Improving the Efficiency of the Transfer Press at Kvadrat High Performance Textiles

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Bachelor Thesis, Industrial Engineering & Management

21 August 2023

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Improving the Efficiency of the Transfer Press at Kvadrat High Performance Textiles

Solving a machine scheduling problem with raw material selection to improve the efficiency.

Publication date : 21/08/2023

Revision number : V1.0

Number of pages : 57

Number of appendices : 6

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Preface

Dear reader,

In front of you lies my bachelor thesis titled “Improving the Efficiency of the Transfer Press at Kvadrat High Performance Textiles”. This thesis serves as the final assignment of the bachelor’s program in Industrial Engineering and Management of the University of Twente.

To start off, I would like to thank Kvadrat High Performance Textiles for providing me the opportunity to learn and conduct research in a field typical for Industrial Engineering and Management. Secondly, I would to thank all my colleagues at KHPT for their support and assistance. I would specifically like to thank Werner and Luuk for their input and guidance throughout the research period.

Furthermore, I wish to thank my first supervisor, Marco Schutten for his attention to detail, critical reflection on my writing style, and assistance. I would also like to thank my second supervisor, Leo van der Wegen for his clear feedback and cooperation, which enhanced the quality of this report.

Finally, I would like to express my gratitude to my family, friends and loved ones for their support and understanding throughout the process of writing this thesis.

Max Haasewinkel

August, 2023

Management summary

Problem identification

Kvadrat High Performance Textiles, located in Eibergen processes textile. The company struggles with low efficiency in phase 3 of the production process where the textile is colored. The transfer press colors the textile by using transfer paper. The machine frequently starts for small production runs, leading to high waste and low efficiency. The company presents the problem of having a low efficiency while using the machine and desires to improve the production plan by using a different scheduling strategy. We formulate the action problem and research question as follows:

Action problem: The efficiency of the TP-3 is too low, resulting in high waste and production costs.

Research question: How can the current scheduling strategy be improved to increase the efficiency of the transfer press at KHPT?

The company does not monitor the efficiency of the transfer press; therefore, first we investigate the current situation to see what the efficiency of the TP-3 actually is.

Current situation

An operator uses the transfer press to color the raw material according to specifications of the customer. The operator sets the machine up and inserts the raw material, which takes 45 minutes. The production plan determines the number of setups needed and consequently, the efficiency.

The current scheduling method assigns the orders a raw material roll, which is used to process the material and schedules the order in a production plan. The number of raw material roll changes needed to complete processing determine the total setup time. Therefore, we consider the assigning of raw material to the production order in addition to the scheduling strategy. The current strategy is to schedule orders in order to minimize earliness and tardiness, and cluster the orders assigned to same raw material roll in the same production week. The company's strategy in assigning raw material is to fit the orders, to the fullest raw material roll where an order can fit, and to use raw material rolls to their full extend when the warehouse is getting to its maximum, so the empty rolls can be discarded.

Experimental setup

We approach the problem of assigning orders to raw material rolls and the scheduling problem by splitting the problem in 2 parts: the raw material problem and the scheduling problem. The assigning of raw materials is categorized as a one-dimensional bin packing problem. There is no literature available that addresses both problems at once, therefore we decide to separate the problem. We solve the bin packing problem by splitting the problem into smaller subproblems. In each subproblem, we consider only one type of orders and raw material rolls. By solving all sub-problems, we solve the bin packing problem as a whole.

We formulated a solution approach where we select raw materials for the orders and schedule these. We constructed a model that begins by allocating orders to raw material rolls, and then proceeds to determine the production schedule. The company aims to fully use all raw material on the rolls. Therefore, we first assign raw materials to the orders. Once the orders have been assigned to raw materials, they can be scheduled accordingly.

To allocate orders to bins, we use the best-fit heuristic. This heuristic assigns an order to the bin that has the highest load and can fit the order. To optimize the solution an order splitting heuristic is used, which reduces the number of leftover bins after production, by using the bins to their capacity. This heuristic aims to decrease the used number of raw material rolls after processing in the warehouse, which is convenient for operators to find the raw material needed.

Due to the complexity of the scheduling problem, a heuristic is used to provide a solution capable of providing insights in a strategy that is effective in improving the efficiency of the TP-3. The heuristic of the proposed solution method is the SST (shortest setup time) priority rule which selects the next job based on the lowest setup time between jobs. In order to evaluate the effectiveness of the proposed solution, we compare it to the current scheduling method referred to as CURR. CURR is based on first minimizing earliness/tardiness and then clustering orders of the same bin in the same production week.

We assume only Monday and Thursday can be selected as production day such that other processing tasks can be completed in other production days. Mondays and Thursdays are most convenient since the load on the production phase is split in an even manner.

Results

The findings reveal that the best-fit bin packing heuristic does not effectively utilize the bins to their full capacity. Therefore, the outcomes of the bins are improved by the order splitting heuristic, and the results are presented in Table 1. The reduced number of bins remaining after production decreases the inventory level of the remaining bins by 16%, making it more convenient for operators to find the raw material roll required for production.

Instance	Best-fit number of bins	Order splitting heuristic number of bins	Difference	Bins filled by order splitting heuristic	Bins left after production using the order splitting heuristic
1	38	37	1	3	21
2	21	20	1	2	11
3	27	26	1	2	11
4	32	31	1	4	18
5	24	23	1	3	11
6	29	27	2	3	18
7	29	29	0	3	16
8	32	30	2	3	14
9	22	22	0	2	15
10	26	25	1	2	11
11	27	26	1	1	13
12	36	36	0	6	16

Table 1 Results bin packing model

The results of the scheduling model demonstrate that the SST heuristic outperform CURR in every aspect, except for average earliness in every instance. The efficiency of the TP-3 increases by 17% on average by using SST compared to CURR when using the output of the bin packing model. The earliness of the solution can be explained by the fact that the heuristic prioritizes scheduling jobs as soon as an opportunity arises, leading to jobs being scheduled much earlier than required. However, this approach offers the advantage of completing each job quickly, resulting in a low average tardiness. Additionally, due to the reduced number of setups, waste is significantly reduced as well. Table 2 presents the results of the scheduling model.

Instance	Production month	Efficiency (CURR)	Efficiency (SST)	Average earliness (days) (CURR)	Average earliness (days) (SST)	Average tardiness (days) (CURR)	Average tardiness (days) (SST)	Waste (m) (CURR)	Waste (m) (SST)	Computation time (s) (CURR)	Computation time (s) (SST)
1	March	35%	68%	4.51	8.21	2.75	0	325	200	19.15	17.96
2	March	49%	65%	1.33	8.26	0.67	0.20	195	110	19.48	18.78
3	March	52%	65%	2.27	9.62	0.27	0.10	245	145	19.33	18.10
4	March	50%	66%	1.56	10.39	0.33	0.05	300	160	19.98	16.50
5	July	51%	72%	6.77	13.17	0.23	0.01	315	125	23.31	16.85
6	July	52%	66%	3.95	10.49	1.07	0.02	205	140	23.86	17.27
7	July	49%	65%	2.51	8.18	0.55	0.27	295	160	23.75	16.91
8	July	53%	66%	2.70	7.12	1.84	0.71	320	175	24.03	17.12
9	December	52%	64%	4.81	9.15	0.30	0	190	120	22.41	19.24
10	December	50%	66%	4.58	11.43	0.15	0.02	270	140	22.61	18.38
11	December	52%	67%	2.19	8.76	0.31	0	275	145	22.12	19.65
12	December	48%	64%	3.55	8.65	1.44	0.08	390	200	22.96	18.76

Table 2 Results scheduling model

Conclusion

We conclude that, the efficiency of the transfer press can successfully be improved by adopting a scheduling strategy that aims to reduce setup times. In this strategy, the raw material is selected based on the best fit heuristic and an order splitting heuristic which reduces the number of leftover raw material rolls after processing. For the scheduling model, the proposed strategy improves almost every KPI on each demand level in all scenarios when compared to the current strategy. However, the average earliness is noticeably higher in the proposed strategy. This increase is caused by the SST heuristic which schedules all jobs in the first possible position, disregarding earliness and tardiness. Nevertheless, the advantages gained in terms of efficiency and reduction is waste, outweigh the disadvantages of early completion of products.

Lastly, we recommend Kvadrat High Performance Textiles the following:

- Before implementing the proposed strategy conduct research on the effects of implementing the proposed strategy on production in Phase 1/2 and Phase 3/4.
- Investigate the costs and consequences of implementing the proposed strategy for the company.
- Improve the data collection of material availability in the warehouse such that the effect of raw material availability on the planning can be investigated.

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Glossary

BPP	Bin packing problem
CURR	Current scheduling method
KHPT	Kvadrat High Performance Textiles
SST	Shortest setup time
TP-3	Klieverik GTC-141-3500 machine

1.Introduction

Section 1.1 introduces the company where the research takes place. In Section 1.2, we identify the problem and form a problem cluster to identify the core problem. In Section 1.3, we formulate the research questions, define the research scope, and outline the deliverables.

1.1 Kvadrat High Performance Textiles

Kvadrat High performance Textiles, located in Eibergen is the first company to use metallized textile and produces plisse blinds/curtains. Kvadrat acquired Verosol B.V. in 2019, and the company now consists of two separate companies: Kvadrat High Performance Textiles and Kvadrat Shade Assembly. Kvadrat High Performance Textiles functions as the textile production facility, while Kvadrat Shade serves as the assembly plant for the final product. The facility Kvadrat High Performance Textiles has approximately 40 employees and Kvadrat operates globally with nearly 1,000 employees. Their product range includes roller blind solutions with various types based on transparency, reflectiveness, metallization, and color. One of their most known products is the Silverscreen 202, renowned for its high reflection and energy efficiency. This product has a clear see through as well as 85% reflection, which results in better heat and solar management. Kvadrat is renowned for its expertise in the extensive production processing of textiles, particularly those that require metallization. These types of textiles undergo a special treatment using a metallization machine.

Figure 1 shows the layout of the production site, where all textile processing occurs. Kvadrat High Performance Textiles is organized in 4 phases, grouped together as Phase 1/2 (highlighted in blue and grey) and Phase 3/4 (highlighted in green and yellow). In Phase 1/2, the material undergoes washing, treatment, metallization, and texturing. Phase 3/4 involves coloring, testing, pleating, and cutting the material to the required sizes. After the four production phases, the material is sent to Kvadrat Shade Assembly or other partners for assembly. Each production phase has high configurability depending on the material, dimensions, and requirements specified by the customer.

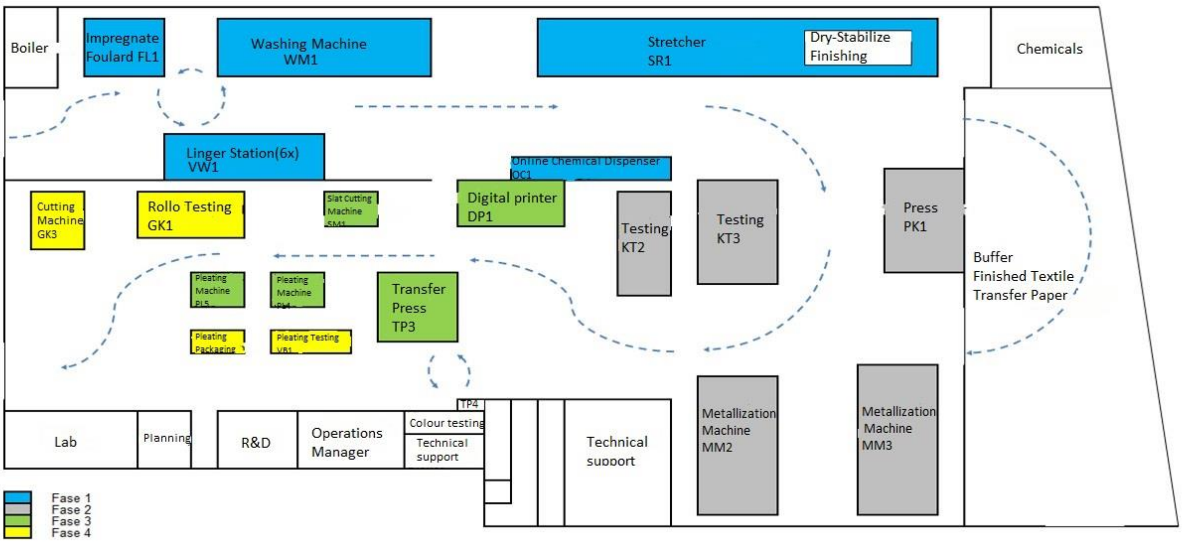

Figure 1 Production lay-out

1.2 Problem identification

In this section, we introduce the problem context of the research. Following the problem context, we describe the action problem, discrepancy between norm and reality, and the problem cluster. In the problem cluster, we select the core problem to solve in our research.

1.2.1 Problem context

The company has set a goal of reducing gas and electricity consumption in the future to achieve carbon neutrality. The management acknowledges that there are currently production issues that withhold them from using all resources efficiently. The company operates in a 2-shift configuration for textile production: from 06:00 to 14:00 and from 14:00 to 22:00, Monday through Thursday. On Fridays, only a morning shift from 06:00 to 14:00 is scheduled for production.

The planner makes the production plan in Excel. The strategy is make-to-stock for the products offered from the catalogue; for the remainder this is make-to-order. The ERP system contains the customer order data and due dates for orders. The system bases the production plan on the availability of machines. As there are only 3 employees working on Phase 3/4, not all machines can be operated at the same time. Therefore, the planner decides when the TP-3 is turned on and used during a shift. The planner decides which roll of raw material is used for producing the finished products. The orders are clustered and assigned to a raw material roll. When a used roll is not sufficient for the production orders, the planner decides whether a new roll is used or a combination of a used roll and a new roll. The planner makes the production planning based on experience and intuition. The production plan itself is based on just in time (JIT) scheduling, which does not aim to reduce waste, setup times or other criteria.

Phase 3 of the production process involves the use of the transfer press (TP-3), which is a heat press specifically designed for applying color to textile. Each time a textile roll is processed in the machine, there is a feed loss resulting in waste. Moreover, the TP-3 consumes a significant amount of electricity during warm-up and is frequently started for small production runs, leading to a low efficiency. The production plan determines whether the TP-3 is started and which orders are processed. Currently, the TP-3 is not being used efficiently. The management aims to adapt the production schedule to improve the efficiency of the TP-3 in production. The action problem is formulated as follows: “The efficiency of the transfer press is too low.”

Formula 1 defines efficiency as the time period t from the start, when the machine is started, to the end, when the machine is turned off. The processing time is defined as the duration it takes for the machine to complete all tasks, not considering setup time.

$$Efficiency(\%) = \frac{Processing\ time\ in\ time\ period\ t}{Processing\ time + setup\ time\ of\ the\ TP3\ in\ time\ period\ t} \quad (1)$$

The company’s objective is 70% efficiency or above for the TP-3. Meeting this target would lead to reduced production costs and energy usage per product and support the company’s efforts to become carbon neutral.

The efficiency of the TP-3 is between 35-53%. The current production planning results in a high number of setups, which leads to unnecessary feed losses. Moreover, there is no strategy to determine the production sequence, because the production plan specifies the tasks in random order.

1.2.2 Problem cluster

Figure 2 displays the problem cluster, which illustrates the interconnected problems within the company. The cluster shows the issues related to the action problem, identified through semi-structured interviews conducted with management, operators, and planner.

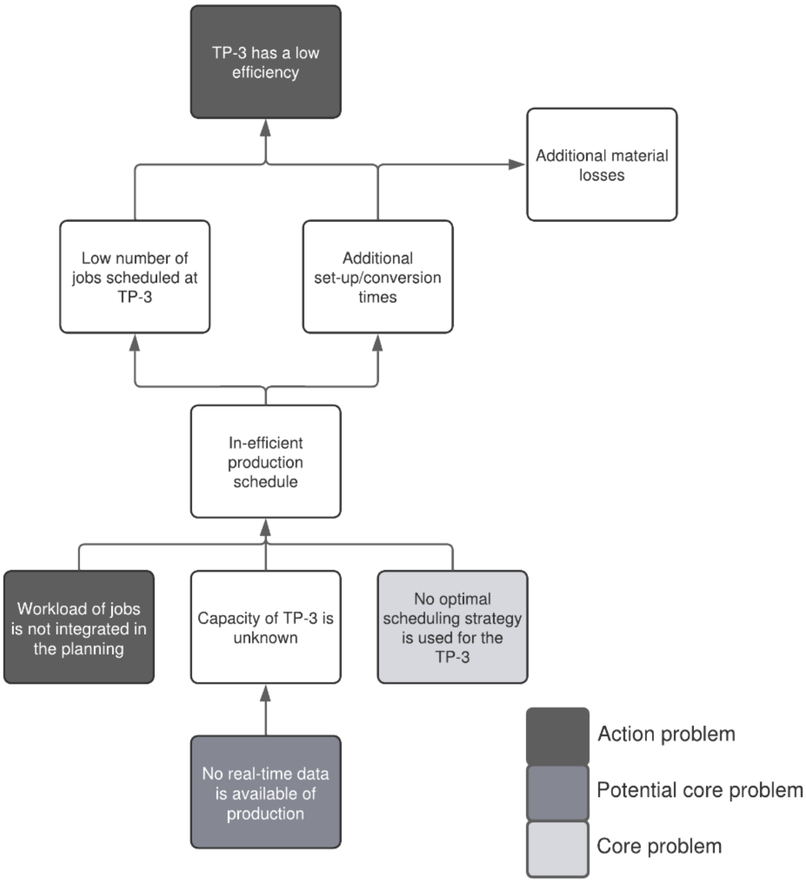

Figure 2 Problem cluster

The action problem is presented in dark grey in Figure 2, which is caused by two factors. Firstly, there is a low number of jobs assigned to the TP-3 when the machine is used, leading to high electricity usage. The issue is caused by the production plan lacking knowledge on the TP-3's production capacity. The ERP system uses the incorrect setup time, making it challenging to predict the required time accurately. Consequently, the planner plans fewer orders in a day. We investigate the processing times and characteristics of the TP-3 in Chapter 2. There is also a lack of monitoring equipment on the machine, making it difficult to obtain precise estimates of the time required for orders on the TP-3.

Secondly, there is additional setup time needed by having to change raw material rolls often. The production plan does not aim to reduce the number of setups, which leads to high setup time. The production plan follows a just-in-time scheduling approach where setup times are not prioritized. Each setup requires a new feed in the machine, resulting in 5 meters of unprocessed material which is discarded as waste. The current selection of raw material for the jobs leads to a high number of setups due to the frequent need to change raw material rolls during production. The lack of an optimal scheduling strategy for the TP-3 is the root cause of the scheduling problem within the production plan.

1.2.3 Core problem

In order to solve the action problem of improving the efficiency of the TP-3, we select the core problem from the problem cluster (Heerkens & van Winden, 2017). There are three possible core problems, of which only one we choose as the core problem.

1. **No real-time data is available of production.**

The availability of real-time data is crucial to monitor the time required for tasks. The lack of this data results in having little insight in the performance of production. The capacity of the TP-3 is unknown, resulting in an inefficient production plan. However, this problem cannot be solved without the use of monitoring equipment. The company does not allow observations of employees therefore, this problem is not suitable to be the core problem.

2. **Workload of the jobs is not integrated in the production plan.**

The workload estimation is essential for determining the number of orders to assign to the TP-3. There is information available on the completion of job times however, the setup times used in the planning of the TP-3 are incorrect. This can result in either fewer jobs being assigned, reducing productivity, or an excessive workload that leads to unfinished work within the given time. Consequently, the time allocation in the planning process directly affects the feasibility of the production plan. However, solving the workload estimation issue alone does not guarantee an overall improvement in efficiency, which is why it is not chosen as the core problem.

3. **No optimal scheduling strategy is used for the TP-3.**

The current scheduling strategy does not aim to minimize the setup time required for raw material roll changes in the production process to obtain a high efficiency. Therefore, we choose improving the scheduling strategy as the core problem. By improving the scheduling strategy we aim to improve the efficiency of the TP-3, by reducing the number of setups required in production.

1.3 Research design

In this section, we formulate and explain the research context, research scope, and research questions. Moreover, we discuss the limitations of this research.

1.3.1 Research context

Before formulating the research questions, it is important to provide further explanation regarding the research context. In the production plan, orders are assigned to raw material rolls, with the length of an order varying from 30 meters up to the maximum length of a raw material roll. However, if a raw material roll contains less than 35 meters of material, it becomes unusable for production due to the minimum order length requirement of 30 meters. The TP-3 generates 5 meters of waste, making it impossible to meet the minimum order length, resulting in the raw material roll being discarded as waste. This highlights the significance of optimizing raw material utilization to minimize waste.

The goal is to improve the scheduling strategy to improve the efficiency of the TP-3. In addition, we also consider assigning raw material to the orders, known as the 1-dimensional bin packing problem. This problem has a substantial impact on the production process.

1.3.2 Research scope and deliverables

In this research, we aim to provide a solution to the selected core problem of improving the efficiency of the TP-3 at KHPT within the available research time. Production Phase 1/2, where there is generally sufficient finished material for the TP-3, are outside the scope of this research. Furthermore, ordering policies, minimum stock levels, and employee performance differences are also excluded from the research scope. In this research, we consider only the one-sided coloring processing of materials on the TP-3. Other processes such as thermosetting, cutting, and two-sided coloring are disregarded since they occur rarely (less than 40 times per year) and accounts for less than 1% of the total processing volume.

We provide the following deliverables:

- Conceptual model for scheduling using the TP-3
- A model which selects raw material for the orders
- An advisory report detailing a strategy that improve the efficiency of the TP-3 at KHTP

1.3.3 Research questions

We formulate the research question as follows: How can the current scheduling strategy be improved to increase the efficiency of the transfer press at KHPT? To answer this research question, we divide it into manageable sub-research questions. The sub-research questions are as follows:

1. *What is the current situation of the production process at the transfer press?*
2. *Which methods and theories are discussed in literature on 1-dimensional bin packing and scheduling strategies that may help to improve the efficiency of the transfer press machine?*
3. *How can the theory be used for an improved scheduling strategy on the TP-3?*
4. *How does the improved scheduling strategy perform compared to the current situation?*

Problem analysis

1. *What is the current situation of the production process at the transfer press?*
    a. *What are the production processes, and how are these connected?*
    b. *How is the production plan made?*

The first question aims to analyze the current production process and the performance. We answer this question by using available data and conducting interviews with management, employees, and the planner. We answer the research question by providing flowchart of how materials pass through production and an overview of the performance.

The second question focuses on how the planner constructs the production. The production plan is primarily based on experience of the planner, so obtaining an overview how the planner constructs the production plan is vital to analyze which strategy he/she uses. To achieve this, we conduct an unstructured interview with the planner to identify the criteria and constraints used in creating the production plan. We then create a flowchart illustrating the planner's steps and compile a list of criteria and constraints

Formulating solutions

2. *What scheduling methods are available for the bin packing problem and machine scheduling problem to improve the efficiency of the transfer press?*

The question aims to explore available methods and theories for improving the efficiency of the transfer press. Additionally, we require knowledge is to be able to assign raw materials to orders.

The selection of raw material for orders is known as a 1-dimensional bin packing problem. To gather relevant information on scheduling strategies and 1-dimensional bin packing, we conduct a systematic literature review.

3. *How can the theory be used for an improved scheduling strategy on the TP-3?*
    a. Which scheduling strategy fits the current production plan?
    b. How can a suitable model be constructed for the TP-3?

The goal is to provide advice to the company on adjusting the scheduling strategy to improve the efficiency of the TP-3. This involves identifying the current scheduling strategy and constructing a suitable model for the TP-3 in which the current strategy can be compared to a new strategy. A policy for raw material selection needs to selected as well. Additionally, we choose suitable scenarios to assess the performance of the scheduling strategies. To gather the necessary information, we conduct semi-structured interviews with both management and the planner.

Choosing solution

4. *How does the improved scheduling strategy perform compared to the current situation?*

To evaluate the performance of scheduling strategies, we implement these using Visual Basic Applications (VBA). Our investigation focusses on the effects of material selection on the warehouse and material usage in addition to efficiency only. We compare the outcomes of the proposed strategy and the current strategy through experiments, considering factors such as efficiency and key performance indicators (KPIs). The results are incorporated into the advisory report for the company.

1.3.4 Limitations

As stated in the scope, the production focus is restricted to the TP-3. Consequently, the incoming material for processing is limited to the material present in the warehouse. Furthermore, no material is allowed to be cut into smaller widths.

The data gathering method via direct observations is limited due to management's restriction on timing employees using stopwatches or tracking devices. However, the use of time-related data available from completion times in the ERP system is allowed. Consequently, the gathering of data is primarily based on historic data, which is subject to certain limitations.

2. Current situation

In this chapter, we address the first research question about the current situation of the production process at the transfer press. In Section 2.1, we provide an in-depth description of the production process and the various phases of production. In Section 2.2, we analyze the transfer press itself, providing an overview of the different steps involved in production and determining the processing and setup times. Moving on, Section 2.3 involves the production planning and scheduling process, examining how decisions are made regarding the planning. We evaluate the performance of the production plan in Section 2.4. We summarize our findings in Section 2.5

2.1 Production process

In this section, we first briefly explain the data gathering method. Next, we discuss the production phases in the company. We introduce flowcharts to display the steps involved in the production process. The production steps can differ depending on the processing requirements.

2.1.1 Interviews and data gathering

We assess the current situation of production at the TP-3 by conducting semi-structured interviews with operators planner and management. Appendix A describes detailed information about how the interviews were conducted. Figure 3 illustrates the processing steps involved in the different phases.

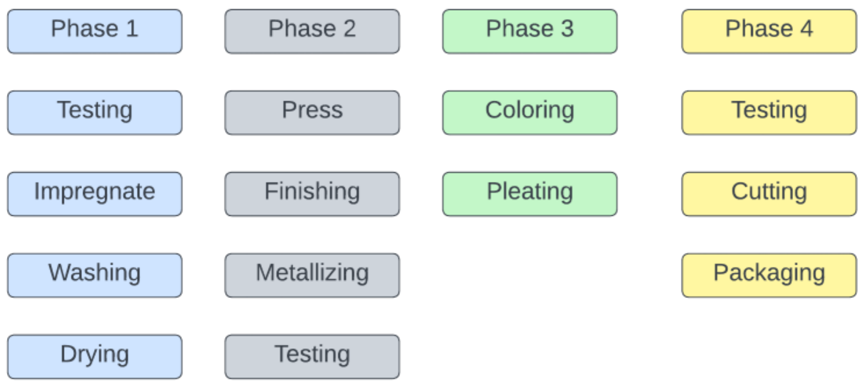

Figure 3 Schematic of production steps

2.1.2 Phase 1/2

In Phase 1/2, 3 operators are responsible for operating the machines to process the material. As a result, it is not possible for all machines to be operated simultaneously.

Phase 1 focuses on processing the raw material through impregnation, washing, and drying. During this phase, an operator is responsible for using multiple machines to apply the necessary properties required in the final product.

Phase 2 involves the processing of the material through metallization, pressing, and pre-finishing. In this phase, an operator utilizes the machines to press a pattern onto the material and pre-finish the textile, enabling successful metallization. Operators use metallization machines to apply a thin layer of aluminum on one side of the material to provide reflectiveness.

Figure 4 shows the steps the operators take in processing. The material is stored in the warehouse if the product requires coloring, otherwise it is moved to phase 3 of production.

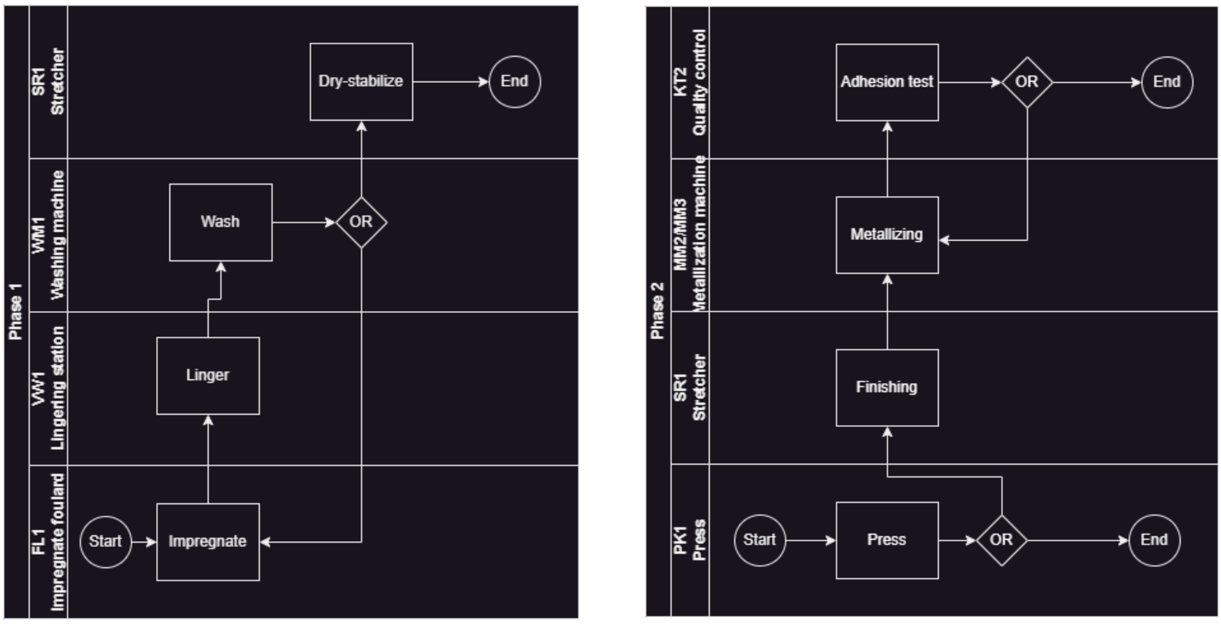

Figure 4 Production phase 1 and phase 2 respectively

2.1.3 Phase 3/4

In Phase 3/4, a total of 3 operators are available, and each operator can only work on one machine at a time. Due to this limitation, the TP-3 cannot be operated every day, as the remaining stations cannot maintain the same production rate. To ensure a smooth flow within the department, the TP-3 is only turned on twice a week. The material moves slowly through Phase 3, taking two days in total.

This phase is highly relevant for our research because the TP-3 is used in this production phase. It is worth noting that all the material processed on the TP-3 is retrieved from the warehouse. Figure 5 shows the processing steps involved in Phase 3.

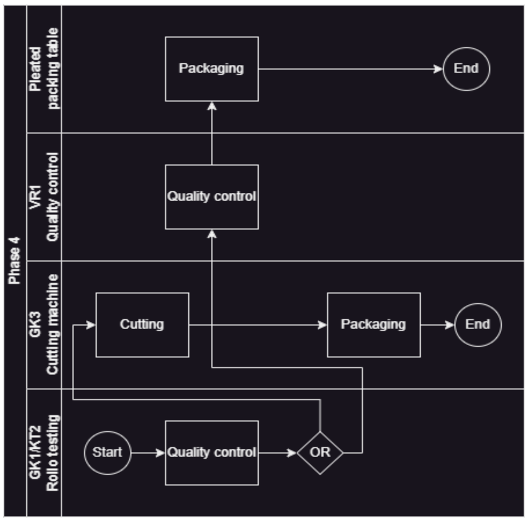

Figure 5 Production phase 3

Phase 4 involves quality checking, cutting the materials to appropriate sizes, and packaging. The specific machines used depend on the product requirements. Figure 6 illustrates the necessary processing steps to complete the product, the product moves through phase 4, taking two days in total.

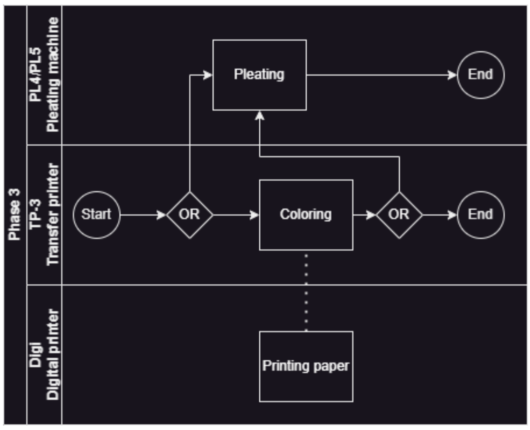

Figure 6 Production phase 4

During the processing of the material, KHPT recognizes two types of faults: local faults and repeating faults. Local faults can be addressed by cutting out the damaged portion of the material. However, repeating faults pose a more significant challenge as they require resizing or discarding the entire order.

The occurrence of faults disrupts production planning, resulting in rushed orders and negative impacts on overall production efficiency. To compensate for these disruptions, more material needs to be processed than what is initially required by demand.

2.2 Production process of the transfer press

In this section, we focus on the production process of the transfer press. We include the TP-3 layout, the loading phase for production, the production phase itself, and the unloading phase of the TP-3 machine. We investigate the production steps to determine if the schedule allows for sufficient time for all processing steps.

2.2.1 Schematic

We analyze the schematic of the TP-3 to understand its basic working principles and identify specific characteristics relevant to the research. The goal is to create a conceptual model that aligns with the features of the TP-3, such as the processing time and setup time.

KHPT uses the Klieverik GTC-141-3500 transfer press, which belongs to Klieverik's high volume roll to roll line of machines. Klieverik is a Netherlands-based company and specializing in rotary thermos-processing machines for advanced textiles. The machine has a drum with a diameter of 1070mm and a working width of 3200mm. Figure 7 provides a schematic of the transfer press setup.

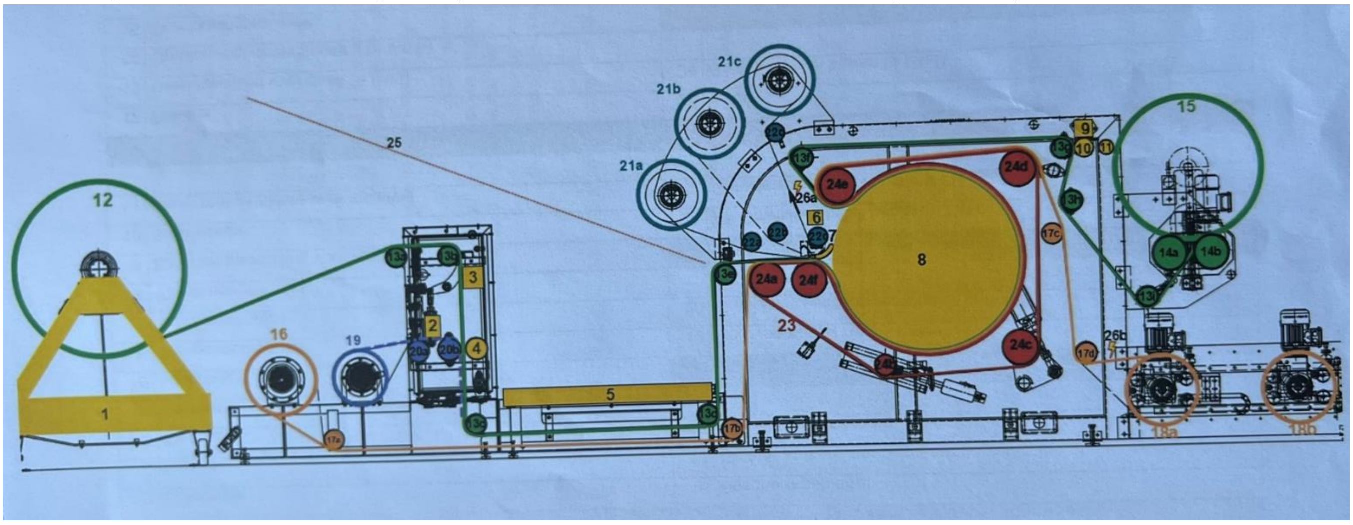

Figure 7 Schematic of the TP-3

The machine operates with a total of 5 input rolls, namely 12, 16, 19, 21a, and 21b. Additionally, there are 4 output rolls, designated as 14a, 15, 18a, and 18b.

During operation, the uncolored textile material is placed on a dock and guided through the machine by a roller system until it reaches the heated drum (8). The textile material wraps around the drum while being protected by a layer of protection paper. Simultaneously, the textile material is pressed against transfer paper, which enables the transfer of colors. The protection paper serves the purpose of shielding the textile material from overheating.

After passing through the rollers and drum, the textile material is rewound onto an output roll designated as 15. The protection paper, on the other hand, follows a separate set of rolls, including Roll 16, until it reaches the drum. Finally, the protection paper is rewound onto a separate roll, identified as 14a.

The feed paper (Roll 19) runs parallel to the textile material and serves as a feeding mechanism during the startup phase of the machine. The feed paper is wound onto the same rewind roll as the colored textile (Roll 15).

The transfer paper (Rolls 21a and 21b) can be positioned at two different locations within the machine. It runs alongside the uncolored textile and is pressed against the heated drum. This compression allows the color from the transfer paper to transfer onto the textile material, resulting in the desired coloring effect.

After the transfer process, the transfer paper follows a series of rollers until it reaches a roll designated as 14, where it is rewound for future use.

2.2.2 Operating the TP-3

Figure 8 provides all production steps required to color a roll of textile. The entire process is divided into three parts: loading, production, and unloading.

During the loading phase, an operator is responsible for several tasks. Firstly, the operator checks the order list to determine if it is feasible to complete the given order. Next, the operator collects all the necessary materials required for processing the order, ensuring that the feed and protection paper have enough paper remaining.

After gathering all the required materials, the operator proceeds to insert them into the machine. Once everything is properly in place, the operator initiates the machine's operation and begins feeding the feed paper into the machine.

The loading phase typically takes around 45 minutes. If there is insufficient time to complete an order within the available timeframe, the operator will refrain from loading the machine with that particular order and stop production.

In the production phase, the operator proceeds to attach the textile material to the feed paper, which is then connected to the rewind roll (15). Simultaneously, the used transfer paper is rewound onto the transfer paper rewind roll (14a). Throughout the coloring process, the machine operates at a speed of 6 meters per minute.

However, it is important to note that towards the end of the roll, the machine experiences a loss of tension because, the roll is empty or the material in the machine is separated from the raw material roll. This loss of tension results in the last 5 meters of textile on the roll being

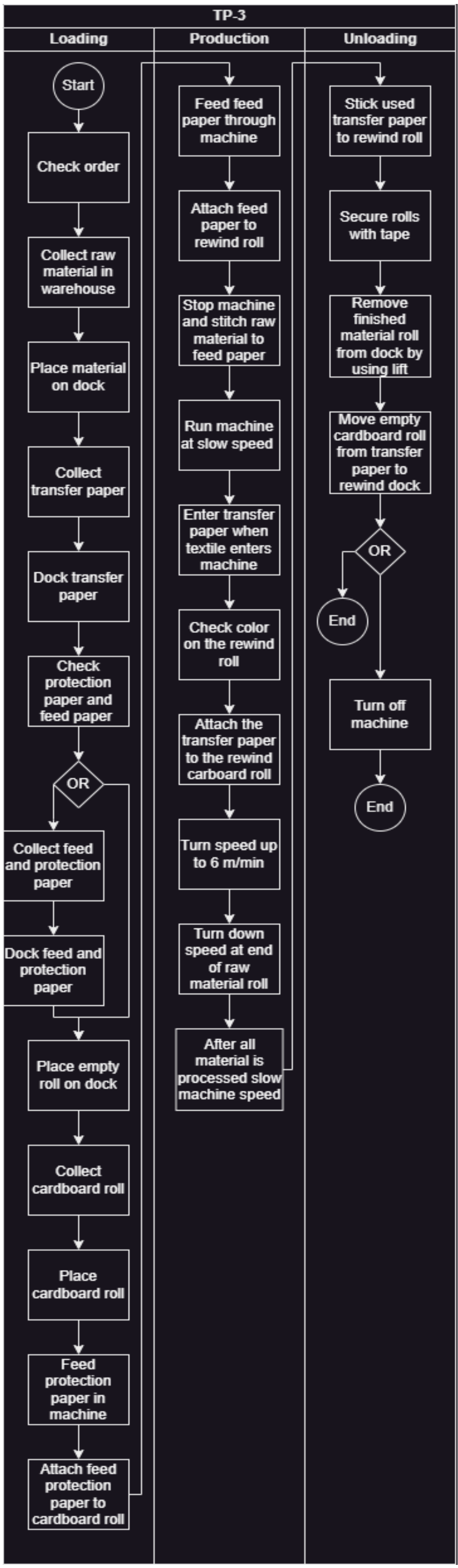

Figure 8 Flowchart of the processing steps of the TP-3

colored poorly. This issue is independent of the roll's length and presents a challenge for KHPT as they aim to reduce waste output while simultaneously improving efficiency.

During the unloading phase, the material is removed from the machine, and the rewind rolls are changed. It is worth mentioning that operators are not specifically assigned a dedicated time for unloading. Instead, the setup time of 45 minutes includes the time required to unload all the material from the machine. The machine is turned off either when there are no orders remaining or when there is no more available time for further processing.

2.3 Production planning and scheduling of the TP-3

Firstly, we discuss the production planning and scheduling method used in the company to understand how the production planning is made and utilized. Then, we investigate the specific scheduling process for the TP-3.

2.3.1 Production planning and scheduling

KHPT currently uses Microsoft Dynamics AX (MSAX) as their ERP software package for production planning. However, it is important to note that MSAX is outdated and is no longer supported since 2021. To address this, the company has planned to replace MSAX with Microsoft Dynamics 365 by 2024.

Despite its outdated status, MSAX is still used across all departments at KHPT for order management and communication regarding orders, due dates, and inventory. When a sales order is received, the planner checks the inventory level to determine if the product is available in the warehouse. Sales orders are accepted directly if the order is placed a month prior to the due date. If the product is not in stock, a production order is generated. Before planning the production order, a master requirement planning (MRP) is used by the planner to ensure the availability of the required materials for manufacturing.

The master production schedule is based on a just-in-time (JIT) backwards planning approach. However, the current system has certain limitations. One of these limitations is that it does not distinguish between preparation work and production tasks, leading to scheduling conflicts where production tasks are scheduled without sufficient preparation work assigned beforehand.

To address this issue, adjustments are made to the ERP system settings. A minimum delay of 22 hours is implemented between the production steps of an order. This ensures that the setup is always scheduled prior to the production task, allowing for proper preparation work and load distribution across the machines. However, a trade-off is that this approach results in a longer throughput time between the start and end of production. In Appendix B, the settings of the ERP system are shown, providing further insight.

While this adjustment helps to solve the scheduling conflicts and ensures that preparation work is given priority, it does come with the drawback of increased overall throughput time. This is a trade-off that KHPT has considered in order to optimize their production scheduling process.

The planner at KHPT uses a combination of MSAX recommendations and his/her own expertise to schedule orders. An Excel file is used for scheduling production orders, which is updated daily. The excel file is updated by running the master production schedule of MSAX and exporting the planned production orders to the excel file. The production orders are scheduled in sheets based on production weeks and categorized into Phase 1/2 and Phase 3/4. The planner regularly checks the status of active orders, updates their progress, and assigns the next production steps to the operators.

2.3.2 Scheduling strategy of the TP-3

When it comes to the production planning for the TP-3, the planner clusters orders to ensure sufficient work for a production run and meet production order due dates. At the end of each shift, the planner generates a task list of orders to be completed for the next production run.

The planner is responsible for allocating raw material rolls to production orders. If a production order requires more raw material than what is available on one roll, the planner must decide whether to split the order or use a new roll.

In the current allocation strategy, each order is assigned only one raw material roll. The goal is to fit the order perfectly or, if possible, assign the smallest roll available. However, if this is not feasible, the order is split. One part of the order utilizes the remaining material on the current roll, while the other part is allocated to a new roll. The planner sometimes splits orders, in order to raw material rolls which have only a small length remaining. This prevents the warehouse from becoming overcrowded with small material rolls.

To optimize production efficiency, the planner combines orders by assigning two orders that only differ in colors together. This allows for multiple orders to be completed in a single run with one setup. Orders occurring within the same production week and having the same raw material requirement are clustered together. For example, two orders with different color requirements but belonging to the same production week (such as two 802 orders) are combined to reduce setup time.

2.4 Performance

We first investigate the performance of production on output and hours used. Next, we evaluate the performance of the TP-3.

2.4.1 Performance of production

In terms of performance, KHPT monitors the production output in terms of meters produced in Phase 3/4. The waste percentage is closely monitored for the entire production process, along with customer complaints. Since March 2023, the waste percentage is categorized into three types: internal waste, external waste, and empty. Internal waste refers to waste generated during production, such as material cut-offs, handling errors and untreated material. External waste refers to errors already in the raw material before processing. This external waste is compensated by the suppliers by adding supplying additional material.

Figure 9 provides an overview of the production results. On the left side the figure shows the production results and waste per month in 2022. The right side of the figure displays the hours required to produce all products, including setup times scheduled by the production planning. The target waste percentage is set by the management at 7.5%, but it has only been achieved in one month in the past year. There are no specific key performance indicators (KPIs) used at the machine level.

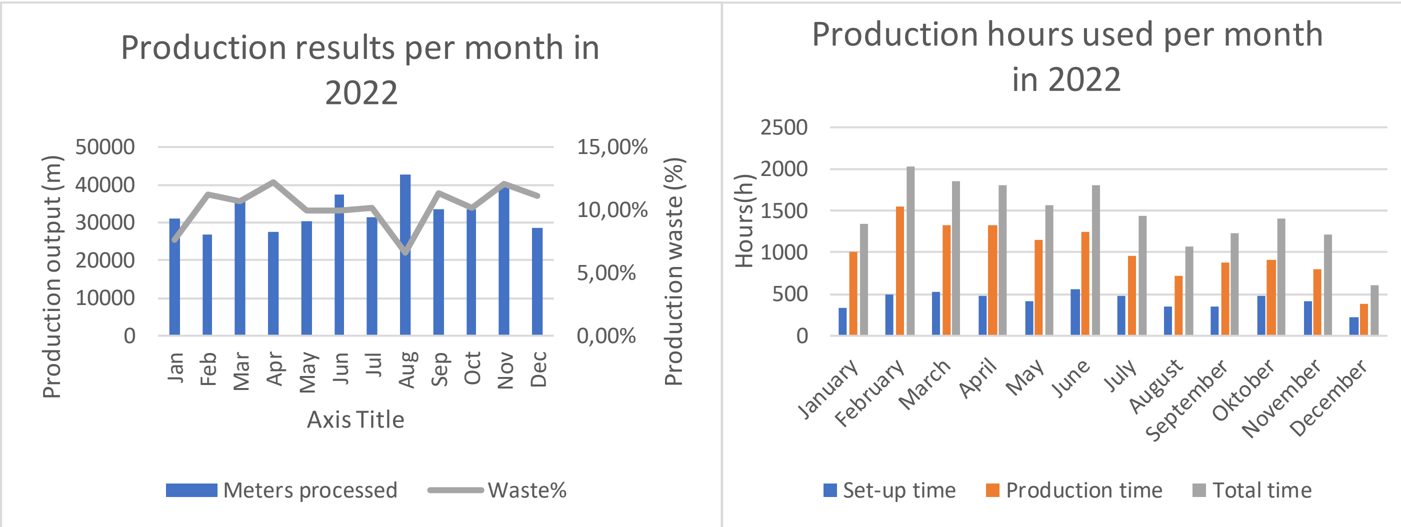

Figure 9 Production results and production time in 2022 per month

2.4.2 Performance of the TP-3

The performance of the TP-3 machine is not actively monitored, as the task completion times are not recorded in MSAX. The schedule is analyzed on performance. In MSAX, a standard set-up time of 15 minutes is assigned to each production order, assuming a processing speed of 5 meters per minute. Memos are used to cluster orders. Sometimes the job list is missing completion times for a production order. The job list presented to the operator contains tasks in a randomized order. Figure 10 shows an example of a job list.

Kvadrat High Performance Textiles — Pagina 1182, 16-5-2023, 13:20:55

Taaklijst

Einddatum	Eindtijd	Ploeg	Leveringsda	Productie	Artikelnummer	Memo	›eveelheid	Nr.	Bewerkin	Status	Uren
13-4-2023	14:20	Middag	20-4-2023	7432215	318509200920240	VRD combi 850 dubbelz 829/356/920 65/35/65lm	65,0	20	Kalander		0,25
13-4-2023	14:33	Middag	20-4-2023	7432215	318509200920240	VRD combi 850 dubbelz 829/356/920 65/35/65lm	65,0	20	Kalander		0,22
13-4-2023	14:48	Middag	20-4-2023	7432228	318129990000240	SALES 23/4 combi 31812 920/790/000 95/35/65 lm	65,0	20	Kalander		0,25
13-4-2023	15:01	Middag	20-4-2023	7432228	318129990000240	SALES 23/4 combi 31812 920/790/000 95/35/65 lm	65,0	20	Kalander		0,22
13-4-2023	15:16	Middag	18-4-2023	7432212	358339990998275	leverenn op as. bij eindkeuren groen/rode as en pallet gebruiken, netto bruto fouten en lengtefouten doorgeven aan Luuk	340,0	20	Kalander		0,25
13-4-2023	16:24	Middag	18-4-2023	7432212	358339990998275	leverenn op as. bij eindkeuren groen/rode as en pallet gebruiken, netto bruto fouten en lengtefouten doorgeven aan Luuk	340,0	20	Kalander		1,13
13-4-2023	18:15	Middag	20-4-2023	7432215	318509200920240	VRD combi 850 dubbelz 829/356/920 65/35/65lm	65,0	30	Kalander		0,25
13-4-2023	18:34	Middag	20-4-2023	7432215	318509200920240	VRD combi 850 dubbelz 829/356/920 65/35/65lm	65,0	30	Kalander		0,33
13-4-2023	18:49	Middag	20-4-2023	7432227	318129990790240	sales 23/4 combi 31812 920/790/000 95/35/65 lm	35,0	20	Kalander		0,25
13-4-2023	18:56	Middag	20-4-2023	7432227	318129990790240	sales 23/4 combi 31812 920/790/000 95/35/65 lm	35,0	20	Kalander		0,12
13-4-2023	19:11	Middag	20-4-2023	7432213	318508290829240	combi 850 dubbelz 829/356/920 65/35/65lm	50,0	30	Kalander		0,25
13-4-2023	19:31	Middag	20-4-2023	7432213	318508290829240	combi 850 dubbelz 829/356/920 65/35/65lm	50,0	30	Kalander		0,33
13-4-2023	19:46	Middag	20-4-2023	7432226	318129990920240	VRD combi 31812 920/790/000 95/35/65 lm	65,0	20	Kalander		0,25
13-4-2023	19:59	Middag	20-4-2023	7432226	318129990920240	VRD combi 31812 920/790/000 95/35/65 lm	65,0	20	Kalander		0,22
14-4-2023	09:29	Morgen	18-4-2023	7432211	358339997180275		350,0	20	Kalander		
14-4-2023	09:29	Morgen	18-4-2023	7432211	358339997180275		350,0	20	Kalander		
14-4-2023	10:39	Morgen	19-4-2023	7432176	358909990936300		100,0	20	Kalander		
14-4-2023	10:39	Morgen	19-4-2023	7432176	358909990936300		100,0	20	Kalander		

Figure 10 Example of a job list

Figure 11 shows the setup times and production times for the first two weeks of 2022. We use the first two weeks of 2022 to assess the current situation with regards to setup time, production time, and efficiency. With an output of 11,358 meters in this period, it belongs to the higher end of the spectrum, where the average is 8,542 meters. This instance of the first two weeks of 2022 serve as a representative example of the TP-3 production plan, because similar instances occur frequently over 2022.

The interviews with operators revealed that the actual throughput rate of the machine is 6 meters per minute instead of the initially assumed 5 meters per minute. Additionally, the setup times were reported to be 45 minutes rather than the previously estimated 15 minutes used in the ERP system.

When this different setup time and processing speed is applied and compared to the original schedule, it becomes apparent that the production time is significantly longer than initially expected. This observation highlights the impact of the revised processing speed and setup times on the overall production process. The required production time is much longer than what is assumed to be in the production plan. The efficiency of the TP-3 using the new calculation method is lower on average than the old method.

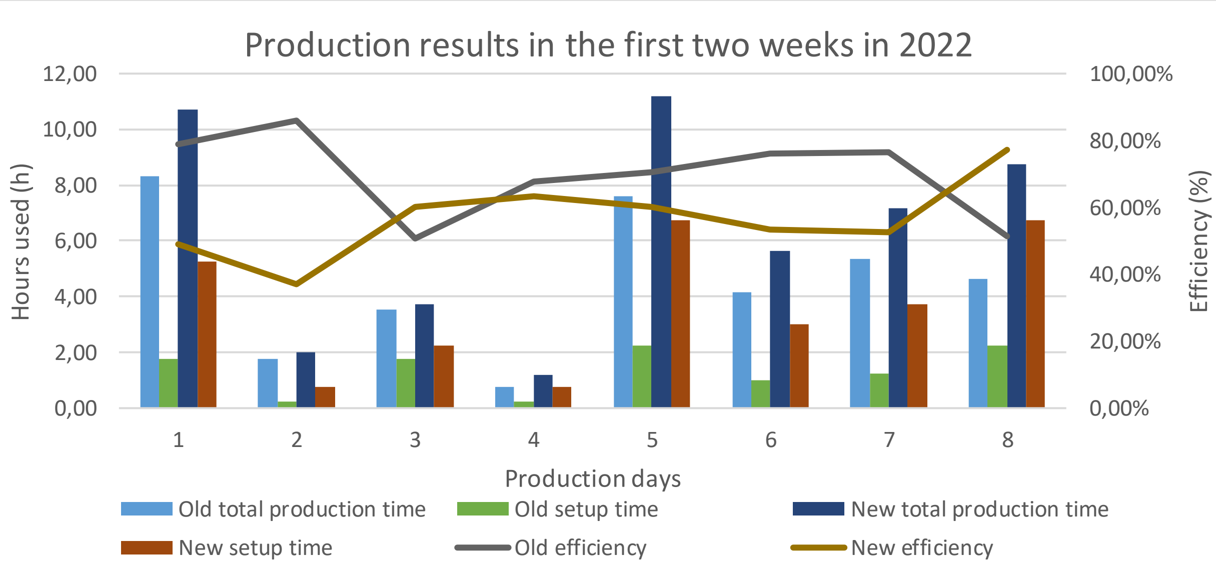

Figure 11 Production and setup time

Figure 12 shows the waste produced by the TP-3 machine during the first two weeks of 2022, measuring it as a percentage of the total production quantity. The waste percentage shows significant variation, with some days involving production of large batches while others involving small runs.

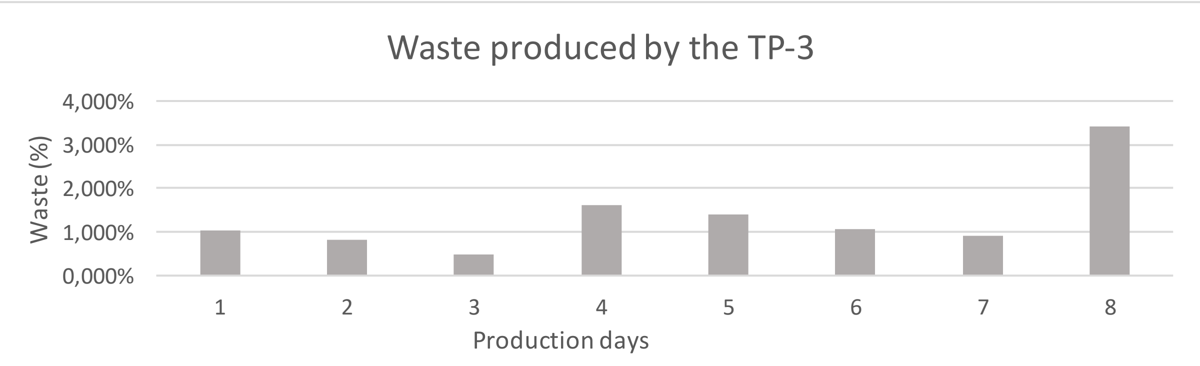

Figure 12 Waste produced by the TP-3

2.5 Conclusion

In conclusion, this chapter provides a comprehensive understanding of the current situation of the production process at the transfer press. It addresses production, the processing steps of the TP-3 machine, the production planning and scheduling, and the performance assessment. We evaluate different types of products, where we discover the different types have the same setup and processing speed.

The ERP system uses incorrect processing times and setup times which it assigns to orders, leading to unrealistic expectations. In contrast to the system's setting of 15 minutes for each order's setup time, it actually takes 45 minutes to initiate production. Similarly, changing to a different roll of raw material also requires 45 minutes for the changeover process. Additionally, the processing speed of 5 meters per minute programmed into the system is incorrect. The interviews revealed that the actual processing speed is 6 meters per minute, regardless of the product type. Consequently, the machine generates 5 meters of waste per feed used. This means that each setup results in 5 meters of waste material.

In each shift, there are 3 operators available, which means that only 3 out of the 5 machines can be used simultaneously. To spread the load over production Phase 3/4, the TP-3 machine is only used twice per week to allow other stations to process material. These constraints impact the scheduling and utilization of the machine.

This current scheduling strategy is based on just-in-time scheduling, where the setup times take up considerable amount of time of the total production time. This strategy leads to a low efficiency on the TP-3 Moreover, due to the incorrect assumptions underlying the current scheduling method, there are instances where the production plan cannot be fully completed. This can result in the need for overtime or the inability to produce all required products within the specified timeframe.

The planner at KHPT selects the material based on the best fitting raw material roll for each order. In some cases, orders may be split to utilize the remaining small rolls to their full extent. This approach allows for efficient use of available resources and helps prevent the warehouse from becoming overcrowded with small material rolls. By carefully managing material allocation and optimizing roll usage, the planner ensures an effective balance between production requirements and warehouse capacity.

The assessment of performance highlights the discrepancies between information provided by employees and the assumptions made by the MSAX system.

3. Literature

In this chapter we address the second research question: What scheduling methods are available for the bin packing problem and machine scheduling problem to improve the efficiency of the transfer press? In Section 3.1, we introduce machine scheduling and discuss the single-machine scheduling problem. In Section 3.2, we discuss the solution methods which can be used to solve the single-machine scheduling problem. In Section 3.3, we discuss the bin packing problem and investigate methods to solve the problem. In the end, we summarize our findings in Section 3.4. In Appendix c, we discuss the systematic literature search.

3.1 Machine scheduling

We first introduce machine scheduling and describe the notation used in machine scheduling problems. Next, we discuss the different machine environments such as a single machine and a flow shop. We then discuss the single-machine scheduling problem and address processing characteristics and constraints.

3.1.1 Introduction to machine scheduling

Machine scheduling is the allocation of resources over time to perform a collection of tasks (Baker & Trietsch, 2018). In a company perspective it involves a constrained optimization problem where an objective is to be optimized (Jain & Meeran, 1999). Machine scheduling problems can be described using a triplet $\alpha|\beta|\gamma$, where α represents the machine environment, β provides processing characteristics and constraints, and γ defines the objective to be optimized. We shortly introduce the most common machine environments described in Table 3. There are several variations on the machine environments with different characteristics in addition to the environments mentioned in Table 3.

Machine environment	Description
Single machine	Jobs have to be processed on a single machine
Parallel machine	Jobs have to be processed by a single machine, however multiple machines are available.
Flow shop	Machines are set in series and all jobs must visit all machines in the same order.
Job shop	Each job has a potentially different processing route and all jobs must visit all machines.
Open shop	Each job has to visit a given number of machines, the processing route is open and can be determined by the schedule method.
Hybrid shop	Instead of having machines in series, there are stages where at each stage there might be a single machine or parallel machines.

Table 3 Types of machine environments (Ruiz, 2015)

3.1.2 Single-machine scheduling

In the single-machine scheduling problem, we consider a set of jobs (J_1, J_2,…, J_n) to be scheduled on a machine. Job J_i has processing time p_i, release time r_i, and due date d_i. After scheduling the jobs, the resulting start time s_i and completion time c_i are apparent. There are multiple variations of single-machine scheduling problems depending on the processing characteristics and the objective.

There are many different processing requirements, each specific to a problem. We only broadly discuss the different processing characteristics in Table 4.

Processing characteristics & constraints	Description
Processing time	The processing time can differ depending on the job.

Release dates	A job can be restricted in processing before a certain time. For example raw material availability can play a role.
Due dates	A job is restricted by the due date, a date before the job has to be processed. Due dates are soft constraints which can be exceeded, resulting in late jobs.
Setups/changeovers	A job can require preparations before processing. For example: setting up the machine, cleaning, and inspecting material. Setups can depend on the job to be processed, which is called sequence-independent. Moreover, setups can depend on the job to be processed and the preceding job therefore, it is sequence-dependent (Allahverdi, 2015).
Sequence constraints	A job can be restricted by preceding job. The most frequent sequence constraint is preemption. Preemption is the suspension of a lower priority job when a higher priority job presents itself during the processing of the lower priority job.

Table 4 Types of processing characteristics (Ruiz, 2015)

There are different objectives, however the most frequent are about makespan, tardiness, and earliness (Uzsoy, 2000). These objectives are described using the Equations 2, 3, and 4 respectively.

$$Makespan = C_{max} = \max(c_1, c_2, \dots, c_n) \ (2)$$

$$Tardiness = \sum_{i=1}^{n} \max(c_i - d_i, 0) \ (3)$$

$$Earliness = \sum_{i=1}^{n} \max(d_i - c_i, 0) \ (4)$$

3.2 Solution methods

In this section, we discuss solution methods. We first discuss exact solutions, in which we discuss the BnB method. Next, we discuss heuristics in which we address a wide range of priority rules and their objective. Lastly, we discuss improvement heuristics, in which we elaborate on steepest descent, simulated annealing, tabu search, and matheuristics.

3.2.1 Exact solutions

Exact solutions find the optimal solution for an optimization problem. However, scheduling problems, including the one being addressed in this research, often belong to the class of NP-hard problems, which makes finding solutions using an exact method impractical for medium to large-scale problems due to the increasing complexity (Brucker, 2007). The computational time required to solve a problem is longer compared to other solution methods, which means the exact approach is not practical for middle to large scale problems.

One exact solution method discussed is the branch and bound (BnB) method, which breaks down the problem into smaller sub-problems (Land & Doig, 1960). The goal of the BnB method is to find a value that minimizes or maximizes the objective function. The BnB method consists of splitting the solution space into parts (branching) over which the upper and lower bound are evaluated (bounding).

The BnB method reduces the number of branches by eliminating branches that cannot lead to an optimal solution. The method evaluates the lower and upper bound of the branches using the objective function. If the branch cannot produce a better solution than the best solution found, the branch is discarded. The BnB method is time-consuming, and even with advancements in processing power, obtaining a quality solution close to the global optimum can still be a considerable challenge for larger problems (Cordone & Hosteins, 2019).

3.2.2 Heuristics

Heuristics are methods that solve a problem without guaranteeing an optimal solution. They are also known as "rule of thumb" (Gere, 1966). These rules are used to quickly determine a solution without considering each individual solution. Therefore, heuristics are most suitable for scheduling problems with a high number of jobs and numerous possibilities. Priority rules can be used to sort jobs based on criteria and assign priorities. These priorities determine the selection when multiple jobs are ready for processing. Priority rules can be static or dynamic, with dynamic rules depending on time while and the static rules do not (Pinedo, 2022).

Priority rules have pros and cons depending on the objective to be optimized and the type of scheduling problem. There are different objectives such as makespan, earliness, and tardiness. The makespan is the time at which all jobs are completed. Earliness and Tardiness are about the time between finishing the job and the due date. The goal is to obtain a schedule which has the lowest objective value. Often maximum lateness which is the most late job in a schedule is concerned or the average lateness of all jobs. Other objectives use weighted jobs in which weights are assigned to jobs according to their importance and used in the objective function.

The SST rule is most suited for reducing setup times between jobs. When there is a constrained problem or there are multiple objective to be optimized, different priority rules can be used. Table 5 shows some of the relevant priority rules. The earliest due date (EDD) prioritizes jobs according to their earliest due date, while the earliest release date (ERD) prioritizes jobs which are available the earliest. Minimum slack (MS) prioritizes jobs based on the time remaining if the job is scheduled next. The job which has the least time remaining is prioritized. Shortest processing time (SPT) prioritizes the job which has the lowest processing time. Weighted shortest processing time (WSPT) assigns priority based on the weight of the job multiplied by the processing time. The WSPT rule prioritizes jobs based on this value from low to high. The shortest setup time (SST) prioritizes jobs which have the lowest setup time. The ATC rule combines the MS and WSPT rule which prioritizes jobs based on the shortest processing time and the time remaining if a job is scheduled next.

Rule	**Objective**
Apparent tardiness cost (ATC)	Minimize total weighted tardiness
Earliest due date (EDD)	Minimize maximum lateness
Earliest release date (ERD)	Minimize variance in throughput times
Minimum Slack (MS)	Minimize maximum lateness
Shortest processing time (SPT)	Minimize average waiting time
Weighted shortest processing time (WSPT)	Minimize average weighted waiting time
Shortest setup time (SST)	Minimize setup time

Table 5 Priority rules(Gahm et al., 2019)

3.2.3 Improvement heuristics

Improvement heuristics are improvement methods that try to improve a solution. Improvement heuristics start by making changes to the initial solution which result in a neighbor solution. An improvement heuristic can accept the neighbor solution or reject the solution based on the acceptance criteria of the improvement heuristic. By accepting the solution, the accepted solution can be changed in an attempt to improve the solution. There are different improvement heuristics available which each have different strategies on accepting and treating neighboring solutions. We discuss the following improvement heuristics: steepest descent, simulated annealing, tabu search, and matheuristics.

Steepest descent

Steepest descent (SD) is a method that searches for a better solution. SD compares neighboring solutions to the current solution and accepts the best neighboring solution if it is better than the current solution. The method stops if there is no neighboring solution that is better than the current solution. This method leads to a local optimum, which means that the neighboring solutions are not better than the current solution. The local optimum is not necessarily the best solution.

Simulated Annealing

Simulated annealing (SA) is a method for solving optimization problems (Kirkpatrick et al., 1983). The method compares the current solution to a neighboring solution and always accepts a better solution. The method probabilistically decides whether to accept or reject a worse neighboring solution. SA accepts worse solutions in order to try to escape from a local optimum and explore solutions in different neighborhoods. The computational time required for SA is large compared to priority rules, because SA requires a lot of solutions to be compared.

Tabu Search

Tabu Search (TS) is another method for solving optimization problems (Glover, 1986). TS uses a memory structure that can discourage or prevent the method to visit previously visited solutions depending on the memory structure the solution is added to. The memory structure can be short, medium or long-term. The method accepts worse solutions if no neighboring solution is better than the current solution or the neighboring solution is on the tabu list.

Matheuristics

Matheuristics use mathematical programming (MP), which aims to minimize or maximize a certain objective in combination with improvement heuristics. The aim is to utilize MP to enhance or create improvement heuristics, or use improvement heuristics to improve MP. The improvement of improvement heuristics through MP primarily focuses on improving local search, in which MP defines a suitable neighborhood to explore (Cota et al., 2021). An example is when dealing with a multi-objective function, a matheuristic can be employed to discover non-dominant solutions on the pareto front (Deb & Jain, 2014).

3.3 Bin packing

In this section, we first introduce the bin packing problem and formulate the problem using equations. Next, we discuss heuristics, in which we discuss different priority rules which can be used to solve the problem. Lastly, we address improvement heuristics, in which we discuss different search algorithms.

3.3.1 Bin packing problem

The bin packing problem (BPP) is an optimization problem where items of varying sizes need to be packed into limited number of bins. Each item *i* has weight w_i and must be assigned to a bin. The bins have capacity c and this capacity must not be exceeded. Therefore, each item's weight is less than the bin's capacity; otherwise, the item cannot fit. If an item cannot be fitted, for instance if the number of bins is too small to fit all items, the solution is infeasible. The number of bins is generally set to the number of items available, similar to the knapsack problem (Martello & Toth, 1990). The objective for this problem is to minimize the number of bins used. The problem can be formulated as an integer linear program shown in equations 5-11.

$$\min \mathrm{z} = \sum_{i=1}^{n} y_i \quad (5)$$

$$\text{subject to } \sum_{j=1`}^{n} w_j\, x_{ij} \leq c y_i, \qquad i \in N = \{1, \dots, n\}, (6)$$

$$\sum_{i=1}^{m} x_{ij} = 1, \qquad \forall\, j \in M\; = \{1, \dots, m\}, \qquad (7)$$

$$y_i = 0\; or\; 1, \qquad i \in N, (8)$$

$$x_{ij} = 0\; or\; 1, \qquad i \in N, j \in M\; (9)$$

$$where\; y_i = \begin{cases} 1\; if\; bin\; i\; is\; used \\ 0\; if\; bin\; is\; not\; used \end{cases} (10)$$

$$where\; x_{ij} = \begin{cases} 1\; if\; item\; j\; is\; assigned\; to\; bin\; i \\ 0\; otherwise \end{cases} (11)$$

Similar to the scheduling problem, there are multiple methods to solve this optimization problem. Heuristic approaches, search algorithms, and dynamic programming can be used to formulate near-optimal solutions. One approach is to relax certain linear programming (LP) constraints and allow fractional bin packing (Karmarkar & Karp, 1982).

3.3.2 Heuristics

Similar to machine scheduling, heuristics can be used to pack items into bins. The most widely used benchmark is the first fit decreasing (FFD) heuristic. The heuristic method sorts items in descending order of size and assigns these to the first bin the item can fit. In case an item does not fit into existing bins, a new bin is used. The FFD heuristic uses less than 1.7 times the number of bins the optimal solution uses (Dósa & Sgall, 2014). Other heuristics such as next fit (NF) and first fit (FF) can also be employed to fill the bins.

3.3.3 Improvement heuristics

The same improvement heuristics mentioned in Section 3.2 can be used for the bin packing problem as well. In addition to the already mentioned improvement heuristics, there are specific improvement methods that can be used for the bin packing problem. El-Ashmawi and Abd Elminaam (2019) propose the squirrel sorting algorithm (SSA) to solve the bin packing problem. SSA is based on the movement of squirrels, where squirrels move from one place to another. SSA is faster and yields better results than other popular algorithms such as: particle swarm optimization (PSO) and the crow search algorithm (CSA).

The sorting of the initial sequence used in improvement heuristics can significantly impact computational time and performance. Therefore, we discuss sorting methods which can be used in conjunction with an improvement heuristics such as SD, SA, TS, Matheuristics, and other methods.

Zigzag sorting algorithm

This sorting algorithm first creates a list of the items sorted in decreasing order. The algorithm creates a second list, which is used as a sorted list. The algorithm chooses from the first list, the item closest to half the capacity of the bin (½c) and sets this as first item on the second list. The algorithm fills the second list by choosing items from the first list. The algorithm alternates between left neighbor and the right neighbor of the first item in the first list to select the item to be put on the second list. The resulting list is in zigzag order, where a small item is followed by large item, and a large item is followed by a small item. The advantage is that medium sized items are close with medium sized items and larger items close to smaller items (Fu & Banerjee, 2020). This can result in better packed bins, which can result in less bins required.

3.4 Conclusion

The goal of this chapter is to answer the second research question: What scheduling methods are available for the bin packing problem and machine scheduling problem to improve the efficiency of the transfer press?

We first introduced machine scheduling in Section 3.1, where we describe the different machine environments. The machine environments range from single machine to hybrid shop depending on the number of machines and the processing characteristics. In single-machine scheduling we consider a set of jobs (J_1, J_2,…, J_n) to be scheduled on a machine. There are multiple variations of single-machine scheduling problems depending on the processing characteristics and the objective.

Next, we discussed the solution methods for machine scheduling problems in Section 3.2. There are many different solution method such as exact methods, heuristics, and improvement heuristics. Exact solution methods find the optimal solution for an optimization problem, however the computational time required is longer than other solution methods. Heuristics are methods that solve a problem without guaranteeing an optimal solution. Priority rules can be used to quickly determine a solution without considering all options. Improvement heuristics are improvement methods that try to improve a solution. We discussed a variety of improvement heuristics such as: SD, SA, TS, and matheuristics.

Finally, we discussed the bin packing problem in Section 3.3. The bin packing problem (BPP) is an optimization problem where items of varying sizes need to be packed into limited number of bins. Each item *i* has weight w_i and must be assigned to a bin. Similar solution methods as the machine scheduling problem can be used for the BPP. Heuristics such as the first fit decreasing (FFD) can be used to quickly solve the BPP. Moreover, improvement heuristics can be used, where specifically the sorting of the initial sequence of the item can impact the computational time and performance.

4. Solution approach

In this chapter, we answer the third research question: How can the theory be used for an improved scheduling strategy on the TP-3? In this chapter, we describe the solution approach for solving the scheduling problem of the TP-3. This chapter builds upon the findings of the current situation and literature review in Chapters 2 and 3.

In Section 4.1, we discuss the problem of the TP-3, the solution approach for the problem of the TP-3, and assumptions. We split the problem into 2 parts: the bin packing problem and the single-machine scheduling problem. In Section 4.2, we describe the solution approach for the bin packing problem, where we also discuss the specific problem of the TP-3. Moreover, we discuss the best-fit heuristic and the order splitting heuristic, which we use to improve the solution. In Section 4.3, we discuss the solution approach for machine scheduling problem, in which we discuss the problem and justify the choices for the setup of the model. In addition, we discuss the shortest setup time and the current scheduling method which we use for experimenting. In Section 4.4, we discuss the measures that we use as key performance indicators in Chapter 5. Finally, Section 4.5 concludes the chapter.

4.1 Problem, solution approach, and assumptions

In this section, we first discuss the problem of the TP-3. Next, we discuss how we split the problem of the TP-3 in 2 parts. Moreover, we discuss how we plan to solve these sub-problems. Lastly, we discuss the assumptions and simplifications in the solution approach.

4.1.1 The problem of the TP-3

The company faces the challenge of deciding what to produce, determining the suitable material to be used, and scheduling orders. A diverse range of products is processed, each requiring its own specific raw material. For instance, raw material of type 802 cannot be used to produce a product of type 812. The raw material is supplied in the form of rolls, and orders are assigned to these raw material rolls. Multiple raw material rolls are available for selection. For example, when processing an order for type 812, there may be multiple rolls available with the right raw material.

During production, the machine at KHPT requires a setup whenever a raw material roll is fed into it. A high number of setups lead to a low efficiency. The number of setups depends on the production plan.

Figure 13 shows an example in which two orders for product type 812 and two orders for product type 815 are considered in the production plan. The brackets indicate the assigned raw material roll numbers, while the black bars represent the setup time. The figure demonstrates that reducing setup time is only possible when using the same raw material roll consecutively for multiple orders.

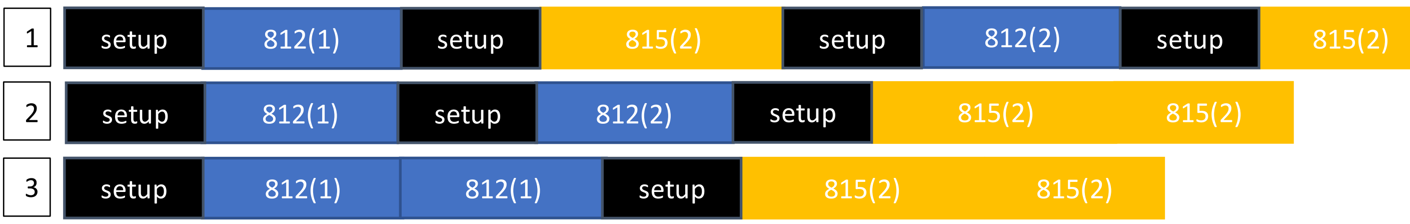

Figure 13 Three production plan examples

4.1.2 Solution approach for the TP-3

We adopt a stepwise approach in which we select raw material and schedule the order, tackling the bin packing and machine scheduling problem separately.

KHPT places significant emphasis on utilizing raw materials effectively due to their high cost. Therefore, we solve the bin packing problem first to ensure raw materials are assigned efficiently. By addressing the bin packing problem first, we aim to prevent situations where certain raw material rolls remain unused in production, despite containing a substantial amount of material.

As mentioned earlier, there are different types of orders. For each order type, there is one type of raw material roll. Therefore, we consider the bin packing problem as consisting of smaller bin packing problems with each a different type of orders and raw material rolls. By solving these smaller bin packing problems individually for each order type, we effectively solve the bin packing problem as a whole.

The bin packing model takes the orders and available raw material rolls as inputs. The model then assigns each order to a raw material roll. Once the orders are assigned a raw material roll, the orders can be scheduled in the production plan. The scheduling model uses the output of the bin packing problem to determine whether a setup is required between orders. The number of setups is influenced by the allocation of orders to bins, as switching a raw material roll requires a setup. The scheduling model determines the start and end times of each order and generates a production schedule. The outcome of the scheduling model is a production plan.

Figure 14 illustrates the relationship between these problems in terms of input and output.

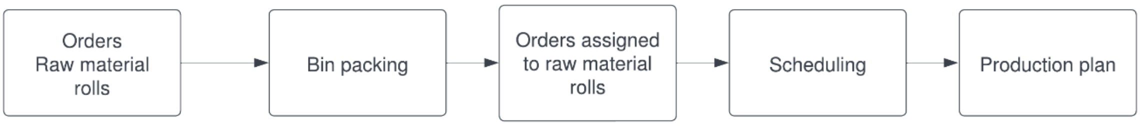

Figure 14 Solution approach

4.1.3 Assumptions and simplifications

In the context of the problem of the TP-3, we make the following assumptions and simplifications:

- There is always enough raw material available for processing (unlimited bins).
- New material rolls have the same capacity.
- There is one used raw material roll available per type, which has a capacity lower than a new material roll.
- All setup times are 45 minutes.
- A setup always results in a 5-meter waste.
- The operators are only available on 2 days for production in a week (Mondays and Thursdays) to process material for the TP-3. On other days the operators have to complete other tasks.
- No overtime is allowed.

4.2 Solution approach for the bin packing problem

In this section, we discuss the solution approach for bin packing. Next, we discuss the bin packing problem, best-fit heuristic, and order splitting heuristic.

4.2.1 Solution approach BPP

In order to pack the bins, we define a suitable approach to solve the bin packing problem. There are many different algorithms available to use for the bin packing problem, as described in Chapter 3. We choose a 2-step approach, where we first find a solution using a heuristic, which we later improve. The 2-step approach allows us to first find a solution which is not necessarily the optimal solution and improve this solution.

KHPT aims to use raw materials roll to their full capacity, therefore we decide to use the best-fit heuristic, found in Section 3.2. The Best Fit heuristic shows good results for bin packing, with an approximation ratio 1.7 (Dósa & Sgall, 2014). The Best Fit heuristic also performs well in minimizing the remaining space in bins. All bin types are discussed in Appendix D.

The bin packing model can only assign an order to a bin if there is sufficient capacity remaining. This can lead to raw material rolls containing material that will not be used accumulating in the warehouse, unlikely to be used in the future. This poses a problem in the warehouse, because space is limited. Therefore, we propose our own order splitting heuristic to reduce the number of bins used and to fill bins up to their capacity. The order splitting heuristic is based on the bin packing decisions of the planner, outlined in Section 2.4.

In Chapter 3, we introduced multiple solution methods that can provide a solution. Due to time constraints and the goal of improving TP-3 efficiency, we do not use an improvement heuristic to try to improve the solution.

4.2.2 Bin packing problem

The problem at KHPT has raw material of different types and sizes available, therefore the capacity of bins can differ. The bin packing problem we discussed in Section 3.3 is modified to allow the different bin capacities. Given a set $I = \{x_1, \dots, x_n\}$ of items, let w_i be the respective weight of each item. There exists a set of bins $B = \{y_1, \dots, y_b\}$ with capacity c_j. The BPP consists of grouping the items in the bins in such a way that the sum of the weights does not exceed c_j, and the number of bins used is minimal.

4.2.3 Best-fit heuristic

The best-fit (BF) heuristic is an algorithm for bin packing. The heuristic requires a list of items of different sizes as input. The best-fit algorithm assumes all bins have the same capacity, however in our situation as described in Section 2.4 there are used bins, which have a smaller capacity than the new bins. Therefore, we modify the BF algorithm such that bins can have different capacities adjusted to the characteristics of the company. Currently, there is one used raw material roll present. When a new bin is used, its capacity depends on the type (refer to Appendix E for more details). The BF algorithm takes the following steps:

1. Go through all items, one by one
2. Pack the item into the most full bin where it fits
    a. If such a bin is found, the item is placed into this bin
    b. If no such bin is found, a new bin is opened with capacity c_j and the item is placed into this bin

4.2.4 Order splitting heuristic

The order splitting heuristic focuses on improving the solution generated by the best-fit heuristic. It achieves this by splitting orders to fill bins to their capacity. This heuristic is derived from the current method of order splitting discussed in Section 2.4. The order splitting heuristic works in the following way: first, it calculates the remaining capacity of the bins in use. If two or more bins are being used, the heuristic can be implemented to further improve the solution. However, if only one bin is being used, the solution cannot be improved through the order splitting heuristic.

First, we filter the used bins. Bins with a remaining capacity exceeding 100 meters are insufficiently packed. The order splitting heuristic's goal is to fill these bins up to the capacity. Raw material rolls with a remaining capacity below 100 meters can either be discarded or used for testing. Only bins with a remaining capacity above 100 meters are added to a list. We sort the list in ascending order based on the remaining capacity.

We select the first bin in the list as the receiver; this bin receives a portion of an order to fill it to its capacity. Next, we need to select the donor bin. We choose the smallest order in the list as the donor, this is the last order. This order is split into two parts: Part A with a length equal to the remaining capacity of the receiver bin, and Part B with a length equal to the remaining length of the order. We add Part A to the receiving bin.

We calculate the remaining capacity of all bins in use. Then, we add Part B to the most full bin where it fits. We repeat the order splitting heuristic until only one bin remains in the list

Figure 15 shows an example of the order splitting heuristic.

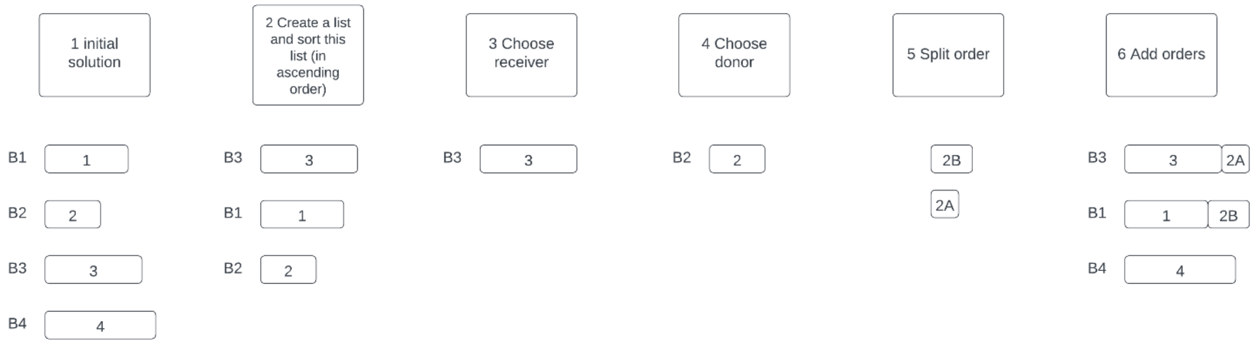

Figure 15 Example of the order splitting heuristic

4.3 Solution approach for the machine scheduling problem

In this section, we discuss the solution approach for machine scheduling. Next, we discuss the machine scheduling problem, the current scheduling method, and shortest setup time priority rule.

4.3.1 Solution approach machine scheduling

To improve the efficiency of the transfer press, we choose a scheduling strategy that prioritizes efficiency. A wide variety of methods are available that can solve the scheduling problem. The exact methods discussed in Chapter 3 require extensive computational time, making them undesirable. Consequently, we adopt a different approach by using heuristics to obtain a solution.

To assess the performance of the solution strategy, the current strategy is compared to the proposed strategy. As mentioned in Section 2.4, the identified method for scheduling jobs is based on the "just-in-time" approach. Currently, the scheduling strategy is to minimize early/tardiness and subsequently clustering the jobs that share the same production week and bin. We discuss the details of the current solution method in Section 4.4.

We base the heuristic used for improving the current situation on both the literature discussed in Section 3.2 and our own insights. The high number of setups required causes the observed low efficiency. As Section 2.3 highlights, setups become necessary when switching raw material rolls. Therefore, effectively decreasing setup times can be achieved by reducing the number of raw material changes.

To achieve this objective, we use the shortest setup time (SST) priority rule. This rule selects a job based on the lowest setup time. We compare the efficiency of this strategy to the efficiency of the current strategy to evaluate its effectiveness.

4.3.2 Machine scheduling problem

In simple terms the scheduling problem consists of 2 parts:

- Deciding the sequence of jobs to be processed on the TP-3
- Determining the start time of each job.

Each job $J = \{x_1, \dots, x_n\}$ requires to be processed on the TP-3. The jobs have a raw material roll assigned which is used in processing.

The TP-3 can process only one job at a time, and there are sequence dependent setup times between jobs, depending on whether the raw material roll needs to be changed. The setup time and the finish time of the previous job restrict the start time of the next job. If job j is processed after job i, a setup time of s_{ij} is incurred. Moreover, the minimum start time of job j is constrained by the previous job, denoted as c_i. The minimum start time of job k assuming it will be scheduled next is constrained by $s_j \geq (c_i + s_{ij})$. The completion time is computed as $c_j = s_j + p_j$.

4.3.3 Current scheduling method

The current scheduling method (CURR) is derived from the current situation described in Chapter 2. This scheduling method serves as benchmark to which we compare the SST scheduling method. The objective of this scheduling strategy is to minimize earliness and tardiness when scheduling production orders. The planner exports the schedule and makes adjustments by clustering orders of the same type within the same production week. Similar to the planner, the CURR method also clusters orders of the same type within the same production week. This clustering helps reduce waste generated by the TP-3. However, as a consequence, some orders may be produced too late. We confirmed CURR is in line with the scheduling method used in the company by communicating the method to the planner. The pseudo code of CURR is in Appendix E.

4.3.4 Shortest setup time

In Section 3.2, we introduced the shortest setup time (SST), which has the objective of minimizing setup time. The efficiency of the TP-3 is influenced by the amount of setup time required during processing. By reducing the number of required setups, the waste produced by the TP-3 is also reduced. Theoretically, this priority rule would improve the efficiency and waste management of the TP-3. The priority rule evaluates the current job and determines the setup time of the remaining jobs to be scheduled. The pseudo code is in Appendix F.

4.4 Solution key performance indicators

In this section, we describe how we evaluate the performance of the solution methods. We discuss efficiency and specify other KPIs which help to examine other aspects aside from efficiency. We choose KPIs based on the literature found in Chapter 3 and situation described in Chapter 2.

4.4.1 Efficiency

The objective is to improve the efficiency of the TP-3. Efficiency is evaluated based on the production plan, which represents a specific time period in this problem. As mentioned in Section 1.2, efficiency is defined as processing time/(processing time + setup time) over a period of time.

4.4.2 Other KPIs

Apart from efficiency, we consider other objectives that are relevant, such as material waste, average earliness, and average tardiness. The calculation of material waste involves multiplying the number of setups on production days by the waste generated in each setup. Average earliness and average tardiness are determined by comparing the due date with the completion time. Assessing early and tardiness is crucial to examine the impact of the solution on meeting the due dates.

The objectives are shown in equations 11-15:

Efficiency $\eta = \frac{\sum_{j \in J} \{p_j\}}{\sum_{j \in J} \{p_j + s_{j-1,j}\}} (11)$

Total waste: $W_{tot} = \frac{\sum_{j \in J} \{s_{j-1,j}\}}{45 \; minutes \; of \; setup} * 5 \; (in \; meters) (12)$

Average earliness: $T_{early} = \frac{\sum_{j \in J} \max(d_j - c_j, 0)}{number \; of \; jobs} (13)$

Average tardiness: $T_{tardy} = \frac{\sum_{j \in J} \max(c_j - d_j, 0)}{number \; of \; jobs} (14)$

4.5 Conclusion

The main goal of this chapter is to answer the research question: How can the theory be used for an improved scheduling strategy on the TP-3?

We answer this question by first describing the problem of the TP-3. We decide to split the problem in 2 parts: the bin packing problem and the machine scheduling problem. We first address the bin packing problem, because KHPT puts high emphasis on utilizing raw material efficiently. This involves assigning orders to raw material rolls, effectively utilizing bins, and reducing leftover material on raw material rolls. We use a two-step approach for the bin packing model, by first using the best-fit heuristic followed by the order splitting heuristic. We address scheduling problem secondly, using the bins provided by the bin packing model in the scheduling problem as input.

For the scheduling problem, we choose the shortest setup time (SST) heuristic with the goal to minimize the setup times and to improve the efficiency of the machine. We define the current scheduling method (CURR) which focuses on minimizing earliness and tardiness while clustering orders within the same production week. The main objective is to improve the efficiency of the transfer press. Additional KPIs are identified: average earliness, average tardiness, and total waste. The KPIs help to evaluate the solutions, in addition to the main objective of improving the efficiency of the TP-3.

5. Experiments

In this chapter, we conduct the experiments to answer the last research question: How does the improved scheduling strategy perform compared to the current situation? We use the model defined in Chapter 4 to perform experiments in order to compare the results of the proposed strategy to the current scheduling strategy. The setup of the experiments are discussed in Section 5.1, concerning the time frame, problem instances, and raw material availability. In Section 5.2, we discuss the bin packing outcomes, and in Section 5.3, the results of the scheduling experiments. Lastly, we conclude our findings in Section 5.4.

5.1 Experiment design

In this section, we discuss the problem instances used in the experiments. We provide an overview of the raw material rolls and elaborate on the raw material availability.

5.1.1 Problem instances

To evaluate the various scheduling strategies under different conditions, we determine suitable scenarios. Additionally, we establish problem instances for these scenarios that can be used for experiments. We determine the problem instances based on the production quantities processed by the TP-3. It is not possible to use sales order data since there is a discrepancy between production quantities and sales. This difference is caused by faults, leading to larger quantities being produced compared to what is actually sold.

Section 2.4 mentions that orders are directly accepted if they are placed at least one month prior to the due date. Hence, the scheduling time frame for orders is also established as one month, in line with the acceptance policy.

We select the scenarios for the experiments based on different demand levels: low, normal, and high. To evaluate the demand, we have the option to consider either the total number of meters processed or the number of orders. The total number of meters processed indicates the required processing time, excluding setups. On the other hand, the number of orders indicates the quantity of orders that have to be scheduled. Consequently, we choose to use the number of meters processed as the metric for demand evaluation because, it present an indication of how much work should be done. We categorize the number of meters into the following ranges for each demand level: low (10,000-14,500), normal (14,500-16,000), and high (16,000-25,000).

We select March, July, and December as the production months for the experiments. These months are chosen to offer scenarios that represent different periods of the year. Specifically, March represents high demand, July represents normal demand, and December represents low demand.

It is important to acknowledge that the available production days may differ for each month due to factors like holidays. These variations are considered when designing the experiments to ensure realistic and representative scenarios for each selected production month.

We base Instances 1, 5, and 9 off the job data of March, July, and December 2022, respectively. For the remaining instances, we use sampling. The available data of KHPT contains multiple variables and covers only one year, which makes it unreliable for fitting a distribution function to generate instances. To overcome this limitation, we sample the historical data from 2022 to obtain a subset of instances that accurately represent the range of production orders and scenarios at KHPT.

Table 6 presents the scenarios used for the bin packing model. It should be noted that certain orders had to be excluded from the dataset due to errors, which results in lower lengths and number of jobs.

Instance	Scenario	Number of jobs	Total length(m)
1	March 1	80	22,788
2	March 2	52	10,908
3	March 3	75	14,426
4	March 4	80	16,461
5	July 1	69	17,063
6	July 2	64	14,298
7	July 3	74	15,717.7
8	July 4	82	18,476
9	December 1	64	11,654
10	December 2	63	14,614
11	December 3	73	15,939
12	December 4	88	19,273

Table 6 Instances used in the bin packing model

5.1.2 Raw material availability

In order to establish the raw material inventory for the bin scheduling problem, we consider the current situation outlined in Section 2.4. Since there is no historical data accessible regarding inventory levels, we generate a set of bins using a random function. The minimum capacity is set at 35 meters, while the maximum capacity is limited by the size provided by the raw material supplier, described in Appendix D.

This approach introduces variability in the capacity of the used bins available, which closely mirrors the actual raw material bins present at KHPT. There is only one available used bin, aligning with the current situation in the warehouse. Table 7 provides an overview of the bin types utilized and the available used bins in the warehouse.

Type (width) (mm)	121 (220)	236 (220)	802 (190)	802 (240)	802 (275)	802 (300)	812 (240)	815 (240)	816 (240)	825 (240)	833 (200)	833 (275)	849 (240)	850 (240)	878 (240)	882 (240)	883 (240)	890 (240)
Maximum capacity (m)	1250	1500	1000	1000	750	750	3500	3500	3500	1000	1000	750	1500	1500	1250	1000	1000	1000
Used bin capacity (m)	1086	879	839	279	556	470	1238	1855	2090	165	643	225	172	241	623	745	482	228

Table 7 Bin types

5.2 Bin packing

In this section, we address the influence of waste on bin packing and assess the outcomes of the bin packing model.

5.2.1 Waste considerations in bin packing

In Table 8, we compare the number of bins required in two situations: one where 5 meters of additional material is added to all orders to account for waste loss, and the other where the original situation without accounting for waste loss is considered. We restrict the comparison to using only instances 1, 5, and 9 of the problem, as time restrictions limit the scope of the analysis.

	Original situation	5 meters added	Difference
March	38	38	0
July	23	24	1
December	22	22	0

Table 8 Bin packing outcomes

The difference is in the bin of type 812 (240) which could fit with one bin less if the 5 meters of waste are not included in the calculation. Therefore, to stay as close to the original situation, we decide not to incorporate the 5 meters of waste in the length.

KHPT offers textile in lengths of multiples of 30, so 30, 60, 90, and so on. In the production plan, the lengths of the production orders already include additional material to compensate for potential feed loss during production, ensuring enough material is available for the final product.

5.2.2 Results bin packing

The results obtained from the bin packing best-fit heuristic in combination with the order splitting heuristic are in line with the current method of assigning raw material to orders. Unfortunately, there is no benchmark to which the results can be compared to. Therefore the planner evaluates the results and found the results are comparable to the current situation. Table 9 illustrates the variations in the solution when only using the best-fit heuristic versus incorporating the order splitting heuristic for all instances.

The use of the order splitting heuristic has a significant impact on the warehouse. On average, there is a 16% reduction in the number of leftover bins after production, resulting in more available space within the warehouse. Although the warehouse can accommodate a maximum of 70 raw material rolls, it is important to note that these rolls are stacked on top of each other. Resulting in having fewer rolls in the warehouse. Having fewer rolls is more convenient to operators, as they are required to unstack less raw material rolls.

Instance	Best-fit number of bins	Order splitting heuristic number of bins	Difference	Bins filled by order splitting heuristic	Bins left after production using the order splitting heuristic	Computation time (s) (best-fit)	Computation time (s) (order splitting heuristic)
1	38	37	1	3	21	8.72	1.21
2	21	20	1	2	11	8.43	1.32
3	27	26	1	2	11	8.41	1.17
4	32	31	1	4	18	8.23	1.22
5	24	23	1	3	11	8.12	0.94
6	29	27	2	3	18	8.19	1.02
7	29	29	0	3	16	8.22	1.06
8	32	30	2	3	14	8.16	1.01
9	22	22	0	2	15	8.52	1.12
10	26	25	1	2	11	8.63	1.22
11	27	26	1	1	13	8.26	1.05
12	36	36	0	6	16	8.59	1.29

Table 9 Results of bin packing model

The production schedule is also affected by the split orders. If the schedule determines that the bin should not be produced in one run, a split order can result in two setups instead of one. Therefore, we are investigating whether the raw material rolls that are filled can be processed within a production day. The bins, which have lengths ranging from 750 to 1500 meters, require approximately 2-4 hours of production time. Since there are 12 hours of production time available, the order splitting heuristic does not result in additional setups. We assume that the splitting of orders does not generate any additional waste due to the production time.

5.3 Machine scheduling

In this section, we define the settings of the machine scheduling model. Moreover, we discuss the results of the SST heuristic compared to CURR.

5.3.1 Settings

In Section 4.5, we defined KPIs for the experiments, which consist of: average earliness, average tardiness, and total waste. Although we treat TP-3 as a single machine scheduling problem, it is actually interconnected with other processing steps in the production process, as detailed in Section 2.2.

The improved bin packing outcomes provide the instances used in the scheduling model, which are provided in Table 10.

Instance	Production month	Demand (m)	Jobs
1	March	23,010	84
2	March	10,998	54
3	March	14,580	76
4	March	16,626	85
5	July	17,148	72
6	July	14,502	67
7	July	15,942	78
8	July	18,642	85
9	December	11,754	66
10	December	14,736	65
11	December	15,960	74
12	December	19,434	94

Table 10 Instances used in the scheduling model

5.3.2 Results machine scheduling

We compare the results of the machine scheduling solution from the proposed strategy to the current strategy based on the KPIs and the main objective's outcomes. Table 11 illustrates the performance of the SST and CURR heuristic in terms of KPIs. We confirmed with the planner that the schedules are in-line with the production plan, with one exception. The difference in production schedule is that the current production schedule takes into account the limitations of the following production steps, while our schedule does not. The pleating machines have a maximum weight limit for raw materials, this requires the heavy rolls to be wound down and separated into 2 rolls. However, the benefits of producing a larger role outweigh the costs of having to split a roll exceeding this weight limit.

SST demonstrates better efficiency compared to the current situation, however with an average increase in earliness of 6.06 days. The SST heuristic aims to assign a job to each available time period until all jobs are scheduled, which contributes to the higher earliness. Additionally, the proposed strategy reduces waste by 55% compared to the original situation. The computational time of the SST heuristic is slightly faster.

Instance	Production month	Efficiency (CURR)	Efficiency (SST)	Average earliness (days) (CURR)	Average earliness (days) (SST)	Average tardiness (days) (CURR)	Average tardiness (days) (SST)	Waste (m) (CURR)	Waste (m) (SST)	Computation time (s) (CURR)	Computation Time (s) (SST)
1	March	35%	68%	4.51	8.21	2.75	0	325	200	19.15	17.96
2	March	49%	65%	1.33	8.26	0.67	0.20	195	110	19.48	18.78
3	March	52%	65%	2.27	9.62	0.27	0.10	245	145	19.33	18.10
4	March	50%	66%	1.56	10.39	0.33	0.05	300	160	19.98	16.50
5	July	51%	72%	6.77	13.17	0.23	0.01	315	125	23.31	16.85
6	July	52%	66%	3.95	10.49	1.07	0.02	205	140	23.86	17.27
7	July	49%	65%	2.51	8.18	0.55	0.27	295	160	23.75	16.91
8	July	53%	66%	2.70	7.12	1.84	0.71	320	175	24.03	17.12
9	December	52%	64%	4.81	9.15	0.30	0	190	120	22.41	19.24
10	December	50%	66%	4.58	11.43	0.15	0.02	270	140	22.61	18.38
11	December	52%	67%	2.19	8.76	0.31	0	275	145	22.12	19.65
12	December	48%	64%	3.55	8.65	1.44	0.08	390	200	22.96	18.76

Table 11 Results scheduling model

The issue of early completion times of jobs has the potential to disrupt production at the TP-3 or in subsequent production steps. A possible solution is to try to improve the solution obtained by the SST heuristic. To achieve this, one option is to apply simulated annealing, which can be used to try to improve the solution. Another approach is to explore the use of a different construction heuristic, which may offer alternative methods for sequencing and assigning jobs to minimize average earliness.

When comparing the problem instances, we found there is no relation between demand level and efficiency as expected. One noteworthy instance is instance 1 which performs worse using the CURR heuristic compared to other instances on efficiency. Instance 1 has the highest demand of all instances, which could be why the CURR heuristic performs much worse.

The CURR heuristic demonstrates the poorest performance for the problem instances 1, 5, and 9 when considering the average earliness, which uses the production data from the respective month in 2022. In contrast, the SST algorithm does not show the same pattern, suggesting that this correlation may be coincidental. Furthermore, there is no observable relationship between waste, average tardiness, and varying demand levels.

5.4 Summary

In this section, we addressed the fourth research question: How does the improved scheduling strategy perform compared to the current situation? To answer this question, we conducted experiments on instances based on company data. Problem instances are considered based on low, normal, and high demand, however no conclusions can be drawn on the demand levels. The bin packing results were evaluated, where first the feed loss was considered and its impact on the results. The feed loss did impact the bin packing results, however the production orders were already given additional meters to be able to meet the desired lengths in 30 meter multiples. The outcomes of the bin packing model were improved to utilize the bins more effectively than the solution of the best-fit heuristic by using the order splitting heuristic.

We used the scheduling model to perform the experiments with the proposed solution and the current solution. We found that the SST heuristic is better than CURR on all KPIs except earliness. The SST heuristic is on average 6.06 days earlier finished compared to the old situation.

6. Conclusion and recommendations

In this chapter, we draw conclusions and form recommendations based on the results found in the previous chapters. We discuss the different answers found of the sub questions in order to answer the research question in Section 6.1. Section 6.2 addresses the recommendations on how to integrate the proposed solution and explore different possibilities for further research. Moreover, it discusses the limitations in the research.

6.1 Conclusion

In this section, we answer the sub research questions and the research question.

6.1.1. Sub research questions

We started the research by examining the current production process at the transfer press in the first sub-question, which focused on understanding how products flow through the production stages and how the production plan is developed. The production process consists of four production phases, where the product is processed depending on the specific requirements of the product. The TP-3 plays a role in phase 3, in the coloring of the textile. The steps involved in the coloring of textiles include material collection, machine setup, material insertion, and textile processing. Subsequently, the finished material is removed from the machine, and the rolls are extracted.

In terms of efficiency in production, the management did not allow observations to determine the efficiency, instead we used job lists to assess the performance of the production plan. The efficiency was determined over a period of 2 weeks of production in the first weeks of 2022, which was a normal production period. We found the number of setups occurring were high, resulting in low efficiency, which is caused by the current production strategy.

We examined the production planning by conducting interviews with the planner to determine the strategy used for production using the TP-3. The production planning involves exporting production orders and clustering them into production weeks to minimize the number of required setups. The material is allocated to orders based on the best fit, and orders are split to utilize the remaining portions of raw materials. The selection of raw material rolls also affects the number of setups.

After conducting an investigation into the current situation, we proceeded to explore the methods and theories discussed in the literature regarding 1-dimensional bin packing and scheduling strategies for improving the efficiency of the transfer press machine. Our research revealed heuristics, exact methods, and search algorithms for both problems, all aimed at finding solutions based on specific objectives.

For the scheduling strategies, we discovered numerous priority rules designed to improve specific objectives. While there were no priority rules specifically aimed at enhancing efficiency, we found the SST (shortest setup time) rule which focuses on reducing the number of setups, which aligns with the objective of this research.

For the bin packing problem, there are also multiple options available. However, the Best-fit priority rule stands out as it aims to select bins based on their ability to accommodate the most load and effectively utilize the available capacity in the bins.

We then explored how the theory could be used for the scheduling strategy for the TP-3. There is no literature available on assigning material to orders and scheduling these orders simultaneously. Therefore, we adopt a stepwise approach, tackling the bin packing and scheduling problem separately. We first solve the bin packing problem, because the management of the company puts high emphasis on using raw material rolls to their full extent. We then solve the scheduling problem and use the solution of the bin packing model as input.

We solve the bin packing problem, where different types of orders are assigned to different types of raw materials by splitting the problem into smaller problems. The subproblem considers only one type of products and one type of bin, making it much easier to solve the problem. By solving all the subproblems we have solved the bin packing problem as a whole.

For the bin packing problem, we choose to use the best-fit heuristic along with an order splitting heuristic. The order splitting heuristic splits orders, and fills bins up to their capacity, to reduce the number of raw material rolls in the warehouse after production and use all material on the rolls.

For the scheduling problem, we choose to use the SST heuristic as solving strategy. We compare the SST heuristic to the current solving strategy denoted as CURR. CURR is based on first scheduling orders on production days with objective to minimize earliness and tardiness, after which the strategy clusters the orders in the same production week. This strategy follows the current production planning strategy, identified in Section 2.4.

In addition to efficiency, we identified other key performance indicators (KPIs) such as average tardiness, average earliness, and waste.

Finally, we determine the best scheduling strategy for the transfer press by conducting experiments comparing our proposed strategy to the current strategy. Our findings indicate that the order splitting heuristic implemented for bin packing effectively reduces the number of bins used by 3.2% while maintaining the desired capacity. Consequently, this results in a decrease in the number of raw material rolls remaining in the warehouse after production by 16.1%. By minimizing the raw material rolls in the warehouse, operators can easily locate the required raw materials for production.

We found that the efficiency of the TP-3 increased by 17% on average using SST compared to CURR. The only downside of this strategy is that the orders are completed an average 6.06 days earlier on average than CURR. CURR aims to minimize the earliness and tardiness of production, sacrificing efficiency and waste. For the transfer press, the best strategy is to run as large batches as possible, and clustering orders which have the same early due date to produce at a moment as early as possible.

6.1.2 Research question

How can the current scheduling strategy be improved to increase the efficiency of the transfer press at KHPT?

By addressing the sub-research questions, we can now provide an answer to the main research question. The current scheduling strategy can be significantly improved by using the proposed strategy, which uses the SST priority rule. By adopting a strategy which reduces the setup times between jobs, the company can improve its efficiency of the TP-3 significantly. This strategy also makes use of the best-fit heuristic, followed by the order splitting heuristic, ensures optimal usage of raw materials without accumulating of raw material rolls in the warehouse. This is important to prevent warehouse from overflowing, which can disrupt the operators' ability to locate the necessary materials for production. The proposed strategy demonstrates improvements in efficiency, waste reduction, and average tardiness across all instances. However, it should be noted that the average earliness increases, potentially leading to accumulation in the finished goods warehouse. Nevertheless, the advantages gained in terms of efficiency outweigh the disadvantages of early completion of products.

We could only achieve the desired norm of 70% efficiency once out of the 12 instances. The fraction of setup time remains relatively high compared to the processing time, indicating that further reductions in setup time are necessary to reach the desired efficiency level.

6.2 Discussion and recommendations

In this section, we discuss the limitations of the research and the recommendations to the company.

6.2.1 Discussion

We limited the research scope to the coloring process on the TP-3, excluding thermosetting as a production process on the machine. This decision was made based on the relatively small impact of thermosetting on production. The material requiring thermosetting treatment is processed after production phase 2 when there is capacity remaining in the planning. The colored material is stored in the warehouse, while the thermosetting material is placed next to the machine. Since the demand for thermosetting is low, its processing can be completed without significantly interfering with production operations. Moreover, we did not take into consideration the limitations in following production steps. This can lead to colored rolls which are too heavy for processing. The operators then need to split the rolls in order to be able to use the material. The benefits in of producing a larger role outweigh the costs of having to split a roll exceeding the weight limit.

In the experiments, we made the assumption that there is always sufficient material available in the warehouse for production purposes. However, it is important to note that not all materials are always consistently available, which can result in certain orders being unable to be processed according to the assigned production plan. Unfortunately, due to the unavailability of historical data regarding warehouse inventory, we were unable to evaluate the influence of material availability on production planning. Additionally, we could not compare the results of the bin packing model with the current material selection. Consequently, our assessment was limited to examining the impact of material selection on the warehouse. Future research can focus on investigating the effects of material availability on production planning, providing valuable insights in this area.

The proposed solution using the SST heuristic provides a solution, however this may not be the optimum solution given the objective of efficiency. To improve the solution even further, local search methods such as simulated annealing or tabu search can be used to try to improve the solution. We recommend to focus on improvement heuristics to improve the model.

Lastly, it is important to note that the model we used in this research is based on a deterministic environment, which does not fully account for real-world factors such as machine breakdowns and varying setup times. Therefore, future research should aim to evaluate the proposed solution under stochastic circumstances. By testing the model in stochastic conditions, it can be exposed to changing and more challenging scenarios. For example, the effects of machine breakdowns on the system can be observed, providing valuable insights into the robustness and adaptability of the proposed solution.

6.2.2 Recommendations

Based on the observed results of the proposed models, we recommend implementing the scheduling strategy that focuses on reducing setup times to improve efficiency of the TP-3. The proposed strategy consistently outperforms the current strategy across various scenarios and demonstrates better efficiency in all instances. To thoroughly evaluate the impact of the strategy on the entire production process, we suggest conducting further research. For example a flow shop model can be used to assess the overall effect of the strategy on production performance.

We further recommend improving the data collection process as it currently only provides information on the current availability of raw materials in the warehouse. Gathering historical data on raw material rolls would enable research on the impact of raw material availability on production planning. This data would make it possible to compare to compare the results of the current strategy of assigning raw material to orders to the bin packing strategy used in this research.

This research focusses on evaluating the performance of the model, rather than considering the costs and consequences. However, it is important to assess the costs and consequences before implementing the proposed solution. Therefore, future research efforts should be dedicated to thoroughly investigating the costs and consequences before implementing the model.

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Appendices

Appendix A: Semi-structured interviews

This interview is meant to improve on what is already known of production, find out how the production phases are interconnected, and assess the situation of production. We require information about the production process to be able to make a conceptual model. The interviews are split into 2 parts: part 1 is about the TP-3 specific and part 2 concerns the production planning.

The participants are informed about informed consent, the goal of improving the efficiency of the TP-3, and the possible consequences of the results of the research. The participants are able to withdraw their opinion at all times, and will be anonymous.

Part 1:

- How does the material move through the machine?
- What are the set-up times and conversion times?
- The job lists provide 15 minutes per order for set-up is that enough?
- What is the running speed of the machine?
- How is waste made on the machine?
- On which days is material processed on the TP-3?
- Which types of products can be processed on the TP-3?
- Is the production plan too hard or too lean?
- How do you choose raw material for an order?

Part 2:

- How is the production plan constructed?
- What time horizon does the planning have and when are orders made?
- How do you decide what raw material to assign to an order?
- What is the current scheduling strategy?
- What is the main objective and the KPIs used in for scheduling?

Appendix B: Settings Microsoft Dynamics AX

The settings of the ERP system are shown in Figure 16. The setup time is configured as 15 minutes in the system to allow operators to perform preparation work. The processing speed is set at 5 meter per minute in the settings of the machine, therefore the processing time is set at 1.00. The waiting time is set at 14 hours, meaning the ERP system assumes the product is available for production 14 hours after being processed by the TP-3.

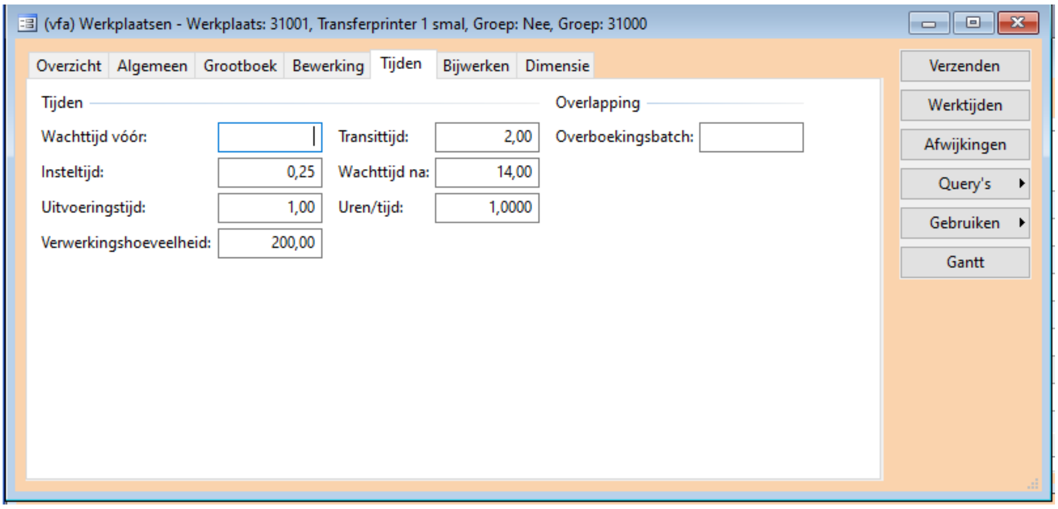

Figure 16 Settings of the ERP system

Appendix C: Systematic literature search

Research question

*"Which **methods** and **theories** are discussed in literature on 1 dimensional **bin packing** and **scheduling** strategies to improve the **efficiency** of the transfer pressing **machine**?"*

The research questions can be formulated differently by using synonyms or changing the order of the key words. The key words are expressed in bold.

Inclusion and exclusion criteria

The inclusion and exclusion criteria are used to shape the search in such a way to obtain relevant articles. The arguments why criteria are included and excluded are added in the Table 12 for clarity.

Inclusive/exclusive	Criteria	Argument(s)
Inclusive		
	Papers about machines	The study is about machine scheduling
	Academic papers/books	The author should have an academic background
	Published after 1970	Theories are often refined, therefore it should be maximum 50 years old
	Papers about scheduling methods	Should be about scheduling, not improving the production of the machine.
Exclusive		

	Papers not available	The paper should be available to be able to be read.
	Multi machine job scheduling	Single machine job scheduling is the subject, therefore multi machine job scheduling is disregarded.
	Cloud computing	Material about cloud computing and minimizing computational time is not part of the research.
	2 or 3-dimensional bin packing	The research is about a 1 dimensional bin packing problem.

Table 12 Inclusive/exclusive criteria

Databases

There are many databases that can be used as a source to find relevant academic literature. For literature on the topic of operations research and general engineering literature the following databases are used: Scopus and Web of Science. For general direction google scholar is used as a search engine to find some reading material. Google scholar is however not a database and is therefore disregarded in the literature search.

Search log

The search strings are used to find sources in the 2 databases. The sources are exported to Endnote 20 where the exclusion criteria are filtered. In some search strings and additional search string is formulated if there were too many or too little results, this is added in the comment section. Total a number of 129 sources were present which were filtered on duplicates and exclusion criteria leading to 8 sources left. The screening is based on reading the title first, then the abstract and if necessary the introduction chapter of the source.

Search string	Scope	Date	Date result range	Number of entries
Scopus				**88**
Title((Model or Theory) AND Efficiency and Machine) AND Key(Scheduling)		26-04-23		18
Title((Model or Theory) AND Efficiency and Machine) AND Key(Scheduling AND Bin packing)				0
Title((Model or Theory) Efficiency AND Scheduling)				39
Title((Model or Theory) Efficiency AND Scheduling) AND NOT energy				21
Title((Model or Theory) Efficiency AND Scheduling AND bin packing)				0
Title((Model or Theory) AND efficiency) AND Title-abs-key(bin packing AND Scheduling)				12
Title((Model or Theory) AND efficiency) AND Title-abs-key(bin packing)				7
Title((Bin Packing))AND key-title-abs(efficient) and not energy				115
Title(bin packing problem) AND title-abs-key(efficient) AND NOT title-abs-key(cloud or two or three or 2 or 3)				30
Web of Science				**41**
Title((model or theory) AND efficiency AND machine) AND key(scheduling)				5

Title((model or theory) AND efficiency AND machine AND (bin packing)) AND key(scheduling)				0
Title((model OR theory) AND efficiency AND scheduling)				35
Title((model OR theory) AND efficiency AND scheduling) AND NOT All field(energy)				19
Title((Model or Theory) Efficiency AND Scheduling AND bin packing)				0
Title(bin packing)AND all fields(Scheduling AND efficiency)				12
Title((Bin Packing))AND key-title-abs(efficiency)				62
Title((Bin Packing))AND all fields(efficiency) AND NOT all fields(cloud or two or three or 2 or 3)				8
Total				129
Duplicates				-10
Selection based on inclusion/exclusion				-110
Left for review				8

Table 13 Search log

Conceptual matrix

The following sources are used and set up in a concept matrix to present a clear overview what parts the sources address and how these can be used.

Source	Machine scheduling	Algorithms for bin scheduling	Heuristics for bin scheduling	Constrained bin problem
1		X	X	
2		X		
3	X			
4		X		
5			X	X
6		X		
7			X	X
8		X		X

Table 14 Conceptual matrix

Sources found

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Appendix D: Order sizes for all raw materials

The types 812, 815, and 816 are bought as 2x 1750 and are stitched together for processing, therefore 3500 meters is the size available for the TP-3.

Type	Capacity raw material in meters
121	1250
236	1500
802	1000 for width (200,240) 750 for (280, 300)
803	1000 for width (200,240) 750 for (280, 300)
812	3500

815	3500
816	3500
825	1000
833	1000 for width (200) and 750 for width (275)
849	1500
850	1250
878	1250
882	1000
883	1000
890	1000

Table 15 Raw material roll sizes

Appendix E: Pseudo code CURR

```
Sub schedule_pseudo_INIT()
'Initialize jobs to schedule


For Each job In jobs_to_schedule
        'find closest production days to due date
Loop
For Each bin In bin_job
        'if the production day are within the same week, the orders are clustered on the earliest production day
Loop
While jobs_to_schedule > 0
    'Schedule all jobs on the preferred production day, the clustered jobs have no setuptime inbetween.
    'add setuptime between the switching bins
     If time_remaining < job Then
        'add to earlier production slot if possible.
        'else add to later production slot
        jobs_to_schedule = jobs_to_schedule - 1
     End If

Loop

End Sub
```

Figure 17 Pseudo code CURR

Appendix F: Pseudo code SST

```
Sub schedule_pseudo_SST()
'Initialize jobs to schedule
While jobs_to_schedule > 0
    If current_job = 0 Then
        'Select earliest job in schedule
        'add setuptime
        jobs_to_schedule = jobs_to_schedule - 1
    End If
    If current_job <> 0 Then
        'Find the bin of current job
        If current_job = bin_job Then
            'find all jobs on this bin
        End If

        If jobs_on_bin = 1 Then
            'select earliest job in schedule
            'add setuptime
             jobs_to_schedule = jobs_to_schedule - 1
        End If
        If jobs_on_bin > 1 Then
            'schedule earliest job if possible with time restrictions, remove job from jobs_on_bin
            'Otherwise try to find new job and add setuptime
            'if no job can be found, schedule on the next available production day.
             jobs_to_schedule = jobs_to_schedule - 1
        End If
    End If
Loop

End Sub
```

Figure 18 Pseudo code SST