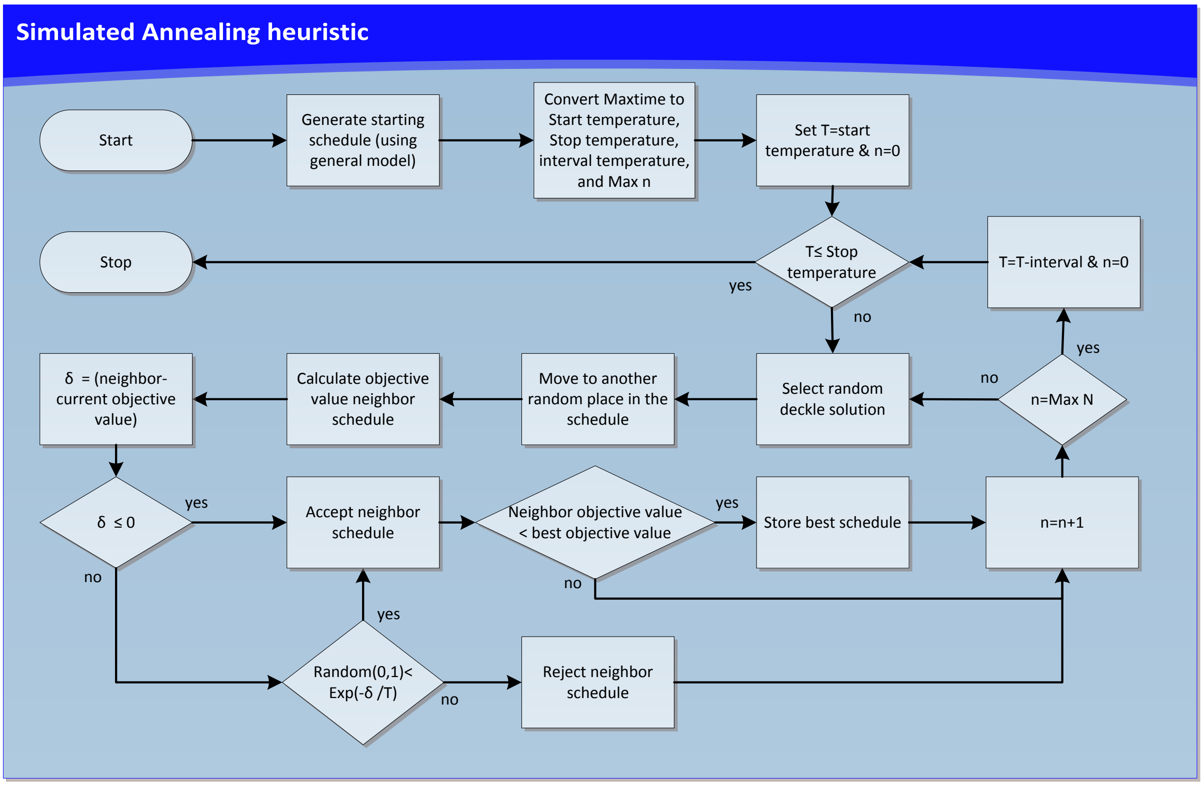


Figure 4.10 Algorithm structure of the simulated annealing heuristic

There is only a relatively small amount of computational time available. Therefore we decided that max N should be a relatively small number. We chose to use ten iterations per temperature (max N = 10). The interval temperature is dependent on the available time, time needed per iteration, start temperature (StartT), stopping temperature (StopT), and max N (see Equation 4.23). In this way we need on average the available time for the simulated annealing algorithm.

$$IntervalTemperature = \frac{\max N * (StartT - StopT)^2 * TimePerIteration}{AvailableTime} \tag{4.23}$$

A random deckle solution is selected and moved to another random place in the schedule. The objective value of this current solution is calculated. From this we calculate the δ, which is the current objective value minus the previous objective value. If δ is smaller than zero we accept the solution. Otherwise, we accept the solution with a probability that is calculated by Equation 4.24. If the objective value is improved compared with the best objective value we store the schedule as the best schedule found so far. See Figure 4.10 for the graphical representation of this heuristic.

$$P\{\text{accept solution} \mid \delta > 0\} = e^{-\frac{\delta}{T}} \tag{4.23}$$

ADAPTIVE SEARCH (AS) HEURISTIC

The AS algorithm is a construction heuristic that sequentially adds deckle solutions to a schedule. The performance of these schedules is evaluated each iteration of the algorithm. If the objective function is better than the best solution then store the current schedule as the best schedule. The current schedule is emptied and a new schedule is constructed via the construction heuristic. See Figure 4.11 for the graphical representation of this AS algorithm. Constructing new solutions is based on the priorities of the deckle solutions. The AS algorithm uses priorities based on the tardiness of orders and setup time of a deckle solution. In order to calculate the setup time of a deckle solution we need to store the flute combination of the previous deckle solution. We construct a subset ADS of the to schedule deckle solutions (SD). The deckle solutions in this subset are not yet scheduled by the AS Algorithm and do not have a fixed sequence. The setup time ($SetAS_{ds}$) is estimated by Equation 4.25. The tardiness of deckle solutions ($TTarAS_{ds}$) is based on the difference between the current start time (CSTAS) and the latest start time of an order for the corrugator machine that is in deckle solution ds.

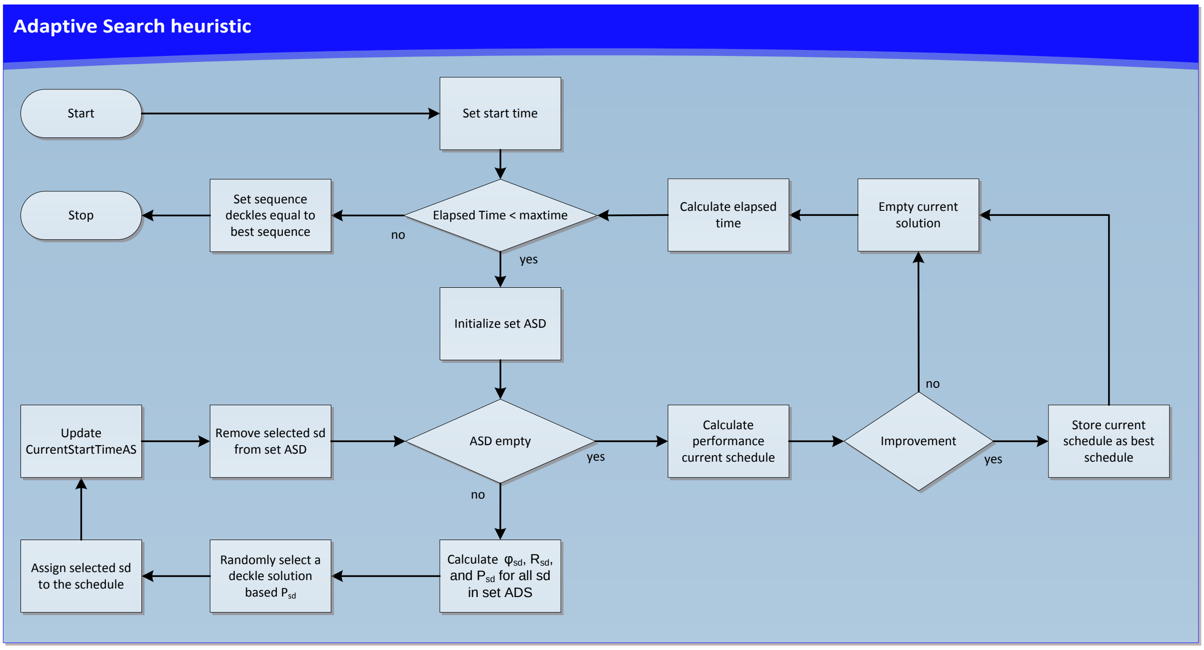


Figure 4.11 Algorithm structure of the adaptive search heuristic

$$SetAS_{ds} = SetFC_{PrevFC\ ,\ FC_{ds}} \qquad \forall\, ds \in ADS \qquad (4.25)$$

$$TTarAS_{ds} = \sum_{o|\mathrm{OinDS}_{o,ds}=1} \max\{0; \mathrm{CSTAS} - \mathrm{LSTCor}_o\} \qquad \forall\, ds \in ADS \qquad (4.26)$$

The calculation of the priority (φ_{ds}) is based on the objective function for the corrugator schedule. This priority uses an estimation of the setup time and finishing time. From these priorities we can calculate the regret (R_{ds}) and probabilities (P_{ds}) that a deckle solution is chosen as next deckle solution in the schedule. For the probability calculation we use α=10. The estimation may be unreliable in case of unavailability of the corrugator machine. However, taking into account the unavailability would require more computation time. We use the estimation because we can then investigate more solutions.

$$\varphi_{ds} = TTarAS_{ds} - 50^*\mathrm{SetAS}_{ds} \qquad \forall\, ds \in ADS \qquad (4.27)$$

$$R_{ds} = \varphi_{ds} - \min_{ds \in ADS} \{\varphi_{ds}\} \qquad \forall ds \in ADS \tag{4.28}$$

$$P_{ds} = \frac{(R_{ds}+1)^{\alpha}}{\sum_{ds \in ADS} (R_{ds}+1)^{\alpha}} \qquad \forall ds \in ADS \tag{4.29}$$

The elapsed time is calculated after each iteration of the AS heuristic. If there is time left (elapsed time < maxtime) a new iteration of the AS algorithm is started. Otherwise the sequence of the deckle solutions is set to the best sequence found by the AS algorithm.

We determine the alpha by running the heuristic for four different situations. With each situation we tested what the average objective value, minimum objective value, maximum objective value, and the standard deviation was for different alpha (α = 10, 15,..., 50, 55). In three of the four situations we found the minimum objective value with an alpha of 35. Also the differences in average, maximum, standard deviation with using another alpha are acceptable. Therefore we use an alpha of 35 for our model. See Appendix K for the results of the four situations.

4.4.3. *INTEGRATING CORRUGATOR AND CONVERTING SCHEDULING*

Finding a good corrugator schedule does not necessarily mean that we also find a good converting schedule. This is because the latest start time does not take into account waiting time at the converting machines. However, in most cases the jobs have waiting time and this can result in tardiness of orders. Another important point is that we do not to take into account the workload when scheduling the corrugator machine. Because of this, WOC idle time can occur at one or more of the converting machines. To make sure the corrugator schedule is not conflicting with the converting machine we integrate the two schedules. We do this by using the lexicographical optimization technique. This means that we first optimize based on one criterion and after that we optimize based on another criterion. We use a restriction that states that the objective of the first optimization should stay the same or should improve (if the optimal is not found). We added this restriction because tardiness of orders is more important than WOC idle time.

We do this by checking which deckle solution produces most tardy orders. Then we evaluate a new schedule where this deckle solution is produced earlier in the schedule. If this results in a decrease in the number of tardy orders we accept this new solution. Otherwise we reject the solution. This is done for an amount of time that can be defined in the model.

After we optimized based on tardiness, we optimize based on WOC idle time. We calculate the WOC idle time in front of each job on a converting machine. For each deckle solution the WOC idle times of the orders in that deckle solution are summed up. The deckle solution with the most total WOC idle time is then produced at another time in the schedule. If this results in a decrease in the total WOC idle time and the number of tardy orders is the same or less we accept the new schedules. Otherwise we reject the new schedules. This is done for a certain amount of time that is defined for each alternative.

4.4.4. *PROACTIVELY COPING WITH UNCERTAINTY*

We deal with a production process that has many uncertainties, e.g., machines may break down, unavailability of personnel, lower than expected processing speeds, etcetera. Therefore it is important to take into account uncertainty proactively instead of reactively what is currently done. In Chapter 3 we discussed the five approaches for coping with uncertainty. The only one that is interesting for DS Smith is the proactive robust scheduling approach where durations are increased or idle time is inserted. Stochastic and fuzzy scheduling are not applicable for DS Smith because of the unavailability of probability functions and the high number of jobs that are performed each day.

Gao (1995) uses the mean time between failures and the mean repair time to determine the average duration of a job on a certain machine (called temporal protection). See Equation 4.30, where P is the estimated processing time, F is the mean time between failures and D is the mean repair time.

$$Expected\ duration = P + \frac{P}{F} * D = P * (1 + \frac{D}{F}) \qquad (4.30)$$

$$TPTJ_{o,m} = (PTJ_{o,m} + SetJ_{o,m}) * Factor_m \qquad \forall\ o,m \qquad (4.31)$$

However, we do not have any information of the mean time between failures and the mean repair time. We do have information of all stops of the machines that took longer than one minute. But this information is not always reliable and there are also stops that may be a result of the schedule, e.g., WOC, Waiting on full Pentek, idle times, etcetera. We can see that using the mean time between failures and the mean time to repair is nothing more than multiplying the estimated processing time with some factor >1. We use this factor for the calculation of the expected total production time ($TPTJ_{o,m}$) for our model ($PTJ_{o,m}$ is the processing time of order o on machine m and $SetJ_{o,m}$ is the setup time of order o at machine m) (See Equation 4.31). The only thing we need to do is setting a factor for each converting machine ($Factor_m$).

In order to determine these factors we asked for the opinion of the production and expedition planners. They mention that the scheduled finishing times increase on average 2-3 hours for the converting machines looking at a range of 24 hours. Therefore we propose to use a factor for each machine of 1.1. This would imply that at each machine there are on average 2.4 hours of unexpected events each day. This is a rough estimation of the average delay due to unexpected events. Therefore, this factor needs to be evaluated and updated in order to improve the robustness of a schedule. We do not use temporal protection for the corrugator machine. This machine is more reliable than the converting machines and has a lower number of stops with in total less stopping time per day. The increase in scheduled total production time does not affect the first possible starting times of jobs on the same machine. So if no unexpected events occur, then preceding jobs on that machine can start earlier until they reach their first possible starting time. In this way we delete the buffer for unexpected events of the already finished job. This is important because otherwise this could result in an accumulation of buffers and may result in idle time of machines.

4.4.5. Overview alternative solutions

The objective of this research is to give an integrated solution. Therefore we combine the alternatives formulated in the previous subsections. The order selection process is the same for all alternatives. Then for the CSP we are going to test the current objective (trim loss) and a new objective. In Chapter 5 the different alternative objective functions are discussed and evaluated and the best alternative objective is chosen. After the CSP we are going to generate a corrugator schedule with the 1-Opt heuristic, AS algorithm, SA algorithm, and according to the general corrugator module. Finally all the jobs are first scheduled according to the FIFO rule and a load balancing iteration is performed. After that, we run the integrated corrugator and converting scheduling procedure. We test in total eight alternatives (see Figure 4.12).

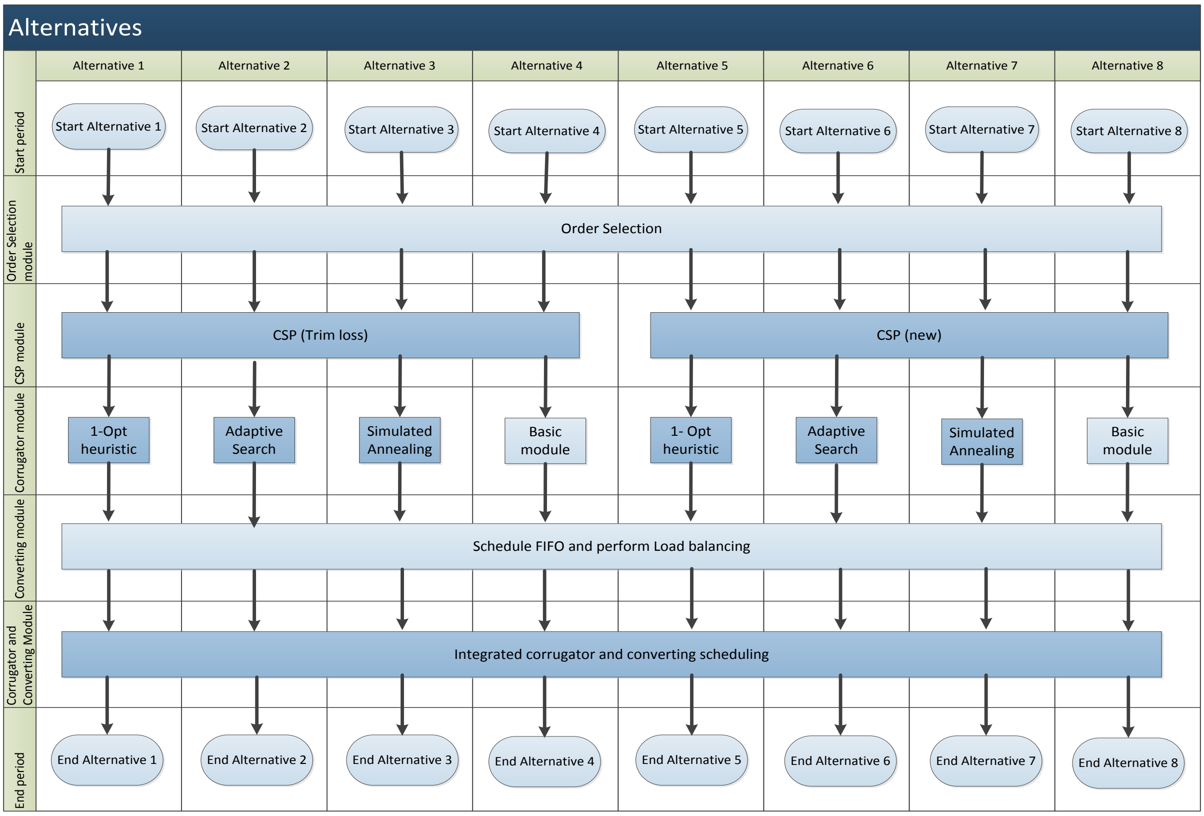


Figure 4.12 Overview of the alternative solutions

4.5. Conclusions

In this chapter we formulated the general model. This model consists of an order selection module, a cutting stock module, a corrugator scheduling module, a converting module, and a Pentek module. We formulated alternatives for the cutting stock module, corrugator module, and we formulated an alternative that integrates corrugator and converting scheduling. The alternatives for the CSP are different in the objective function of the ILP model. The current objective function is to minimize on trim loss. The alternative objective functions are minimizing the total run length, minimizing on production costs, and minimizing on production costs including waste and time loss of changes (CI and paper width). The alternatives for the corrugator scheduling are two local search methods: a 1-Opt heuristic and a simulated annealing heuristic, and an adaptive search heuristic that is a construction heuristic. Finally we integrate the corrugator and converting scheduling by making decisions for rescheduling of the corrugator schedule that are dependent on the converting schedule. We evaluate the alternatives in Chapter 5.

5. EVALUATING ALTERNATIVE SOLUTIONS

In Chapter 4 we formulated the general model, alternative objective functions for solving the cutting stock problem, and formulated alternative solutions. This chapter answers the fourth research question: "*What is the best alternative for the cutting stock and scheduling problem at DS Smith?*"

In this chapter we evaluate the alternative solutions. In Section 5.1 we evaluate the alternative CSP objective functions. Section 5.2 evaluates the alternative solutions and selects the best solution. Section 5.3 elaborates on the differences of the selected solution with the current situation and how this selected solution may be used. Finally in Section 5.4 we give conclusions.

5.1. ALTERNATIVE CUTTING STOCK PROBLEM OBJECTIVES

In this section we evaluate the alternative CSP objective functions and select the best objective function.

5.1.1. EXPERIMENTAL DESIGN

In Chapter 4 we formulated alternative objective functions for the CSP. These alternative objective functions are evaluated using the orders with a due date between 1-1-2014 and 30-4-2014. The first week is used for the warm-up period and the last week is used as cool-down period. For the order selection we use a simplified version of the order selection module (see Section 4.3.1.). We use a simplified version because in this way the selected orders are the same within each alternative.

We simplify the order selection by using a rolling horizon of 12 hours. During this horizon 350000 m2 of corrugated board can be selected. We use the same sets of orders as in the general model, i.e., a set of orders that must be selected and a set of orders that can be selected. All the orders in MO are selected and orders in the set CO are added when not enough m^2 is selected for a specific board grade. If there is still capacity left then orders in the set CO are added until the capacity of the corrugator is filled. After the order selection the CSP is solved and the horizon will be shifted 12 hours. This process is repeated until 30-4-2014 is reached.

Because the order selection is the same for all alternatives, the deckle solutions contain the same orders. This means that we can perform a pairwise T-test for the deckle solutions. For the CI jobs we cannot perform a pairwise T-test because they are not comparable, i.e., deckle solutions may have a different number of CI jobs of different length and use different paper widths. We are evaluating the alternatives based on: trim loss (Euro and m^2), total run length, number of paper widths used, number of CI jobs used, and total costs based. We exclude the alternative where the waste and time loss of paper width and CI job changes is taken into account in the objective function. Solving the ILP with this objective function takes too much time. Moreover, the differences with the other cost objective function are small. We perform a sensitivity analysis on the production cost per hour and the speed of the corrugator machine (200 m/min and 250 m/min). In order perform the sensitivity analysis we defined 20 alternatives for the cost objective function. For the minimum trim loss objective function and minimum run length objective function we only defined one alternative, i.e., the cost and speed of the corrugator machine do not have an impact on the found deckle solutions by these objective functions. For an overview of the 22 alternatives see Appendix J.

5.1.2. RESULTS

The results of the experiments are shown in Table 5.1 and Table 5.2. In these tables we outlined what the change in percentage was between alternative 1 (the current objective function) and the other alternatives. All differences in total run length, number of widths used, the baseline costs, trim loss cost and m^2 are significant with 97.5% certainty (tested with the pairwise t-test). The differences in number of CI jobs in a deckle solution are only significant between alternative 1 and 2. However, this change is relatively small, i.e., a reduction of 0.037 CI job per deckle solution (-0.94%).

Alternative	Total Run length (m)	% Change	# Widths	% Change	# CI jobs	% Change
1 (trim loss)	16460774	0.00%	1.632	0.00%	3.805	0.00%
2 (run length)	15996689	-2.82%	1.373	-15.86%	3.768	-0.98%
3 (cost 200; speed 200)	16342967	-0.72%	1.590	-2.57%	3.805	*0.00%*
4 (cost 400; speed 200)	16264669	-1.19%	1.562	-4.26%	3.799	*-0.15%*
5 (cost 600; speed 200)	16214399	-1.50%	1.539	-5.70%	3.795	*-0.28%*
6 (cost 800; speed 200)	16156073	-1.85%	1.514	-7.19%	3.792	*-0.34%*
7 (cost 1000; speed 200)	16133379	-1.99%	1.503	-7.87%	3.797	*-0.22%*
8 (cost 1200; speed 200)	16106124	-2.15%	1.495	-8.39%	3.803	*-0.05%*
9 (cost 1400; speed 200)	16091700	-2.24%	1.490	-8.67%	3.811	*0.14%*
10 (cost 1600; speed 200)	16080277	-2.31%	1.479	-9.36%	3.793	*-0.33%*
11 (cost 1800; speed 200)	16067998	-2.39%	1.473	-9.72%	3.810	*0.12%*
12 (cost 2000; speed 200)	16062542	-2.42%	1.463	-10.32%	3.800	*-0.14%*
13 (cost 200; speed 250)	16363005	-0.59%	1.596	-2.17%	3.797	*-0.22%*
14 (cost 400; speed 250)	16290827	-1.03%	1.570	-3.78%	3.804	*-0.03%*
15 (cost 600; speed 250)	16246490	-1.30%	1.553	-4.82%	3.805	*0.00%*
16 (cost 800; speed 250)	16206591	-1.54%	1.530	-6.22%	3.792	*-0.34%*
17 (cost 1000; speed 250)	16156073	-1.85%	1.514	-7.19%	3.792	*-0.34%*
18 (cost 1200; speed 250)	16136804	-1.97%	1.506	-7.71%	3.799	*-0.17%*
19 (cost 1400; speed 250)	16110752	-2.13%	1.495	-8.39%	3.803	*-0.07%*
20 (cost 1600; speed 250)	16097722	-2.21%	1.491	-8.59%	3.799	*-0.17%*
21 (cost 1800; speed 250)	16090285	-2.25%	1.489	-8.76%	3.807	*0.03%*
22 (cost 2000; speed 250)	16080277	-2.31%	1.479	-9.36%	3.793	*-0.33%*

Table 5.1 the total run length, the number of widths used, and the number of CI jobs used for each alternative. The italic grey numbers are the non-significant differences.

From these results we conclude that taking into account the cost of the corrugator results in a reduction in total run length. The higher the costs, the higher the reduction in total run length. The same holds for the number of widths used. Both reductions have a positive effect on the available capacity of the corrugator machine. The shorter the total run length needed, the more capacity is left for additional orders or a reduction in overtime needed. Next to this, reducing the number of paper widths used in a deckle solution results in a reduction of changeover time and changeover waste. The maximum reduction in run length is -2.82% since this is the minimum run length option. Also the minimum run length option (alternative 2) has the highest reduction in number of widths used (-15.86%). This can be explained by the fact that in order to reduce the total run length, we need to maximize the utilization of the width of the corrugator machine.

However, minimizing on total run length has a high impact on the trim loss. The total trim loss measured in m² increases with 9.17% and the trim loss measured in cost increases with 7.84%. This is much more than the increase in trim loss when minimizing on cost. Taking €2000 as production cost per hour results in an increase in trim loss in m² of 4.05% and increase in trim loss cost of 3.36%. This is less than the half of the percentage change of alternative 2, while the extra reduction in run length by alternative 2 is only 0.4% (2.82% instead of 2.42%). Another interesting result is that the increase in square meters trim loss is higher than the increase in trim loss cost. An explanation may be that there are large differences in cost per square meter per board grade.

Alternative	Baseline Costs	% Change	Trim Loss m^2	% Change	Trim Loss costs	% Change
1 (trim loss)	€ 963.792	0.00%	1831333	0%	€ 528.939	0.00%
2 (run length)	€ 992.393	2.97%	1999192	9.17%	€ 570.406	7.84%
3 (cost 200; speed 200)	€ 961.659	-0.22%	1835676	0.24%	€ 529.876	0.18%
4 (cost 400; speed 200)	€ 961.437	-0.24%	1843789	0.68%	€ 531.715	0.52%
5 (cost 600; speed 200)	€ 962.159	-0.17%	1852965	1.18%	€ 533.807	0.92%
6 (cost 800; speed 200)	€ 963.852	0.01%	1865854	1.89%	€ 537.081	1.54%
7 (cost 1000; speed 200)	€ 964.907	0.12%	1872929	2.27%	€ 538.745	1.85%
8 (cost 1200; speed 200)	€ 966.620	0.29%	1882578	2.80%	€ 541.143	2.31%
9 (cost 1400; speed 200)	€ 967.787	0.41%	1888413	3.12%	€ 542.667	2.60%
10 (cost 1600; speed 200)	€ 968.860	0.53%	1894589	3.45%	€ 544.117	2.87%
11 (cost 1800; speed 200)	€ 970.314	0.68%	1901707	3.84%	€ 545.865	3.20%
12 (cost 2000; speed 200)	€ 970.957	0.74%	1905436	4.05%	€ 546.725	3.36%
13 (cost 200; speed 250)	€ 961.854	-0.20%	1834255	0.16%	€ 529.571	0.12%
14 (cost 400; speed 250)	€ 961.383	-0.25%	1840591	0.51%	€ 530.975	0.38%
15 (cost 600; speed 250)	€ 961.610	-0.23%	1846404	0.82%	€ 532.374	0.65%
16 (cost 800; speed 250)	€ 962.308	-0.15%	1854736	1.28%	€ 534.210	1.00%
17 (cost 1000; speed 250)	€ 963.852	0.01%	1865854	1.89%	€ 537.081	1.54%
18 (cost 1200; speed 250)	€ 964.727	0.10%	1871644	2.20%	€ 538.465	1.80%
19 (cost 1400; speed 250)	€ 966.266	0.26%	1880805	2.70%	€ 540.695	2.22%
20 (cost 1600; speed 250)	€ 967.244	0.36%	1885620	2.96%	€ 541.998	2.47%
21 (cost 1800; speed 250)	€ 967.907	0.43%	1889229	3.16%	€ 542.835	2.63%
22 (cost 2000; speed 250)	€ 968.860	0.53%	1894589	3.45%	€ 544.117	2.87%

Table 5.2 the total baseline cost, trim loss produced measured in m², and trim loss produced measured in cost for each alternative

The total baseline cost includes costs that are certainly made (production cost per hour, board grade cost, and cost of paper width and CI job changes). When calculating with €200, €400, or €600 production cost per hour we get a reduction in total baseline cost. Using production cost per hour that are higher than €600 results in an increase in total baseline cost. However, this increase is only 0.77% when using €2000 as production cost per hour.

We also calculate the differences in total cost when taking into account different baseline cost for the corrugator machine. We exclude the cost of paper width and CI job changes because the differences in total costs caused by these costs are only small. We include the cost of lost sales in the baseline cost. Given that the capacity of the corrugator machine is 600000 of m² corrugated board per day. We estimate the cost of lost sales by Equation 5.1. So if the profit margin per m^2 is €0.01, the cost of lost sales per hour production is €250. Together with the management of DS Smith we decide that the profit margin per m^2 of corrugated board sheet is around € *confidential*. This means that we have around € *confidential* of lost sales per hour production. The total production cost per hour are then around € *confidential* euros.

$$\text{profit margin per hour production} = \frac{600000}{24} * \text{profit margin per m}^2 \qquad (5.1)$$

See Figure 5.1 for the differences in cost with the minimum trim loss alternative for different production cost per hour. An important observation is that when the production costs per hour are €1100 or more there is always a cost decrease.

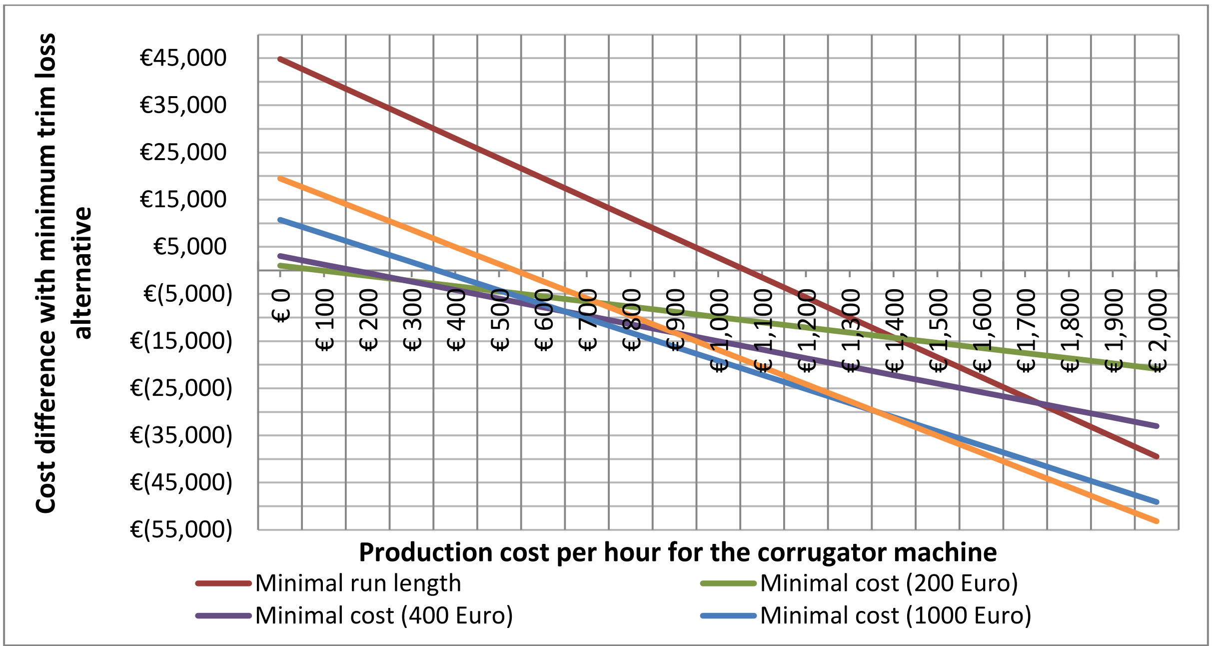


Figure 5.1 Cost difference with minimum trim loss alternative for different production cost per hour

5.1.3. CONCLUSIONS

From the results of the experiments we conclude the following:

- Using the trim loss objective is only the best option when the production cost per hour of the corrugator machine is less than €100 per hour.
- Using the run length objective is never the best option looking at a range of the production cost per hour of the corrugator machine between €0 euro and €2000 per hour.
- The solutions found by using the cost minimization objective are dependent on the costs per hour production of the corrugator machine.
- Using the cost minimization objective with cost of the corrugator of €0 results in the same solutions as by using the trim loss objective.
- Using the cost minimization objective with production cost of the corrugator machine that is near to infinity is the same as using the minimum run length objective.
- The higher the average speed of the corrugator, the smaller the effect of the production cost per hour of the corrugator machine.
- The cost minimization objective is a flexible objective. The same solutions as with the trim loss and run length objective can be obtained by changing the production cost per hour of the corrugator machine.

We propose the cost objective for solving the CSP at DS Smith. Given that the minimum production costs per hour of the corrugator machine are at least € *confidential* per hour, we conclude that using the minimum trim loss objective is never the best choice. Using the minimum run length objective is also not a good choice. The same solution is found as when the production costs per hour of the corrugator machine are near to infinity. We propose to use € *confidential* production costs per hour. The minimum costs are at least € *confidential* and we decided that the costs of lost sales are around € *confidential* per m^2 of corrugated board sheet; this is around € *confidential* per hour production. This objective function gives good results even if this estimation is not correct. The cost deviation would only be 0.06% when the production costs per hour would be €1600 and 0.07% when the production costs would be €600. Therefore we conclude that using € *confidential* is a robust choice for solving the CSP.

5.2. ALTERNATIVE INTEGRATED SOLUTIONS

The cutting stock problem module is only one module of the whole solution. Therefore we also need to test several solutions that combine the alternatives of the modules.

5.2.1. PERFORMANCE MEASUREMENT

In Chapter 3 we discussed performance measurement for production scheduling. Bandinelli *et al*. (2005) propose a framework based on three domains: the effectiveness, robustness, and flexibility domain. However, for the evaluation of the alternative solutions only the effectiveness is important. The alternatives score the same on robustness and flexibility, so there is no need to include this. The effectiveness domain measures the effectiveness of a schedule. So this measures the performance under a steady-state situation. For the evaluation of the alternative solutions we are using the following criteria:

TARDINESS

We split up the tardiness criteria in average tardiness, total tardy orders, and % tardy orders. This is not the average tardiness of all orders, but the average tardiness of tardy orders. It is important to know how much the tardiness of an order is on average. If there are many tardy orders that are only one hour finished too late it is less bad than having less tardy orders that are one day finished too late. Orders that are a few hours finished too late can still be delivered on time in most cases. We also need to know how many orders are tardy and what percentage of the orders is tardy.

- Average tardiness
- Total tardy orders
- Percentage tardy orders

EARLINESS

The earliness measures how much time the order is finished before the delivery date. If an order is delivered too late, the earliness becomes zero. We use the average earliness of orders because having a high average earliness means having many finished products. This costs capital investment and an increase in warehouse capacity is needed. Therefore it is preferable to produce JIT and keep the average earliness low.

- Average earliness

Trim loss

Trim loss is currently the only factor for solving the CSP. We defined another objective function that also takes into account the production costs. Therefore it is necessary to analyze what the effect on the average trim loss is when we use another objective function.

- Average trim loss %

Output of the corrugator machine

The output of the corrugator machine is used for the performance measurement since the corrugator machine is the bottleneck of the plant of DS Smith. We expect that the alternatives that use the cost objective function have a lower average run length per deckle solution. This means that less capacity is needed. However, a decrease in average run length per CI job results in lower average speeds (see Section 4.3.3).

- Total run length
- Total square meters produced
- Average run length of an deckle solution
- Average run length per CI job

Waiting time and fill rate of the PENTEK

Currently the Pentek causes problems when the fill rate becomes too high (>75%). Therefore it is important to know the average and maximum fill rate of alternative solutions. Moreover, the average waiting time per order is also important because high average waiting time probably results in a high average fill rate.

- Average waiting time per order
- Average fill rate
- Maximum fill rate

WOC idle time

The WOC idle time needs to be minimized in order to produce efficiently. Therefore we need to know the average WOC idle time before an order and the total WOC idle time per machine.

- Average WOC idle time before an order
- Total WOC idle time per machine

Simplicity

The last criterion is about the simplicity of the solution. Simple solutions are easier to implement and understand. This increases the probability of a successful implementation.

5.2.2. Experimental design

The eight alternatives formulated in Section 4.4 needs evaluation. We do this by first creating an initial situation (warm-up period). This is done by running the model for two weeks by the general model. After that we solve the next two weeks using each alternative. In this way we can compare the alternatives. The warm-up period is from 17-3-2014 until 30-3-2014. Then we run the model for the next twee weeks with each alternative, so until the current date is 14-4-2014. We do not need a cool-down period because the data of jobs that are finished before 14-4-2014 are not changing anymore. We analyzed our results with jobs (corrugator and converting) that started after 30-3-2014 and finished before 14-4-2014. We use a scheduling horizon of one and a half days (36 hours) and a rolling horizon of half a day (12 hours).

For the unavailability of machines we use the actual predictable unavailability for each machine. The last minute personnel unavailability, corrective maintenance, and other stop causes are included in the stops for each machine. We use historical data about the stops to estimate the results of a schedule. The achieved total production times are the estimated total production times plus any stops that occurred between the starting and finishing times of a job for the machine at which the job is processed.

The stochastic nature of the processing and setup times cannot be used in the experiments. We do not have any information about the probability functions. Moreover, it would also have been a problem to get information about the current state of the system (produced quantities and actual production times) in a timely manner. It is also not possible to solve the CSP with the alternative minimization objective. Solving the CSP must be done in the ERP system of DS Smith and there is no possibility to adjust the minimization objective.

Performing multiple replications for each alternative is not possible due to the time limitation. Given that solving the problem for one scheduling instance takes about one hour. Solving all the alternatives for the two weeks only once already takes 1*20 (there are 20 scheduling instances in 2 weeks of production)*8=160 hours. Doing multiple replications would take too much time. Therefore, the used approach to test the alternatives is justified. The corrugator module is run for ten minutes and the integrated corrugator and converting scheduling is run for 30 minutes for alternatives 1, 2, 3, 5, 6, and 7. Alternatives 4 and 8 only run the corrugator module as in the general model and the integrated corrugator and converting scheduling heuristic is run for 50 minutes.

5.2.3. RESULTS

We discuss the results of the eight experiments in this subsection. We elaborate on the performance of the alternatives on the different criteria. In each table with results we marked the performance red when the performance is unacceptably low.

OUTPUT OF THE CORRUGATOR MACHINE

From Table 5.3 we see that there is some deviation in the number of deckle solutions produced in the two weeks. The biggest difference is between alternative 7 and 8 (-9.09%). Also the total run length and square meters produced show the same differences (see Table 5.4). Both alternative 4 and 8 (both only use the integrated corrugator and converting scheduling) show the lowest number of deckle solutions, total run length, and total square meters produced. So from a capacity point of view these alternatives are not interesting. The average number of CI jobs per deckle solution does not show large differences. The same holds for the average run length of a deckle solution and the average run length of CI jobs (largest difference 1.1% and 1.7%). However, we see that the alternatives that use the cost objective function for the CSP show a shorter average run length than the comparable ones that use the trim loss objective (1-5, 2-6, 3-7, and 4-8). This supports our conclusion (see Section 5.1) that using the cost objective function requires less capacity.

Alternative	(1) # deckle solutions	(2) Av. # CI jobs ds	(3) Av. run length ds	(4) Av. run length CI job	(5) Total run length	(6) Total m^2 produced
1 (1-Opt –trim)	384	2.33	6465	2863	2482377	5462257
2 (SA – trim)	384	2.34	6446	2846	2475082	5445242
3 (AS – trim)	383	2.39	6658	2879	2550122	5600046
4 (Int – trim)	369	2.34	6445	2854	2378031	5240608
5 (1-Opt – cost)	392	2.33	6409	2846	2512236	5558454
6 (SA – cost)	384	2.35	6396	2827	2455891	5447416
7 (AS – cost)	396	2.42	6488	2806	2569289	5697044
8 (Int – cost)	360	2.38	6444	2827	2319911	5139604

Table 5.3 The results per alternative in the simulated two weeks: (1) The total number of deckle solutions used, (2) the average number of CI jobs in a deckle solution, (3) the average total run length per deckle solution in meters, (4) the average run length per CI job in meters, (5) the total run length produced in meters, and (6) the total squared meters produced. In red the results that are unacceptable.

TRIM LOSS

The alternatives show an average trim loss percentage ranging from 6.28% until 6.67% (see Table 5.4). This is much higher than the *confidential* % that has actually been produced. This is due to the order selection module of our model and the minimum run length restrictions of the corrugator machine.

Alternative	Trim %	Corrected trim %
1 (1-Opt – trim)	6.28%	5.46%
2 (SA – trim)	6.67%	5.80%
3 (AS – trim)	6.47%	5.56%
4 (Int – trim)	6.28%	5.49%
5 (1-Opt – cost)	6.47%	5.65%
6 (SA – cost)	6.53%	5.69%
7 (AS – cost)	6.39%	5.47%
8 (Int – cost)	6.43%	5.62%

Table 5.4 The trim loss % and the corrected trim loss % per alternative in the simulated two weeks.

If we correct for deckle solutions that have a run length that is 2000 or less, we get a trim loss percentage that deviates between 5.46% and 5.8%. These deckle solutions are restricted by the minimum run length restriction per paper width. It is justified to correct for these deckle solutions, because in the actual situation the production planners would look for additional orders that are outside the two sets MO and CO or would look for any upgrading possibilities to increase the needed run length. Upgrading is not included in our order selection module. Therefore it is logical that we find a higher average trim percentage for all alternatives. Alternatives 1, 3, and 4 score the best on trim loss % (both corrected and not corrected). However, these results do not reflect reality because the actual order selection approach is different and performs better.

TARDINESS AND EARLINESS

Just as with the number of deckle solutions, there are also some differences in the number of orders produced by each alternative (see Table 5.5). Most alternatives show comparable number of orders produced. Only alternative 4 and 8 show a relatively low amount of orders and alternative 7 shows a relatively high amount of orders. However, the differences in tardy orders are larger. Alternative 3 and 7 (that use the AS heuristic) show a high number of tardy orders and tardy percentage (118 and 106 tardy orders and 14.92% and 13.22%). Even if we correct this by not taking into account orders that are four hours or less tardy we get a high tardiness percentage (12.53% and 9.85%). If the orders are finished at most four hours too late there is a high probability that they are delivered on the same day as the delivery date, only a few hours later. These orders are not counted as tardy orders at DS Smith. Alternatives 2 and 5 show the lowest number of tardy orders and tardy percentage (58 and 56 tardy orders and 7.3% and 7.04%). The corrected tardiness % is relatively 2.89% and 2.76%.

Alternative	(1) # orders	(2) # tardy orders	(3) % tardy orders	(4) corrected % tardy orders	(5) Average Tardiness	(6) Average Earliness
1 (1-Opt – trim)	801	63	7.87%	4.12%	0.26	1.04
2 (SA – trim)	795	58	7.30%	2.89%	0.26	1.01
3 (AS – trim)	790	118	14.92%	12.53%	0.76	1.29
4 (Int – trim)	779	78	10.01%	3.98%	0.32	0.93
5 (1-Opt – cost)	796	56	7.04%	2.76%	0.31	1.07
6 (SA – cost)	790	72	9.11%	4.43%	0.30	1.00
7 (AS – cost)	802	106	13.22%	9.85%	0.68	1.28
8 (Int – cost)	779	77	9.88%	4.75%	0.30	0.88

Table 5.5 The results per alternative in the simulated two weeks: (1) the number of orders produced, (2) the number of tardy orders produced, (3) the percentage of orders that are tardy, (4) the corrected percentage of order that are tardy, (5) the average tardiness per tardy order, and (6) the average earliness per early order. In red the results that are unacceptable.

The OT performance in the simulated two weeks was *confidential* % (so *confidential* % tardy orders). The average OT performance was *confidential* % in 2013. We see that only alternative 2 and 5 have a better tardiness percentage. However, when we correct the tardiness we see that there is a large improvement compared to the actual situation. Moreover, there are also customer specific agreements about the on time delivery of orders. There are customers that have an agreement that orders must be delivered in a certain week. However, for these orders a delivery date is communicated, but we did not correct for this. We also did not correct for orders that are inventory replenishments. We do not do this because we want a production process that meets its internal due dates. When the internal due date is met there is a high probability that the delivery date with the customer is also met.

Waiting time and WOC idle time

When we look at the average waiting time of orders in the Pentek, we see that there are large differences (see Table 5.6).

Alternative	(1) Average Waiting time (hours)	(2) Average WOC (minutes)	(3) Total WOC (hours)	(4) Average fill rate
1 (1-Opt – trim)	6.42	5.99	74.13	58.71%
2 (SA – trim)	6.42	7.53	92.54	58.96%
3 (AS – trim)	10.31	7.51	91.31	81.05%
4 (Int – trim)	5.70	9.71	116.99	68.12%
5 (1-Opt – cost)	7.06	5.72	70.40	46.86%
6 (SA – cost)	6.04	7.84	95.81	47.11%
7 (AS – cost)	9.58	4.45	54.70	86.15%
8 (Int – cost)	4.89	9.79	117.99	54.94%

Table 5.6 The results per alternative in the simulated two weeks: (1) the average waiting time of orders in the Pentek measured in hours, (2) the average WOC idle in front of each converting job measured in minutes, (3) the total WOC idle time measured in hours, and (4) the average fill rate of the Pentek. In red the results that are unacceptable.

The AS heuristics (Alternatives 3 and 7) show the highest average waiting time and the integrated corrugator and converting alternatives (4 and 8) show the smallest average waiting time. However, these alternatives also have the highest average WOC idle time. This is logical because having no waiting time means having WOC idle before the order. So having less waiting time probably results in having more WOC idle time. The 1-Opt heuristic alternatives (1-5) show the lowest average WOC idle time.

Alternatives 5 and 6 show comparable average fill rates of around 47%, which is a good average fill rate according to the supplier of the IT system of the Pentek. Alternatives 3 and 7 show an average fill rate that is above 80%. Currently the corrugator machine is shut down when the fill rate of the Pentek is 75% or more. So these two alternatives are certainly not preferred. It is remarkable that alternative 4 has a high average fill rate (68%) since it has a relatively low average waiting time. An explanation may be that orders with a low number of stacks have a small waiting time, where orders with many stacks in the Pentek have a high average waiting time. High waiting time of orders with many stacks results in more stacks that need to wait in the Pentek, so a higher fill rate.

From Table 5.7 we can see that machines: 729, 728, and 419 show the most waiting time. These machines had the most unavailability in the simulated two weeks.

Alternative	735	729	728	436	426	425	419
1 (1-Opt – trim)	4.9	6.6	8.1	5.1	5.5	7.5	9.3
2 (SA – trim)	4.5	9.3	5.9	6.2	5.2	7.9	8.2
3 (AS – trim)	12.0	10.2	7.5	9.2	10.4	12.3	10.5
4 (Int – trim)	5.1	6.2	6.1	5.5	4.0	6.7	8.1
5 (1-Opt – cost)	6.4	5.5	7.5	5.1	6.4	9.8	11.0
6 (SA – cost)	5.6	6.9	7.4	5.2	4.6	6.3	8.1
7 (AS – cost)	9.5	11.0	9.2	8.9	7.8	12.2	8.3
8 (Int – cost)	5.1	6.5	6.6	4.6	3.5	3.5	7.1

Table 5.7 The average waiting time for converting jobs per converting machine per alternative in the simulated two weeks measured in hours.

5.2.4. *PROPOSED ALTERNATIVE*

We give a final score for each alternative on each performance criteria. See Table 5.8 for the overview of the scores of the alternatives. From the results we conclude the following:

- The alternatives that use the AS heuristic (alternatives 3 and 7) are not preferable because of the high tardiness, waiting time and fill rate of the Pentek.
- The alternatives that only use the integrated corrugator and converting scheduling (alternatives 4 and 8) are not preferable because of the lower output (deckle solutions, orders, and total square meters produced) and the high WOC idle time at converting machines.
- Alternatives 1, 2, 3, 4, and 7 are not preferable because of their high average fill rate of the Pentek. These alternatives would cause to much idle time caused by a high utilization of the Pentek.
- All alternatives score worse than the actual situation when we look at trim loss.
- The differences in average waiting time between alternatives and the converting machines are high.

Alternative	Tardiness	Earliness	Output	Trim loss	Waiting time	WOC idle time	Fill rate	Simplicity
1 (1-Opt – trim)	+	+/-	+/-	-	+/-	+	+/-	+
2 (SA – trim)	++	+/-	+/-	-	+/-	+/-	+/-	-
3 (AS – trim)	--	-	+/-	-	+/-	+/-	--	-
4 (Int – trim)	+/-	+	-	-	+	-	-	+
5 (1-Opt – cost)	**++**	**+/-**	**+**	**-**	**-**	**+**	**+**	**+**
6 (SA – cost)	+	+/-	+/-	-	+/-	+/-	+	-
7 (AS – cost)	--	-	+	-	-	+	--	-
8 (Int – cost)	+/-	+	-	-	+	-	+/-	+

Table 5.8 Final results: the trim loss results of all alternatives are worse than the current situation and comparable. Therefore, these all get the score - and in bold the proposed alternative.

We propose alternative five that uses the 1-Opt heuristic and the cost minimization objective for the CSP. This alternative scores overall the best. The 1-Opt heuristic scores best on tardiness. It also scores well on the output of the corrugator machine, WOC idle, simplicity, and the fill rate of the Pentek. Another important aspect is that all the other alternatives score at least on one criterion unacceptable and alternative five does not score unacceptable on any criterion. Moreover, it is a simple heuristic that uses random swaps in order to find better solutions. This is understandable for most people. This improves the probability on a successful implementation. The main improvement in performance of this alternative compared with the current situation is that the tardiness of orders is decreased. The tardiness percentage is decreased from *confidential* % to 7.04% and if we correct for orders that are only four hours tardy we get a tardiness percentage of 2.76%. The other performance criteria are hard to compare with the current situation. The data about these criteria are not present or are not reliable.

5.3. COMPARISON PROPOSED MODEL WITH CURRENT SITUATION

The difference between the proposed model and the current situation is large. The order selection module selects orders without the input of production planners and deckle solutions are also accepted without feedback loops of the production planners. We therefore elaborate on some of these important differences and the impact of these differences.

ORDER SELECTION MODULE

In the current situation there is no support for the production planners in selecting orders that enter the cutting stock problem module. The production planners select orders based on some company directives. These directives are based on delivery dates, workload machines, and waste. The difference between the current situation and the proposed model is that we integrated these directives in an automated module where no input is needed of the production planner. An advantage is that it saves time. Another advantage is that an automated module always selects according to the directives. However, this may also be a disadvantage. In some situations it is preferable that the directives are not followed and the production planners select extra orders and/or are upgrading the board grade of orders. In this way the trim loss can be further minimized.

From the results of the different alternatives we see that the trim loss of the alternatives is much higher than the actual trim loss. This can be addressed by the fact that order selection is a difficult process that is hard to automate. There are a lot of different situations where different decisions/directives may be required. Our proposed order selection module does not give preferable results. However, it can be used to give an initial set of orders that are selected. The production planners could then check this set of orders and make changes to it, i.e., unselecting selected orders and selecting unselected orders. We also looked at machine selection when we selected orders. We allocated the jobs to machines with the lowest workload. Currently, this is only done when booking an order. The machine allocation can only be manually changed.

CUTTING STOCK PROBLEM MODULE

The ERP system DS Smith is using gives multiple feasible deckle solutions. The production planner can select the deckle solution that fits best the preferences. In our proposed model the production planner does not have any influence in which deckle solution is chosen. This saves time and the optimal solution is always selected. This is the optimal solution given the minimum cost objective function instead of the currently used minimum trim loss objective. However, bad deckle solutions may be chosen because the production planner is not involved in the deckling process. Currently, the production planners go back to the order selection process if they find a deckle solution that has a trim loss that is too high. To tackle this problem a feedback loop from the production planner may be required to make sure the trim loss is minimized. It is not important that the production planner should select a certain deckle solution but that the planner makes sure that the right orders are selected.

CORRUGATOR SCHEDULING MODULE

Currently, the production planners add the deckle solutions sequentially to the corrugator schedule. Then they check if there are any problems occurring with this schedule. If there does, they change this schedule. An important difference with the proposed model is that we are looking for alternative schedules that have an improved performance based on tardiness and setup time. The advantage is that multiple solutions are checked. Therefore we may find better solutions that the production planner could not come up with. However, not all restrictions are included in the corrugator scheduling module. Therefore it is important that there is a feedback loop where the production planner checks the feasibility of the found solution.

CONVERTING SCHEDULING MODULE

The converting scheduling module schedules all jobs based on the FIFO principle. This is preferable for the automated handling of stacks in the Pentek. However, sometimes it is preferable to have another schedule that clusters jobs based on tools. Also tardiness of orders may be a reason to not schedule based on the FIFO principle. Therefore, this module also needs a feedback loop.

We add a load balancing procedure to the module. This procedure checks if changing the machine routing would result in decrease in waiting time or tardiness. Currently, this is done manually when there is WOC idle time or tardy orders. However, before this load balancing can be used the tool availability needs to be integrated in the module.

Another improvement of the proposed model is that it uses a method for coping with uncertainty in the converting scheduling module. It adds slack time in order to buffer for any unpredictable stops of machines. In this way the schedule is more robust and reliable. Robust and reliable production schedules require less rescheduling decisions and may result in an improvement in scheduling performance.

PENTEK MODULE

This module is developed because currently there is no possibility for the production planners to take into account the Pentek. This Pentek module models the Pentek and its conveyors. An overview is given to the production planners with the estimated fill rates of the conveyors with a different width and the total Pentek fill rate is estimated for the current planning horizon. In this way the production planners see if any problems may occur due to a high fill rate of the Pentek. This was a big problem in 2013. *confidential* % of the time the corrugator machine was idle due to a full Pentek. This are around *confidential* days of lost production (*confidential* hours). So the costs of the idle time caused by a full Pentek are € *confidential* using the determined production cost per hour of € *confidential*. The idle time does not only result in higher costs, it also causes problems regarding the tardiness of orders. With the insights generated by this module, idle time of the corrugator machine can be decreased by timely making rescheduling decisions.

5.4. CONCLUSIONS

In this chapter we defined the performance indicators that we used for the evaluation of the alternative solutions. These indicators are: tardiness of orders, earliness of orders, output of the corrugator machine, average trim loss percentage, average waiting time of orders, WOC idle time of converting machines, the average fill rate of the Pentek, and the simplicity of the alternative.

We tested three alternative CSP objective functions; the current objective (trim loss minimization), the run length minimization, and the cost minimization. For the cost minimization we performed a sensitivity analysis on the production cost per hour and the average speed of the corrugator. We showed that the run length and cost objective function have a significant decrease in run length and number of paper widths used per deckle solution. However, this also resulted in a significant increase of the trim loss. We proposed the cost objective function with taking the production cost per hour of € *confidential*. This is a robust alternative, even when the actual costs are deviating between €600 and €1600, i.e., the maximum increase in cost is only 0.07%. The minimum trim loss objective is only preferable when the production costs per hour are €100 or less.

We tested the eight alternative solutions by simulating the performance of the solutions for week 14 and 15 in 2014. We have information about the stops and unavailability of machines. In this way we simulated how the alternative solutions would have performed during the simulated two weeks. Alternative 5, that uses the 1-Opt heuristic and cost minimization objective is proposed as the best solution. This alternative has the best overall score and performs best on tardiness and WOC idle time (only 2.76% corrected tardy orders and 70 hours of WOC idle time in the simulated two weeks). The alternatives (3 and 7) that use the AS heuristic show a performance on tardiness and tardy percentage that is unacceptable. They also show a bad performance on earliness of orders and the fill rate of the Pentek. The alternatives (4 and 8) that only use the integrated corrugator and converting schedule show a good performance on earliness and waiting time. However, they do perform badly on tardiness, output of the corrugator, and WOC idle time.

In Section 5.3 we compared the proposed solution with the current situation. Many activities of the production planners in the current situation are automated in the proposed solution. However, the model cannot run autonomously. There are many specific situations that are not embedded in the solution. The order selection module is a good example. When the proposed solution runs autonomously the trim loss is around 6.5%. This is much more than in the current situation where the average trim loss is *confidential* %. This difference is caused by upgrading board grades and violating the maximum order selection horizon of seven days. Another point is that the tool availability is not embedded in the solution. Therefore some machine routings may not be possible because there are not any tools available.

The corrugator scheduling module is able of finding good solutions that improve the overall solution looking at tardiness. The production planners should only check for any special situations or small changes that improve the solution. Building a schedule is not necessary anymore. Another important improvement is that the Pentek module gives a good insight in the future fill rate of the Pentek and of the different conveyors in the Pentek. Idle time because of a high utilization of the Pentek can be predicted and timely rescheduling decisions can be made. Other improvements are the load balancing options when selecting the orders and scheduling the converting machines. In this way waiting time and WOC idle time may be decreased. The method for coping with uncertainty improves the reliability of the production schedule that may result in an improvement in scheduling performance.

6. IMPLEMENTATION

We have formulated the general model and alternatives in Chapter 4. In Chapter 5 we have evaluated the different alternatives and proposed the solution that uses the 1-Opt heuristic and the cost objective function for the CSP. This chapter discusses the important subjects regarding implementation of this proposed solution and answers the following research question: "*What are the implementation issues of the proposed alternative?*"

Section 6.1 describes important implementation issues of this planning and scheduling module. Section 6.2 provides a framework for the evaluation of production scheduling. Section 6.3 discusses impact factors. Section 6.4 discusses parts of the proposed solution that may be implemented separately. Finally, Section 6.5 gives conclusions.

6.1. IMPLEMENTATION ISSUES

Implementation of the proposed solution raises some issues. In this section we describe some of the important issues.

COMPLEXITY AND LIMITATIONS OF THE ERP SYSTEM

The proposed solution is a complex solution. This complexity is required to achieve the stated research goals. However, this complexity makes it hard to implement the solution. The people who need to implement the solution should know why certain decisions are made and how the solution method works. Next to this, DS Smith is currently using an ERP system that is limited. The functionalities of the proposed solution cannot be integrated or are hard to integrate in this ERP system. One solution for this would be to implement the whole solution in a separated system that must be linked with the current ERP system of DS Smith. Another option would be to implement parts of the solution. We elaborate on this in Section 6.4.

CHANGE OF TASKS AND DECISION SUPPORT

The tasks of the production planners change when the solution is implemented. Some tasks that are currently done are not needed anymore. Moreover, the focus of the tasks will be more on monitoring and controlling the production schedule. This requires training of the production planners about the way the proposed solution works. For a successful implementation it is important that the production planners understand how the solution works and why it is making certain decisions. Otherwise the planners would not accept the new way of working and the solution would not result in the expected improvements. The production planners also need to know how to use the information that the solution gives them. This helps them in making the right (re)scheduling decisions.

COMPANY STRATEGY

The production planners are not the only people who should know the objectives for production scheduling. It is important that this is known company wide. The production employees that execute the schedule must also accept these schedules. If the acceptance and understanding of the production employees is low, they will probably not work according to these schedules. This affects the reliability and robustness of a production schedule and the stability of the production process. Moreover, the sales employees must also understand the objectives for production scheduling. They must understand why the production planners make certain decisions in order to make the right agreements with the customer.

Most important is that the strategy of management is clear and constant. Currently the production planners get the idea that management is constantly shifting in strategy (waste minimization, output maximization and quality). The perception is that the focus depends on the performance in the last weeks/months and that management is not looking at the long term. Agreements must be made about the objectives of production scheduling. Constantly changing the strategy probably results in solving one problem but creating another. As mentioned by Hoogeveen (2005), if only one indicator is used, the schedule is likely to be unbalanced, no matter what indicator is considered. So constantly shifting between indicators could only make the schedule even more unbalanced.

6.2. EVALUATING PRODUCTION SCHEDULING

This section provides a framework for evaluating production scheduling. This framework is developed because within DS Smith there is the need to have directions for evaluating a production schedule.

6.2.1. THE DIFFERENT STAKEHOLDER OBJECTIVES

We elaborate on the different internal stakeholders with their objectives and wishes in Appendix G. Out of the stakeholder analysis we found that timeliness of orders, lost production time, robustness, and ease of working are important objectives and wishes.

TIMELINESS OF ORDERS

With timeliness of orders we mean that orders are delivered on time to the customer, but are also not finished too early. If orders are finished too early the finished goods inventory increases which results in higher costs but also require warehouses capacity. In order to assess the timeliness we use tardiness and earliness of orders as performance criteria. We measure tardiness as the total time that an order is finished after its latest finishing time. It is important that we do not take the on time delivery at the customer for the measurement of tardiness. Even if an order is finished on time it is possible that the order is not delivered on time. The production planners do not have any influence on this. So this cannot be linked with the performance of a production schedule or scheduler. It is important to know the average earliness per order that is scheduled. When this is too high the orders are on average scheduled to early and probably the finished goods inventory increases. If it is low and disruptions occur the orders may become tardy.

LOST PRODUCTION TIME

Lost production time is an important indicator for DS Smith. Especially the lost production time of the corrugator machine because this is the bottleneck machine. This can be linked with the setup times of the corrugator and the fill rate of the Pentek.

ROBUSTNESS

Robustness is important for the production and expedition planners. The more robust a schedule becomes the less rescheduling actions need to be taken. We link this robustness of the schedule with the waiting time of orders in the Pentek. If the waiting time of orders in the Pentek is low the fill rate is probably also low. A low fill rate of the Pentek results in a lower probability of problems caused by the Pentek. Problems caused by the Pentek probably have an impact on the production schedules. Moreover, the reliability of the scheduled setup and production times also determine how robust a schedule is. If the scheduled setup and production time deviate too much, then the schedule does not reflect the actual situation and rescheduling may be needed after a while. Another variable to be taken into account is the willingness of the production employees to work according to the schedule. If production employees do not work according to the schedule the schedule needs to be changed. The timeliness and clearness of the communication about the schedule is important for the robustness of the schedule. This also has an impact on the willingness to work according to the schedule. Last minute changes frustrate the production employees.

EASE OF WORKING

The ease of working is important for the production employees of both the corrugator and converting machines. This is linked with setups. Setups are perceived as a cause for a high workload and a necessary evil. Next to this, the number of paper widths used is also an important factor. The more paper widths are used the more paper reels need to be changed. This also results in a high workload.

6.2.2. THE EVALUATION FRAMEWORK

In this section we formulate the evaluation framework for production scheduling at DS Smith. In the previous section we elaborated on the four main objectives of the stakeholders. However, not all four objectives can be used for the evaluation framework. The objective of the production employees (ease of working) cannot be used. Setups of the corrugator are already included in the lost production time objective. Moreover, the number of paper widths used in a deckle solution is an outcome of the CSP. The production planners do not have any impact on this, given a certain objective. Next to this, the setups at converting machines are of low priority and minimizing these setups may result in conflicts with other objectives. Therefore, we exclude the ease of working objective from the evaluation framework. The framework is divided in three domains; effectiveness, efficiency, and robustness (see Figure 6.1). They represent the remaining three objectives.

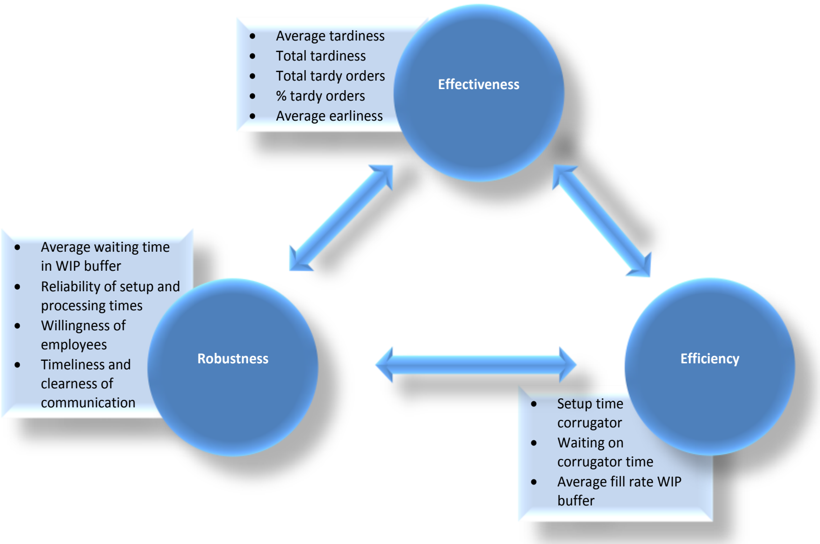


Figure 6.1: Evaluation framework with three domains: effectiveness, efficiency, and robustness.

EFFECTIVENESS DOMAIN

The effectiveness domain is linked with the timeliness of orders objective, i.e., the goal is to meet customer demands. We can measure the performance of a schedule by calculating the sum of the tardiness of all orders currently scheduled and the average tardiness per order. However, it is also important how many orders are tardy. So we also calculate the sum of all tardy orders that are currently scheduled. The performance indicators of the effectiveness domain are:

- Total tardiness
- Average tardiness

- Total tardy orders
- % tardy orders
- Average earliness

EFFICIENCY DOMAIN

The efficiency domain is linked with the lost production time. We measure the lost production time with the following indicators:

- Setup time of the corrugator machine
- Waiting on corrugator idle time per converting machine
- The average fill rate of the Pentek

ROBUSTNESS DOMAIN

The robustness domain measures in what degree the production actually works according to the schedule. We measure the robustness with the following indicators:

- Average waiting time of orders in the Pentek.
- Reliability of setup times and processing times
- Willingness of production employees to work according to the schedule
- Timeliness and clearness of schedule communication

6.3. IMPACT FACTORS

Certain factors (decisions and the characteristics of the production process) determine in a high degree the performance of the proposed solution. Therefore, this section provides an overview of the impact of these factors in each module.

ORDER SELECTION MODULE

Within the order selection module, the parameters used to determine the sets MO and CO determine in a high degree the performance of the CSP and the degree to which the workload can be balanced. In general the larger the set of orders the more the trim loss can be minimized. This means the larger the parameter settings for MO and CO the more the trim loss can be minimized. However, increasing the range for the set MO is not preferred. Increasing the range probably results in an increase in earliness and increase in finished goods inventory. Moreover, the strategy of DS Smith is to produce JIT. Decreasing the parameter settings of MO and CO would result in a smaller set of orders. This probably leads to an increase in trim waste. So this is also not preferred.

CUTTING STOCK PROBLEM MODULE

The module for solving the CSP uses four important restrictions. These are the minimum trim loss, maximum trim loss, minimum run length per CI job, and the minimum run length per paper width restrictions. The minimum trim loss and maximum trim loss restrictions limit the number of feasible patterns. The stricter the two parameters are set, the smaller the set of feasible cutting patterns. The smaller the set of feasible cutting patterns the higher the total trim loss.

The minimum run length restrictions do not limit the number of feasible cutting patterns but limit the set of feasible solutions. Again, it holds that the stricter the restrictions, the smaller the solution set and the higher the total trim loss.

All these four restrictions are set up because they are limitations of the corrugator machine. When making future decisions about a possible new corrugator machine these limitations should be taken into account. In the meanwhile, projects should be started in order to decrease the impact of the limitations.

Corrugator scheduling module

The most important parameters for corrugator scheduling are the parameters used for the objective function. These are the parameter settings for the weights of the different indicators in the objective function. The impact of these parameters on the solution is high. Setting the focus on tardiness may result in a schedule with more setup time. Focusing on setup time may result in a schedule with tardiness. So it is important to find a good balance between these two indicators.

Converting scheduling module

Important decisions for converting scheduling are the different routing possibilities for orders. The more routing possibilities for orders the more flexible the production process. Limiting the routes has a negative effect on the performance of the production process in terms of flexibility, WOC idle time, and waiting time. Moreover, the shift planning also has a large impact. Taking a machine out of the schedule during a certain shift, results in unavailability of that machine for eight hours. When the corrugator is producing orders for this machine then these orders also need to wait in the Pentek for eight hours. Resulting in an increase in fill rate of the Pentek and this may cause problems for other orders and machines.

Pentek module

The drying time that is needed for some board grades has a high impact on the fill rate of the Pentek. Drying time increases the average throughput time of stacks in the Pentek and blocks conveyors. Finding a solution to decrease the drying time would decrease the fill rate and the downtime caused by a high utilization of the Pentek. Not placing the drying order in the Pentek but somewhere else may be another solution. These orders would then not block conveyors and would not increase the average throughput time and fill rate of the Pentek.

6.4. Implementing parts of the solution

As stated in Section 6.1 implementing the whole proposed solution is a difficult task. Therefore it might be interesting to implement parts of the solution.

Pentek module

Currently the production planners do not have a tool to get insight in the future fill rate of the Pentek. The Pentek module gives an overview of the estimated fill rates of the Pentek. This is an interesting module that might be implemented in the current ERP system of DS Smith. With this module the production planners can make better and timely rescheduling decisions. This may result in a more robust schedule that requires less last minute changes and a decrease in downtime caused by a high utilization of the Pentek. This module also gives insight in the usage of the different conveyors in the Pentek.

Cutting stock problem module

The module for solving the CSP is also interesting for partial implementation. The current way of solving the CSP takes a lot of time while the proposed module solves the problem in a very short time. The main difference is that the production planner does not have to make decisions about which deckle solutions to accept. This module takes away tasks of the production planners. The time that is saved by this module can be used by the production planners to monitor and control the current production schedule. Another important improvement is that the proposed solution uses the cost minimization objective. By using the cost objective, deckle solutions are found that use less capacity and have less paper width changes. By changing the production cost the focus can be shifted to decrease the run length or trim loss.

Performance measurement scheduling

The production planners only have insight in the waiting time and setup time of an order. There is no performance indicator that shows what the average waiting time is or what the total setup time within the planning horizon is. Also the WOC idle time is only visible in the Gantt chart and is not showed in total time. The total/average tardiness and tardy orders is also not visible. Implementing indicators that show the performance of the schedules would give the production planners insight in their (re)scheduling decisions. When implemented, they can make their decisions based on the change of these indicators.

Coping with uncertainty

Currently, the production schedules at DS Smith do not cope with uncertainty of machine availability. The proposed model uses a method of coping with uncertainty. Slack time is added in order to buffer for uncertainty. This might be an interesting part of the model to implement in the current ERP system. There are many stops by the converting machine (on average 2-3 hours a day per machine). Including this method for coping with uncertainty may lead to improved reliability of the production schedule. This may result in less rescheduling for production. Also the expedition planners would benefit from a more robust and reliable production schedule.

6.5. Conclusions

In this chapter we discussed the implementation issues for implementing the proposed solution. The most important issues are that the solution is a complex one that is hard to implement in the current ERP-system. Knowledge about the solution needs to be transferred to the production planners. In this way the production planners understand the reasons behind the decisions that the solution makes. Next to this, they can also make better (re)scheduling decisions themselves. The last implementation issue is that there must be a clear and steady company strategy regarding the scheduling objectives. The balance must be found between output, waste, and timeliness of orders. Important success factor for this is that everybody within the company understands and supports the strategy.

Within DS Smith there is the need to have an evaluation framework for assessing the performance of a schedule. Timeliness of orders, lost production time and robustness of the schedule are important scheduling objectives. We formulated an evaluation framework that consists of three domains, the effectiveness, efficiency, and robustness domain.

Some decisions that are used in the modules have a high impact on the performance of the solution. We discussed for each module the most important decisions. Finally, we discussed parts/modules of the integrated solution that could be implemented in the current system instead of the whole integrated solution. This could be preferable because of the complexity and difficulty in implementing the whole solution. Implementing parts of the solution may help the production planners in making the right (re)scheduling decisions.

7. CONCLUSIONS AND RECOMMENDATIONS

This chapter provides final conclusions of this research in Section 7.1. In Section 7.2 we provide the limitations of this research. Section 7.3 provides recommendations for DS Smith that has to do with planning and scheduling. Finally, in Section 7.4 we discuss subjects for further research.

7.1. CONCLUSIONS

In the current situation at DS Smith problems occur in the production process that are caused by production planning and scheduling. One of the problems is that machines become idle and orders that become tardy. An important aspect of the scheduling process is solving the cutting stock problem (CSP). The outcomes of the CSP are deckle solutions that need to be scheduled on the corrugator machine. The performance of the corrugator machine is affected by these deckle solutions. Moreover, the corrugator schedule has a large impact on the converting schedule. This project should deliver a solution that models the process of order selection, solving the CSP, scheduling the corrugator machine, scheduling the converting machines, and monitoring and controlling the Pentek (WIP buffer). Therefore, we define the following main research question:

"How should DS Smith Packaging B.V. solve the cutting stock problem and generate production schedules in order to find a good balance between minimizing waste, minimizing idle times of machines, and maximizing the on time delivery performance of orders?"

We performed a literature study about performance measurement for production scheduling, the cutting stock problem, heuristics applicable for production scheduling, methods for coping with uncertainty, and combinations of the cutting stock problem and scheduling. The literature on these subjects is extensive. However, there is no model that solves all problems at once. Moreover, the situation at DS Smith is more complex than the ones that are solved in literature. Therefore we need to develop a new model that is capable of solving the CSP and production scheduling for the situation at DS Smith.

We propose a model that solves the different problems in modules. Solving the problem at once is too complex, i.e., the single problems are already NP-hard problems. We split the problem in five modules: an order selection module, a cutting stock problem module, a corrugator scheduling module, a converting scheduling module, and a Pentek module. The first four modules are essential for a feasible production schedule. The Pentek module gives insight in the fill rate of the Pentek and the different conveyors.

We defined alternative objective functions for solving the CSP. Currently DS Smith is using the trim loss minimization objective. Alternatives are a minimum run length objective (minimize the used capacity), a cost objective that takes into account production cost per hour, and a cost objective that also takes into account the costs of changeovers (paper width changes and Corrugator Instruction (CI) job changes). However, this last alternative makes the problem harder to solve and requires too much computational time while the extra benefits are only small. We tested the current objective function and the alternative objective function by simulating the performance over a period of four months (1-1-2014 until 30-4-2014). The alternative objective functions showed a significant decrease in run length and number of paper width changes needed and a significant increase in trim loss. The current trim loss objective is only the best option when the production costs per hour are €100 or less. The minimum production costs per hour are € *confidential* and when taking into account the cost of lost sales, the production costs per hour are € *confidential*. A robust solution is found by using the cost objective with production costs per hour of € *confidential*. The solution deviates at most 0.07% in costs when the costs per hour are between €600 and €1600.

We formulated eight alternatives that use different approaches for solving the modules. There are two approaches for the CSP: the first uses a trim loss minimization objective and the second uses a cost minimization objective. For solving the corrugator scheduling we used four approaches. The first approach uses a 1-Opt heuristic. A random deckle solution is selected and inserted at another place in the schedule. This schedule is accepted if the performance on setup time and tardiness increases. The second alternative uses a simulated annealing (SA) heuristic to find good solutions. The third is based on the adaptive search (AS) construction heuristic. The last only uses an integrated corrugator and converting scheduling heuristic. The first three alternatives also use the integrated corrugator and converting scheduling heuristic. However, this is run for a smaller amount of time. We propose the alternative that uses the 1-Opt heuristic and the cost minimization objective for the CSP as best solution (alternative 5). It scores best on tardiness (2.76% corrected tardy orders) and also scores well on other criteria. The alternatives that use the AS heuristic (3 and 7) score poorly on tardinessand has a high average fill rate of the Pentek. The alternatives that use the integrated corrugator and converting scheduling heuristic (4 and 8) are not preferable because they generate a low output of the corrugator machine

We also formulated an evaluation framework for production scheduling at DS Smith. The proposed solution is a complex solution that is hard implement in the current ERP system. However, partly implementing the solution is a possibility. The Pentek module gives good insights in the future fill rate of the Pentek. This could assist the production planners in making important (re)scheduling decisions that decreases the idle time caused by a high utilization of the Pentek. Another important improvement that can be implemented is the new objective function for the CSP. The cost objective decreases the total run length and the number of paper width changes per deckle solution. This is important because the corrugator machine is the bottleneck of the plant in Eerbeek. Implementing the method for coping with uncertainty improves the robustness and reliability of production schedules. This may improve the scheduling performance and also expedition planning would benefit from a more robust and reliable production schedule.

The aim of this research was to deliver a solution that models the different tasks of the production planners. We modelled the different tasks and automated them. The solution gives valuable insights in the planning process and important subjects for improvement. Parts of the solution may be implemented that assist the production planners in making better (re)scheduling decisions. Overall, this research provides valuable insights that help DS Smith in improving their production planning and scheduling. This may lead to a decrease in waste, idle time of machines, and an increase in the on time delivery. This helps DS Smith in being more competitive in the market and to meet customer demands.

7.2. LIMITATIONS

The proposed solution has some limitations. The first limitation is that it uses a heuristic for the scheduling problem. These heuristics do in general not find the optimal solution. However, the solutions found are generally good starting solutions. The complexity of the model results in high computational time needed to find optimal solutions. This means that solving the problem to optimality is not feasible because of the time constraints, i.e., a solution must be found within one hour.

Another limitation is that this solution does not take into account the tools. The tools determine the setup time required for converting machines and determines if a machine routing is available. Also taking into account the tools may result in a reduction in setup time and therefore an improvement in available time for production.

The third limitation is that inventory availability is not taken into account. Inventory availability highly determines the feasible cutting patterns and therefore also determines the performance on trim loss. The complexity of the CSP increases because then also a decision needs to be made which cutting patterns are assigned to the restricted width if there are not enough reels.

The simulation of the different alternatives is also a limitation. We can only give statements about the performance in the simulated two weeks. We did not perform multiple replications. The performance in other weeks may be different. However, we did not have time to do multiple replications or simulate over more than two weeks. Another limitation of the simulation is that it does not take into account the stochastic nature of the setup and processing times.

The last limitation is that this solution is specially developed for DS Smith Eerbeek. This probably makes the model not applicable for other organizations.

7.3. RECOMMENDATIONS

The first recommendation is about the allocation rules for stacks that are placed on conveyors in the Pentek. Currently these allocation rules do not take into account the schedule and also do not take in account the future fill rate of the Pentek. Moreover, stacks are not always placed on a conveyor of the smallest width. This may result in problems with unavailability of wide conveyors while small stacks are placed on it. So our recommendation is that these allocation rules should be reconsidered and improved. This would reduce the downtime caused by the Pentek. Also increasing the number of conveyors would be beneficial for the reduction in downtime caused by the Pentek and flexibility to change the sequence of jobs.

Another recommendation about the conveyors of the Pentek is that DS Smith is currently using seven different widths of conveyors. The more widths that are available the more complex the allocation becomes. We recommend that the number of widths of conveyors is decreased.

Some board grades require drying time in the Pentek. This drying time increases the throughput time and results in an overall higher fill rate of the Pentek. Not placing stacks of these board grades in the Pentek would decrease the average throughput time of stacks in the Pentek and decrease the fill rate of the Pentek. Our recommendation is that these stacks are not placed in the Pentek. Another possibility would be to decrease the needed drying time.

We also started a spinoff project of this research that had its focus on reducing the trim loss at the corrugator machine. An important result of this project was that an increase of available paper widths would increase the number of feasible cutting patterns. This increase in feasible cutting patterns leads to a significant decrease of trim loss. A recommendation is to investigate what the possibilities are to increase the number of available widths. Currently the warehouse capacity is not sufficient for additional paper widths.

The last recommendation is about the reliability of the schedule. Currently the reliability of the schedules are not tested and assessed. The planned setup and processing times depend on several parameters in the ERP-system. Our recommendation is that the reliability of the setup and processing times needs to be tested and evaluated and if necessary the parameters in the system need to be changed. This would increase the robustness and reliability of the schedules.

7.4. SUBJECTS FOR FURTHER RESEARCH

During this research project we observed several subjects for further research. The first subject for further research is to determine the probability distributions of processing and setup times. The proposed way of coping with uncertainty is limited because the probability distributions are unknown. When these probability distributions are known better approaches to cope with uncertainty may help DS Smith to make their schedules more robust and reliable.

Another subject for further research is on the order selection process. The focus of this research was on solving the CSP and scheduling the corrugator and converting machines. However, the order selection process has a high impact on the found solutions. Therefore it might be interesting to start a new project that focuses on the order selection process.

BIBLIOGRAPHY

Aarts, E., & Korst, J. (1989). *Simulated Annealing and Boltzman Machine.* Chichester: Wiley.

Al-Fawzan, M. A., & Haouari, M. (2005). A bi-objective modal for robust resource constrained scheduling. *International Journal of Production Economics*(96), 175-187.

Arbib, C., Marinelli, F., & Pezzella, F. (2012). An LP-based tabu search for batch scheduling in a cutting process with finite buffers. *International Journal of Production Economics*(136), 287-296.

Aytug, H., Lawley, M. A., McKay, K., Mohan, S., & Uzsoy, R. (2005). Executing production schedules in the face of uncertainties: A review and some future directions. *European Journal of Operational Research*(161), 86-110.

Bandinelli, R., Cavalieri, S., & Terzi, S. (2005). Proposal of a framework for the evaluation and comparison of production schedules.

Bolat, A. (2000). An extended scheduling model for producing corrugated boxes. *International journal of Production Research*(38), 1579-1599.

Bookbinder, J. H., & Higginson, J. K. (1986). Customer Service vs Trim Waste in Corrugated Box Manufacture. *Operational Research Society, 37*(11), 1061-1071.

Cerny, V. (1985). Thermodynamical apporach to the traveling salesman problem: An efficient simulation algorithm. *Journal of Optimisation Theory and Applications*(45), 41-51.

Davenport, A. J., Gefflot, C., & Beck, J. C. (2001). Slack-based techniques for robust schedules. *Seventh International Conference on Principles and Practive of Constraint Programming.* Paphos, Cyprus.

De Snoo, C., Van Wezel, W., & Jorna, R. J. (2011). An empirical investigation of scheduling performance criteria. *Journal of Operations Mangement*, 181-193.

Dyckhoff, H. (1990). A typology of cutting and packing problems. *European Journal of Operational Research*(44), 145-159.

Eglese, R. W. (1990). Simulated Annealing: A tool for Operational Research. *European Journal of Operational Research*(46), 271-281.

Etzioni, A. (1964). *Modern organizations.* Eaglewood Cliffs: Prentice Hall.

Evans, G. W. (1984). An overview of techniques for solving multiobjective mathematical programs. *Management Science*(30), 1268-1282.

Freeman, R. E. (1984). *Strategic managment: A stakeholder approach.* Bosten: Pitman.

Fry, T. D., Armstrong, R. D., & Lewis, H. (1989). A framework for single machine multiple objective sequencing research. *Omega*(17), 595-607.

Gao, H. (1995). *Building robust schedules using temporal protections- an emperical study of constraint based scheduling under machine failure uncertainty.* Master's Thesis, University of Toronto, Department of Industrial Engineering.

Gilmore, P. C., & Gomory, R. E. (1961). A linear programming approach to the cutting-stock problem. *Operations Research*(9), 849-859.

Gilmore, P. C., & Gomory, R. E. (1963). A linear programming approach to the cutting-problem, Part II. *Operations Research*(11), 863-888.

Glover, F. (1989). Tabu search-part I. *ORSA Journal on computing*, 190-206.

Glover, F. (1990). Tabu search-part II. *ORSA Journal on computing*, 4-32.

Goldratt, E. (1997). *Critical Chain.* The North River Press.

Goulimis, C. (1990). Optimal solutions for the cutting stock problem. *European Journal of Operational Research*(44), 197-208.

Haessler, R. W., & Sweeney, P. E. (1991). Cutting stock problems and solution procedures. *European Journal of Operational Research*(54), 141-150.

Hans, E. W., Herroelen, W., Leus, R., & Wullink, G. (2007). A hierarchical apporach to multi-project planning under uncertainty. *Omega, 35*(5), 563-577.

Herroelen, W., & Leus, R. (2005). Project scheduling under uncertainty: survey and research potentials. *European Journal of Operational Research*(165), 289-306.

Hoogeveen, H. (2005). Multicriteria scheduling. *European Journal of Operational Research*(167), 592-623.

Hsu, T. C. (2006). New expression of scheduling performance measures. *International Journal of Production Research, 44*(15), 3147-3158.

Johnson, D. S., Aragon, C. R., McGeogh, L. A., & Schevon, C. (1987). Optimization by simulated annealing: An experimental evaluation, Part I. In *AT&T Bell Laboratories.* NJ: Murray Hill.

Kempf, K., Uzsoy, R., Smith, S., & Gary, K. (2000). Evaluation and comparison of production schedules. *Computers in Industry*(42), 203-220.

Kirkpatrick, S., Gelat, C. D., & Vecchi, M. P. (1983). Optimization by Simulated Annealing. *Science*(220), 671-680.

Kolisch, R., & Drexl, A. (1996). Adaptive Search for solving hard project scheduling problems. *Naval Research Logistics*(43), 23-40.

Ku, H., Rajagopalan, D., & Karimi, I. A. (1987). Scheduling in batch processes. *Chemical Engineering Progress*(83), 35-45.

Landeweerd, H. R., & Mantel, R. J. (1995). Design and operational control of an AGV system. *International Journal of Production Economics, 41*, 257-266.

Leon, V. J., Wu, S. D., & Storer, R. H. (1994). Robustness measures and robust scheduling for job shops. *IIE Transactions*(35), 32-43.

Mehta, S. V., & Uzsoy, R. (1998). Predictable scheduling of a job shop subject to breakdowns. *IEEE Transactions on Robotics and Automation, 3*(14), 365-378.

Mehta, S. V., & Uzsoy, R. (1999). Predictive scheduling of a single machine subject to breakdowns. *International Journal of Computer Integrated Manufacturing*(12), 15-38.

Méndez, C. A., Cerdá, J., Grossmann, I. E., Harjunkoski, I., & Fahl, M. (2006). State-of-the-art review of optimization methods for short-term scheduling of batch processes. *Computers and Chemical Engineering*(30), 913-946.

Metropolis, N., Rosenbluth, A. W., Rosenbluth, M. N., Teller, A. H., & Teller, E. (1953). Equation of state calculations by fast computing machines. *The journal of chemical physics*(21), 1087-1092.

Mitchell, R. K., Agle, B. R., & Wood, D. J. (1997). Toward a theory of stakeholder identification and salience: Defining the principle of who and what really counts. *Academy of management review*(22), 853-886.

Neely, A., Gregory, M., & Platts, K. (2005). Performance measurement system design: a literature review and research agenda. *International Journal of Operations & Production Management*, 1228-1263.

Pierce, J. F. (1964). *Some Large Scale Production Problems in the Paper Industry.* NY: Prentice-Hall.

Pinto, J. M., & Grossman, I. E. (1998). Assignment and sequencing models for the scheduling of process systems. *Annals opf Operations Research*(81), 433-466.

Rodriguez, M. A., & Vecchietti, A. (2013). Integrated Planning and Scheduling with Due Dates in the Corrugated Board Boxes Industry. *Industrial & Engineering Chemistry Research*(52), 847-860.

Salancik, G. R., & Pfeffer, J. (1974). The bases and use of power in organizational decision making: the case of universities. *Administrative Science Quarterly*(19), 452-473.

Savsar, M., & Cogun, C. (1994). Analysis and modelling of a production line in a corrugated box factory. *International Journal of Production Research, 32*(7), 1571-1589.

Stakeholder salience. (2014). Retrieved May 19, 2014, from stakeholdermap: http://www.stakeholdermap.com/stakeholder-analysis/stakeholder-salience.html

Stoop, P. P., & Wiers, V. C. (1996). The complexity of scheduling in practice. *International Journal of Operations & Production Mangement, 16*(10), 37-53.

Suchmann, M. C. (1995). Managing legitimacy: Stargeic and institutional approaches. *Academy of Management Review*(20), 571-610.

Sweeney, P. E., & Paternoster, E. R. (1991). Cutting and packing problems: An updated literature review. *Working Paper No. 654*.

Vonder, S. V., Demeulemeester, E., & Herroelen, W. (2008). Proactive heuristic procedures for robust project scheduling: an experimental analysis. *European Journal of Operational Research, 3*(189), 723-733.

APPENDIX

APPENDIX A: APPROACH AND STRUCTURE OF THE LITERATURE REVIEW

In this appendix we describe the approach and structure of our literature review. We searched for scientific literature using the search engine Scopus. We divided the search in eight subjects: evaluation of scheduling, review of production scheduling, Simulated Annealing, Adaptive Search, Tabu Search, scheduling in the corrugated board industry, uncertainty in production scheduling, cutting stock problem and the integrated cutting stock and scheduling problem.

For each subject we defined search criteria. These criteria can be found in Table A.1. Out of the eight searches we found in total 1834 relevant articles. To only include useful articles we defined excluding and including criteria for each subject and we sorted on times cited.

- Evaluation of scheduling: Articles that have another scope than the evaluation of scheduling are excluded. Also articles that are not about production scheduling are excluded.
- Review of production scheduling: Only select articles that are reviews of production scheduling.
- Simulated Annealing: Include articles that review or propose simulated annealing approaches for production scheduling.
- Tabu Search: Include articles that review or propose Tabu Search approaches for production scheduling.
- Adaptive Search: Include articles that use adaptive search for production scheduling
- Cutting stock problem: Exclude 2-, 3- and multi-dimensional cutting stock and packing problems. Also exclude heuristic approaches.
- Coping with uncertainty: exclude articles that are not about production scheduling

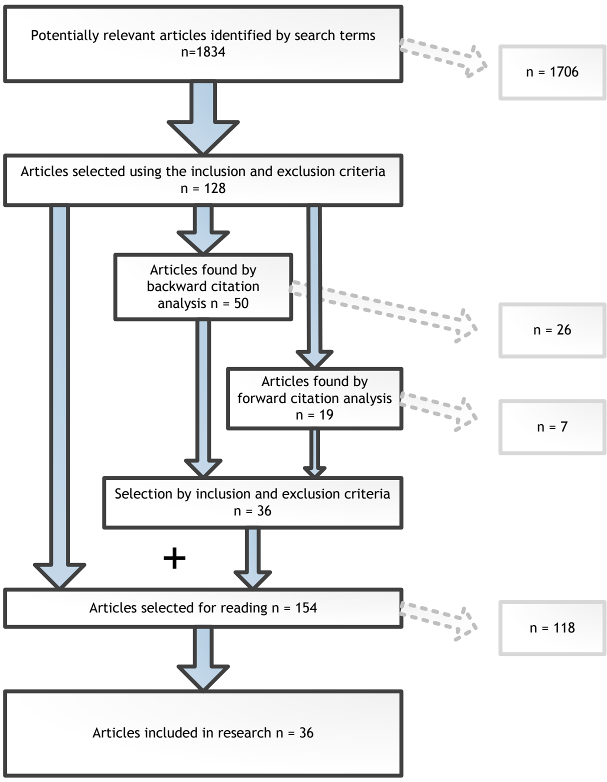


Figure A.1 Quantitative report literature review

Based on the above excluding and including criteria we selected 128 articles that we have quickly read to determine if we are going to include in our research. We also performed a forward and backward citation analysis from which we also selected 36 articles to read. After quickly reading/scanning the 154 articles we ended up with 36 articles that we included in our research.

Subject	AND criteria	OR criteria	Search	1e selection
Evaluation of scheduling	Title: Title: Title, Abstract, and Keywords: Production	- Evaluation - Measurement - Measures - Performance - Scheduling - Schedules	181	10
Review of production scheduling	Title: Title, Abstract, and Keywords:	- Review - Production - Scheduling - Schedules	45	6
Simulated Annealing	Title: Simulated Annealing Title, Abstract, and Keywords:	- Scheduling - Schedules	529	26
Adaptive Search	Title: Adaptive Search Title, Abstract, and Keywords:	- Scheduling - Schedules	21	2
Tabu Search	Title: Tabu Search Title, Abstract, and Keywords:	- Scheduling - Schedules	197	17
Scheduling in the corrugated board industry	Title: Corrugated Title, Abstract, and Keywords:	- Scheduling - Schedules	14	6
Cutting stock problem	Title:	- Cutting stock problem - Trim loss	170	43
	Title: NOT two-dimensional			
	Title: NOT packing			
Integrated Cutting stock and scheduling problem	Title, Abstract, and Keywords:	- Integrated - Integrating - Combined - Combining	21	8
	Title, Abstract, and Keywords:	- Scheduling - Schedules		
	Title, Abstract, and Keywords:	- Cutting stock problem - Trim loss		
Uncertainty	Title, Abstract, and Keywords: - Uncertainty - Production scheduling - Robust		82	10
Total articles			1834	128

Table A.1: Search terms for literature in Scopus

APPENDIX B: CUTTING STOCK PROBLEM

B.1: ILP FORMULATION

Indices

p	Cutting patterns
w	Paper widths
cspo	Orders that need to be solved by the CSP

Parameters

asc	Continuous {0,inf}	Average speed of the corrugator machine in m/hour
cc	Continuous {0,inf}	Cost of the corrugator machine in euros per hour
BigM	Continuous {0,inf}	Auxiliary parameter used for constraints 4.3 & 4.5
mrlci	Integer {0, inf}	The minimum run length for a CI job
mrlw	Integer {0, inf}	The minimum run length for a paper width
tww	Continuous {0,inf}	Time waste per paper width change
twp	Continuous {0,inf}	Time waste per pattern change
tl_p	Continuous {0,inf}	Trim loss of pattern p
gw_p	Continuous {0,inf}	The gross width of pattern p
$pwp_{p,w}$	Binary {1,0}	Indicates if paper width w is used for pattern p
$pno_{p,cspo}$	Integer {0, inf}	The number of sheets next to each other for order o in pattern p
rq_{cspo}	Integer {0, inf}	The requested order quantity of order cspo
ono_{cspo}	Integer {0, inf}	The number of products that come out of one sheet of order cspo
sl_{cspo}	Continuous {0,inf}	The sheet length of order cspo
cbg_{bg}	Continuous {0,inf}	Cost of corrugator board sheet per m² of board grade bg

Variables

RLP_p	Continuous {0,inf}	Run length of pattern p
AP_p	Binary {0,1}	Indicates if pattern p is active
APW_w	Binary {0,1}	Indicates if paper width W is active
PQ_{cspo}	Continuous {0,inf}	The planned quantity of order cspo

Objective function

$$\text{Min Z } = \sum_p RLP_p * tl_p$$

Alternative objective functions

$$\text{Min Z } = \sum_p RLP_p * \left(1 + \frac{tl_p}{100}\right)$$

$$\text{Min Z } = \sum_p RLP_p * \left(\frac{cc}{asc} + tl_p * cbg_{bg}\right)$$

$$\text{Min Z } = \left(\sum_p \left(\frac{RLP_p}{asc} + AP_p * twp\right) + \sum_w \left(APW_w * tww\right)\right) * cc + \left(\sum_p \left(RLP_p * tl_p + 3gw_p * AP_p\right) + \sum_w \left(APW_w * 7w\right)\right) * cbg_{bg}$$

Constraints

$$RLP_p \geq mrlci * AP_p \qquad \forall \text{ p}$$

$$RLP_p \leq BigM * AP_p \qquad \forall \text{ p}$$

$$\sum_{p} RLP_p * pwp_{p,w} \geq mrlw * APW_w \qquad \forall \text{ w}$$

$$\sum_{p} RLP_p * pwp_{p,w} \leq BigM * APW_w \qquad \forall \text{ w}$$

$$PQ_o = \sum_{p} \frac{RLP_p * pno_{p,o} * ono_o}{sl_o} \qquad \forall \text{ o}$$

$$PQ_o \geq rq_o * 1.04 \qquad \forall \text{ o}$$

$$PQ_o \leq rq_o * 1.06 \qquad \forall \text{ o}$$

B.2 PSEUDO CODE GENERATING CUTTING PATTERNS

Parameters

MinTrim	Continuous {0,inf}	Minimum trim loss required
MaxTrim	Continuous {0,inf}	Maximum trim loss when two orders are combined
sw_{cspo}	Continuous {0,inf}	The sheet width of order cspo
nw_p	Continuous {0,inf}	The net width of pattern p
$MaxOut_{cspo}$	Integer {0, inf}	The maximum number of sheets of order cspo next to each other

Variables

$CurOut_{cspo}$	Integer {0, $MaxOut_{cspo}$}	The current number of sheets of order cspo next to each other

Pseudo code

```
For (cspo) do
        MaxOut_cspo = ⌊MaxWidth / OrderWidth_cspo⌋
        If (MaxOut_cspo >7) then
                MaxOut_cspo = 7
        Endif
        CurOut_cspo =MaxOut_cspo
Endfor

For (cspo) do
        For (w|WidthAvailable_w,bg=1) do
                While (CurOut_cspo>0) do
                        If (CurOut_cspo *sw_cspo+MinTrim) ≤ w then
                                Add new pattern p to set cutting patterns
                                gw_p = w
                                nw_p = CurOut_cspo *sw_cspo
                                tl_p = gw_p - nw_p
                                pwp_p,w = 1
                                pno_p,cspo = CurOut_cspo
                        Endif
                        CurOut_cspo = CurOut_cspo -1
                Endwhile
                CurOut_cspo = MaxOut_cspo

                For (cspo2|cspo2 > cspo) do
                        While (CurOut_cspo2>0) do
                                If (CurOut_cspo *sw_cspo+ CurOut_cspo2 *sw_cspo2+MinTrim ≤ w) and
                                (CurOut_cspo *sw_cspo+ CurOut_cspo2 *sw_cspo2+MaxTrim ≥ w)  then
```

```
                    Add new pattern p to set cutting patterns
                    gw_p = w
                    nw_p = CurOut_cspo *sw_cspo + CurOut_cspo2 *sw_cspo2
                    tl_p = gw_p - nw_p
                    pwp_p,w = 1
                    pno_p,cspo = CurOut_cspo
                    pno_p,cspo2 = CurOut_cspo2
                Endif

                CurOut_cspo2 = CurOut_cspo2 - 1

                If (CurOut_cspo2=0) then
                    CurOut_cspo2=MaxOut_cspo2
                    CurOut_cspo=CurOut_cspo-1
                Endif
            Endwhile
            CurOut_cspo =MaxOut_cspo
            CurOut_cspo2=MaxOut_cspo2
        Endfor
    Endwhile
Endfor
```

Appendix C: Model indices, parameters, and variables

Indices

bg	Board grades
c	Conveyors
ci	CI jobs
ds	Deckle Solutution
m	Converting machines
o	Orders
t	time

Parameters and variables

$ASC_{ci,bg}$	Continuous	Average speed of the corrugator for CI job ci of board grade bg
cbg_{bg}	Continuous	The cost of board grade bg per m^2
cl_c	Continuous	The length of conveyor c
$CMO_{o,t}$	Continuous	Current meters of stacks occupied of order o on time t
CSTAS	Continuous	Current starting time, used for the Adaptive Search algorithm
CurrentTime	Continuous	The current time on which the scheduling is performed
$CusIm_o$	Continuous	The customer importance of order o
$Factor_m$	Continuous	Factor for coping with uncertainty for converting machine m
$FCon_{c,t}$	Continuous	Fill rate of conveyor c on time t
FP_t	Continuous	Estimated fill rate of the Pentek on time t
$FTDS_{ds}$	Continuous	Finishing time of deckle solution ds
$LFTCor_o$	Continuous	Latest finishing time for order o on the corrugator machine
$LSTCor_o$	Continuous	Latest starting time for order o on the corrugator machine

$MaxSC_{bg}$	Continuous	Maximum speed of the corrugator machine for board grade bg
$MaxTS_{ci}$	Continuous	Maximum speed of the cutting tools for CI job ci
$MCI_{o,ci}$	Continuous	Meters of stacks produced by CI job ci for order o
mcl_{m}	Continuous	Length of the machine conveyor of machine m
$MCon_{c,t}$	Continuous	Meters occupied of conveyor c on time t
MinSC	Continuous	Minimum speed of the corrugator machine
$MMCon_{t,m}$	Continuous	Meters occupied of the machine conveyor of machine m on time t
$MP_{o,t}$	Continuous	Meters of stacks produced of order o on time t
$OinDS_{o,ds}$	Binary	Indicates if order o is in Deckle Solution ds
$OinCI_{o,ci}$	Binary	Indicates if order o is in CI job ci
$NOinCI_{o,ci}$	Integer	Indicates how many sheets of order o are produced next to each other in CI job ci
φ_{ds}	Continuous	Priority of deckle solution ds
P_{ds}	Continuous	Probability of deckle solution ds
PlanHor	Continuous	Planning horizon for scheduling
R_{ds}	Continuous	Regret of deckle solution ds
$Route_{o,s}$	Element	The machine on which order o is routed for production step s
$SCor_{ci,bg}$	Continuous	Speed of the corrugator machine of CI job ci of board grade bg
$SetAS_{ds}$	Continuous	Setup time of deckle solution ds for the AS algorithm
$SetDS_{ds}$	Continuous	Setup time of deckle solution ds
$SetFC_{fc1,fc2}$	Continuous	Setup time of the corrugator based on flute combinations fc1&fc2
$SetJ_{o,m}$	Continuous	Setup time of converting job of order o on machine m
SH_{o}	Continuous	Stack height for order o
sl_{o}	Continuous	Sheet length of order o
$StaCI_{o,ci}$	Integer	The number of stacks produced of order o in CI job ci
$STCI_{ci}$	Continuous	Starting time of CI job ci
$STJ_{o,m}$	Continuous	Starting time of a converting job of order o on machine m
sw_{o}	Continuous	Sheet width of order o
TH_{o}	Continuous	Thickness of the corrugated board of order o
TMO_{o}	Continuous	Total meters of stacks of order o
$TPTCI_{ci}$	Continuous	Total production time of CI job ci
$TPTJ_{o,m}$	Continuous	Total productiontime of a converting job of order o on machine m
TTarAS	Continuous	Total tardiness of deckle solutions for the AS algorithm
TTardDS	Continuous	Total tardiness of the deckle solutions
$WTardDS_{ds}$	Continuous	Weighted tardiness of deckle solutions ds

APPENDIX E: SETUP TIMES CORRUGATOR

In Table E.1 the setup times of the corrugator machine are shown dependent on the corrugator rolls that need to be placed in the different masters.

From \To		Master1	B		C		E		R		C	B	E	E
		Master2		B		C		E		R	B	E	B	E
Master1	Master2	Flute Combination	*B*	*B*	*C*	*C*	*E*	*E*	*R*	*R*	*BC*	*EB*	*BE*	*E*
B		*B*	*Confidential*											
	B	*B*												
C		*C*												
	C	*C*												
E		*E*												
	E	*E*												
R		*R*												
	R	*R*												
C	B	*BC*												
B	E	*EB*												
E	B	*BE*												
E	E	*EE*												

Table E.1 Setup times corrugator (setup in minutes)

APPENDIX F: TRANSPORTATION TIMES

In Table F.1 the internal transportation times between machines are shown measured in minutes.

From\ To	61	171	419	425	426	436	728	729	735
61	*Confidential*								
171									
419									
425									
426									
436									
728									
729									
735									

Table F.1 Transportation time (minutes)

Appendix G: Stakeholder analysis

Determining the performance of a production schedule can be very hard. There are many stakeholders that have different objectives and wishes. In order to make a good decision about the importance each stakeholder and their objectives and wishes we are mapping out the stakeholders based on the framework of Mitchel *et al.* (1997). They use the stakeholder definition of Freeman (1984): *"any group or individual who can affect or is affected by the achievement of the organization its objectives"* (Freeman, 1984, p. 48).

Mitchell *et al.* (1997) propose a framework based on three stakeholder attributes: power, legitimacy, and urgency. Power can be defined as *"the ability of those who possess power to bring about the outcomes they desire"* (Salancik & Pfeffer, 1974, p. 3). Etzioni (1964) categorizes power by the type of resource used to exercise it; coercive power (physical resource of force, violence, or restraint), utilitarian power (material or financial resources), and normative power (symbolic resources).

Legitimacy can be defined as *"a generalized perception or assumption that the actions of an entity are desirable, proper, or appropriate within some socially constructed system of norms, values, beliefs, and definitions"* (Suchmann, 1995, p. 574). Mitchell *et al.* (1997) state that legitimacy is imprecise and hard to operationalize. However, it is a crucial attribute of the stakeholder analysis.

Mitchell *et al.* (1997) propose a definition for urgency that is based on two attributes: time sensitivity and criticality. Time sensitivity relates to the degree to which delay in the claim or relationship is unacceptable. Criticality relates to the importance of the claim.

These three attributes result in eight different kinds of stakeholders that are shown in Figure C.1. The stakeholders that are in area 1, 2 and 3 are latent stakeholder. They only have one of the three attributes and these can be categorized as the least important stakeholders. Stakeholders in areas 4, 5, and 6 are called expectant stakeholders. They have two attributes and have a medium importance. The definitive stakeholder has all three attributes and is of high importance for the organization.

Assessing the internal stakeholders at DS Smith

We now discuss the different internal stakeholders regarding a production schedule at DS Smith. For each stakeholder we discuss their position and their objectives and wishes regarding a production schedule.

Sales

The sales department, internal and external sales employees, is a dependent stakeholder. The sales department has the attribute legitimacy because their actions are dependent on the Voice Of the Customer (VOC) of DS Smith. They want orders to be delivered on time and in the right quantity (VOC). The sales department also has the attribute urgency. Their claims are time-sensitive and also are important because they are customer oriented.

Production employees corrugator machine

The production employees of the corrugator machine are dependent stakeholders. They want a schedule that minimizes setups. Setups require much handling and the workload increases. This is an important claim because setups result in less time available for production. Because the corrugator machine is the bottleneck machine this claim is urgent and so the stakeholder has the attribute urgency. They also have the attribute legitimacy because minimizing setup of the corrugator machine is generally accepted as an important objective.

PRODUCTION EMPLOYEES CONVERTING MACHINES

The production employees of the converting machines are discretionary stakeholders. Their wish is to have a schedule that takes into account converting setup time. This means that they want orders to be clustered. So orders with the same dies, ink, or punch should be scheduled after each other. This reduces the workload of operators and makes it easier. This claim is legitimate because this is appropriate when possible. However, in most cases this is not possible or conflicting with the corrugator schedule. Also the converting machines are not the bottleneck so the production employees do not have the attribute urgency.

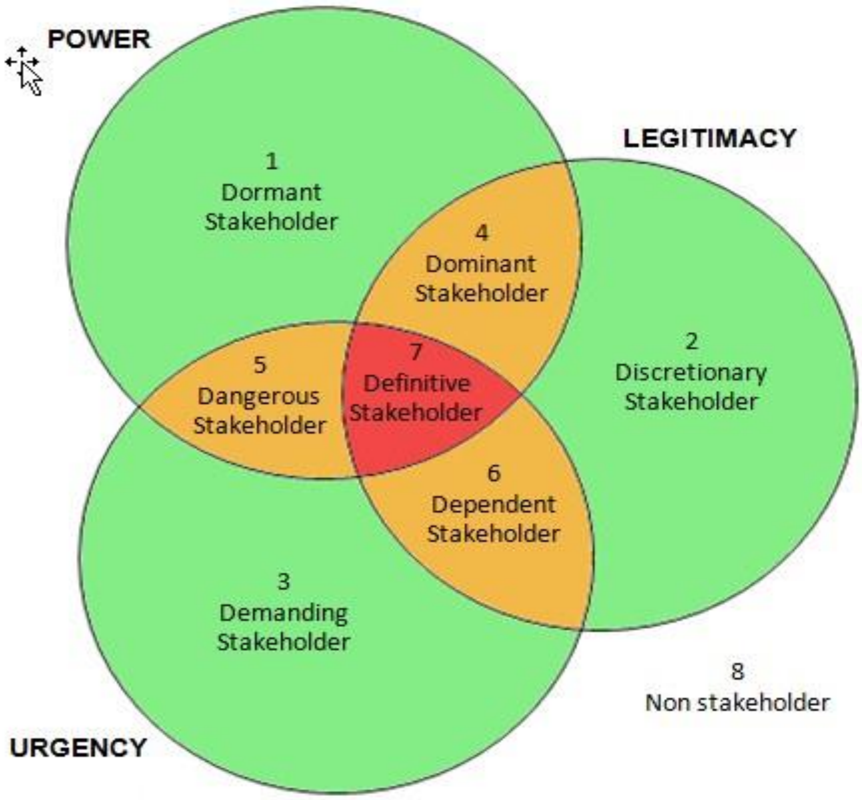


Figure C.1 (Stakeholder salience, 2014)

PRODUCTION PLANNERS

The production planners are definitive stakeholders. They have the power to change the schedule because it is their job to change and make production schedules. Their actions are also legitimate and urgent. It is of great importance that they schedule the production process as efficient as possible. The production planners have the objective of minimizing the tardiness of orders and next to that minimizing setup at the corrugator and minimizing waiting on corrugator downtime by the converting machines. Moreover, they also have the wish to have a schedule that is reliable and robust. Unreliable and not robust schedules result in situation where a schedule needs to be rescheduled. This causes the production planners to have extra work.

Expedition planners

The expedition planners are dependent stakeholders. Their actions are both desirable and urgent. However, they do not have the power to change production schedules. They work with the schedule that the production planners made. Just like the production planners the expedition planners wish to have a production schedule that is reliable and robust. When the schedule changes, there is a probability that an expedition schedule is conflicting.

(Production) management

Management is a definitive stakeholder. They have the power, are legitimate, and have urgent claims. Their objective is a production schedule that results in a production process that produces maximum output and meets customer demands. This means that they want to minimize setups and downtimes, because this results in a reduction in throughput. They also want to minimize the tardiness of orders.

Overview

The stakeholders and their attributes are summarized in Table 1. We can see that there are three dependent stakeholders, one discretionary stakeholder, and two definitive stakeholders.

Stakeholder	Attribute			**Type stakeholder**
	Power	**Legitimacy**	**Urgency**	
Sales department		X	X	Dependent
Production employees corrugator		X	X	Dependent
Production employees converting		X		Discretionary
Production planners	X	X	X	Definitive
Expedition planners		X	X	Dependent
(Production) management	X	X	X	Definitive

Table C.1: Overview stakeholders and their attributes

Out of the stakeholder analysis we found that timeliness of orders, lost production time, robustness, and ease of working are important objectives and wishes.

Stakeholder	**Timeliness of orders**	**Lost production time**	**Robustness**	**Ease of working**
Sales department	X			
Production employees corrugator		X		X
Production employees converting		X		X
Production planners	X	X	X	
Expedition planners			X	
(Production) Management	X	X		

Table C.2: Different objectives for production scheduling

APPENDIX H: PENTEK OVERVIEW

This appendix gives an overview of the Pentek module. Figure H.1 gives a representation of the fill rate of the Pentek and Figure H.2 gives a representation of the fill rates of the seven different conveyors and the meters occupied of the conveyors in front of the machines. We also give the pseude code used to determine the fill rate(s).

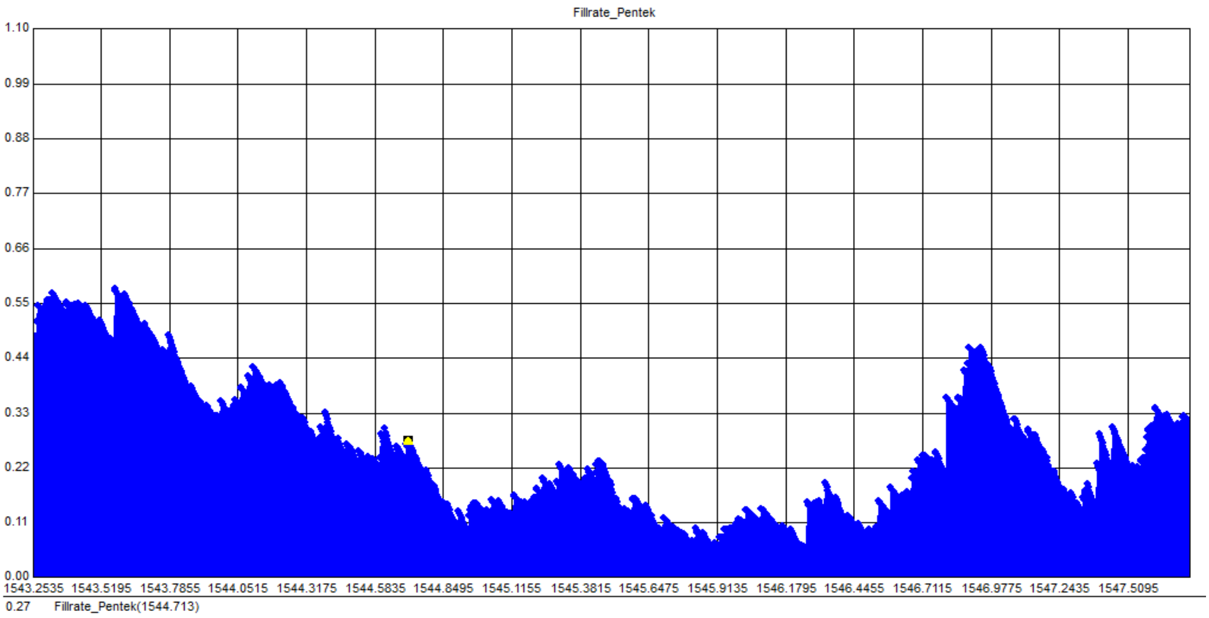


Figure H.1 Pentek fill rate

Figure H.2 Overview conveyors

Pseudo code:

$MCon_{c,t} = 0$
$MMCon_{t,m} = 0$
$MP_{o,t} = 0$
$CMO_{o,t} = 0$

```
for (t) do
 for (s|s=1) do
  for (o|(FST_o - DT_o) ≤ t) do
   for (c|(sl_o<WC_c and sl_o≥WC_c-1))do
    for (m|Route_o,s = m and FTJ_o,m > t) do
```

$$\mathrm{MP}_{o,t} = \sum_{ci|OinCI_{o,ci}=1} \left(\frac{\mathrm{MCI}_{\mathrm{o,ci}}}{\max\left\{1; \dfrac{\mathrm{TPTCI}_{ci}}{\min\left\{\mathrm{TPTCI}_{ci};\ \mathrm{t}-\ \mathrm{STCI}_{ci}\right\}}\right\}} \right)$$

$$\mathrm{CMO}_{o,t} = \mathrm{MP}_{o,t} * \left(1 - \max\left\{0\ ; \frac{\min\limits_{m|Route_{o,1}=m} \left\{TPTJ_{o,m}\ ; t - STJ_{o,m}\right\}}{\dfrac{MP_{o,t}}{TMO_o} * TPTJ_{o,m}}\right\}\right)$$

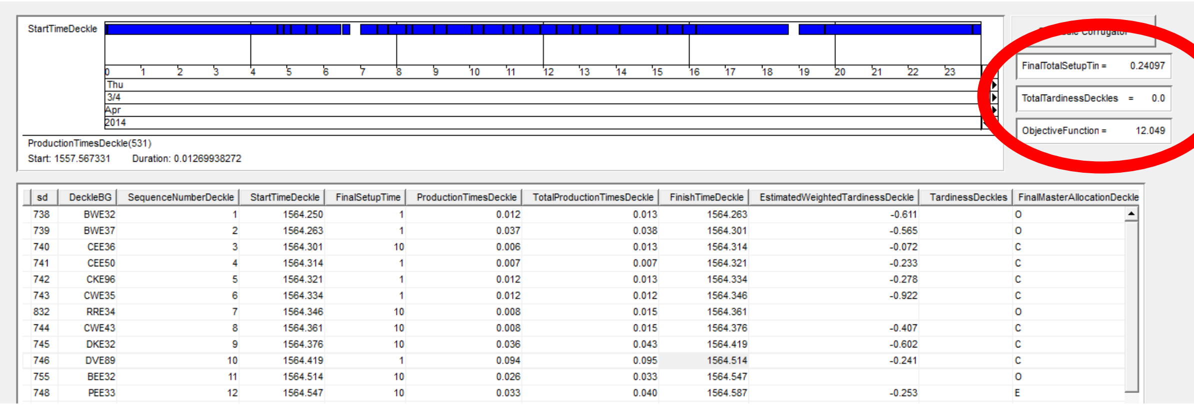
```
     If MMCon_t,m < mcl_m then
          MMCon_t,m = MMCon_t,m + CMO_o,t
          if MMCon_t,m > mcl_m then
               MCon_c,t = MCon_c,t + (MMCon_m – mcl_m)
               MMCon_m = mcl_m
          Endif
     else
          MCon_c,t = MCon_c,t + CMO_o,t
     Endif
    Endfor
   Endfor
  Endfor
 Endfor
Endfor

For t do
 For (c|MCon_c,t > cl_c  and  c<7) do
          MCon_c+1,t = MCon_c+1,t + (MCon_c,t –cl_c)
          MCon_c,t = cl_c
 Endfor
Endfor
```

$FCon_{c,t} = MCon_{c,t} / cl_c$

$$FP_t = \frac{\sum_c MCon_{c,t}}{\sum_c cl_c}$$

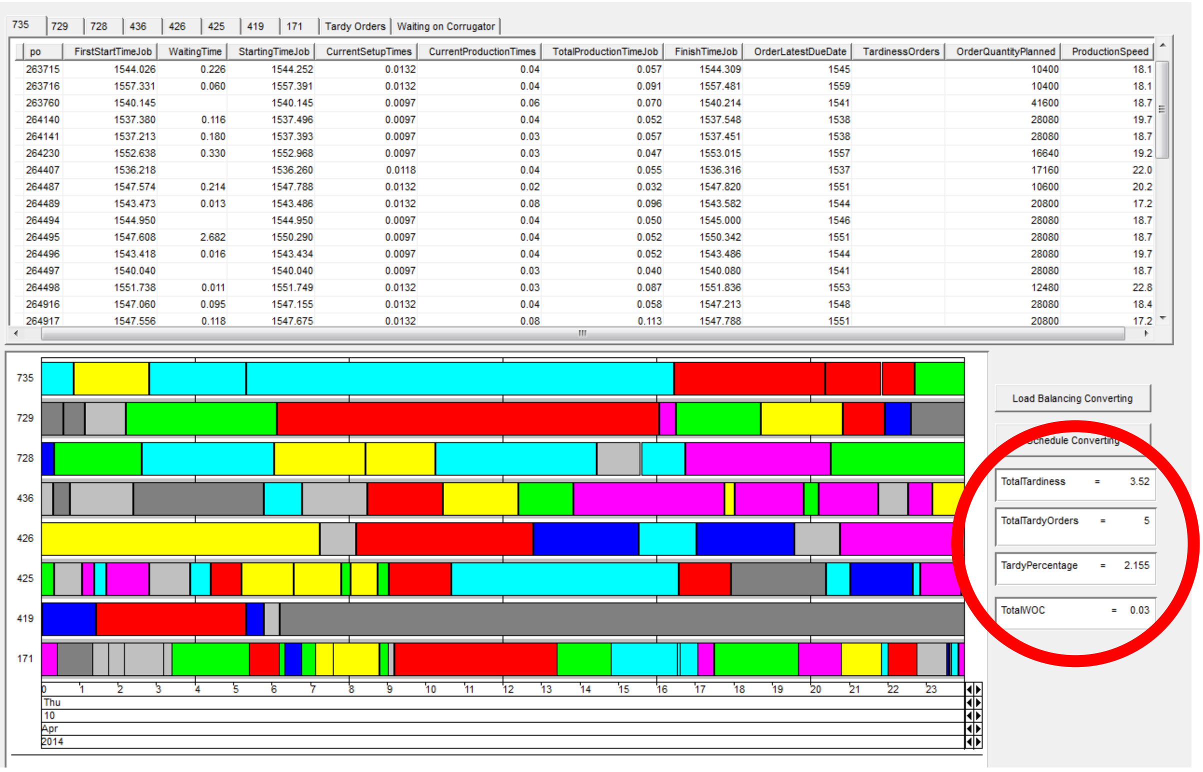
APPENDIX I: CORRUGATOR AND CONVERTING SCHEDULING OVERVIEW

This appendix gives screen shots of the corrugator and converting scheduling modules. In Figure I.1 the screenshot of the corrugator scheduling module can be found and in Figure I.2 the converting scheduling module. In the marked areas the performance indicators are shown.



sd	DeckleBG	SequenceNumberDeckle	StartTimeDeckle	FinalSetupTime	ProductionTimesDeckle	TotalProductionTimesDeckle	FinishTimeDeckle	EstimatedWeightedTardinessDeckle	TardinessDeckles	FinalMasterAllocationDeckle
738	BWE32	1	1564.250	1	0.012	0.013	1564.263	-0.611		O
739	BWE37	2	1564.263	1	0.037	0.038	1564.301	-0.565		O
740	CEE36	3	1564.301	10	0.006	0.013	1564.314	-0.072		C
741	CEE50	4	1564.314	1	0.007	0.007	1564.321	-0.233		C
742	CKE96	5	1564.321	1	0.012	0.013	1564.334	-0.278		C
743	CWE35	6	1564.334	1	0.012	0.012	1564.346	-0.922		C
832	RRE34	7	1564.346	10	0.008	0.015	1564.361			O
744	CWE43	8	1564.361	10	0.008	0.015	1564.376	-0.407		C
745	DKE32	9	1564.376	10	0.036	0.043	1564.419	-0.602		C
746	DVE89	10	1564.419	1	0.094	0.095	1564.514	-0.241		C
755	BEE32	11	1564.514	10	0.026	0.033	1564.547			O
748	PEE33	12	1564.547	10	0.033	0.040	1564.587	-0.253		E

Figure I.1 Corrugator scheduling



po	FirstStartTimeJob	WaitingTime	StartingTimeJob	CurrentSetupTimes	CurrentProductionTimes	TotalProductionTimeJob	FinishTimeJob	OrderLatestDueDate	TardinessOrders	OrderQuantityPlanned	ProductionSpeed
263715	1544.026	0.226	1544.252	0.0132	0.04	0.057	1544.309	1545		10400	18.1
263716	1557.331	0.060	1557.391	0.0132	0.04	0.091	1557.481	1559		10400	18.1
263760	1540.145		1540.145	0.0097	0.06	0.070	1540.214	1541		41600	18.7
264140	1537.380	0.116	1537.496	0.0097	0.04	0.052	1537.548	1538		28080	19.7
264141	1537.213	0.180	1537.393	0.0097	0.03	0.057	1537.451	1538		28080	18.7
264230	1552.638	0.330	1552.968	0.0097	0.03	0.047	1553.015	1557		16640	19.2
264407	1536.218		1536.260	0.0118	0.04	0.055	1536.316	1537		17160	22.0
264487	1547.574	0.214	1547.788	0.0132	0.02	0.032	1547.820	1551		10600	20.2
264489	1543.473	0.013	1543.486	0.0132	0.08	0.096	1543.582	1544		20800	17.2
264494	1544.950		1544.950	0.0097	0.04	0.050	1545.000	1546		28080	18.7
264495	1547.608	2.682	1550.290	0.0097	0.04	0.052	1550.342	1551		28080	18.7
264496	1543.418	0.016	1543.434	0.0097	0.04	0.052	1543.486	1544		28080	19.7
264497	1540.040		1540.040	0.0097	0.03	0.040	1540.080	1541		28080	18.7
264498	1551.738	0.011	1551.749	0.0132	0.03	0.087	1551.836	1553		12480	22.8
264916	1547.060	0.095	1547.155	0.0132	0.04	0.058	1547.213	1548		28080	18.4
264917	1547.556	0.118	1547.675	0.0132	0.08	0.113	1547.788	1551		20800	17.2

Figure I.2 Converting scheduling

APPENDIX J: OVERVIEW EXPERIMENTS CSP

In Table J.1 we show an overview of the 22 experiments used for testing alternative objective functions for the cutting stock problem.

Experiment	Alternative	SubAlternative	Speed Corrugator	Costs Corrugator	Waste width change	Waste CI change	Time width change	Time CI change	Objective
1	1	1	200 m/min	€ 300,00	7 m	3 m	5 min	0,5 min	Trimloss
2	2	1	200 m/min	€ 300,00	7 m	3 m	5 min	0,5 min	Runlength
3	3	1	200 m/min	€ 200,00	7 m	3 m	5 min	0,5 min	Costs
4	3	2	200 m/min	€ 400,00	7 m	3 m	5 min	0,5 min	Costs
5	3	3	200 m/min	€ 600,00	7 m	3 m	5 min	0,5 min	Costs
6	3	4	200 m/min	€ 800,00	7 m	3 m	5 min	0,5 min	Costs
7	3	5	200 m/min	€ 1.000,00	7 m	3 m	5 min	0,5 min	Costs
8	3	6	200 m/min	€ 1.200,00	7 m	3 m	5 min	0,5 min	Costs
9	3	7	200 m/min	€ 1.400,00	7 m	3 m	5 min	0,5 min	Costs
10	3	8	200 m/min	€ 1.600,00	7 m	3 m	5 min	0,5 min	Costs
11	3	9	200 m/min	€ 1.800,00	7 m	3 m	5 min	0,5 min	Costs
12	3	10	200 m/min	€ 2.000,00	7 m	3 m	5 min	0,5 min	Costs
13	3	11	250 m/min	€ 200,00	7 m	3 m	5 min	0,5 min	Costs
14	3	12	250 m/min	€ 400,00	7 m	3 m	5 min	0,5 min	Costs
15	3	13	250 m/min	€ 600,00	7 m	3 m	5 min	0,5 min	Costs
16	3	14	250 m/min	€ 800,00	7 m	3 m	5 min	0,5 min	Costs
17	3	15	250 m/min	€ 1.000,00	7 m	3 m	5 min	0,5 min	Costs
18	3	16	250 m/min	€ 1.200,00	7 m	3 m	5 min	0,5 min	Costs
19	3	17	250 m/min	€ 1.400,00	7 m	3 m	5 min	0,5 min	Costs
20	3	18	250 m/min	€ 1.600,00	7 m	3 m	5 min	0,5 min	Costs
21	3	19	250 m/min	€ 1.800,00	7 m	3 m	5 min	0,5 min	Costs
22	3	20	250 m/min	€ 2.000,00	7 m	3 m	5 min	0,5 min	Costs

Table J.1 Overview of the experiments for alternative CSP objective function testing

Appendix K: Results alpha settings testing

This appendix shows the results of the four tests for choosing the best alpha settings.

Alpha	10	15	20	25	30	35	40	45	50	55
average	26.666	22.153	19.744	18.489	17.765	17.305	17.056	16.856	16.749	16.655
max	35.994	28.754	25.215	25.772	21.903	21.798	20.555	20.561	19.837	19.578
min	19.890	16.578	14.435	14.075	14.191	12.848	13.483	13.128	13.207	13.146
St. dv.	2.352	1.997	1.637	1.409	1.170	1.091	1.000	0.981	0.931	0.944

Table K.1 Results of the alpha test for situation 1

Alpha	10	15	20	25	30	35	40	45	50	55
average	12.792	9.931	8.693	8.164	7.903	7.769	7.736	7.724	7.707	7.689
max	17.680	14.430	11.861	11.124	10.708	9.862	9.692	9.395	9.481	9.115
min	8.728	6.744	6.536	6.536	6.536	6.744	6.744	6.744	6.744	6.744
St. dv.	1.514	1.144	0.875	0.724	0.658	0.635	0.617	0.607	0.605	0.601

Table K.2 Results of the alpha test for situation 2

Alpha	10	15	20	25	30	35	40	45	50	55
average	43.828	35.157	30.910	28.524	26.969	26.241	25.685	25.276	25.073	24.980
max	61.035	50.701	47.482	38.381	38.882	36.515	34.411	35.739	36.438	34.638
min	30.566	23.207	21.626	19.624	19.123	16.692	18.192	18.927	17.272	18.470
St. dv.	4.992	3.947	3.407	2.973	2.787	2.528	2.468	2.385	2.369	2.298

Table K.3 Results of the alpha test for situation 3

Alpha	10	15	20	25	30	35	40	45	50	55
average	17.872	13.784	11.221	9.840	9.114	8.745	8.384	8.167	8.004	7.940
max	24.766	20.277	16.090	14.366	13.061	11.888	11.124	11.646	10.734	10.827
min	12.626	9.316	7.596	7.134	6.713	6.651	6.651	6.651	7.003	6.651
St. dv.	1.897	1.611	1.298	1.061	0.911	0.909	0.914	0.897	0.852	0.841

Table K.4 Results of the alpha test for situation 4