Developing a scheduling model for a cable manufacturer

Master's Thesis

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Master Programme	Industrial Engineering and Management
Specialisation Track	Production and Logistics Management
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Date of submission	March 16th 2015

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Acknowledgments

This research report is a result of my graduation research for my study of Industrial Engineering and Management at the University of Twente. The research is performed at the production department of the Twentsche Kabelfabriek B.V. located in Haaksbergen, the Netherlands. To have the opportunity to perform my graduation research in such an interesting, practical, and unpredictable production facility is something I am very thankful for. Even though the duration of the research was longer than anticipated, it was a very inspiring and valuable learning experience for me. The initial goal of this research was to improve the service level towards customers and to improve the flow of production orders. This goal perfectly suits to my interests and range of study. The philosophy of TKF, my interests, and the theoretical background of my studies are a perfect match, which resulted in an opportunity to work for this fascinating company. I realise I could not have written this research report without the help of many friends and colleagues. Many ideas, practical requirements and limitations, and motivation emerged during one of the many formal and informal conversations. I want to express my gratitude to all who were involved in this research. Some I would like to thank separately.

First of all, I thank my supervisor from TKF, Rik Kienhuis, who provided the opportunity to perform my graduation research. Rik, your help and support during my research period are much appreciated. Furthermore I thank Thijs Ten Have and Stijn Koppelmans for their help, their insight and knowledge on production and production planning. Finally I thank my current colleagues for the opportunity to work on my research during my period of employment at TKF.

I thank my supervisors of the University of Twente, Dr. Ir. J.M.J Schutten and Dr. P.C Schuur for their contribution to the results of this research. Their critical feedback, knowledge, guidance, and constructive advises helped significantly to overcome some of the problems I encountered and are experienced as very valuable.

Last, but certainly not least, I thank my family and friends for their unconditional support during this research. Many thanks to my parents in particular. Your support, ongoing encouragement, and patience have been important to me for successfully completing my education.

Deurningen, 16 March 2015

Tom Bijen

Summary

This research assesses the current methodology of production and production planning and scheduling of one of the production departments of TKF, the Installation department, with the goal to improve these processes. TKF wants to be a reliable partner that delivers high-quality custom cable solutions and focusses on innovative products. Offering custom and innovative solutions result in a higher diversity of production orders and therefore in more changeover trade-offs. To even further differentiate from its competitors, TKFs relatively short lead time is a key selling point. Currently, the production planner manually creates a production schedule for 24 hours in advance. This schedule is based on experience, intuition, and priorities based on product lead times, provided by the ERP system. TKF expects that the planning and scheduling approach can be improved, since the scheduling horizon is only 24 hours. Furthermore, the importance of a standardised and structured scheduling approach increases as the number of customer orders increases. To solve these problems we formulated the following research goal: *''Develop a standardised and structured scheduling approach to facilitate the scheduling process such that the service level and throughput of the Installation department increase and the product lead time decreases''.* We define scheduling as assigning the jobs in a certain sequence over the available machines within the capacity restrictions. A structured and standardised scheduling approach is what is currently missing at TKF to make the production department reliable towards the customer. To achieve the research goal, we stated the research problem as: *"How can TKF improve its production scheduling approach such that it results in an increase of service level and throughput and a decrease of product lead times at the Installation department?"*.

Based on the literature review and analysis of the current situation, we proposed three scheduling alternatives to improve the planning and scheduling processes. Every process has a bottleneck: a critical process whose performance or capacity limits the performance or capacity of the entire production facility. Production planners consider the machine with the highest workload often as the bottleneck machine and they are aware that the bottleneck determines the capacity and flow of the production facility. The first two scheduling alternatives focus on optimising the production schedule of the bottleneck machine. We consider the machine with the highest lateness to be the bottleneck machine, which is obviously influenced by the workload of this machine. The third scheduling alternative uses a technique that is used for many combinatorial optimization problems due to its proven performance and (relative) simplicity. Besides formulating scheduling alternatives, we formulated a different production strategy as well. Each of the three alternatives is adapted to the one piece flow manufacturing principle. We introduced one piece flow manufacturing in order to reduce the lead time, work in progress, and waste and to increase the flexibility of the production department. This resulted in the following three production scheduling alternatives:

1) **Shifting bottleneck heuristic – Extended Jackson Rule**
   The SBH-EDD approach uses the shifting bottleneck heuristic (SBH) to solve the scheduling problem. To solve the single and parallel machine scheduling problems it uses the Extended Jackson Rule and has as objective function to minimise the maximum lateness.
2) **Shifting bottleneck heuristic – Simulated annealing**
   The SBH-SA approach uses the SBH to solve the scheduling problem. To solve the single and parallel machine scheduling problems, it uses the simulated annealing (SA) algorithm and has

objective functions to minimise the maximum lateness, total changeover times, and total idle times. SA requires an initial solution, for which we use the Extended Jackson rule.

3) **Simulated annealing algorithm**
The SA approach uses the SA algorithm to solve the scheduling problem. The SA algorithm requires an initial solution, for which we use the Extended Jackson rule. The objective functions are identical as for Alternative 2.

To formulate the production scheduling alternatives we excluded the insulation processes from the model. The insulation processes are designed for long production runs. Consequently, the one piece flow manufacturing principle results in an unacceptable inefficient production schedule in terms of waste due to changeovers. To ensure an efficient and effective production schedule, we recommend TKF to decouple the insulating processes from the scheduling problem and schedule the insulation process with, for example, a Kanban system. To comply with one piece flow, production orders need to meet several requirements. First, a production order may not consist of more than one reel after the stranding process. Furthermore, the processing time at the bottleneck machines, which are in general the braiding machines, should be around 24 hours. The most important prerequisites to implement one piece flow: a stable process and processing times that are, on average, significantly larger than the required changeover times. A stable process implies reliable processing times and a reliable process (few erroneous products).

The alternative approaches are evaluated on the number of backorders, service level, total changeover time, and lead time. We evaluate both the number of backorders as well as the service level because, due to the introduction of one piece flow manufacturing, even though the number of backorders may increase, the service level may increase as well. We create two variants of each alternative. The first variant, called ‘’normal’’, uses data as they are used currently. The second variant, called “OPF’’, uses data adjusted to the one piece flow manufacturing principle. Table 1 depicts the results of the assessment.

	Service level (%)	Backorders (#)	Lead time (days)	Changeover time (h)
SBH-DR - normal	81,9%	10,0	6,4	235,4
SBH-DR - OPF	90,9%	10,0	5,9	242,1
SBH-SA - normal	82,9%	11,3	6,4	222,6
SBH-SA - OPF	91,2%	9,8	**5,8**	243,3
SA - normal	91,2%	**5,8**	6,8	**211,1**
SA - OPF	**92,8%**	7,8	6,4	224,0

Table 1: Performance alternative scheduling approaches

Based on the analysis of the performance assessment we select the most suitable scheduling approach for TKF. The analysis shows which alternative is the best performing, and whether one piece flow manufacturing yields an improvement.

- Backorders – The number of backorders reflects how many production orders are delivered on or before the agreed delivery date. From Table 1 we conclude that SA-normal results in the fewest number of backorders. However, the number of production orders increases with a factor 1.6 after implementing the one piece flow principle, so a small increase of backorders does not necessarily imply a worse solution. Therefore, the number of backorders alone does not provide a good indication of the performance of the alternatives.

- Service level – The SA-OPF approach is overall the best performing alternative on service level and lead time. For the four data sets, the SA-OPF approach achieved an average service level of 93%, with limited variation over the experiments, while the other alternatives only achieved 82% to 91% with high variation over the experiments. For all time periods, alternatives incorporating the one piece flow manufacturing principle outperform the alternatives that do not incorporate the one piece flow manufacturing principle, even though in some occasions the number of backorders is higher.

- Besides being a reliable supplier, TKF wants to differentiate from its customers by offering customers a short lead time on production orders. The one piece flow approach divides large production orders into several small production orders, reducing the maximum production time per production order from 142 hours to around 24 hours. The implementation of one piece flow reduces the average lead time with 7% with respect to their normal counterpart.

- The increasing numbers of production orders result in a significant increase of total changeover time as well. Compared with the normal production strategy, the one piece flow approaches require on average 6% more changeover time. The impact of the production sequence is the highest at the sheathing processes due to the different materials that are used. Looking at the sheathing processes, the SBH-SA and SA approaches reduce the number of large changeovers significantly compared to their dispatching rule counterparts. Even though the total changeover time required is higher with one piece flow compared to the normal approach, the overall performance improves.

Finally, we conclude that *''Simulated annealing with one piece flow''* suits best to the situation at TKF due to its excellent performance on service level, number of backorders, and product lead time. The running time to solve the scheduling problem with SA-OPF is significantly smaller (one hour) compared to the SBH-SA alternatives (four hours+). We advise TKF to decouple the insulation processes from the scheduling problem to ensure an efficient production schedule. Furthermore, we advise to implement the one piece flow manufacturing principle because it increases the service level and flexibility of the job shop and reduces the product lead times. These improvements come at the cost of 6% more changeover time.

Terms and abbreviations

TKF	Twentsche KabelFabriek
TKH	Twentsche KabelHolding
ERP	Enterprise resource planning system
LSS	Lean Six Sigma
OEE	Overall Equipment Efficiency
KPI	Key performance indicator
WIP	Work in Progress
JSSP	Job shop scheduling problem
MTO	Make to order
MTS	Make to stock
L_{MAX}	Maximum lateness
SA	Simulated Annealing
SBH	Shifting Bottleneck Heuristic
DR	Dispatching Rules
EDD	Earliest due date rule. This research uses the Extended Jackson rule
OPF	One piece flow manufacturing
Scheduling	Assigning jobs in a certain sequence over the available machines within the capacity restrictions
Bottleneck machine	A critical process whose performance or capacity limits the performance or capacity of the entire production facility
Wire drawing	The first step to making a cable. Raw materials are drawn to the required diameter
Insulation	A plastic layer is applied to protect the copper core
Stranding	Multiple insulated cores are combined
Braiding	Wire or steel braiding is applied to protect the cable from external forces
Armouring	Steel tape or wire is applied to protect the cable from external forces
Inner sheath	To protect the cable from armouring or braiding, an inner sheath is applied
Outer sheath	To protect and finish a cable, an outer sheath is applied

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1 Introduction

The Twentsche Kabelfabriek (TKF) is a company that provides innovative and custom cable solutions for customers worldwide. The innovativeness of products changed the ratio between make to stock and make to order products. Now make to order (MTO) products become increasingly important, TKF faces difficulties delivering these products on time to their customers. This research aims to improve the production planning and scheduling approach such that the service level increases and additionally the lead times decrease. This rapport also serves as a graduation thesis for the education Industrial Engineering and Management with Production and Logistics Management as specialisation track.

Currently, the planner manually creates a production schedule for 24 hours in advanced. This schedule is based on experience and a buffer ratio which indicates the ratio between the time until the delivery date and the number of remaining operations of a job. The planner schedules the MTO products, after which he decides which make to stock (MTS) products he includes. Again, these decisions made are based on intuition. TKF expects that the planning and scheduling approach can be improved, since the scheduling horizon is only 24 hours. Also, the importance of a decent scheduling approach increases as the number of customer orders increases.

Due to a lack of sales that lasted several years, TKF had a reorganisation to save the company from bankruptcy. The locations Lochem and Haaksbergen merged to one factory in Haaksbergen. After this reorganisation, the decision was made to implement the lean philosophy to reduce costs and increase efficiency even more. Many projects have been (and still are) executed to implement lean management within the organisation. By providing a production planning and scheduling approach that results in an efficient production plan, this report complies with the philosophy the company pursues.

This chapter proceeds with introducing TKF and analysing the problems TKF currently encounters. Section 1.1 provides a general description of TKF and in Section 1.2 we define the problem situation. The problem situation contains the analysis of the current situation, research demarcation, and formulation of the research objectives and research questions. Section 1.3 provides the research approach we use to answer the research questions and finally meet the research objectives.

1.1 Introduction to the Twentsche kabelfabriek

The **Twentsche kabelfabriek** is a developer and producer of cable solutions for customers worldwide. Fibre-optic is one of these solutions that are widely used nowadays. The company was founded in 1930 when it produced low-voltage cables, and later on the first telephone and medium-voltage cables. In 1973, it acquired the German company Grenzlandkabel Gmbh before the Twentsche kabel holding was established (TKF, 2013). The main production facility is located in Haaksbergen, the Netherlands, but TKF has a production facility in China as well. Currently, TKF employs over 425 people and had an annual turnover of 180 million euro in 2012. For its production, TKF has 4 independent but cooperating production departments: the Multi-Conductor, Fibre Optic, Energy, and Installation departments. Each of these departments has its own management (a value-stream manager, quality engineer, capacity planner, process engineer, and shift-leaders). The ambitions and aspirations are captured nicely in its mission statement (TKF, 2013);

"Our inspiration comes from developing, selling and manufacturing innovative, high-quality cable concepts. In situations of defiant requirements for functionality and reliability of cable connections, we are the partner"

Figure 1.1: The first cable factory

As the mission statement implies, the main goal of TKF (as any producing company) is to sell products. To be able to differentiate from competitors, it develops and produces innovative and qualitative solutions. Another aspect that distinguishes TKF from other companies is that customer intimacy is a priority; TKF helps creating a solution when a customer has a problem. The markets it targets can be divided into 5 segments: infrastructure & construction, telecom, energy, marine & offshore, and industry. To give an impression of the variety of products, we give some examples:

- Medium and high voltage cables
- Fibre optic cables
- CATV coaxial cables
- Signal and telecommunication cables and wires
- Lead sheathing data and energy cables
- Low voltage distribution cables
- Telephone cables and wires
- Data cables
- Installation cables and wires
- EMC motor cables

In 1980, the **Twentsche kabel holding** (from now on abbreviated to **TKH**) was established as a result of the acquisitions of several Dutch and German companies. The main office of the TKH-group is located next to TKF in Haaksbergen, the Netherlands. Currently, it consists of over 70 independent subsidiaries, which are located in more than 20 countries, and had in 2012 a little over 4700 employees. Figure 1.2 shows that the annual turnover is steadily increasing since 2009 and was 1.1 billion euro in 2012. The biggest portions of the companies within TKH are research and development related, thus their contribution to the total turnover is limited.

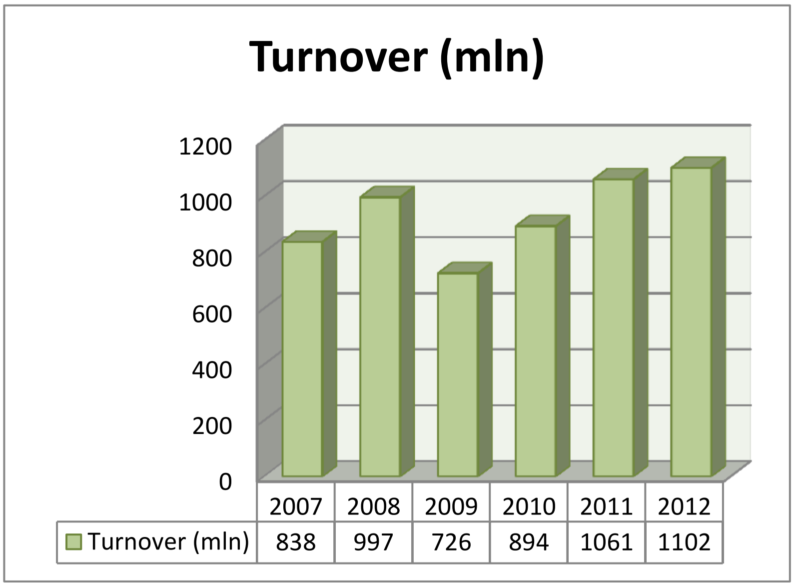


Figure 1.2: Turnover TKH-Group 2007-2012

1.2 Problem identification

TKF wants to be a reliable partner that delivers high-quality custom cable solutions and focusses on innovative products. To even further differentiate from its competitors, a relatively short lead time is a key selling point. Due to these custom and innovative solutions, the production environment shifted from high volume & low variety to low volume & high variety. Producing according to a low volume & high variety strategy means a high diversity of production orders resulting in more changeovers / setups and other trade-offs. Consequently the complexity of production planning and scheduling increases. TKF expects an increase in demand for MTO products, causing the planning and scheduling processes become increasingly important. TKF realises that it does not fully utilise the production processes' capabilities and it expects that the production planning and scheduling approach can be improved whereas the service level, utilisation of machines, products´ lead time, and output of the production department do not meet the set standards. TKF recently started implementing lean six sigma (LSS) projects concerning continuous improvement of business processes. In order to improve the production planning and scheduling approach, the decision was made to initiate this research.

By means of interviews with the materials control manager, production planner, machine operators, and time spent at the production department, we identified recurring problems regarding the planning and scheduling processes. The most frequently mentioned recurring problems are:

- The absence of a structured scheduling approach
- The absence of a standardised scheduling approach
- The manual scheduling approach
- The short term planning horizon

Currently, the production planner manually makes a production schedule for the upcoming 24 hours with the support of an Excel tool, which visualises the cumulative workload in hours at each production process that has been released so far, and NaVision. NaVision is an ERP system that gives an overview of the planned and unplanned production orders per machine, with their corresponding processing times, changeover times, materials required, previous and next production processes, current status, and order information. Besides the Excel tool and the ERP-program, the production planner uses a planning board to create a Gantt-chart in order to monitor the progress of the production orders and to determine the production sequence. When making a production schedule, the primary goal is to maximise the service level. Even though the ERP-program provides information about the production orders such as the latest delivery date, it does not make any trade-offs or scheduling decisions. As said, the Excel tool visualises the workload in hours per production process. By means of several rules and guidelines, the machine operators decide the production sequence themselves. The production planner makes the trade-offs and determines the production sequence per machine. The production planner aims to schedule these machines as efficiently as possible by clustering identical or comparable orders. The output of the insulation (the first processing step) machines determines the product mix in the production cell. The production planner has no insight in the actual schedules at the other machines. To avoid a standstill of these machines, he schedules a product mix that ensures sufficient work at all machines.

Besides Navision, there are no mechanisms, procedures, or rules available to perform these tasks. This makes that the scheduling process heavily relies on the intuition and experience of the production planner, resulting in a dependency of the production planner. It is difficult to find a replacement for a process that is unstructured and non-standardised. Due to the fact that TKF is an innovative company, new products are not an exception. The value of the intuition and experience when scheduling these products is limited and thus the desire to obtain a more standardised approach arises.

Alongside with the manual scheduling approach, a production plan for a longer horizon is lacking. Due to the manual scheduling approach it is hard to take future orders into consideration, resulting in that most decisions are based on daily information and problems are solved ad-hoc without considering any long term effects. Considering that the horizon of the schedule is only 24 hours, it occurs that rush or rework orders are inconvenient. Due to complexity and the required flexibility, it is difficult to ensure a profitable production schedule without any optimisation support (Harjunkoski et al., 2013). Clustering orders with similar characteristics can result in a better flow in the production department, as it reduces the number of changeovers during a period and results in longer production runs of production orders with similar characteristics. Currently, clustering of production orders only happens when orders within the 24 hour scheduling horizon can be combined.

Essentially, there are 2 different types of production orders: orders consisting of make to order (MTO) products and make to stock (MTS) products. In the remainder of this report we refer to orders consisting of MTO or MTS products as MTO orders and MTS orders. MTO orders are orders that arise when a customer places an order, so when a customer order is accepted the production process has yet to begin. MTS orders are orders to replenish the stock, so not directly related to a customer order. From this stock, customer orders are fulfilled. The priority of the production planner is scheduling the MTO orders because these contain a delivery date that is agreed upon with the customer. The production planner attempts to allocate capacity as efficiently as possible so he adds, if possible, MTS orders of products whose inventory level is below their minimum stock level. In terms of efficiency this is beneficial, but in terms of service level and backorders, it can have rather adverse consequences. To make a schedule, the planner has to assess the orders scheduled at each individual machine to make the trade-off which order to start, which is difficult to do by heart. The production planner has to take the flow within the production department into account and ensure that all machines have work available for processing. This flow is disturbed by rework orders which require reprocessing. Some production orders, regular or rework, are critical in terms of due date. In situations when the production order is critical, the production planner has a last trump to overrule the rules in terms of an urgency card. A production order with an urgency card gets the highest priority and takes precedency at all processes.

To conclude our analysis: the current scheduling process is unstructured and non-standardised, due to the lack of mechanisms and tools, and it depends on the intuition and experience of the planner. The scheduling process is getting more complicated since the product mix has changed: the shift to low volume & high variety results in making more trade-offs which is more difficult to do manually. Also, the currently short planning horizon forces the planner to schedule production orders and solve problems ad-hoc without taking future consequences into account. The second main consequence of the short scheduling horizon is the inability to cluster production orders to create longer runs of similar products. These problems will become more urgent since production management expects an increase in demand. The production planner uses a manual approach and a 24 hour scheduling horizon. The priority of production orders to schedule is first rework orders, then MTO, and finally MTS in case there is production capacity remaining. The planner aims to maximise the service level while taking the continuous flow of products within the factory into account by minimising the number of changeovers and by ensuring that each machine has work available. The main consequences of the current scheduling approach are an unacceptable service level, a poor utilization of machines, long lead times, and an insufficient throughput of the production department. Summarising this section results in the following main research question:

"How can TKF improve its production scheduling approach such that it results in an increase of service level and throughput and a decrease of product lead times at the Installation production department?"

1.2.1 Causes & effects

This section provides a summary of the most occurring and influential problems of Section 1.2 and visualises the relationships between problems in a causal diagram. As mentioned before, the motivation for this research is the expectation of management that the planning and scheduling process can be improved. The central problem is: *''poor delivery performance of the Installation department''*. After analysing the current production planning and scheduling approach, the most important (core) problems that can be influenced are:

- The absence of a structured scheduling approach
- The absence of a standardised scheduling approach
- The manual scheduling approach
- The short term planning horizon

Not all problems and causes of problems have been mentioned or explained in the problem analysis because they are either less relevant, fall outside the scope of this research, or are not suggestible. For the understanding and completeness of this analysis however, it is necessary to elucidate these problems.

Make-to-order production: To reduce the amount of stock and to be able to produce custom cables with a competitive lead time, TKF decided to increase the proportion make-to-order. We do not take this cause into consideration because it is a marketing strategy decision made by the management. Strategic decisions fall outside the scope of this research.

Low volume & high variety: To satisfy customers' needs, TKF produces innovative and custom made cable solutions instead of cables for the 'big market'. This strategy results in wider variety of different production orders. The objective of this research is to propose a scheduling approach that is able to cope with this. Therefore, we do not take this problem into consideration. We let these decisions outside the scope of this research.

No production scheduled: Due to the shift to low volume & high variety, the set of production orders contains various production routes. When creating the schedule, it is important to take subsequent processing steps into account to ensure that all machines are occupied. However, it occurs that the set of production orders is not providing sufficient work for a certain machine. When there is no work available for a machine, the utilisation of this machine decreases. As stated in the research question, the focus of this research is to increase the throughput and the service level of the Installation department, making machine utilisation a secondary objective. For this research, we assume that either the machine utilisation increases when producing with an (near) optimal schedule or the idle time is caused by a lack of demand for these machines.

Short term scheduling horizon other departments: Besides the Installation department, other departments have a manual scheduling approach and use a short scheduling horizon approach. When other departments have rush orders that need processing at the Installation department, it causes scheduling problems at the Installation department. We do not take this problem into consideration because this research focusses on the scheduling approach of the Installation department.

Delivery date set too optimistic: It occurs that the sales department does not take the workload of the production department into account, therefore accepting a workload that cannot be processed in time. Another aspect is that due to the competitive lead times, there is little room for errors which eventually increases the impact of such errors.

Poor quality of production: The quality of the production determines the number of rework orders. The focus of this research is improving the scheduling process and not the production process. Even though the number of rework orders influences the performance of a schedule, we leave this problem outside the scope of this research. Figure 1.3 visualises the relationship between problems causing a poor performance of the Installation department.

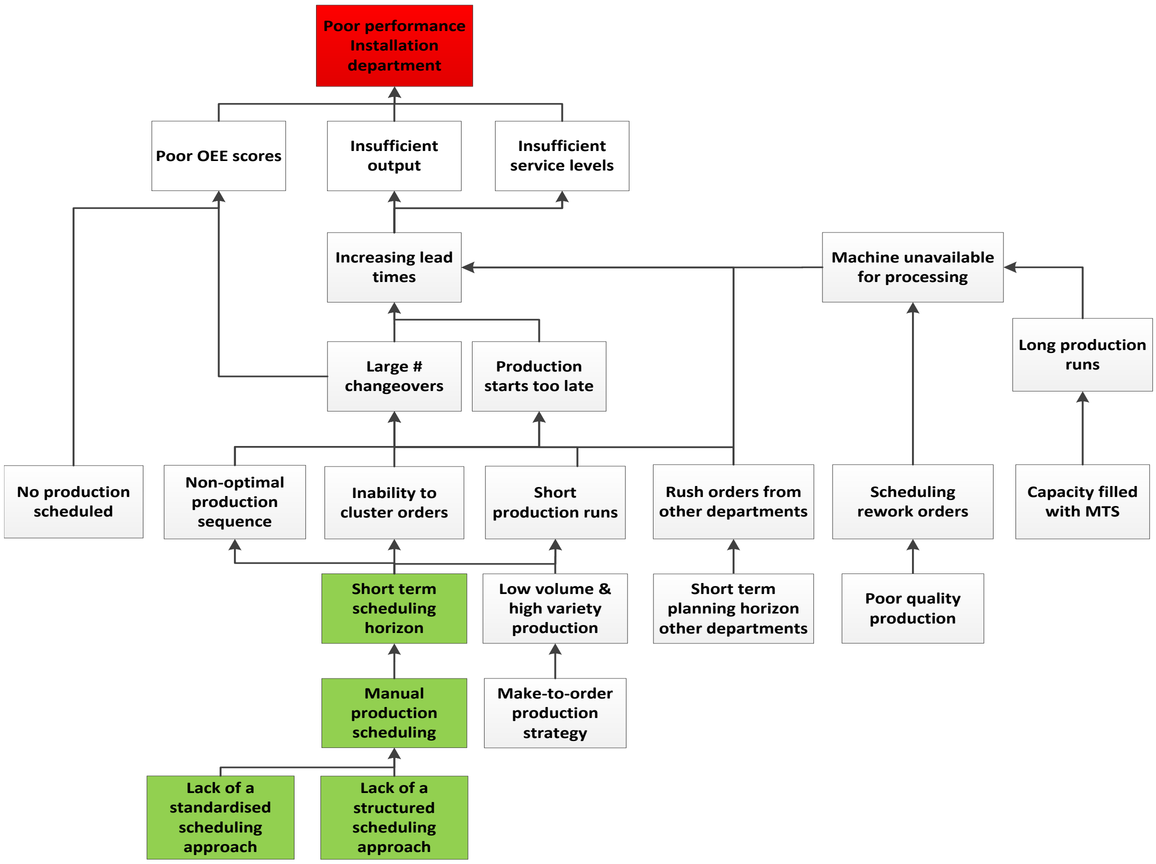


Figure 1.3: Causal diagram

1.2.2 Project demarcation

We restrict the scope of this research to short term production scheduling. As mentioned in Section 1.2, the production activities at TKF are divided in 4 separate production departments namely Installation, Energy, Multi-Conductor, and Fibre-optic. This research focusses on the production scheduling of the Installation department only. The Installation production department mainly produces cables for the marine & offshore, building, and utility industry. As mentioned, this research focusses on production scheduling for the Installation department and not processes prior or subsequent to this department. The sales, purchasing, R&D, quality control, production management (i.e. personnel scheduling), and inventory management activities are outside the focus of this research as Figure 1.4 shows. With the focus on customer service level, product lead time, and machine utilization of the Installation department, we restrict this research to their production processes. Therefore, we exclude wire rod drawing, the purchase of raw materials, inventory handling, quality checks, and the delivery of finished goods towards the customer from this research. For this research we assume that raw material is available when a production order is accepted.

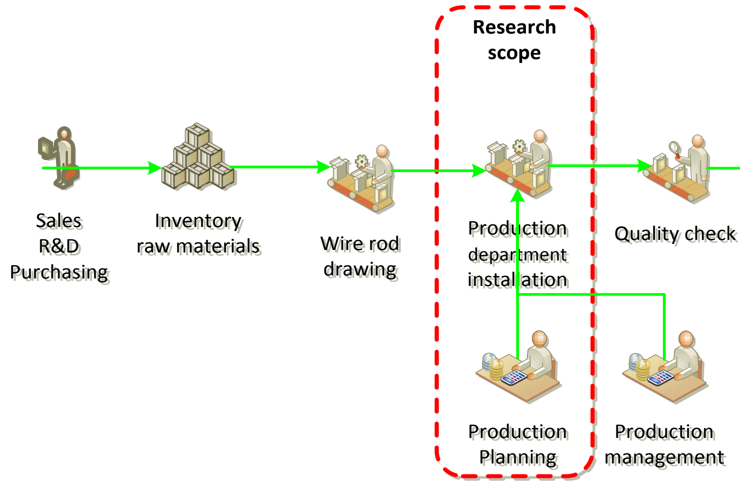


Figure 1.4: Research scope

We decide to leave several activities outside the scope of this research, but we expect that some of these activities need to be addressed as well. To create a production schedule, input from several departments is required. The exchange of information, cooperation between several departments, and the alignment of strategies are critical for a successful scheduling process. After all, production scheduling has not only a close relation with the production process, but is also influenced by the availability of raw materials, the number of sales, product development, and the delivery date promises from production towards sales and from sales towards the customers.

1.2.3 Research objectives

In order to answer the research question, this report has to develop a suitable scheduling approach that will help with the decision making of the production planner. This approach will assist the production planner by extending the scheduling horizon. This model facilitates scheduling by standardising and structuring the process. The final objective of this research is to propose a scheduling approach that increases the service level, throughput, and capacity utilisation and additionally reduces the lead time of products. These goals are consistent with the objectives of a proper scheduling approach as stated in Pinedo (2009). The research objectives are captured in the following research objective:

''Develop a standardised and structured scheduling approach to facilitate the scheduling process such that the service level and throughput of the Installation department increase and the product lead time decreases''

To meet these research objectives, we provide a set of deliverables. The deliverables of this research are:

- A tool that results in a feasible production schedule
- A tool that assists the production planner in making more efficient production schedules
- A tool that visualises the effect of scheduling decisions
- A structured and standardised approach to create a production schedule
- A scheduling approach that is aligned with the LSS philosophy
- Key performance indicators for decision making and future monitoring

The first deliverable of this research is a tool that provides a production schedule. This tool has to assist the production planner in making more efficient production schedules by using a longer scheduling horizon. As mentioned in Section 1.2.1 the production planner lacks a clear overview of the schedule he created. By providing a visual overview, the planner is able to see effects of scheduling decisions and facilitates the decision of which MTS order to include. By scheduling with a tool, the scheduling process becomes more structured and standardised, reducing the impact of intuition and experience. Since this research is one of many business improvement projects, it is important to align this report as well as the approach with this philosophy. Finally, this research provides a set of key performance indicators (KPIs) to assess the current and future scheduling approaches. KPIs assist with decision making and enable monitoring of the future situation.

1.2.4 Research questions

In Section 1.2 we provided a brief explanation of the problem, together with the main research question: *"How can TKF improve its production scheduling approach such that it results in an increase of service level and throughput and a decrease of product lead times at the Installation production department?"***.** To answer the main research question, we formulate several research questions in order to make this comprehensive question manageable. Aggregating the answers to these research questions provide the required data and knowledge to answer the main research question. These research questions ensure a structured and organised research approach.

First we want to know what literature is available about planning and scheduling approaches and how to improve the latter. Furthermore, we need to know what the required parameters and variables are for a planning approach for the development of alternative approach. By performing a literature study we identify alternative solution approaches, identify relevant key performance indicators, and get more familiar with the terminology and other relevant aspects of scheduling processes.

1. What literature is available regarding improved scheduling approaches?
    1.1. How to position the planning and scheduling processes?

   1.2. How to classify the planning and scheduling processes?
   1.3. What scheduling approaches are available in literature?
   1.4. What are the key performance indicators of a scheduling approach?

The next step is to get familiar with the production processes in order to identify and understand the practical restrictions and preferences we need to take in to account when developing a scheduling approach. To find improvement opportunities we discuss the current scheduling approach, after which we assess the current scheduling approach in order to assess the proposed solution approaches.

2. What is the current situation of the production and scheduling processes?
   2.1. What are the current production processes?
   2.2. What are the current scheduling processes?
   2.3. What is the performance of the current scheduling approach?

After understanding the current production and scheduling processes and the practical restrictions and preferences, we develop alternative scheduling approaches. Research question 3 leads to alternative scheduling approaches, after which we determine which is best suitable for TKF (research question 4).

3. Which of the developed planning approaches suits best to the situation of TKF?
   3.1. What are the practical restrictions?
   3.2. What is the performance of the solution approaches?
   3.3. Which of the solution approaches is the best suitable scheduling approach for TKF?

After research question 4, we identified which alternative provides the most beneficial results. The final research question remaining is:

4. What is the best method to implement the selected solution approach at TKF?
   4.1. What is the impact of the selected solution approach to other business processes?

Ultimately, the answers to the research questions and finally the answer to the main research question leads to the fulfilment of the objective of this research:

''A standardised and structured scheduling approach to facilitate the scheduling process such that the service level and throughput of the Installation department increase and the product lead time decreases''

1.3 Research design

In this section we provide the structure of this research report. Figure 1.5 shows the project design we use for this report, together with the goals we want to achieve in each chapter and the method used to achieve this goal. This research design is a result of the research questions defined in Section 1.2.4. Each chapter answers at least one of the research questions. As the red arrow indicates, this is an iterative approach.

Chapter 1 provides the problem formulation, containing the problem analysis, demarcation, objectives and research questions. Chapter 2 provides the used literature regarding the positioning of the research problem, identification of alternative planning and scheduling approaches, background information on lean six sigma, and the key performance indicators that are used to evaluate the current and alternative planning and scheduling approaches. Chapter 3 provides a description of the current production and scheduling processes, and we perform measurements in order to assess the current scheduling approach. In Chapter 4 we develop the alternative scheduling approaches and Chapter 5 provides the results of the assessment of the formulated alternatives. After the assessment we are able to make a decision on which of these planning and scheduling alternatives is best suitable for the problem situation at TKF. In Chapter 6 we formulate conclusions and recommendations regarding implementation.

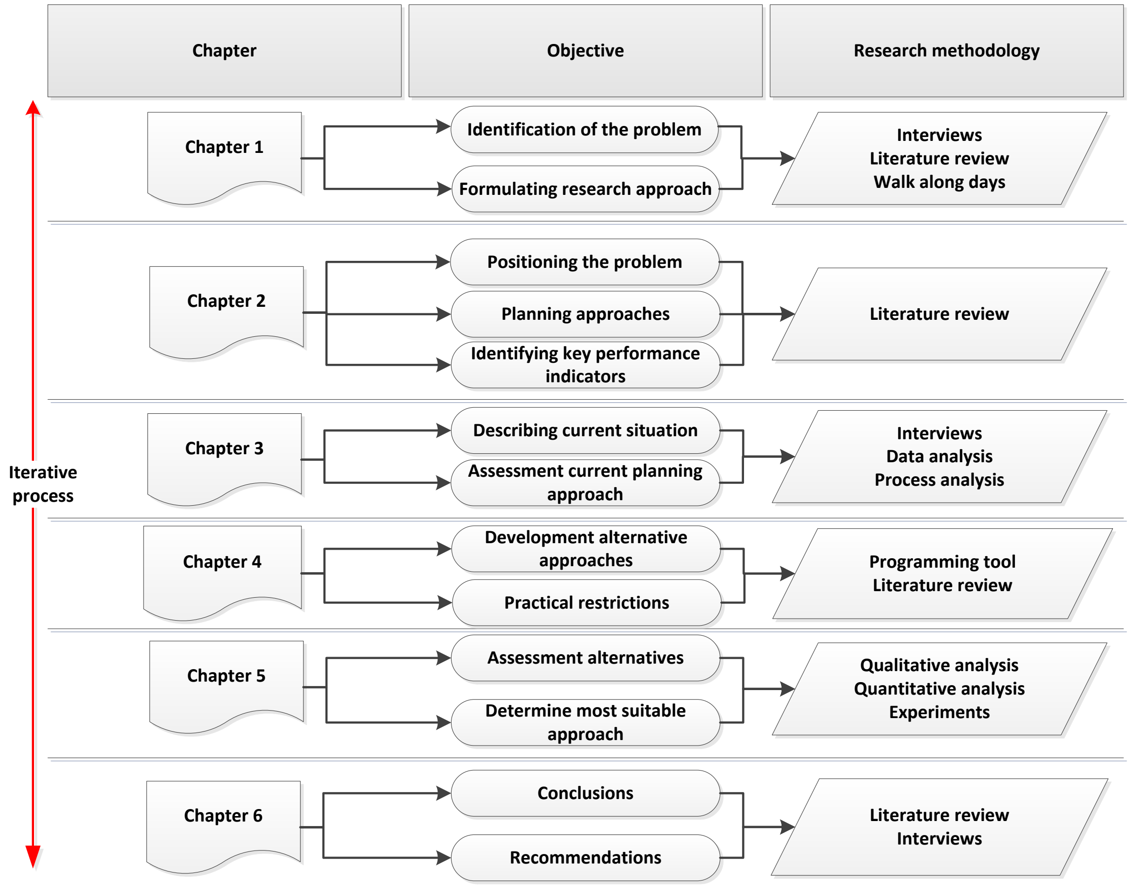


Figure 1.5: Research design

2 Literature review

This chapter describes and elucidates the literature required for this research in order to answer *"What literature is available regarding improved scheduling approaches?".* First, Section 2.1 identifies the hierarchical levels of planning and scheduling and aim to answer research question 1.1*: "How to position the planning and scheduling processes?"* Answering this research question enables us to find appropriate literature. To ensure the literature review provides relevant information we classify the production department in Section 2.2. In Section 2.3 we answer research question 1.2: *''What scheduling approaches are available in literature?''*. We perform a literature research to identify relevant scheduling methodologies and approaches. Section 2.4 provides background information on lean six sigma. This research is a result of the implementation of the lean philosophy within TKF, and to understand the motivation, it is important to be familiar with this philosophy. Section 2.5 provides an overview of key performance indicators and answers research question 1.3: *"What are the key performance indicators of a scheduling approach?".*

2.1 Positioning

With the help of the hierarchical planning framework we answer the research question *"how to position the scheduling processes?"*. Planning and scheduling is relevant on various levels within a company. By positioning the problem we define the research area by restricting to the most relevant aspect of planning and scheduling. Figure 2.1 displays the hierarchical planning framework developed by Zijm (2000). For the Y-axis, Anthony (1965) proposed three hierarchical levels of planning and scheduling activities: the long term (strategic), the medium term (tactical) and the short term (online and offline operational) activities. For the x-axis, Zijm (2000) distinguishes three different management aspects: technological planning, resource capacity planning, and material coordination.

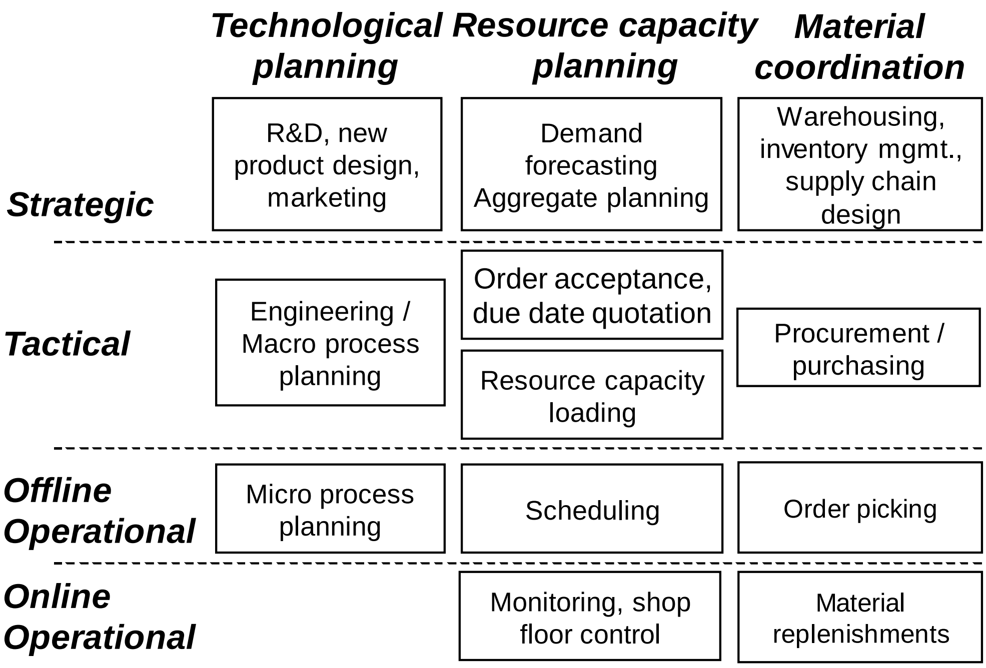


Figure 2.1: Hierarchical planning framework by Zijm (2000)

For this research we limit ourselves to the resource capacity planning because this focusses on production planning. Concerning resource capacity planning Zijm (2000) distinguishes 4 different planning levels. First we describe each of the hierarchical levels before we identify which category this research covers.

The strategic level concerns the long term decisions, generally made by high level management. Resource capacity planning addresses problems relating product mix planning and general workforce planning. Strategic planning does not assume any information about customer specific orders, but uses aggregated or forecasted data as input for, for example, LP (linear programming) models. This model contains a considerable amount of uncertainty and is on general used as an estimator for the future. At this stage, management defines the capacity available for production, decides whether to make or buy a part, and produces a rough workforce planning (Hans, 2001). The tactical level planning aims to allocate resources as efficiently as possible. Resource allocation starts with the order acceptance process which consists of dividing orders in jobs, determining precedence relations, estimated processing times, and calculating a reliable external due date for customer orders (Hans, 2001). Next, resource loading is executed to determine the internal due dates and the capacity required to process these orders. Tactical planning is used at a medium term when usually only aggregated data, such as a rough capacity or workload estimation, is available and therefore subject to a considerably large uncertainties. The strategic level provides the capacity available, i.e., it determines the regular capacity. Despite the capacity boundary, in a manufacturing environment capacity is often flexible because capacity can be expanded by adding irregular capacity or by outsourcing production orders. Irregular capacity often invokes additional costs (overtime or hiring personnel) and is not desirable. At this stage we determine the amount of regular and irregular capacity available for scheduling (Hans, 2001). Detailed information about the customer orders is still unavailable, which generally is acquired after order acceptance. The operational level planning focusses on short term decisions to produce a production schedule that fits within the restrictions provided in the previous stages. The production capacity (regular and irregular) is determined on the strategic and tactical levels and is considered as fixed at the operational level (Wullink et al., 2004). We define scheduling as assigning the jobs in a certain sequence over the available machines within the capacity restrictions. At this stage, the objective usually is to meet the internal due dates, set at a higher hierarchical level, with the help of a scheduling heuristic or an optimisation model (Zijm, 2000). At this stage, the degree of uncertainty is still significant due to machine break downs or other disruptions in the process as a result using deterministic data as input for the scheduling model (Wullink et al., 2004).

The strategic planning falls outside the scope of this research due to the fact that the regular capacity is fixed. Expanding capacity requires a substantial investment which is unwanted at this moment. At TKF the decision whether to add irregular capacity or not, is made only days before the moment it is necessary. In literature, daily decisions are short term decision, and therefore we decide to leave the tactical planning outside the scope of this research since it concerns medium term decisions (months). The focus of this research is devoted to the offline and online operational level. The time horizon of the operational level is several weeks. The operational level encompasses scheduling activities and shop floor control.

2.2 Manufacturing designs

Besides the positioning within the hierarchical framework, it is important to classify the production process in order to find suitable planning and scheduling literature. This section answers research question 2.2: ‘’*How to classify the planning and scheduling processes?’’.* The production strategy of TKF is to have a mix of MTS and MTO products. Several products are produced according to the make-to-stock strategy because they are fast movers (products with a high and predictable demand). However, an increasing amount of products is produced with the MTO strategy. TKF increases its amount of MTO products because the product variety increases due to the unique solutions it offers. To offer a competitive lead time and to cope with the increasing demand for these products, it is important to use a suitable scheduling method. The advantage of producing fast moving products using the MTS strategy is the reduction of the lead time to customers. Regarding the innovative solutions, the customers of TKF rarely request instant availability of products. Therefore, a short, competitive lead time suffices. Aslan et al. (2012) state that it is decisive that the selected scheduling approach is suitable for the type of production facility otherwise it will not yield the expected results. To find a suitable scheduling approach, we classify the current production facility. Pinedo (2009) distinguishes 4 different manufacturing models namely:

- Single machine
- Parallel machines
- Flow shop
- Job shop

In single and parallel machines models, a job consists of operations that can be processed on either of the available machines. In job and flow shops, a job usually consists of a number of operations that have to be processed on several different machines. Each job has a predetermined route throughout the factory. In a flow shop, all jobs have the same route, i.e., all jobs visit the same machines in the same sequence. In a job shop however, the routes of jobs may differ for each job as shown in Figure 2.2. Job shop models are successful in environments with a high diversity of products that have specific parameters and routing (Aslan et al., 2012). Extensions to the general flow and job shop models are flexible flow and job shop models. In a flexible flow and job shop environment, processing steps can consist of multiple machines in parallel and jobs may be processed at any of these machines. These models often have the objective to minimise the makespan, the number of jobs that are completed too late, or minimising the maximum lateness.

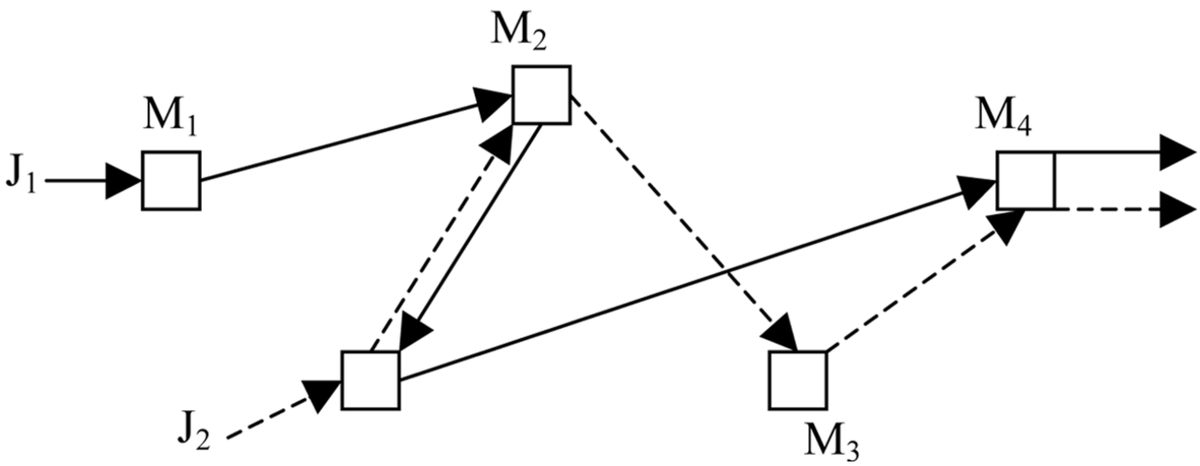


Figure 2.2: Classical job shop design (Pinedo, 2009)

- Project planning and scheduling models

Project planning and scheduling are used whenever a large project, such as the construction of an airplane or a building, has to be carried out. A job consists of a number of operations that may or may not have precedence relations. Some jobs have to wait until others are finished, while other jobs can start any time. Often, for project planning and scheduling, the assumption is made that resources are unlimited, so that a job can start when its predecessors are completed. More difficult projects contain workforce constraints, meaning that for a particular operation, multiple operators are required with specific skills. The result of workforce constraint is that it occurs that a certain job is allowed to start, but is not able to due to the unavailability of an operator. When creating a project plan or schedule, the objective is to minimise the makespan (Pinedo, 2009).

- Automated material handling models

Automated material handling models are used when an automated system, such as a conveyor belt or AGV, controls the movement of jobs. The system also controls when and where jobs are processed. Besides the regular release and completion times of jobs at certain machines, the automated systems impose constraints as well. For example, when the AGV is occupied or the buffer of the subsequent machine is full, an available job that needs processing at that machine cannot be transported (blocking). This type of manufacturing model is used in industries where flexible or paced assembly lines are used. Examples are the assembly of cars and electronics (Pinedo, 2009).

- Lot scheduling models

Lot scheduling models encompass decisions made for long and medium term scheduling. First, these models determine the size of a production order, and second, it determines the sequence for production. These models are widely used in the oil industry, where changeover and inventory costs are relatively high. Another application is the regular retail industry. In this case, the setup costs are equal to the ordering costs. The objective is to make a trade-off between holding costs and changeover / ordering costs (Pinedo, 2009).

- Supply chain planning and scheduling models

In supply chain planning and scheduling models several other models are integrated in to a single model. For example, the first stage is lot scheduling to determine the lot sizes, after which a single machine model solves the machine scheduling problem. The different stages of a supply chain planning and scheduling model may be executed at the same point in time, but the horizon of each stage may differ. The planning horizon is often medium term (several months). Therefore, a supply chain planning often uses product families rather than individual product types due to the fact that individual demand often is hard to predict. A planning model determines the average demand for each family and calculates the optimal lot size for this family. The model provides a more general plan, for example, it does not take sequence dependent changeover times and costs in to account because this increases the complexity significantly. For a medium term plan, a high detailed plan is not required. The objective of a planning model is to optimise the trade-off between inventory and changeover costs (lot-sizing). The scheduling horizon is often short term (several weeks). At this stage, the accuracy of the schedule increases. A scheduling model aims to optimally sequence the products in order to minimise the changeover costs. At this stage, the sequence dependent changeover times, demand, release date, and delivery date are determined (Pinedo, 2009).

After analysing the production process at TKF, we conclude that the manufacturing process corresponds best to the job shop model because not all jobs have the same sequence of operations, jobs have to be processed fully before it can be transferred to the next machine, and each machine can only process one job simultaneously. Consequently, we classify our scheduling problem as a job shop scheduling problem (JSSP).

2.3 Production planning and scheduling approaches

In this section we collect and review information on the available production planning and scheduling approaches in order to answer research question 1.3: *"What scheduling approaches are available in literature?"*. In Section 2.2 we classified the production facility at TKF as a job shop and concluded that the scheduling problem is a JSSP.

Jain & Meeran (1999), Blazewicz et al. (1996), and Tan & Khoshnevis (2000) discuss multiple approaches to solve the job shop scheduling problem. Some of the proposed approaches have been tested on several problems to test the quality of the generated solution and the required computational time. We discuss frequently mentioned methods that we encountered during our literature study. Solution approaches to solve the JSSP, or any combinatorial optimisation problem, can be divided in 2 categories: exact and approximation approaches. Exact approaches provide optimal solutions, but their running time can often not be bounded by a polynomial function of the problem size. The running time of a solution approach is measured by the upper bound of the number of mathematical operations it has to perform. Therefore, the running time increases when the problem size increases. Approximation approaches provide feasible, not necessarily optimal or even near optimal, solutions in relatively short running time. Practical problems, with hundreds of jobs, are extremely large and hard to solve to optimality. To overcome this problem, approximation heuristics became more attractive regardless the fact that these do not necessarily provide an optimal solution. Practice shows that an optimal solution is not always required. A near optimal, or ''good'', solution often suffices.

Exact approaches

The most straightforward exact approach to solve the JSSP is complete enumeration, which means that each feasible solution is evaluated. At the end of the algorithm an optimal solution is acquired. Blazewizc et al. (1996) and Jain & Meeran (1999) discuss the branch and bound method as a strategy for complete enumeration, and mathematical models such as Mixed Integer Linear Programming (MILP) and Integer linear programming (ILP) to solve the JSSP. The idea of branch and bound is to estimate, for each branch, its best solution by calculating its lower bound. Each branch represents a subset of feasible solutions. The advantage of this approach is that when the lower bound exceeds the current best solution, the entire branch can be removed from the tree since it will not improve the current best solution. Therefore, there is no use in investigating this subset any further. Jain & Meeran (1999) conducted an experiment and concluded that B&B results optimal solutions. In large experimental settings however, the B&B algorithm did not find a solution because large problems contain a large number of feasible solutions. Due to the lack of a method to find strong lower bounds at an early stage, the computational time to solve larger instances is relatively high.

Approximation approaches

To be able to solve larger problem instances, approximation approaches are a viable alternative. Jain & Meeran (1999) distinguish two types of approximation heuristics namely the constructive and improvement (local search) algorithms. Constructive algorithms, such as greedy randomized adaptive search and dispatching rules, start without an initial solution and construct (build) towards a solution. Simulated annealing, iterative improvement, and tabu search are examples of improvement algorithms. Simulated annealing is evaluated by Van Laarhoven et al. (1992), He et al. (1996), and Naderi et al. (2010) and they claim that simulated annealing provides near optimal solutions within very little computational time. Vaessens et al. (1996) conclude that local search algorithms (such as simulated annealing) outperform all other techniques. The results of the experiment performed by Jain & Meeran (1999) show that tabu search and the shifting bottleneck heuristic provide for most experimental settings the best solution. Hybrid approaches use a combination of multiple approaches and are able to provide a better solution than the individual methods would provide (Jain & Meeran, 1999). The shifting bottleneck heuristic for example, is a combination of schedule construction and schedule improvement. Van Laarhoven et al. (1992) compared the shifting bottleneck heuristic with the simulated annealing heuristic and came to the conclusion that simulated annealing has the potential of finding a better solution than possible with the shifting bottleneck heuristic. The difference in makespan, however were small. The running time of simulated annealing however, is significantly longer (Jain & Meeran, 1999).

2.3.1 Job shop production

Job shop models describe production facilities with a certain number of machines, jobs and routes, and therefore applicable to the situation of this research. The description of the job shop model this research uses is the following: A job shop consists of a set of m machines on which a set of n jobs have to be processed. If job j requires processing on machine i, it is referred to as operation O_{ij}. The processing time of job j on machine i is denoted by p_{ij} (Pinedo, 2009). All machines are available at time t=0, each machine can process at most one job simultaneously, and each job has to be fully processed before it can be transferred to the next machine.

It is important to define the job shop scheduling problem since it has many variants. To classify our production process we use the notation of Graham et al.(1979). Processes are denoted in the following manner: $\alpha|\beta|\gamma$. α denotes the machine environment, β denotes the job characteristics, and γ denotes the objective function that the schedule aims to optimise. The first characteristic of α ($\alpha_1\alpha_2 \ldots \alpha_n$), $\alpha_1 \in \{1, J\ F, O, P, Q, R\}$, denotes the machine environment. If α_1 = J, α_1 = α_1 = F, or α_1 = O then we have respectively a job, flow, and open shop environment, and if α_1 = 1 then we have single machine environment. Finally, if α_1 = P, α_1 = Q, or α_1 = R then we have respectively an identical parallel, uniform machine, and unrelated machine environment. The second characteristic α_2 indicates the number of machines, if this is a fixed number. The next parameter to be determined is ß ($ß_1ß_2 \ldots ß_n$), which denotes the job characteristics such as release dates, due dates, changeover times, precedence relations, and pre-emption. In some cases precedence relations between jobs are required meaning that job j cannot start before job k. Pre-emption means that jobs are allowed to leave a process before it is completed. The last parameter to identify is γ, the objective function the schedule aims to optimise (Graham et al., (1979). Frequently used objective functions are the minimisation of L_{MAX} and the minimisation of C_{MAX}.

2.3.2 Disjunctive graph representation

The literature study revealed that inter alia the shifting bottleneck heuristic, simulated annealing, and tabu search algorithm heavily rely on the lengths of the longest paths in the disjunctive graph. Each instance of the job shop scheduling problem can be represented by a disjunctive graph G. Graph G consists of a set of nodes (N), a set of arcs (A and B). Jobs consist of several operations (O_{ij}), and each operation is represented by a node with weight p_{ij} (processing time). Besides all operations, the set of nodes contains two dummy nodes, s and t. The nodes s and t are respectively the source and the sink of the graph. The conjunctive arcs (A) between two nodes represent the route of each job. The arc $O_{ij} \rightarrow O_{kj}$ indicates that job j has to be processed on machine i, before it can be processed on machine k. The disjunctive arcs (B) link two operations that belong to different jobs that have to be performed on the same machine. Initially, disjunctive arcs do not indicate the sequence of jobs, but show what operations a machine has to process. Based on the conjunctive and disjunctive arcs, the longest path in graph G is calculated. The disjunctive arcs indicate the sequence. A feasible schedule corresponds to a set of disjunctive arcs that result in an acyclic graph.

To explain the functionality of the disjunctive graph we use the same problem instance consisting of two jobs and two machines. The characteristics of the jobs are depicted in Table 2.1. The machine sequence indicates the sequence of operations, job 1 and 2 both have to be processed on machine 1, before they are allowed to be processed on machine 2. The sequence of machine M_1 is $O_{11} – O_{12}$ and the sequence of machine M_2 is $O_{22} – O_{21}$. Figure 2.3 displays a feasible solution of this instance.

Jobs	Machine sequence	Processing times
1	1,2	$p_{11} = 2$ $p_{21} = 6$
2	1,2	$p_{12} = 3$ $p_{22} = 6$

Table 2.1: Data used in the example

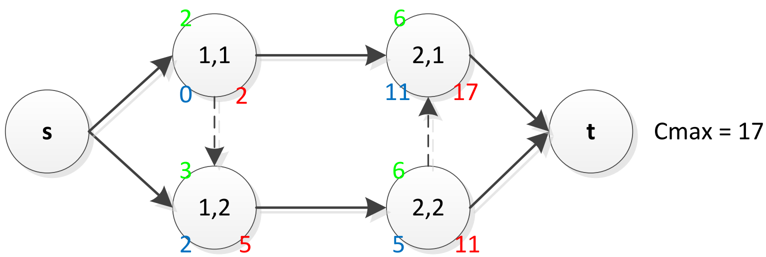


Figure 2.3: Disjunctive graph example

The length of the longest path from s (start node) to node O_{ij} defines the earliest possible starting time (r_{ij}) of operation O_{ij} (indicated in blue) and the length of the longest path from node O_{ij} to t (end node) defines the due date (d_{ij}) of operation O_{ij} (indicated in red). p_{ij} denotes the processing time of an operation and is depicted in green. The makespan of a set of jobs is equal to the longest path from node s to node t and is in the example equal to 17. The graph also displays the precedence relations between the different operations of a job by placing conjunctive arcs (solid lines) between related nodes. The production sequence on the 2 machines is displayed by the arrows of the disjunctive arcs (dashed lines). A set of disjunctive arcs belong to the same machine. Based on the disjunctive and conjunctive arcs we calculate the earliest possible start time and latest possible completion time of each job. Initially, when the heuristic starts, none of the disjunctive arcs contain arrows to indicate the sequence yet and is the makespan equal to the maximum cumulative of the processing times of each job.

2.3.3 Scheduling approaches

First, we discuss solution approaches designed for job scheduling. The first approach we discuss is using dispatching rules due to their simplicity to use and implement. Second, we discuss the shifting bottleneck heuristic because it is designed for the minimization of the makespan in a job shop.

Dispatching rules

Dispatching rules, or priority rules, provide good approximation solutions for the JSSP (Pinedo, 2009), depending on the objective function. With the help of some sort of rule, jobs are sorted and scheduled in a specific order. Dispatching rules are used to determine which task to allocate to a resource, when that resource becomes available. Dispatching rules are ideal when many scheduling decisions need to be made quickly, as is the case with a low volume & high variety product mix. Many dispatching rules are available. To avoid a long enumeration of dispatching rules, we briefly mention the most common ones.

One of the simplest dispatching rules is first come - first serve where orders are sorted and scheduled in the order they arrive. Hopp & Spearman (2008) state that this rule does not work well in complex job shop environments. Earliest due date, shortest processing time, longest processing time, and total work are just a few of the alternative dispatching rules. Which rule to choose depends on the objective function the scheduler aims to minimise or maximise. Two types of dispatching rules can be distinguished: dynamic and static dispatching rule. With static dispatching rules, the priorities of operations do not change over time in contrast to dynamic dispatching rules.

Shifting bottleneck heuristic

The shifting bottleneck heuristic, as proposed by Adams et al. (1988), is a heuristic to solve job shop scheduling problems. The shifting bottleneck heuristic is an iterative improvement algorithm and provides a good approximation for the JSSP. The shifting bottleneck heuristic decomposes the JSSP in to single machine problems, schedules the single machines by minimising a certain objective function, and selects the bottleneck machine. This algorithm heavily relies on the disjunctive graph G, which we explained in the previous section.

SBH starts with labelling every machine as a non-bottleneck machine. Algorithm 1 provides the basic steps of the shifting bottleneck heuristic. The procedure starts with an empty list of bottleneck machines, after which the objective function for the job shop is calculated based on graph G. Second, it solves the single machine scheduling problem for each of the machines. The machine with the highest maximum lateness (L_{max}) is considered to be the next bottleneck machine. The bottleneck machine is scheduled according to the schedule that is created with the single machine scheduling problem and is considered to be “fixed”. Because a schedule is “fixed”, graph G changes whereby the values of the parameters r_{ij}, p_{ij}, and d_{ij} need to be updated. r_{ij} denotes the release date of operation O_{ij}, i.e. the can-start time, and d_{ij} denotes the due date of operation O_{ij}. Between iterations (apart from the first iteration), previous found bottleneck machines are rescheduled to improve the solution even further. The non-bottleneck machines are solved again with the single machine scheduling problem, and a new bottleneck machine is selected. This repeats until $M = M_0$ (Adams et al., 1988). To provide a near optimal schedule, several heuristics are available to solve the single machine scheduling problems and the bottleneck optimisation. Examples of approaches to solve the single machine scheduling problems are the dispatching rules, Carlier's algorithm (Carlier, 1982), Schrage's algorithm, or one of aforementioned the iterative heuristics.

Algorithm 1: General SBH

Step 1 (Initialisation):
- $M_0 = \{\emptyset\}$
- Calculate objective function for the entire job shop.

Step 2 (Analysis job shop):
- Determine r_{ij}, p_{ij}, and d_{ij} for each machine
- Solve the single machine problem for all machines $M \setminus M_0$
- Calculate objective function for each machine

Step 3 (Bottleneck selection):
- Determine the bottleneck machine k
- Schedule bottleneck according to the schedule provided in step 2
- Add machine k to M_0
- Calculate new objective function for the entire job shop.

Step 4 (Bottleneck optimisation):
- Do for all machines $h \in (M_0 \setminus k)$
- Remove the arcs from machine h from graph G
- Determine r_{ij}, p_{ij}, and d_{ij} for machine h
- Reschedule and optimise machine h
Step 5 (Stop criterion):
If $M = M_0$ then ***STOP;*** *else, go to* ***STEP 2***

Practical Extensions for the shifting bottleneck heuristic

The basic shifting bottleneck heuristic does not provide a good enough representation of the practical situation. To incorporate practical restrictions, to increase the practical applicability, Schutten (1996) proposes practical extensions for the shifting bottleneck heuristic. In this section we discuss the practical extensions that are applicable to the scheduling problem this research addresses.

Release and due dates

In the original job shop scheduling problem all jobs are available for processing at time t = 0 and the objective is to minimise the makespan of a set of jobs. In practice however, jobs may have different release dates. To incorporate these release dates, we assign weight r_j to the arc from s (start node) to the first operation of job j. This ensures that the first operation of job j cannot start before r_j ($r_{ij} \geq r_j$). Since the objective of this research is to maximise the service level, we need to incorporate the due date of orders, i.e., the moment a job needs to be completed in order to arrive on time for the customer. To denote the due date of a job, d_j is introduced. To incorporate the due dates in our model, we assign weight $-d_j$ to the arc between the last operation of job j and t (sink node) (Schutten, 1996). By assigning the weights r_j and d_j in the disjunctive graph, the longest path of the graph changes from C_{MAX} to L_{MAX}.

Setup times

Between two jobs it may be necessary to set up the machine before it can process the next job. A setup may take a substantial amount of time, and therefore it is necessary to incorporate this time in order to provide a representative schedule. When setting up a machine, the machine is unavailable for processing. The time required to setup a machine depends on the production sequence. Between two identical production orders, the setup will be short because only a minor changeover is required. When, for example, the type of insulation material required and the diameter of the core differ, changeovers takes up to 60 minutes. To incorporate the sequence dependent setup times, $s_{ih,ij}$ is introduced (Schutten, 1998). $S_{ih,ij}$ denotes the setup time required between operation O_{ih} and operation O_{ij}. To include the setup time in our model, we assign weight $s_{ih,ij}$ to the arc between node O_{ih} and node O_{ij}. The incorporation of setup times requires an algorithm since setup time depends on the sequence of jobs.

Parallel machine scheduling

The original job shop problem assumes that each operation requires a specific machine. In practice, an operation may be performed on any of a series of parallel machines. Parallel machine scheduling assigns operations to machines and sequences the assigned operations for each machine. In case the machines are identical, the weights of the nodes do not change during the execution of SBH. The group of parallel machines are seen as one machine when determining the bottleneck. The maximum lateness of the group of parallel machines is the maximum of the maximum lateness of the individual machines. The incorporation of parallel machine scheduling requires an algorithm to solve the parallel machine scheduling problems.

Diverging job routing

The original job shop problem assumes that each job consists of a chain of operations meaning that jobs are processed as a whole at each operation. In practice however, it occurs that parts of jobs have to undergo different processes or in different order. To model this, diverging job routing is introduced. After a certain operation, jobs are divided in several sub jobs with different routes. These sub jobs are scheduled individually with as goal to minimise the maximum lateness of all jobs.

2.3.4 Generic combinatorial optimization methods

Besides scheduling methods dedicated to job shop scheduling problems, several meta-heuristics have proven to be successful when applied to the JSSP. We discuss simulated annealing (SA), tabu search (TS), and greedy randomized adaptive search (GRASP). Literature shows that these algorithms are promising algorithms to solve the JSSP. SA and TS are both improvement algorithms indicating they need to be combined with a construction algorithm such as adaptive search. GRASP is a combination of a construction heuristic and a local search algorithm to improve the latter.

Simulated Annealing

SA is based on the idea of Metropolis et al. (1953) who propose to accept solutions that deteriorate the objective function to allow further exploration of the solution space. Later, Kirkpatrick et al. (1982) adjusted this principle to solve large combinatorial optimisation problems.

The SA algorithm creates alternative solutions by making small changes to a feasible solution in order to find feasible alternative solutions with an improved objective value (Jain & Meeran, 1999). The neighbourhood is the set of all feasible alternative solutions that can be considered within an iteration. A feasible solution after a change is called a ''neighbour solution'' but is not necessarily a better solution. In the case the neighbour solution improves the current objective value, this neighbour solution is accepted (Van Laarhoven et al., 1992).However, when the objective value is worse, the neighbour solution is accepted with probability $P_{AB}(\mathrm{c})$. ''c'' denotes the control parameter, or temperature. When a neighbour solution is accepted, it becomes the current solution. The SA algorithm starts with a predetermined value for the control parameter, C_{Start}. For each temperature the algorithm performs k iterations. After these iterations, the control parameter is multiplied with a cooling parameter α. The SA algorithm terminates when the temperature reaches a predetermined value denoted by C_{Stop}. The acceptance probability, in case of a minimisation problem, is calculated with formula 3.1. The acceptance of worse neighbour solutions allows the heuristic to escape from local optima in order to find the global optima (Aarts & Korst, 1989). A denotes the current solution value, and B denotes the neighbour solution value. The initialisation of the parameters determines the quality and computational time of this heuristic (Artiba & Elmaghraby, 1997).

$$P_{AB}(\mathrm{c}) = \begin{cases} \frac{1}{e^{\frac{\mathrm{A-B}}{\mathrm{c}}}} & \text{If B} \leq \text{A} \\ & \text{else} \end{cases} \tag{3.1}$$

Greedy randomized Adaptive Search

GRASP finds its origin in adaptive search, so to understand GRASP we start with discussing adaptive search. Adaptive search is a generic randomised constructing heuristic proposed by Kolish and Drexl (1996) and is able to provide good initial solutions for combinatorial optimization problems. Adaptive search combines a priority rule and a random search method. When applied to the JSSP, a priority rule provides each operation a priority φ_j. For example, when we choose the earliest due date priority rule, the priority is higher when the due date is closer to the start. Adaptive search uses the priority φ_j to calculate the regret factor r_j for each operation. The regret factor (r_j) is the absolute difference between priority φ_j and the worst priority of all available operations. Whether the worst priority is the minimum or maximum of all priorities depends on the priority rule that is used. The formula to calculate the regret factor, if a higher φ_j implies a higher priority, is give below in formula 3.2 (Kolisch & Drexl, 1996). ''I'' denotes the decision set, i.e. all jobs that are scheduled.

$$r_j = \left|\varphi_j - \min(\varphi_I)\right| \tag{3.2}$$

The higher the regret value implies that not selecting this operation will have a more negative result. Adaptive search does not use the priorities to select an operation, it uses the regret values to calculate the probability P_j that an operation is selected. The higher the probability, the higher the likelihood an operation is scheduled. The probability an operation is selected is calculated with formula 3.3 (Kolisch & Drexl, 1996).

$$P_j = \frac{(r_j + 1)^{\alpha}}{\sum_I (r_i + 1)^{\alpha}} \tag{3.3}$$

The α-parameter ($\alpha \geq 0$) denotes the bias factor which defines the importance of the regret-factor. The lower the value of α is, the more randomised the approach is. Because these "random" solutions can result in schedules of poor quality, an adaptation to the AS is introduced by Feo & Resende (1989). The Greedy Randomized Adaptive Search procedure consists of two phases: a construction phase and local search phase. Each iteration starts with generating a random (greedy) but feasible solution. Second, a local search algorithm investigates all neighbour solutions until a local minimum is found. The best neighbour solution is stored (Feo & Resende, 1989).

Tabu Search

Jain and Meeran (1999) conclude that the tabu search algorithm outperforms several approaches after performing various job-shop scheduling experiments while Zhang et al. (2008) claim that the tabu search heuristic is a promising method for the job shop scheduling problem. Tabu search is a method that aims to improve an initial solution by evaluating all neighbour solutions. After evaluating all neighbour solutions, it accepts the best allowed neighbourhood solution. Accepting solutions that deteriorate the objective function allows the heuristic to move away from local optima in order to reach a global optimum. The last k moves are saved in a *tabu list* to prevent reversing recent moves, meaning that these moves are not allowed in the next evaluation. The move resulting in the accepted neighbour solution is added at the front of the tabu list. When k moves are stored in the tabu list and a new solution is accepted, the first added move of the tabu list is removed. The size of the *tabu* list influences the quality of the algorithm. The tabu search heuristic is terminated when moves do not improve the objective function during a predetermined number of iterations. The algorithm also terminates when a fixed number of iterations are executed. The neighbourhood is the set of all feasible alternative solutions that can be considered within one iteration.

It none of the neighbour solutions provide a better solution than the current solution and a tabu move complies with a certain criteria, the aspiration criteria, the heuristic is allowed to cancel the tabu and accept this solution. A well-known aspiration criterion is to allow solutions that are better than the best solution so far. Many adaptions to the tabu search heuristic have been proposed. For example, by relaxing certain constraints, tabu search accepts infeasible solutions resulting in a much larger search space (Artiba & Elmaghraby, 1997).

2.4 Lean six sigma

TKF has implemented the lean six sigma (LSS) philosophy within its company. To understand the implications of this philosophy it is important to address the theory and ideology behind it. From the business point of view LSS is best described as: a business strategy used to improve business profitability, to improve the effectiveness and efficiency of all operations to meet or exceed customer's needs and expectations (Antony & Banuelas, 2001). LSS reaches these results by reducing lead-times within the value-chain which improves cash flow, eliminates waste, reduces inventory, and increase on-time deliveries (Markarian, 2004). LSS is a combination of two business improvement methods, namely lean manufacturing and six sigma. The combination of these two results in higher benefits than each of these can yield when carried out separately (GoLeanSixSigma, 2014). The strength of LSS is that it is not just an improvement methodology, it is a philosophy, and it is integrated within the company on all levels.

Lean manufacturing is the first method we discuss. Lean manufacturing aims to streamline a process by removing all types of waste. Classical process improvement approaches target the value adding activities of a process and aims to maximise these processes. On the contrary, LSS focusses on the non-value adding processes and aims to minimise these processes. We identify identifies 7 types of waste that are applicable to a manufacturing environment as proposed by Brook (2010):

- Defects – Defects are the most obvious waste. Products that are broken need to be fixed or replaced resulting in extra processing time and (material) costs.
- Overproduction – Producing more products than the customer has ordered results in higher WIP and lead times.
- Waiting – Waiting in queues increases the lead time without adding value to the product.
- Transportation – Unnecessary transporting results in the use of time, money and resources without adding value to the product.
- Unnecessary inventory – Holding inventory that is not required increases the holding and handling cost.
- Unnecessary motion – Non-optimal facility layout or misplaced items result in extra motion.
- Unnecessary processing – Adding more value to a product than a customer is willing to pay for is a waste of resources.

After removing all the wastes it is critical to quickly solve problems that disturb the process. Six sigma is a method to assist with problem solving, and is the second aspect of this process improvement approach. Six sigma provides a structured approach called DMAIC, that stands for define, measure, analyse, improve and control to tackle problems. The power of this approach is its simplicity and clarity (Brook, 2010). Each stage has plain objectives and corresponding actions.

2.4.1 Heijunka

The definition of Heijunka, or production levelling, is: 'the distribution of production volume and mix evenly over time'' (Dennis, 2002). Clustering production orders by itself can reduce setup and fine-tune times, but usually increases lead and idle times and causes excess inventory as well. The objective of production levelling is to balance production quantity as well as production mix which will reduces variation in form of peaks and gaps in the production scheduling. Every product every cycle (EPEC) is one of the principles of Heijunka and is achieved by reducing the production volume until every product returns every cycle. The result is a cyclical schedule as proposed by Glenday and Sather (2006) who state that Heijunka is required to realise a pull production system with continuous flow.

Heijunka is predominantly utilised in large scale production and rarely applied in a low volume high variety environment. However, by forming product families based on manufacturing similarities and scheduling families it is applicable (Bohnen et al., 2013). The first important characteristic of a product family is that product types can be produced in an arbitrary sequence without increasing the time and material losses due to setups and fine-tuning significantly. Second, the production sequence of product types within a family has to be identical (Bohnen et al., 2013).

After product families are defined, it is important to classify these families as runners, runners / strangers or strangers. Runners are products that have high customer demand, high order frequency and a low variation in demand. The other extreme are strangers which have low customer demand, low order frequency and a high variation in demand. Regarding the cyclical schedule, runners and stranger / runners are products that mainly return each cycle while strangers are covered with a certain production slack, reserved for uncommon products.

2.4.2 One Piece Flow

An approach to achieve Heijunka and a continuous flow in a job shop environment is the one piece flow manufacturing principle. One piece can refer to a single product or a small batch, depending on the product. One piece flow manufacturing means that pieces move from operation to operation with as minimal work in process in between operations. A continuous flow means that parts, pieces, or batches move through the production process with minimal stagnation. One piece flow manufacturing aims to reduce the wastes caused by waiting times, transportation, overproduction, inventory, and defects. By dividing production orders in smaller pieces, only that piece requires rework in case a defect is detected resulting in smaller amounts of waste. The cycle time will reduce since pieces are processed at a machine and directly moved and processed at the next machine. One piece flow also improves the flexibility of the job shop because the machines are occupied for a shorter period of time because the processing times per production order decreases. Obviously, in the end the machine still needs to process all pieces, but changes in the production schedule can be realised quickly. A continuous one piece flow also results in lower working capital. The downside of one piece flow manufacturing is that it results in more changeovers at machines. One piece flow manufacturing works best in combination with other lean techniques such as the principles of 5-s or a pull manufacturing system.

To implement one piece flow manufacturing, the production facility must meet certain prerequisites. First, the production processes must be able to produce good products. If too many defects are detected, one piece flow is not possible. Second, the processing times must be consistent, or at least a small variation. Third, machines must be able to process most of the time meaning breakdowns are allowed but the frequency and duration must be low. Fourth, the time required for changeovers must be significant smaller than the processing time of a piece and finally, the layout of the manufacturing environment should be designed such that machines are in flow with the process.

2.5 Key performance indicators

In this section we define and identify key performance indicators to assess the alternative planning approaches and to compare these results with the current performance. This section answers research question 1.4: *"What are the key performance indicators of a scheduling approach?"*. Key performance indicators (KPIs) combine several metrics to yield an assessment of critical key processes. A metric is simply the measurement of a parameter of interest and the combination of metrics results in an indicator (Kister & Hawkins, 2005).

To define and identify the KPIs, we look at the currently used KPIs at TKF and perform a literature study regarding production planning and scheduling. For this research, we distinguish 2 different types of KPIs: quantitative and qualitative KPIs. Quantitative KPIs are preferred because it provides a more unambiguous and objective assessment. However, certain KPIs cannot be measured quantitatively. For these KPIs we use qualitative KPIs.

The main research question of this research is: *"How can TKF improve its production scheduling approach such that it results in an increase of service level, throughput, and a decrease of product lead times at the Installation production department?".* This research question indicates that the main KPIs of this research are service level, throughput, and lead time. Besides these two main KPIs, we defined several other performance indicators to get a better idea of how the alternatives are performing on other important aspects. The following qualitative and quantitative (key) performance indicators are currently used at TKF, or are a result from the literature study.

Hoogeveen (2005), Morton and Pentico (1993), Hopp and Spearman (2008), Hill et al. (2003), and Pinedo (2009) propose several performance indicators for job shop scheduling. The first performance indicator we discuss is the completion time, or makespan, of a set of jobs and is equal to the completion time of the last operation. Other performance indicators are: lateness, tardiness, and earliness of jobs (Hoogeveen, 2005). Lateness provides an indication whether a job is ahead of, on, or behind schedule. Tardiness provides an indication of how long after the due date a job is completed while earliness indicates how long before the due date a job is completed. For each of these KPIs he proposes a weighted objective as well, giving certain jobs a higher priority.

Morton and Pentico (1993) state that maximising throughput, satisfy customers' desire, and minimising penalties for exceeding the delivery date are commonly used objectives for a shop manufacturing environment. Maximising throughput means producing as many products as possible within a certain time period. Satisfying customers' desire is equivalent to meeting a certain service level. Since some customers charge a certain penalty in case jobs arrive too late, minimising these penalty costs is an important measure. These penalties are related with the number of backorders in the scheduling horizon. Depending on the situation, either or both of these performance indicators can be used.

As mentioned in the Chapter 1, short product lead times are considered an important competitive advantage. The lead time consists of the processing, changeover, transportation, and the idle time. The amount of work in process (WIP) influences the lead time, as well as the throughput. When the WIP level is too low, the throughput will decrease. On the other hand, when the WIP level is too high, the lead times will increase significantly (Pinedo, 2009). The number of setups and the amount of irregular capacity are important factors as well because both affect the production capacity, and therefore influence the lead time (Hill et al., 2003). Also, the machine utilisation is influenced by these factors. The idle time of machines, overtime, and the breakdowns are the other factors that influence machine utilisation.

In any production environment, cost is one of the most important aspects. Cost of scheduling indicates the costs related to the scheduling and production of a certain product mix. When we dissect the costs of scheduling, we identify 4 different components namely: cost of material, cost of staff, cost of machine use, and cost of backorders. Setup and overtime costs are the most relevant aspects since the fixed costs, such as cost of machine use and cost of material, cannot be changed (not within the boundaries of this project). To provide an indication of the costs of producing a schedule, we introduce the running time of the model as a performance indicator.

We divide the performance indicator service level in two parts: the internal service level and the external (customer) service level. The internal service level is the fraction of orders (semi-finished products) that is delivered to other departments within the days required for production. Currently, the lead time is set at two days per process, so the days required for production is equal to 2 times the number of processes that a product has to undergo. The external service level, or customer service level, is the fraction of orders (finished products) that is delivered on or before the production delivery date (Hopp & Spearman, 1997). The production delivery date is the final date an order has to leave production in order to be delivered on time. The difference with the customer delivery date is the time required for transport. Because we evaluate the production process, not the transport of products, we subtract the expected days for transport from the customer delivery date to create a production delivery date. The external service level is a performance indicator for the production department as a whole.

Besides the direct results of the schedule, it is important to evaluate the schedule on its own as well. In order to do this, Kister & Hawkins (2006) propose the schedule effectiveness and schedule performance index (SPI) as performance indicators. They state that an acceptable schedule has an effectiveness of at least 65% and a SPI of 80%. Formulas 3.4 and 3.5 give the calculation of these performance indicators (Kister & Hawkins, 2005).

$$\textbf{Schedule effectiveness (\%):} \frac{\textit{Scheduled hours used for production}}{\textit{Labour hours available}} \ x\ 100 \tag{3.4}$$

$$\textbf{Schedule performance index (\%):} \frac{\textit{Budgetted completed work}}{\textit{Budgetted scheduled work}} \ x\ 100 \tag{3.5}$$

The, until now, mentioned performance indicators are quantitatively measurable. However, not all performance indicators can be expressed in numbers or values, and therefore we introduce 2 qualitative performance indicators. The first is the difficulty of using the proposed solution approach. The production planner has to work with the program. The ease of use of the solution approach is important, because this influences the extent to which the approach is used. The second qualitative performance indicator is the impact the solution approach has on other production processes.

Conclusion

In this chapter we provided an answer to research question 1: *"What literature is available regarding improved scheduling approaches?".* First, we positioned the problem in the hierarchical framework and we concluded that our problem is an operational scheduling problem. To identify the type of scheduling problem even further we classified the production facility as a job shop environment, after which we conclude that the problem is a job shop scheduling problem (JSSP). Based on the job shop classification we identified several solution approaches. We distinguish 2 types of scheduling approaches: the job shop scheduling approaches and generic combinatorial problem approaches. The job shop scheduling approaches are designed for job shop environments. The easiest approach is the use of dispatching rules. Dispatching rules order and schedule jobs based on a certain priority rule, such as Earliest Due Date or Shortest Processing Time. The second job shop scheduling approach is the shifting bottleneck heuristic, which decomposes the JSSP in to single machine scheduling problems. As the name suggests, the shifting bottleneck heuristic is a heuristic, and therefore it is unlikely it provides an optimal solution. Due to the large number of machines and production orders, solving the single machine scheduling problems to optimality within a reasonable running time is difficult. To find an acceptable solution, which is sufficient in practice, we propose the use of heuristics to solve the single-machine scheduling problem and to determine the bottleneck machine. The generic approaches have proven to provide near optimal solutions for job shop problems. Simulated annealing, adaptive search, and tabu search are some of the most well-known generic approaches. Adaptive search is a construction heuristic and ideal to get an initial and feasible solution. Simulated annealing and tabu search are pure improvement heuristics. They need to have a feasible solution as input created by for example the adaptive search heuristic or dispatching rules. Heijunka is introduced to comply with the lean six sigma philosophy that TKF pursues. To schedule a low volume & high variety product mix, it is necessary to cluster products based on manufacturing similarities. In the last section of this chapter we proposed several performance indicators to assess the current and future scheduling approaches. Most performance indicators are measurable, i.e. quantitative performance indicators. However, not everything is measurable, and therefore we proposed qualitative performance indicators as well.

3 Analysis of the current situation

In this chapter we answer research question 2 as stated in Section 1.2.4: ‘’*What is the current situation of the production and scheduling processes?’’.* Section 3.1 provides information on the characteristics of a cable, the current production departments, and its production processes. Section 3.2 provides a summary of the production planning approach, before assessing this approach. These sections answer research question 2.1: *“What are the current production and scheduling processes?“*. Section 3.3 provides the assessment of the current planning approach and answers ‘’ What is the performance of the current scheduling approach?’’.

3.1 The production processes

To be able to answer the research question: *“what are the current production and scheduling processes?“*. We first explain what a cable actually is by identifying the different characteristics of cables. Second, we elaborate on the different production departments before we identify the processing steps, from start until finish, that are needed to produce a cable.

3.1.1 Cables

The basis of each type of finished product is a copper conductor: the core (In Dutch: ‘’zielkabel’’). This core can either be massive or consist of several smaller cores stranded together (in Dutch: “samengeslagen”). This core is insulated to protect the cable and user and minimise the energy losses. A cable consists of multiple cores to identify how to connect the cable, the insulation layer of each core is provided with a different colour. The type of finished product determines the structure of the core. Besides the functional cores, a *fill cable* (in Dutch: ‘’vuldraad’’) can be added to make the cable round. If not, and the number of cores in a cable is an odd number then the cable is sector shaped, which is not always desirable.

To protect the cable from static electricity from the environment and vice versa, a thin plastic sheet (called ‘’mika-tape’’) is applied. This tape is wrapped around each copper conductor, before it is isolated. To enforce the cable to withstand forces from for example a shovel, TKF offers two options for armouring. However, contrary to the mika-tape, the copper cores are combined and provided with an inner sheath (in Dutch: ‘’binnenmantel’’) before the armour is applied. The first type of armour is a braided layer of thin copper or steel wires (in Dutch: “vlechten”) and the second type of armour is to wrap round or flat cables of thin metal around the cable (in Dutch: “armeren”). The advantage of braiding is that the cable remains flexible, while with armour the cable gets rigid. Again, the type of finished product determines what the requirements towards protection are. The next step is to provide the cable with the final layer, called an outer sheath (in Dutch: “buitenmantel”), for extra protection. Figure 3.1 shows a cable that consists of multiple isolated massive cores. The cable is provided with an inner sheath, armour, and an outer sheath.

Figure 3.1: A cable with a massive core, insulation, inner sheath, braiding, and outer sheath

3.1.2 Production departments

As mentioned in Chapter 1, TKF has 4 independent production departments: the multi-conductor, fibreglass, energy, and Installation departments. The production departments operate completely independent of other departments. Each department has its own management and performance targets. The logistics department, R&D, inventory of raw materials and finished goods, and the wire factory are shared resources. Figure 3.2 depicts an overview of the buildings at the TKF terrain. It occurs that products move from one department to the other for processing.

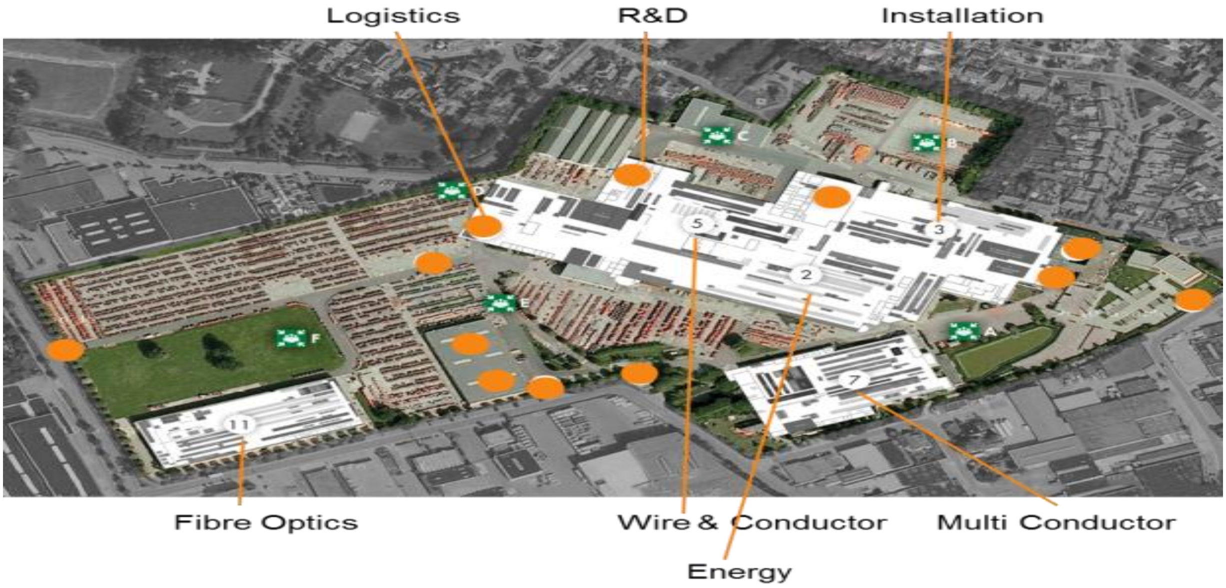


Figure 3.2: Aerial overview of the TKF terrain

The Installation production department is the main focus of this research. Mainly cables for the marine, buildings, and infrastructure industry are produced in this department. Since this production department can produce really small cables, TKF can deliver to the utility market as well. Section 3.1.3 discusses the production processes of this production department.

The Multi-Conductor production department produces instrumentation and the traditional telecom cables. It is located in a separate building as shown in Figure 3.2. The processes are similar to the processes at the Installation department.

The Energy production department produces medium and high voltage cables for the energy industry (up to 150 kV). The energy department is located next to the Installation department as shown in Figure 3.2. The processes at the energy department are similar to the processes at the Installation department.

The Fibre Optics production department produces fiberglass cables. Fiberglass is a recently upcoming trend in the telecom and internet segment. It is located in a separate building as shown in Figure 3.2. This department operates slightly differently from the others since they provide complete solutions (consultancy, connectors, and transformers) whereas the other departments solely deliver the cable.

3.1.3 Production processes

In this section we discuss the production processes of the Installation department. These processes are more or less similar to the processes of other departments. Therefore, we only discuss the Installation department. The specifications of the finished product determine the route and sequence of processes. The basic route for each process is identical. The products that need to be processed are either raw material that arrives from the wire drawing department or semi-finished products that arrive from or go to other departments. Figure 3.3 shows the layout of the production department. As Figure 3.3 shows, the production department is organised in such a way that the basic products are produced in a line (the blue line in Figure 3.3). Producing in a line reduces transporting costs and makes the production department more controllable. Figure 3.3 shows the 3 most used production routes. The blue route is the most basic route; the product is isolated, stranded, and then provided with an outer sheath. The red route includes a braided protection layer and the black route includes an inner sheath and a braided layer as well, after which it is provided with an outer sheath as well. In this section we discuss each of the processing steps in order to understand the trade-offs the scheduler makes when creating a production schedule. We start with the wire department, and even though it falls outside the scope of this research, to form a complete picture of the production process it is necessary to address this part of the production process as well.

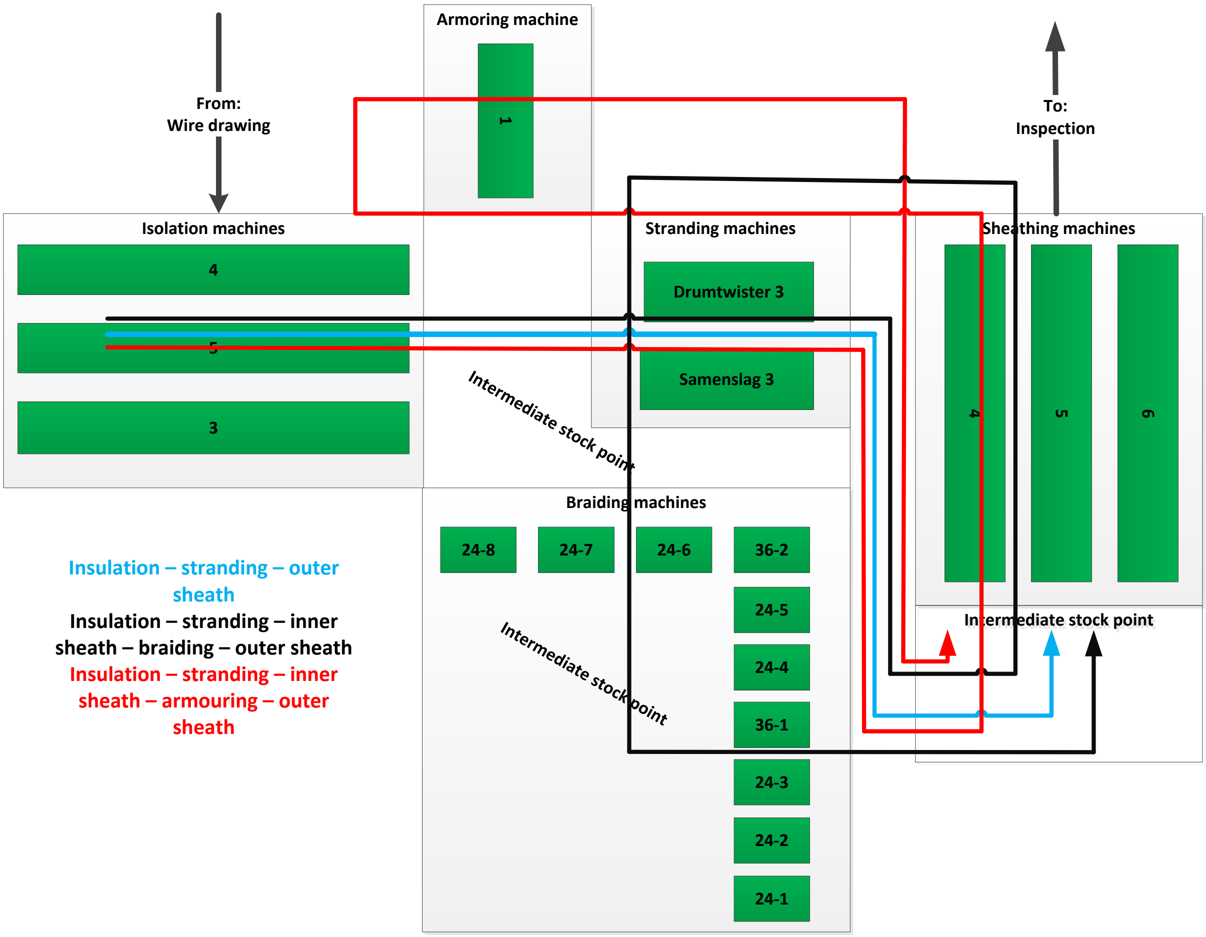


Figure 3.3: Production layout of the Installation department

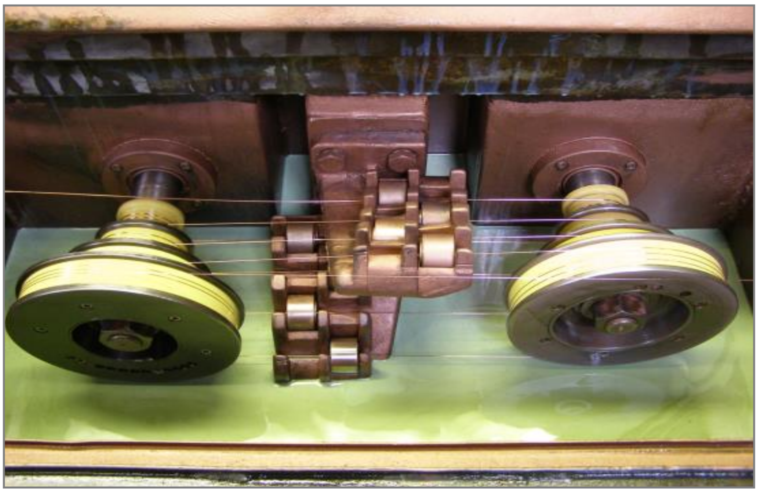


Figure 3.4: The wire drawing process

The wire drawing department draws wires to reduce the diameter of the core cable. The raw material TKF receives is 8mm thick copper. An 8 mm diameter copper cable is too rigid to be processed at the Installation department. To provide a large number of possibilities regarding the diameter, the cable has to be drawn to a smaller diameter. The wire drawing department consists of three machines: *groftrek*, *middeltrek,* and *fijntrek*. Wire drawing is a metalworking process in which wires are pulled through a series of dies (In Dutch: Matrijzen). Each die has a higher rotation speed than its predecessor whereby the cable is pulled, resulting in a longer and therefore thinner copper cable. Figure 3.4 shows an example of a few dies where a wire is pulled through.

The first processing machine, *groftrek*, is capable of reducing the diameter from 8.0mm to 3.0mm and anything in between. If a smaller diameter is required, the copper cable needs to be processed at *middeltrek* that can reduce the diameter from 3.0mm to 1.5mm and anything between. The copper cable needs to be processed at *fijntrek* in order to reduce the diameter to anything below 1.5mm. The cores used at the several departments can either be solid or stranded copper. A solid core means that it consists of one drawn cable, where a stranded core consists of several stranded thinner cores. The main differences between these two types of copper cores are that a stranded cable is much more flexible in terms of bending and when diameters larger than 8.0mm are required a massive core is not possible. Having a wire drawing department is unique in the cable industry, providing TKF a competitive advantage. TKF produces a low volume & high variety product mix, resulting in a demand for a wide range of product diameters and making forecasting really difficult. Having a wire drawing department results in lower inventory of copper, easier to provide unique diameters to the customer, and reduces the lead times because there is no vendor involved.

Figure 3.5: Various insulation cables

The insulation machines apply a plastic insulation layer around the core wire. This insulation layer usually consists of polyethylene (PE) or XLPE because these materials are flexible, tough, and recyclable. Solid PE/XLPE in an extruder is heated to make it liquid. The core wire is pulled through the extruder that applies the PE, after which the cable is cooled down to solidify the PE before it is wound on a reel (Figure 3.5). For the end-user it is important to know which core to connect to for example an outlet or machine. To make each individual core identifiable, the colours of the plastic layer differ as Figure 3.4 shows. Only one colour of core cable can be processed simultaneously due to the fact that the extruder can apply only one colour at a time. To change the colour of the PE, the extruder needs to be cleaned.

Figure 3.6: The insulation process

Currently, TKF owns 3 insulation machines. Each machine has different characteristics, making them suitable for different products. Insulation machine 3 can only process 1,5mm² and 2,5mm² stranded cores and 1,5mm², 2,5mm², 4mm², and 6mm² massive cores. Insulation machine 4 can process stranded, as well as massive cores, with a diameter larger than 10mm². The last machine, insulation machine 5, can process stranded, as well as massive cores, with a diameter smaller than 10mm². These machine characteristics increase the difficulty of planning. For each of the insulation machines, preference is given to produce products in a sequence where the intensity of colours is either decreasing or increasing. For example, when an order consists out of a grey, black, red, and brown core, the preferred preference is black, grey, brown, and finally red. This particular production sequence leads to the shortest setup times since the time to clean the extruder increases when the intensity of colours differs too much.

The stranding machines combine several core cables by stranding (samenslaan) them around each other to make it a solid whole and appropriate for further processing. The reel with finished (processed) cables is rotating, see Figure 3.7, causing the cables to wrap around each other at the process shown in Figure 3.8. This is necessary since finished products rarely consist of a single core cable. Currently, TKF has two machines to process these cables: the *drumtwister* and *samenslag*. The drumtwister is meant for stranding cables with a diameter above 6mm, when more than 8 cores need to be combined, or when a fill cable needs to be added. The samenslag processes the remaining cables (that have: a diameter below 6mm, less than 8 cores, and no fill cable). If required, the drumtwister is capable of processing products that usually are processed at the samenslag. However, vice versa this does not hold.

Figure 3.7: The drumtwister

Figure 3.8: The stranding process

Figure 3.9: The braiding process

The braiding machines braid thin copper or thin steel wires around the cable to protect it from external forces such as a shovel or crane. It is the first of two protection possibilities for cables. A stranded cable, as well as a sheathed cable (see below) can be provided with a protection layer. Small coils, with thin copper or steel, spin around the cable in different directions providing an as high as possible coverage. Figure 3.9 shows the braiding process. The coils are on the bottom of the figure, rotating quickly while moving up and down. The unprotected cable is pulled through vertically. Due to the rotating of the coils and the vertical movement, a thin layer of copper or iron is braided around the cable. Currently, demand in the navy and marine industry is increasing, resulting in an increasing demand in braided cables. To process this demand, TKF owns 10 braiding machines. Just as with the insulation and stranding machines, the machines differ from each other. 6 of the braiding machines are capable of braiding both a copper and iron protection layer, while 4 are capable of only braiding an iron protection layer.

Figure 3.10: Armoured cable

Armouring is the second protection possibility is to provide the cable with a wrapped thin sheet of iron as protection layer. For armouring, TKF has two material options: a round or flat wire. A drawback of armouring is that it makes the cable less flexible compared to braiding. Figure 3.10 shows an example of an armoured cable. The protection layer is merely wound around the cable.

Sheathing is the final step of the production process. The sheathing process is comparable to the insulation process (Figure 3.11) only the options for sheathing material are PVC and XMBH. Sheaths usually are grey or black, while insulation has multiple colour options. The sheathing machines are also used to provide cables with an inner sheath. TKF owns 3 sheathing machines that have different characteristics (Sheathing machine 4, 5, and 6). Sheathing machine 4 can only apply an outer sheath of both PVC and Xmbh. Sheathing machine 5 can both apply an inner sheath as well as an outer sheath. However, this machine can only process PVC. Sheathing machine 6 can both apply an inner sheath as well as an outer sheath, but contrary to machine 5, it can only process Xmbh.

Figure 3.11: The sheathing process

After each production process, cables are wound on **reels** to make it suitable for further processing and for transportation purposes. However, the thickness of the isolated core cables determines the number of kilometres that can be wound on a reel. Obviously, the thicker a cable is the less capacity the reel has. At other production processes, factors as whether the core cable is hammered or massive, the number of cores stranded together, and the thickness of the armour and sheath influence the reel capacity. Table 3.2 provides the capacity for the most common product types after the insulation process. At the insulation production department, each reel can only hold cables of the same colour and diameter due to the fact that at the subsequent station each individual colour is stranded around each other. Especially at the insulation process it is important to produce full reels because the time to replace a full reel with an empty one takes, compared to the production time, relatively long.

Capacity reels		
Diameter	**Hammered**	**Massive**
1,5 mm	28km	40km
2,5 mm	16km	40km
4 mm	20km	20km
6 mm	20km	20km
10 mm	10km	10km
16 mm	10km	-
25 mm	5km	-
35 mm	5km	-

Table 3.2: Capacity reels in kilometers per reel

3.2 The production-planning and -scheduling processes

In Chapter 1 we briefly discussed the current production planning and scheduling processes and the main problems TKF encounters. This section provides a more detailed overview of these processes to get a better idea how to improve the current situations and what the practical restrictions imply.

3.2.1 Production-planning and -scheduling at TKF

As said, a decent and reliable production plan for a longer period of time is currently lacking. This is partially due to the manually scheduling approach and a lack of tools. Furthermore, the link between a core cable and an end-product is missing. For example, a customer orders a certain cable type and this cable type consists of several cores. These cores need to be scheduled individually on the insulation machines, while the production order (end-product) is scheduled on the remaining production machines. Currently the schedule on the insulation lines determines the schedule on the subsequent production lines. To ensure that all machines are occupied, the production planner releases a mix of orders on the insulation line with various routes. The production planner does not schedule the individual machines, but the machine operators need to follow certain rules and guidelines when producing. The most important rule is that every production order needs to be processed within 24 or 48 hours of arrival at that production station, depending on the machine. This rule ensures that products move to their next station within 48 hours, but the production sequence is hard to predict. The operators produce the available orders in a sequence which is ideal for their machines. However, this can have an adverse effect for the subsequent machine. For example, when an order that requires an inner coat is delayed at the coating process, the armouring machines might not have work available or they setup the machine for another type of armour, resulting in unnecessary changeover times.

We divide the jobs at TKF into 2 classes: semi-finished products and finished orders. Semi-finished orders usually do not go through the entire production process and the orders are owned by a different department. Semi-finished orders are processed at other departments before or after processing at the Installation cell. Finished products however, are owned by the Installation department, and generally go through the entire process at the Installation department.

As mentioned in Chapter 1, the planner schedules the production orders manually with a 24 hour scheduling horizon. The basic premise of the production planner is to schedule the insulation processes as efficiently as possible and to ensure the subsequent processes are provided with sufficient work in terms of processing hours. Since the insulation machines have overcapacity, i.e., they are not the bottleneck machines, it is doubtful that this approach yields an optimal schedule. For each production order, NaVision calculates a buffer ratio. The buffer indicates the ratio between the time that is left to complete this order and the predetermined cycle time of the respective product. As said, each production process has to be completed within 2 days. A 0% buffer ratio indicates that the time remaining until the delivery date is equal to 2 times the number of processes. As the delivery date approaches the buffer ratio increases, making the production order more urgent. During this research it occurred frequently that the production of orders start while the buffer ratio was far above 0, meaning that the time remaining to complete the order is shorter than the expected cycle time. Based on this buffer ratio the production planner schedules the MTO products. When a product’s inventory level drops below a certain value, the planner can decide to include a production order (MTS) within the already existing schedule. The objective of the production schedule is to maximise the department’s service level and machine utilisation. The planner manually inserts MTS orders based on the workload and suitability to the current schedule. However, selecting the best MTS order is hard to do when the sequences at the machines is unknown since the planner releases work based on workload and does not know the distribution of the workload (number of reels etc.).

The production planner schedules complete production orders. By ensuring that each production station has lots of work available (48 hours +), the production planner avoids standstill at machines. These production orders vary in length, type, and therefore duration at the production machines. The downside of this approach is a large amount of work in process and long product lead times. Furthermore, long production runs causes blocking of a machine which reduces the flexibility of the production schedule. Especially when rework orders (and rush orders) are not an exception, it is desired that the rework orders (and rush orders) can be reprocessed as soon as possible. When a machine is occupied with a long production order the rework order cannot start immediately, possibly resulting in more lateness. Another disadvantage of long production runs is that production errors have a larger impact and are detected in a later stadium.

The production planner, work planner, team leader, and value stream manager participate in a “lean daily management meeting (LDM)” (Oulette & Petrovich, 2002) at every production station where they discuss the performance (OEE) of this station with the machine operators. During the first two weeks of this research, we participated during these LDMs to get a better understanding of the products, machines, processes, and challenges that management faces. The principle behind lean daily management is that it provides the ability to manage departments, functions, and processes, in which processes are defined, standardised, controlled, and improved by the process owners. LDM is part of the continuous process improvement approach and in practice comes down to managers taking responsibility for problems they can address, and operators giving the chance to speak up about problems they cannot handle themselves. It is also a good incentive for operators, as well as managers, to keep performing. After LDM, they have a daily planning meeting where they discuss the workforce planning and verify its feasibility or that it has to be edited. Furthermore they address the production orders that require extra attention.

NaVision is the Enterprise Resource Planning system used at TKF and is part of Microsoft's Business System Solutions (Microsoft, 2013). TKF uses it to release orders, to schedule orders on machines, to monitor progress, for documentation, and for analysis. NaVision is known for its comprehensiveness, easiness to adjust to the preferences of the user, and the user friendly interface enabling non-professionals to work with it. To extract data from NaVision TKF uses Exsion which is a Microsoft Excel plug-in. With the help of Exsion, NaVision data can be selected and joined. The selected data is downloaded to a separate spreadsheet in Excel.

3.3 Performance assessment current situation

In Section 2.5 we proposed several (key) performance indicators to assess a scheduling approach. In this section we determine which of these KPIs are relevant for this research and assess the current situation in order to answer the research question: "What is the performance of the current scheduling approach?". Some of the proposed KPIs are not relevant for this research simply because they are not applicable, while others are not relevant. We do not assess qualitative performance indicators because these are only relevant for the proposed solution approach. The performance indicators we assess are the following:

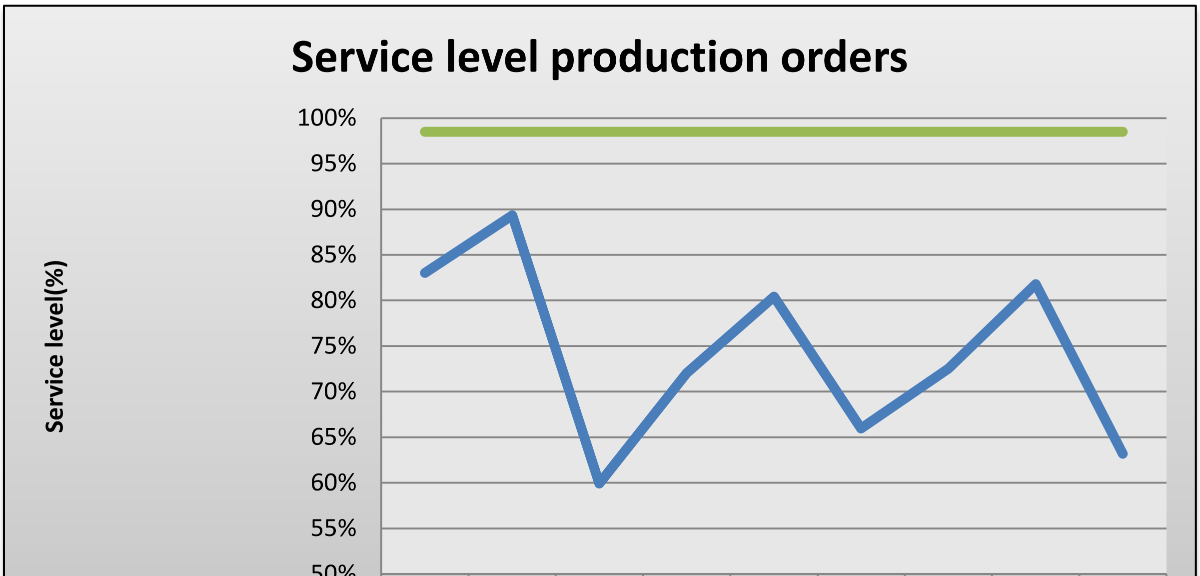
- Service level
  - Internal
  - External
- Machine utilisation
- Irregular capacity

The first performance indicator we discuss is the production department's throughput in product cost price in Euros and meters produced per week. We choose a 1 week period since management reviews the production department's performance each week. For each week management sets a target for the output. On general the target is €90,000 per day of production, which amounts to €450,000 a week. During this research, the production department did not meet this target on multiple occasions. Improving the production schedule can lead to a significant increase in throughput and consequently a higher turnover. Figure 3.12 shows the output for the production department Installation line during the weeks 44-48 of the year 2013 and 4-8 of the year 2014. The throughput is equal to the output (€) of the inspection station meaning that semi-finished products, i.e., products for other departments, are not taken into account.

As mentioned in Chapter 1, one of the goals of this research is to improve the service level. TKF aims to get an external service level of 98.5% at the Installation department. To determine the performance of the production department, we do not only look at the customers' service level, but the production department's service level as well. To do so, we divide the service level in to 2 separate components: the internal and external service level. We determine the service levels by performing data analysis.

The external service level is the fraction of orders that are delivered to the customer on or before the delivery date. However, the production department is not responsible for problems that occur after leaving inspection. To be able to assess the performance of the production department, we introduce the service level of production orders.

After the final inspection, products have to be transported to the customer. To exclude any delays caused by transport, TKF deducts the estimated days required for transportation of the promised delivery date. By deducting these days from the promised delivery date, TKF creates a ''production delivery date''. To assess the production department's service level, we now look at the fraction of products that leave the inspection station on or before the production delivery date. Figure 3.13 provides an overview of the service level of production orders per quarter from 01-01-2012 to 01-03-2014, with an average of 74.24%. We choose to analyse the service level over a longer period of time due to the large deviation within quarters. Selecting, for example, the last 3 months does not provide a reliable representation of the performance. The overview shows the significant fluctuations of the service level of production orders making the production process unreliable and therefore issuing (reliable) delivery dates difficult. The material control manager sets the target service level for upcoming periods based on previous periods. TKF aims to improve its service level of production orders to 98.5% by improving several production aspects, such as production scheduling. This target applies to the service level for production orders, as well as the service levels for both make-to-order and make-to-stock.



	Q1-12	Q2-12	Q3-12	Q4-12	Q1-13	Q2-13	Q3-13	Q4-13	Q1-14
Service level Production orders	83%	89%	60%	72%	80%	66%	73%	82%	63%
Goal Service level	98,5%	98,5%	98,5%	98,5%	98,5%	98,5%	98,5%	98,5%	98,5%

Figure 3.12: Service level production orders

The production service level influences the customers' service level as well. Obviously, when products leave the production process too late, the probability the products arrive late at the destination is significant. This is also reflected in the graphs of the service level. When we compare Figure 3.12 with the Figures 3.13 and 3.14, we clearly see the same pattern. To calculate the customers' service level, we calculate the fraction orders that arrive at the destination on or before the promised delivery date.

In Chapter 1 we stated that there is a clear distinction between make to stock orders and make to order orders. Regarding the service level, we again use that distinction. The service level for MTS items fluctuates, however it never drops below 92%. For the period 01-01-2012 to 28-02-2014 the average MTS order service level was 96.83%, which is close to the goal service level. Figure 3.14 depicts the MTS order service level, where the service level is calculated for 3 months intervals. Figure 3.13 shows the severe fluctuation in service level. For example, Q3-12 has a service level of 98.41%, however Q4-12 only has a service level of 92.82% making it hard to predict a delivery date. As expected, the service level for make-to-stock products is higher than the service level for make-to-order products. Make-to-order products are produced when an order is accepted, thus the probabilities for unexpected and uncalculated delays, due to, for example, machine breakdowns or production errors, exists. Figure 3.14 depicts the behaviour of the MTO service level. For the period 01-01-2012 to 28-02-2014 the average MTO service level was 90.49%, 8% below the level TKF is aiming for.

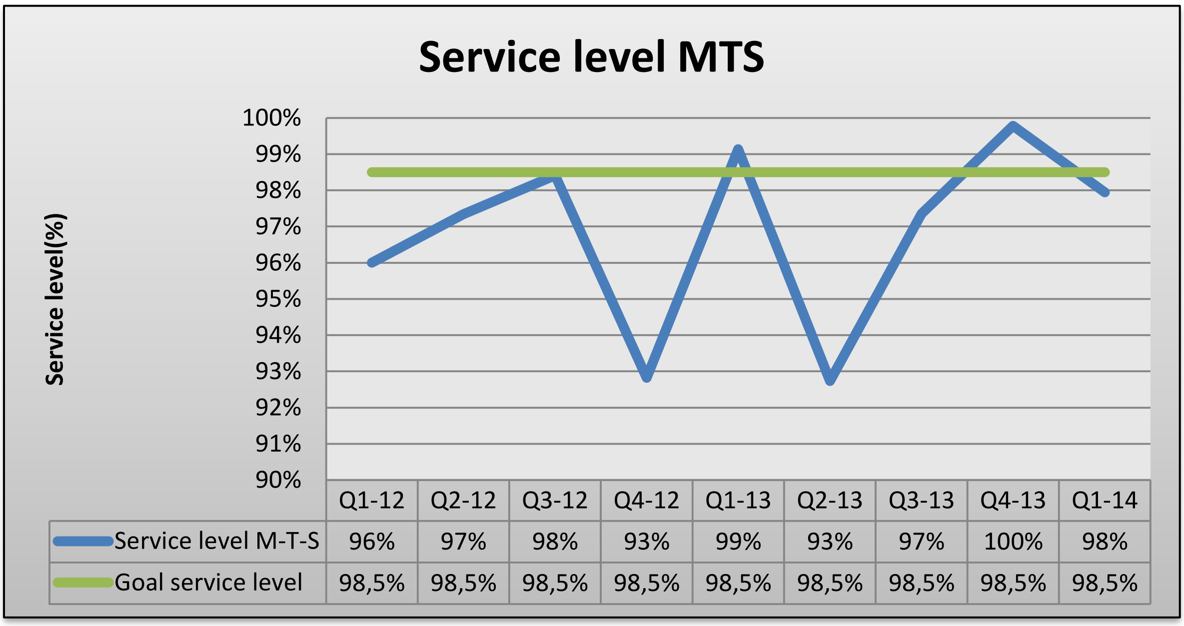


Figure 3.13: Service level MTS

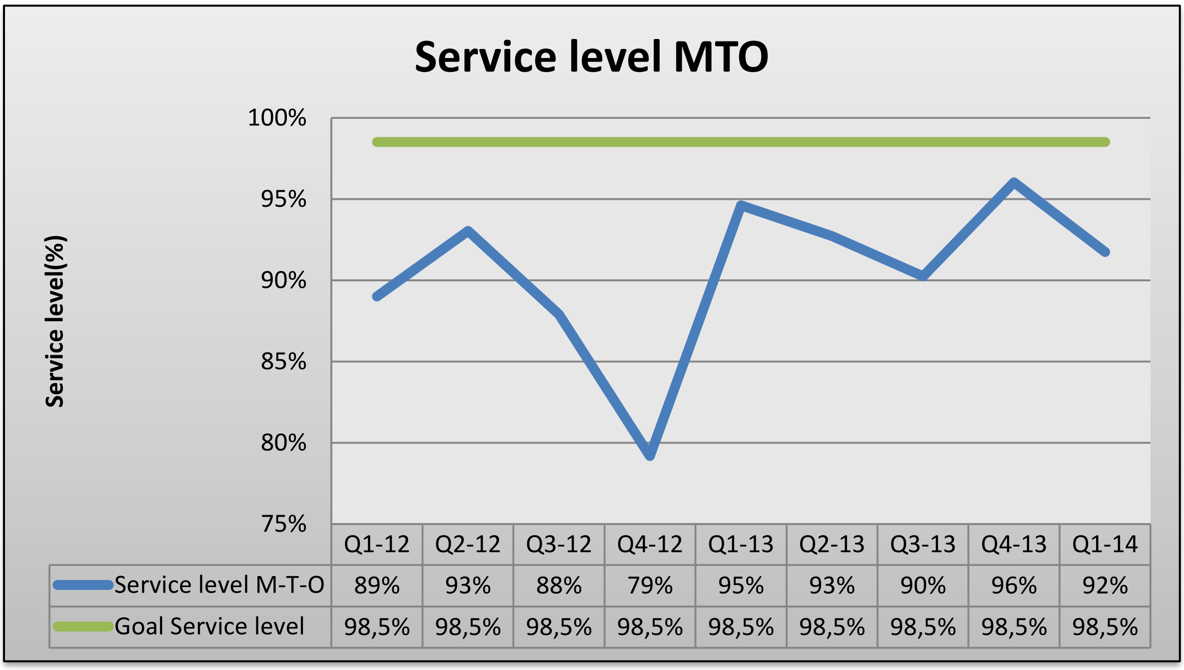


Figure 3.14: Service level MTO

The Internal service level is the fraction of orders that is delivered to other departments within the days required for production. The days required for production is predetermined, and is equal to 2 times the number of processes that a product has to undergo. In 2013 the internal service level was 89.87% which corresponds with 4.8 orders delivered too late each month (Figure 3.15). The internal service level influences both the service levels of other departments as well as the service level of the Installation department, and therefore it is important to increase this service level.

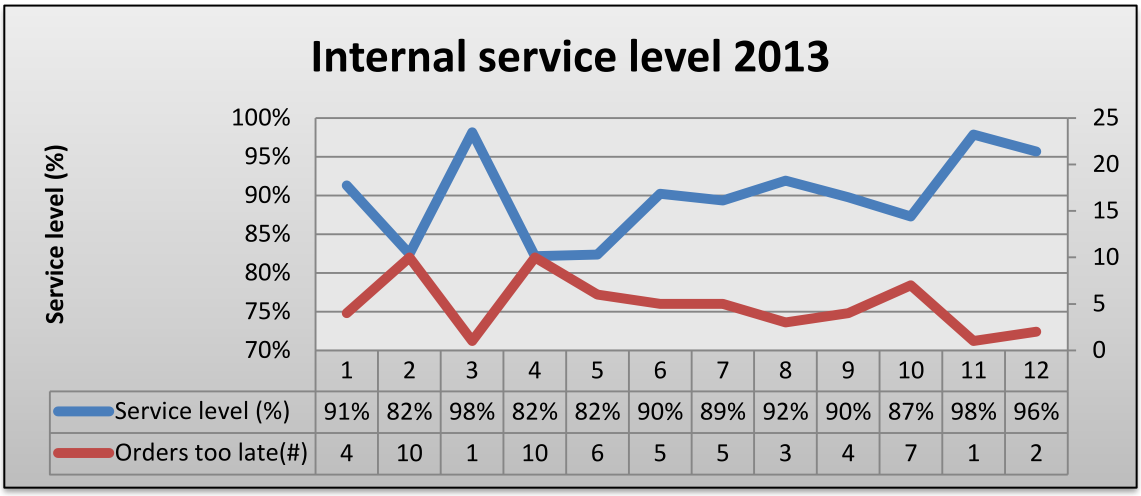
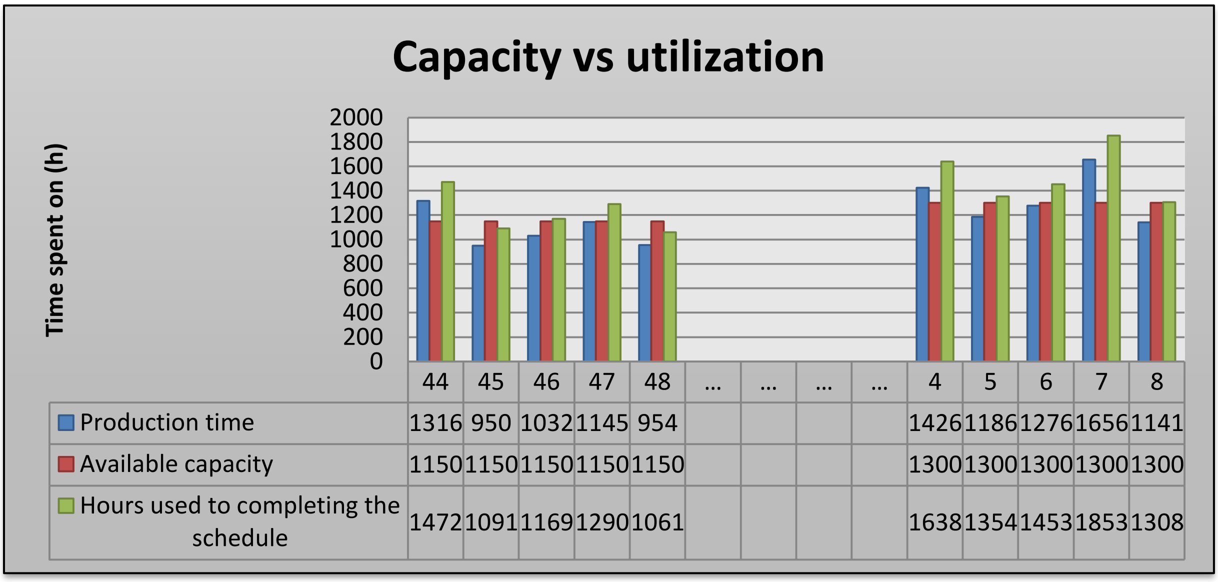


Figure 3.15: Internal service level

The number of hours available for production at each line depends on the number of personnel available during each day. The allocation of staff depends on the available production orders and is not recorded making it difficult to evaluate individual production stations. Therefore, we decide to look at the production department as a whole. During the weeks 44 to 48, 1150 production hours were available, and during the weeks 4 to 8 this was increased to 1300. Figure 3.16 depicts the total hours used for production, and Figure 3.17 shows the distribution of these hours towards several activities in percentage of the total hours. The idle time is the cumulative inactive time of all machines. During idle time, machines are neither processing nor setup for the next production orders, but complete inactive. The setup time is the cumulative time required to setup and adjust a machine between 2 consecutive production orders.

To show how the current planning approach uses the available production capacity to execute its schedule, we calculate the fraction of hours used for certain purposes compared to the total hours used. To provide the distribution of the available production capacity, we use the average fraction of hours that a machine is idle, average fraction of hours used for setups and fine-tuning, average fraction of hours used for production, and the average fraction of hours used overtime (irregular capacity). The idle time is the time that a machine is not processing, being changed over or setup. Irregular capacity is capacity that is not available, however capacity can be expanded by, for example, working in the weekends, hiring additional employees, or outsourcing the process.

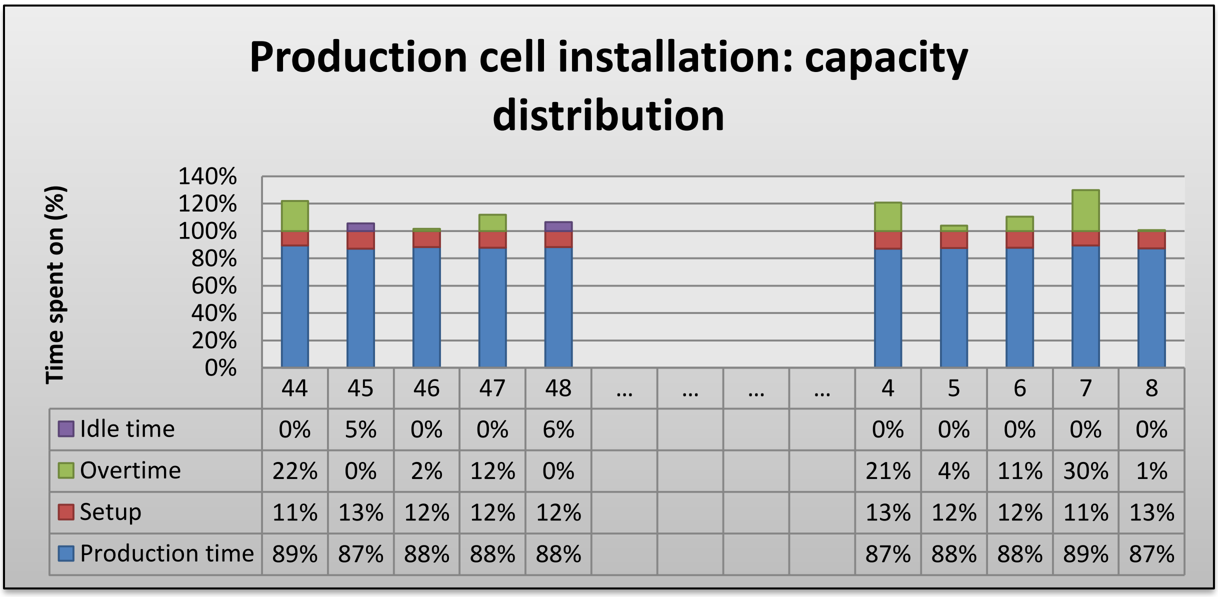
Again we analyse the weeks 44 to 48 and the weeks 4 to 8, because in the weeks 44-48 the demand was below the available production capacity (an average of 1080 with 1150 hours available capacity) and the weeks 4-8 had a demand higher than the available production capacity (an average of 1337 hours with 1300 hours available capacity).



	44	45	46	47	48	…	…	…	…	4	5	6	7	8
Production time	1316	950	1032	1145	954					1426	1186	1276	1656	1141
Available capacity	1150	1150	1150	1150	1150					1300	1300	1300	1300	1300
Hours used to completing the schedule	1472	1091	1169	1290	1061					1638	1354	1453	1853	1308

Figure 3.16: Production capacity vs production time vs production + changeover time

Based on Figure 3.16 we calculated the utilisation of the machines (%) of the current scheduling approach. In the weeks 44 to 48, as well as the weeks 4 to 8, the machines' utilisation is on average 88%. Figure 3.16 also shows that the regular capacity rarely suffices to complete the entire schedule. In the weeks that the hours used for completing the schedule is below the available capacity, machines are idle. To get a better understanding of the distribution of the available capacity, Figure 3.18 shows the percentages of time used for several activities. The percentage of the total time used to complete the schedule that is over time (irregular capacity) there is a significant difference between the 2 intervals. In the weeks 44 to 48, the average overtime is 7% of the total time used. In the weeks 4 to 8 however, this increased to 13%. The time spent to setup machines is in both periods on average 12%. Note that the machine utilisation, over time, idle time, and setup time are based on the hours employees spent on these activities compared to the total hours employees are available. Since not all machines are staffed each day, the idle time of individual machines is significantly higher whereas the machine utilisation will be lower.



	44	45	46	47	48	…	…	…	…	4	5	6	7	8
Idle time	0%	5%	0%	0%	6%					0%	0%	0%	0%	0%
Overtime	22%	0%	2%	12%	0%					21%	4%	11%	30%	1%
Setup	11%	13%	12%	12%	12%					13%	12%	12%	11%	13%
Production time	89%	87%	88%	88%	88%					87%	88%	88%	89%	87%

Figure 3.17: Capacity distribution based on the hours available

Conclusion

The current scheduling approach aims to optimise the service level and machine utilisation. The dispatching rule used is best described as an adapted version of the earliest due date. The current scheduling approach has a 24 hour scheduling horizon. Furthermore, the production planner schedules large production orders which causes blocking at machines, increased lead times, and the impact of erroneous production increases. Furthermore, the operators have several rules that determine to which extent they can determine the production schedule at their machines.

To assess the current planning approach we selected the throughput, internal and external service levels, machine utilisation, and irregular capacity as key performance indicators and performed measurements and data analysis. The external service level consists of 3 parts: service level for production orders, MTS, and MTO. The service level for production orders is 74.24%, and is below the level TKF pursues (98.5%) and is, among other factors, caused by service level problems for MTO, MTS, and other departments. The service levels for MTS and MTO items are respectively 96.83% and 92.82%. We expect that when both of these service levels improve the service level for production orders improves as well. The internal service level is the fraction of orders that is delivered to other departments within the days required for production. In 2013 the internal service level was on average 89.87%. Due to the increasing demand for products produced at the Installation department, the amount of processing that occurs in overtime increased, and the amount of idle time decreased. In the weeks 44-48, on average 7% of the processing time was in overtime, when in the weeks 4-8 this almost doubled to 13%. The amount of time used for changeovers did not change and contributed to 12% of the total time. The utilisation of the machines was in both periods equal to 88%.

4 Developing the scheduling approach

This chapter provides the answer to the research question *''Which of the developed planning approaches suits best to the situation of TKF?''*. We propose new scheduling approaches based on the literature study in Chapter 2 and the analysis of the current situation in Chapters 1 and 3. In Section 4.1 we define general solution approaches and Section 4.2 discusses the practical extensions of the models, the practical restrictions, and finally the assumptions we make to make the model practically applicable. In Section 4.3 we provide the more detailed model description.

4.1 Formulating the solution approaches

As mentioned in Chapter 2, this research uses job shop scheduling approaches to solve the operational scheduling problem and, as the problem description states, it is important that the solution approach incorporates release dates, sequence dependent setup times, diverging job routing, and due dates. In Section 2.3 we discussed several scheduling approaches to solve job shop scheduling problems. In this section, we evaluate the alternative scheduling approaches to make decision on which alternative to use after which we provide a more detailed description on the selected approaches.

To provide a good solution for the scheduling problem, it is critical to incorporate release and due dates because production orders do not arrive at the same point in time and to satisfy the customer a promised delivery date needs to be met. Based on the release and due dates, the model schedules the jobs in order to minimise the maximum lateness to ultimately maximise the service level. Additionally, due dates are important to ensure that (semi-) finished products arrive in time at other production departments so that these departments can meet their delivery dates. Furthermore, it is important to incorporate sequence dependent setup times to provide a practically feasible and efficient solution. The current approach uses standard changeover times and does not consider the production sequence when calculating the makespan of a schedule. To model the sequence dependent setup times, we formulate *product families based on manufacturing characteristics* as explained in Section 2.4.1. Processing products within a family consecutively yields lower changeover losses and therefore a more efficient schedule in terms of machine utilisation. Using product families provides a good approximation of the total setup time required.

To come to alternative solutions we evaluate the scheduling approaches mentioned in Section 2.3. Recall that we mentioned the shifting bottleneck heuristic, dispatching rules, the tabu search heuristic, the greedy randomized adaptive search procedure, and the simulated annealing algorithm as possible solution approaches. We evaluate the alternatives based on simplicity, accuracy, speed, intuitiveness, and flexibility to the practical job shop as proposed by Cordeau et al. (2002). We assign values based on a Likert scale to the alternative approaches. Based on the results of the evaluation we determine which of the alternatives we use to formulate solution approaches.

Furthermore, it is important to include delayed precedence relations to ensure a certain delay between two operations because several operations are processed on the same machine. Initially, all operations on a machine are treated independently, which is not always correct. For example, the sheathing processes are categorised in two categories namely the inner and outer sheath. By treating these operations independently we allow the model to schedule the operation of the outer sheath before the inner sheath is processed. Practically, this is an infeasible schedule, and also referred to as a cycle (Dauzère-Pérèz & Lasserre, 1993). Delayed precedence relations prohibit the model from forming cycles by including a certain delay between inner and outer sheathing.

Jain & Meeran (1999) performed several job shop scheduling experiments with various algorithms and heuristics and evaluated the approaches on accuracy and speed. The results show that the shifting bottleneck heuristic outperforms both simulated annealing and tabu search in terms of speed, especially when the problem size increases. Dispatching rules can provide good solutions, but due to their simplicity it is unlikely that they outperform more sophisticated heuristics. Dispatching rules are straightforward and provide a solution within relatively low computational time. The quality of the solution however, suffers from the simplicity of the approach. Simulated annealing outperformed the shifting bottleneck heuristic and performed slightly better than tabu search on the objective functions (Jain & Meeran, 1999). The main advantage of the shifting bottleneck heuristic is that the shifting bottleneck heuristic is an intuitive approach. Most production planners and managers are aware that the bottleneck machine determines the flow in the factory and aim to optimise this machine, making it easier to gain their support. All approaches use the disjunctive graph to calculate the makespan, lateness, release dates, and due dates. The disjunctive graph (see Section 2.3.2) that is used is easily adaptable to practical situation such as release and due dates, product family changeover times, and parallel machine scheduling.

Criteria / Alternative	Simplicity	Speed	intuitiveness	Accuracy	Flexibility
Shifting bottleneck heuristic	3	4	5	3	5
Dispatching rules	5	5	4	1	5
Simulated annealing	4	3	2	5	5
Tabu search	2	3	1	4	5
Greedy randomised adaptive search procedure	2	2	3	2	5

Table 4.1: evaluation solution techniques

Based on the evaluation of the objectives and Table 4.1, we decide to use the shifting bottleneck heuristic, dispatching rules, and simulated annealing to define solution alternatives. We use the shifting bottleneck heuristic because it is a proven heuristic to solve the JSSP and it corresponds with the reasoning of the production planners at TKF. Second, we use dispatching rules to come with a solution quickly and it matches the highest buffer ratio first approach TKF currently uses. Finally, we use the simulated annealing algorithm to optimise an initial solution. Simulated annealing is a more complex approach and offers the opportunity to evaluate a solution based on multiple objective functions.

With the selected techniques, we propose three alternative solution approaches. Alternative 1 and Alternative 2 use the shifting bottleneck heuristic to solve the JSSP. As mentioned in Chapter 2, the performance of the shifting bottleneck heuristic depends on the methodology used to solve the single and parallel machine scheduling problems. Alternative 1 uses a relatively simple dispatching rule to solve the $1|r_j,s_{gh,ij}|L_{MAX}$ and $P|r_j,s_{gh,ij}|L_{MAX}$ problems where Alternative 2 implements the more complex simulated annealing algorithm. Alternative 3 uses the simulated annealing algorithm to solve the JSSP. Figure 4.1 shows the structure of the different solution approaches. The remainder of this section, Sections 4.1.1, 4.1.2, and 4.1.3, provides a general description of the alternatives.

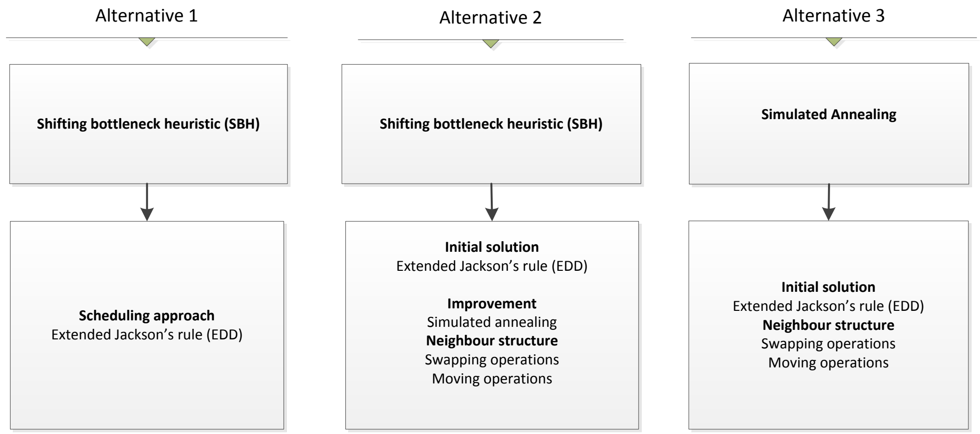


Figure 4.1: Alternative scheduling approaches

4.1.1 Alternative 1: Shifting bottleneck heuristic – Dispatching rules

The first scheduling alternative uses the shifting bottleneck heuristic to solve the scheduling problem. As said in Chapter 2, the literature study, the shifting bottleneck heuristic decomposes the job shop problem in a series of single and parallel machine scheduling problems. For each of the sub-problems it calculates the lateness, and the machine with the maximum lateness is considered the bottleneck. Based on the schedule of this bottleneck machine, the other machines are scheduled. To solve the sub-problems, the original shifting bottleneck heuristic uses an exact algorithm to find the optimal sequence. Practical problems however, consist of many jobs and therefore many possible sequences. To find solutions quickly, we use dispatching rules. Dispatching rules sort the set of jobs based on a certain criteria and based on that sequence, orders are scheduled. Because the main objective of this research is to increase the customer service level, we decide to use dispatching rules that include due dates when calculating the priority values of operations. We introduce the Jackson rule (Jackson, 1955), which sorts jobs based on their due dates from the smallest to largest value (also referred to as the earliest due date). It is proven that the earliest due date dispatching rule yields an optimal solution for single machine scheduling problems when the objective is to minimise the maximum lateness (Barman, 1998) and all jobs are available at time t = 0 (Pinedo, 2009). However, this does not hold for the JSSP of this research where jobs have release dates, making the scheduling problem significantly more complicated (Pinedo, 2009). The schedule provided by the earliest due date dispatching rule can result in the postponement of the production of a set of jobs when the operation with the lowest due date is not available when the machine is available. To provide a better schedule, the Jackson rule is extended to a rule which now states: "at any time T that the machine is available for processing, process without interruption an unprocessed, available job that has the smallest due date" (Schutten, 1996). The second objective of this research is to reduce the total changeover times of machines.

Objective function

The main objective of this research is to improve the customer service level of the Installation department. In order to achieve this, we set the objective of the shifting bottleneck heuristic to minimising the maximum lateness L_{MAX}, with L_{MAX} equal to the maximum lateness of all jobs (Formula 4.1). C_j denotes the completion time of job J_j, and d_j denotes the due date of job J_j. L_{MAX} can either be positive, 0, or negative when a job completes respectively too late, exactly on time, or too early.

$$L_{MAX} = max_{j=1 \ldots n}(C_j - d_j) \tag{4.1}$$

4.1.2 Alternative 2: SBH – Simulated annealing

The second scheduling alternative also uses the shifting bottleneck heuristic to solve the scheduling problem. Solving the single and parallel machine scheduling problems with due date oriented dispatching rules tend provide good solutions when the due dates are tight. When the production capacity exceeds required capacity significantly however, it is likely that the L_{max} objective is optimised to such extent that the jobs are delivered on time. If this is the case, we want to find the most efficient schedule in terms of changeover and idle times. Alternative 2 uses a meta-heuristic (local search algorithm) to solve the sub-scheduling problem. Heuristics are designed to solve a particular optimization problem and because they tend to be greedy they can get trapped in a local optimum. Meta-heuristics are suitable for almost any optimization problem and because it accepts a temporary deterioration it is able to escape local optima, it is more likely to provide a (near) optimal solution.

As said, Alternative 1 and 2 are different in the approach how the single and parallel machine scheduling problems are solved. Recall from Section 2.3.4, where we discussed simulated annealing, that it requires an initial solution. Alternative 2 uses simulated annealing to improve an initial schedule. For Alternative 2 we use the Extended Jackson rule to construct the initial solution. To improve the initial solution, the simulated annealing algorithm modifies the sequence of operations per machine by means of a modification rule to create a neighbour, after which the objective functions of the neighbour solution are calculated and evaluated.

Objective functions

The main objective of this research is to improve the service level of the Installation department. In order to achieve this, we set the primary objective of the SBH to minimising L_{MAX}, with L_{MAX} equal to the maximum lateness of a set of production orders (Formula 4.1). For the sub-scheduling problems we evaluate two other objectives as well. The objectives of the single and parallel machine scheduling problems are classified as primary, secondary, and tertiary objectives. The primary objective is minimising the maximum lateness and minimizing the total machine changeover time is the secondary objective. Finally, when neither the primary nor the secondary can be improved, the model evaluates the total machine idle time (tertiary objective). We are aware that the secondary objective influences the primary and tertiary objectives. We do not include the changeover time in the primary objective, because the model clusters operations with similar characteristics to a certain degree in order to minimise the lateness. We do not want to make a trade-off between lateness and changeover time, because maximising the service level is the main objective, but to stimulate the model to schedule products with similar characteristics subsequently, we make it a separate objective. The same reasoning applies to the idle time.

The sequence in which operations are processed on a certain machine determines the required changeover time between the operations. We use total changeover times rather than changeover costs because to assess the performance of the production processes, TKF evaluates the OEE rather than costs. The third objective is the total idle time, because a machine being idle equals production capacity not being utilised. The idle time is the cumulative difference between the completion time of operation O_{ij} and the start time of operation $O_{i,j+1}$.

4.1.3 Alternative 3: Simulated annealing

The third alternative solution uses only the SA algorithm to solve the scheduling problem and uses the Extended Jackson to construct the initial solution. The sequence in which the machines are scheduled is equal to the sequence of machines in a normal product flow. The SA aims to improve the initial solution by constructing neighbour solutions. Van Laarhoven et al. (1992) propose to alter only the sequence of operations that are part of the critical path because altering the sequence of operations that are not a part of the critical path never yields an improved solution and by altering the critical path of the disjunctive graph, the model only performs (feasible) modifications to the schedule that are potential improvements. To construct neighbour solutions the arc connecting u and v is reversed, where u is part of the critical path and u and v are both operations on machine k. However, the results of simulated annealing do not automatically improve from using a smaller search space. A good initial solution results in faster convergence of the algorithm and thus, results in an increased likelihood that the algorithm finds a local rather than a global, optimum (Ram et al., 1996). Therefore, accepting random worse solutions enables simulated annealing to escape local optima. To construct neighbour solutions, the model randomly selects a machine to improve and interchanges or moves scheduled operations. We do not interchange operations of different machines simply because in practice it is not feasible. The computational time of the model and the quality of the solutions highly depend on the parameter settings. We discuss the determination of these parameters in Section 4.3.3.

Objective functions

As stated in the research objective, we aim to improve the service level of the Installation department. In order to achieve this, we set the primary objective of the SA to minimising L_{MAX}, with L_{MAX} equal to the maximum lateness of a set of jobs (Formula 4.1). Alternative 2 evaluates the objective functions on machine level whereas Alternative 3 evaluates the whole scheduling problem (the job shop) because Alternative 3 does not decompose the scheduling problem in sub-problems. The job shop objective functions are the cumulative result of the objective functions on machine levels.

4.2 Practical extensions, restrictions and assumptions

This section answers research question 3.1: ''*What are the practical restrictions?*'' To make the theoretical model suitable for the practical situation some adaptations are required. A huge advantage of the shifting bottleneck heuristic disjunctive graph is that it can be easily adjusted to deal with practical restrictions, such as release dates and changeover times (Schutten, 1998), by changing the structure of the disjunctive graph. Because the simulated anneal algorithm utilises the same disjunctive graph, the practical extensions apply for Alternative 3 as well. This section provides the practical extensions the model uses to solve the scheduling problem. To illustrate the extensions, Figure 4.2 shows a disjunctive graph with some basic practical extensions.

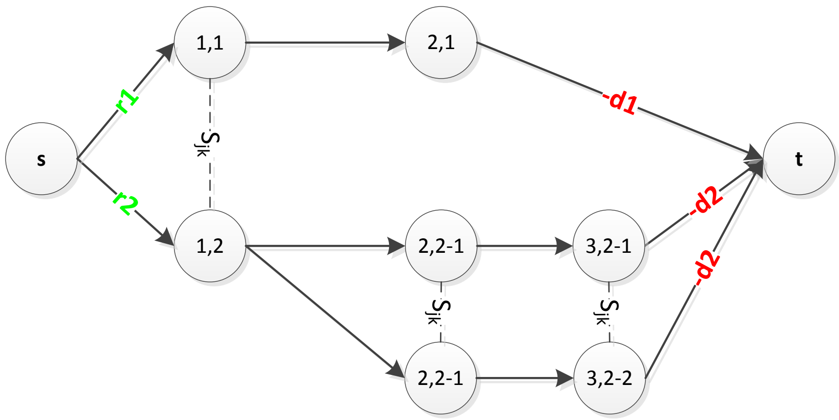


Figure 4.2: Disjunctive graph with release dates, due dates, sequence dependent setup times, and diverging job routing

Release and due dates

In practical situations, production orders often contain release and due dates. The release date is the moment in time the production of the order can start and the due date is the planned completion time of the last operation. As said in Chapter 3, production orders are assigned a certain buffer class indicating the allowed cycle time of those production orders. For example, a production order that requires processing on 3 machines has a buffer of 6 days. By subtracting the assigned buffer class from the due date (customer delivery date) we obtain the release date of that production order. Looking at a set of production orders, the earliest release date of all production orders is considered t=0, the start time for the model. From t=0, we calculate the release and due dates for the total set of production orders. We refer back to Section 2.3.2 for the implementation approach of release and due dates.

Sequence dependent changeover times

The production sequence of a set of operations determines the required changeovers. At each process a product is assigned a certain family to calculate the changeover time for a certain production sequence. Producing consecutive operations that belong to the same product family requires a significant lower changeover than producing consecutive operations from different families. For example, if the products belong to the same product family, only a minor changeover is required such as changing the reels. When the products belong to different families however, the entire machine needs to be adjusted resulting in a significant longer changeover time. In this section we identify the different product families based on machine characteristics and product similarities.

The first process of making a cable is the stranding process. The only changeovers required at stranding are the input and output reels. As said in Chapter 3, the stranding process consists of two machines, the Drumtwister 3 and Samenslaglijn 3. For the Drumtwister, when a production order yields multiple output reels, the full reels have to be replaced with empty ones which takes up to 30 minutes. When the input reels need to be changed however, this requires up to 90 minutes making it attractive to combine production orders at the insulation processes (i.e. cores of multiple production orders at the same reel). The Samenslaglijn 3 has the same changeover characteristics only takes changing full reels 15 minutes and changing the input reels only 30 minutes.

The second process is armouring or braiding. Armouring can be either steel tape or steel wire. Changing steel tape requires a significant smaller changeover compared to changing steel wire. The materials used for braiding can be either copper or iron wire and the types of material determine on which machine the production order needs to be processed because TKF dedicates groups of machines solely to the two types. For both types several variants exists who differ in wire ratio.

The last production process is sheathing. The first characteristic is whether a product needs to be filled and if so, which material is required. The sheathing material can either be XMBZH or PE. Besides sheathing material, the colours of the sheath differ per production order. Changing from one colour to another requires cleaning of the extruders. For filling and sheathing, different extruders are used so if both extruders need to be cleaned or another material is required, extra changeover times are required.

The arcs between operations that require processing on a machine are provided with a weight s_{jk} to indicate the required changeover time between operations. The value of s_{jk} depends on the sequence in which the operations are scheduled. To incorporate the sequence dependent changeover times we created a changeover matrix providing the changeover times required between all identified families. Algorithm 4 is used to determine the changeover times required between two operations and is found in Appendix D. For each operation it identifies the family of the previous operation, compares it with the family of the current operation and determines the type of changeover required.

Transportation times

When a production order completes its processing on a machine, the machine operator needs to perform some test to determine the quality of the product. The operator also has to perform several administrative actions before it can transport the reel to its subsequent process. Based on operators' estimates, we set the transportation time for the solution approaches at one hour. This seems long, but operators prepare and start the next production order to avoid a standstill at their machine prior to the administrative hassle.

Parallel machine scheduling

For the braiding processes, a group of 7 braid machines are available at TKF. A production order can be processed on any of these machines, depending on which is available. Regarding scheduling, first a production order is assigned to one of the machines and the machines are scheduled separately. Since the machines are more or less identical in terms of capabilities and production processes we formulate $P|r_j,s_{gh,ij}|L_{Max}$ sub problems. Figure 4.3 provides a visual example of parallel machine scheduling. The blue lines depict the sequence belonging to a single machine and the brown lines depict a sequence on 2 parallel machine. In this example consists process 2 out of 2 different machines and are scheduled separately. The algorithm in the solution model first selects the first available machine, assigns the first available operation with the lowest due date to this machine, and schedules the operation on the machine (Appendix C).

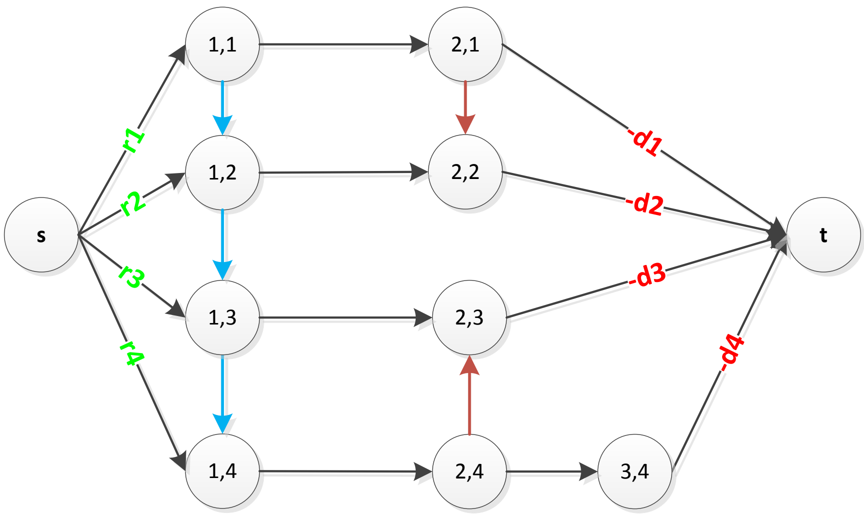


Figure 4.3: Representation of scheduled parallel machines

Delayed precedence relations

The scheduling problem of this research contains machines that perform more than one type of processing. The sheathing machines apply both the inner and outer sheaths. The original shifting bottleneck heuristic treats these processes independently. When scheduling this machine a direct cycle can occur and therefore the schedule would be infeasible. A practical example of cycling is when the outer sheath of job 1 is applied before the inner sheath of job 2, while operation 2 is scheduled first on the interstitial process. Due to this, the model cannot schedule the outer sheath of job one because the interstitial process of job 1 is waiting for the processing of the inner sheath of job 2 and vice versa. Dauzère-Pérès and Lasserre (1993) incorporated delayed precedence constraints to overcome this problem. By forcing a certain delay between the processing of several operations, we force the model to schedule these operations in a feasible sequence (Dauzère-Pérèz & Lasserre, 1993). To incorporate delayed precedence constraints in the shifting bottleneck heuristic, each of the machine scheduling algorithms should be changed to deal with these restrictions (Dauzère-Pérèz & Lasserre, 1993). For the models of this research it requires changes to the single and parallel machine scheduling algorithms.

One piece flow manufacturing

Due to the high variety in production orders in terms of size, processing times, number of reels, routing, and product types, Heijunka is currently not achievable. In Section 2.4.2 we discussed the one piece flow principle as a tool to achieve Heijunka. The advantages of one piece flow manufacturing are an increase in flexibility, reduction of WIP, reduction of lead times, and more control over the flow within the production cell. The downside of one piece flow is an increase of changeover time because a set of production order consists of more separate reels. Implementing one piece flow at insulation is too inefficient due to relatively large changeover times in proportion to the processing time. Furthermore, production orders in Navision denote final products and are linked to a series of processing steps, starting at stranding. First, the cores are considered a required material for the final product rather than a processing step and because of this, it is highly difficult to extract the processing steps of the cores and join them with the final product. At the insulation machines it is important to cluster cores with similar characteristics in order to minimise changeover times and maximise efficiency. Additionally, the insulation processes encompass various practical restrictions that are difficult to incorporate in the model such as processing for other departments several days in a week. The point in time and duration of these practical restrictions however, are variable and depend on the workload of both departments as well as the production schedule of the other departments. Since the insulation process has overcapacity compared to its subsequent processes, it is not necessary to let the sequence on the insulation machines influence the sequence on the bottleneck machines. Ultimately, we decide to exclude the insulation machines from the scheduling problem and solve the insulation scheduling problem separately. The implementation however, is outside the scope of this research.

As said, it occurs frequently that production orders consists of multiple reels which results in machine blocking. Therefore, we decide to propose alternatives that include the one piece flow principle. To model the one piece flow principle we do not need to alter the disjunctive graph, since it only results in an increase of production orders. To determine how to divide the "old" production orders in to the new one piece production orders we look at the reel capacity and production times. A production order cannot consist out of multiple reels and each reel cannot have a processing time longer than 24 hours on any of the machines. The latter mainly refers to the braiding processes which is generally the most time consuming process. To model one piece flow we require an algorithm that determines the maximum reel length and processing times after which an "old" production order is broken down into sub orders, which are scheduled separately.

Overall equipment efficiency

To compensate for disturbances we divide the processing times with a decreasing factor (<1). By increasing the processing times we create buffer for unexpected breakdowns, material unavailability, and excessive changeover times due whatever reason. The OEE calculates the machine utilisation by dividing the theoretical available processing time by the actual processing time. It is important to note that the OEE value includes idle time and changeover times so the capacity this research uses is an underestimation of the actual capacity. Initially we use a decreasing factor of 0.70, the historical performance based on the overall equipment efficiency data of a year. To incorporate the decreasing factor in the models, we divide the processing time by the decreasing factor. In Chapter 5 we evaluate and discuss the impact of this factor on the different KPIs by performing a sensitivity analysis.

Assumptions

This section discusses the assumptions we make to make the problem manageable because incorporating all practical restrictions and anomalies would result a model that is too complex. For the alternative solution approaches we make assumptions concerning reel capacity, machine capacity, processing and setup times, and maximum inventories.

The first assumption we make is that the 70% OEE is a correct representation of the machines' productivity. Second, we assume that all machines are available when work is scheduled and third,

we assume that all machines are available from Sunday 22:00 until Friday 22:00. Based on these assumptions we calculate the available production capacity.
To model the one piece flow principle we use the maximum cable length on a reel to determine the size of the production order. To determine the maximum length of a production orders, we extract the data from NaVision. For this research we assume that this data is representative for the actual situation. The next assumption we make concerns the production speed and changeovers times of machines. The production speed is extracted from NaVision and is determined by R&D based on product and machine capabilities. For the models we assume that the production speed, and therefore processing times, is correct and invariable. The same assumption is applicable for production order information and production order routing. Furthermore we assume that once a production order is accepted and entered in the ERP system, this production order is not modified. Finally, we assume that the buffer classes are correct and representative for the required production processes.

Both of the solution alternatives do not schedule the insulation processes. However, to produce an end product isolated cores are required. For the models we assume an infinite buffer of insulated cores is available to ensure that all production orders can start. Besides the insulated cores we assume that all other materials and tools are available the moment a production order starts.

4.3 Detailed model description

In Section 4.1 we discussed the selected solution approaches in general, and in Section 4.2 we discussed the practical extensions and restrictions to make the models more sophisticated and practically applicable. This section describes in more detailed the models used for the alternative approaches. We provide detailed description on the dispatching rules, shifting bottleneck heuristic, and simulated annealing algorithm as we integrated these in the solution models.

4.3.1 Dispatching rules

Dispatching rules are a rather simple method to come to a solution. The dispatching rule this research uses is the Extended Jackson rule. For both the single and parallel machine scheduling problems an algorithm is required to sort the unprocessed operations and to select the first available unprocessed operation. Appendix B shows the pseudo codes of the algorithms.

4.3.2 Shifting bottleneck heuristic

In Chapter 2 we briefly discussed the shifting bottleneck heuristic but since the methodology is the foundation of two alternative approaches we provide a more detailed explanation in this section. The shifting bottleneck heuristic decomposes the scheduling problem into single machine scheduling problems, making it easier to comprehend. As the name suggests, the premise of this approach is to find the bottleneck machine. Based on the single machine schedules the heuristic determines which of the machines is the most critical machine based on a certain objective function. The objective is to minimise the maximum lateness in order to maximise the service level and therefore the machine with the maximum lateness is the bottleneck machine. First we identify the required notations we use for the models.

Notation

L_{max}	*Maximum lateness*
r_j	*Release date of job j*
d_j	*Due date of job j*
C_j	*Completetion time of job j*
O_{ij}	*Operation of job j on machine i*
r_{ij}	*Release date of job j on machine i*
d_{ij}	*Due date of job j on machine i*
p_{ij}	*Processing time of job j on machine i*
$s_{ij,ik}$	*Sequence dependent changeover time between operation j and k on machine i*

Table 4.2: Notation of the shifting bottleneck heuristic

The shifting bottleneck heuristic is an iterative machine-based technique that decomposes the job shop scheduling problem into a set of single machine scheduling problems as proposed by Adams et al. (1988). The quality of the overall schedule depends on the quality of the schedules of the individual machines. Aytug et al. (2014) state that the sequence in which machines are scheduled determine the quality of the final schedule to a great extent. The primary exertion of the heuristic is prioritising the machines in an order that dictates the sequence in which they are scheduled (Bülbül, 2011). The heuristic consists of several components: The disjunctive graph representation, a sub-problem formulation (in this research $J|r_j,s_{gh,ij}|L_{Max}$ & $P|r_j,s_{gh,ij}|L_{Max}$) to schedule all machines in the order a criticality measure dictates (in this research L_{max}), and a rescheduling formulation that re-evaluates and reoptimises previous bottleneck machines. To illustrate the heuristic, Figure 4.4 shows the cyclic nature of this approach. As the pseudo code (Algorithm 1) in Chapter 2 indicates, the aforementioned steps repeat until all machines are considered bottlenecks and all bottlenecks have been re-optimised.

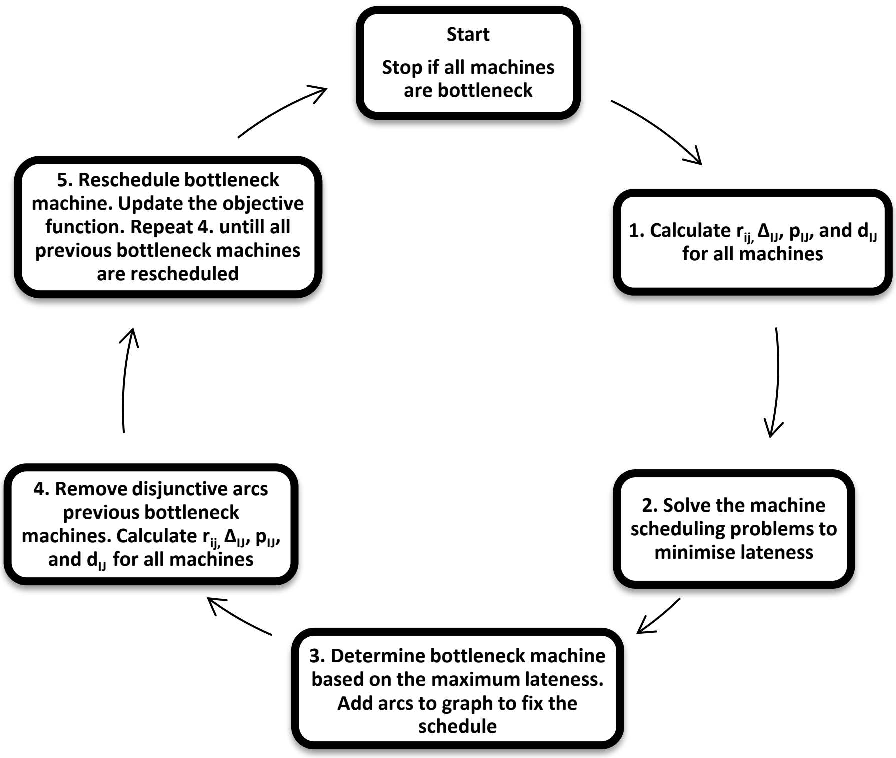


Figure 4.4: The shifting bottleneck heuristic visualised

First, we remove the disjunctive arcs to relax all machine constraints after which we calculate the release and due dates of all operations. Next, we schedule each machine and based on these schedules, we calculate the lateness per operation which is either negative (operation completes before the required due date), 0 (operation completes on the required due date), or positive (operation completes after the required due date). The machine with the maximum lateness is considered the bottleneck machine. We use the following formula to determine the bottleneck of iteration k: $L_{MAX}(k) = \max_{i \in M-M_0} L_{Max}(i)$. The sequence of the selected bottleneck machine is updated in the disjunctive graph by inserting disjunctive arcs, indicating the precedence relations between operations. Based on the updated graph, the release and due dates are recalculated for the next iteration. From the second iteration onwards, the heuristic repeats itself. A new bottleneck machine is determined, after which each of the previous bottleneck machines are rescheduled in the sequence they were selected. To reschedule a bottleneck machine, the disjunctive arcs of the bottleneck machine are removed, release and due dates are recalculated, and the machine is rescheduled. The single and parallel machine scheduling problem can be solved with several methods such as simulated annealing and dispatching rules. For clarification we included a simple example of the shifting bottleneck heuristic in Appendix A.

4.3.3 Simulated annealing

This section discusses the simulated annealing algorithm in more detail. In Chapter 2 we discussed possible solution approaches including the simulated annealing algorithm, however it is important to elaborate on this to get a better understanding of the method and its implications. This section starts with identifying the parameters and variables required for the SA algorithm.

Parameters	
c_{Start}	*Start temperature*
c_{Stop}	*Stop temperature*
c	*Control parameter (current temperature)*
β	*Number of transitions per iteration*
α	*Decreasing factor*
Variables	
$L_{Current}$	*Maximum lateness of the current solution*
L_{Best}	*Maximum lateness of the best-so-far solution*
L_{NS}	*Maximum lateness of the neighbour solution*
$S_{Current}$	*Total changeover time of the current solution*
S_{Best}	*Total changeover time of the best-so-far solution*
S_{Ns}	*Total changeover time of the neighbour solution*
$I_{Current}$	*Idle time of the current solution*
I_{Best}	*Idle time of the best-so-far solution*
I_{NS}	*Idle time of the neighbour solution*
P_{AB}	*Acceptance probability of the neighbour solution*
k	*Number of the current iteration*
$S_{ij,ik}$	*Changeover time between operation j and operation k on machine i*

Table 4.3: Notation of the simulated annealing algorithm

Figure 4.5 depicts the structure of the simulated annealing algorithm that is used for the job shop scheduling problem as well as the single and parallel machine scheduling problems in Alternative 2. The model starts with initialising the parameters and determines the initial solution for each of the machines, in this case using the Extended Jackson rule. Next, the model determines the objective values belonging to the current solution. For every iteration, the model performs β transitions where it formulates a neighbour solution by altering the sequence of the critical machine. To modify the current solution the model uses two different modification rules. The probability that modification rule 1 or modification rule 2 is applied is 0.5.

1) *Exchanging position within the schedule of an operation with a second operation*
2) *Moving an operation from its current position to a randomly chosen position within the schedule*

Alternatives 2 and 3 differ in the approach to select which machine to optimise. The shifting bottleneck heuristic of Alternative 2 selects the machine for scheduling and reoptimisation, and simulated annealing is used to optimise the scheduling problem for the individual machine. For Alternative 3, to improve the solution, the simulated annealing algorithm selects a machine randomly and aims to improve the schedule on this machine. For Alternative 2, as well as Alternative 3, the model calculates for each of the neighbour solutions its objective values and compares it with the best-so-far and current solution. The simulated annealing algorithm accepts the neighbour solution in case the neighbour solution is at least as good as the current solution. If the neighbour solution also improves the best-so-far solution, it replaces the best-so-far solution. However, in case the neighbour solution does not improve the current solution it still accepts the neighbour solution as the new current solution with a certain acceptance probability $P_{AB}(C)$, which is calculated using Formula 4.2. After the model evaluated β neighbour solutions, the control parameter c is multiplied with the decreasing factor α and the aforementioned procedure is repeated until c is smaller than C_{Stop}.

$$P_{AB}(c) = e^{\frac{L_{Current} - L_{NS}}{c}} \tag{4.2}$$

As said, Alternatives 2 and 3 evaluate multiple objectives and therefore it is important to note the priorities between the objective functions. Minimising the maximum lateness is the absolute main objective of this research, so any improvement of this objective is accepted. For the model this has the following consequences. Only if the primary objective remains the same, the model evaluates the secondary objective function ($S_{Current}$). The third objective ($I_{Current}$) is evaluated in case the primary and secondary objectives are neither improved nor deteriorated. We are aware that the maximum lateness is affected by both the total changeover time and idle time, but we decide that the secondary and tertiary objectives are sufficient subordinate to the primary objective to focus primarily on lateness. Furthermore, because the model incorporates the sequence dependent changeover times, the model will cluster product families if it benefits the lateness. The numerator of Formula 4.2 is adjusted to either $L_{Current} - L_{NS}$, $S_{Current} - S_{NS}$, or $I_{Current} - I_{NS}$, depending on the objective that is evaluated.

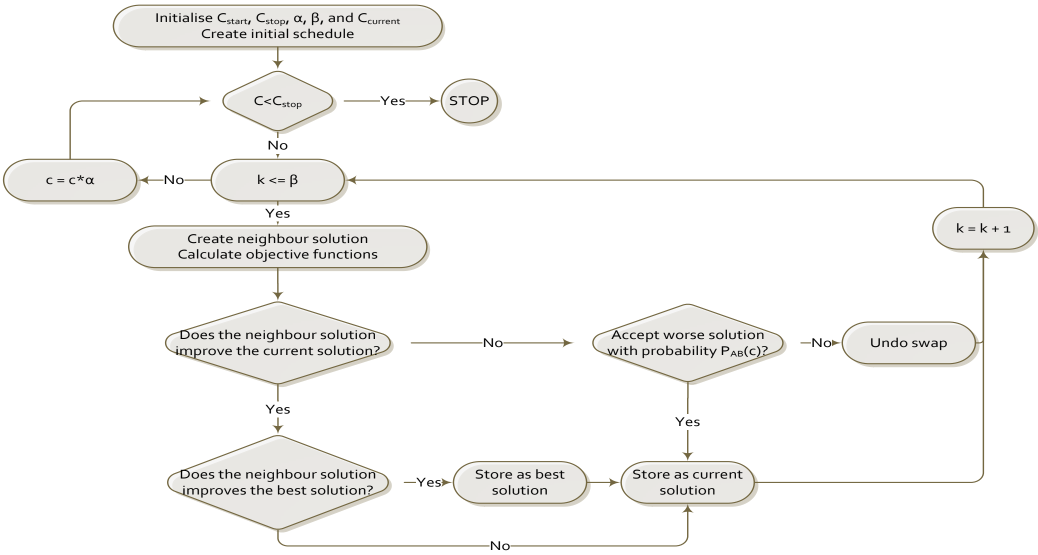


Figure 4.5: Machine scheduling with SA

5 Results

This chapter provides the performance evaluation of the proposed alternatives. The results of the evaluation ultimately lead to the answer to: "*Which of the developed planning approaches suits best to the situation of TKF?"*. Section 5.1 first addresses the experimental structure, after which the results are presented. To evaluate the impact of the slack factor, Section 5.2 presents the results of the sensitivity analysis. Afterwards, in Section 5.3 we select the most suitable scheduling approach based on the results of Section 5.1 and Section 5.2.

5.1 Performance evaluation

Currently it is not possible to perform a test run or a shadow run because the organisational changes the model requires are too substantial. Producing insulated cores on Kanban or on stock is currently not arranged and requires significant production layout modifications. The three alternative approaches are assessed based on the objective functions from Chapter 4. In addition, Chapter 2 discusses several performance indicators which we utilise to compare the alternatives mutually.

Experimental structure

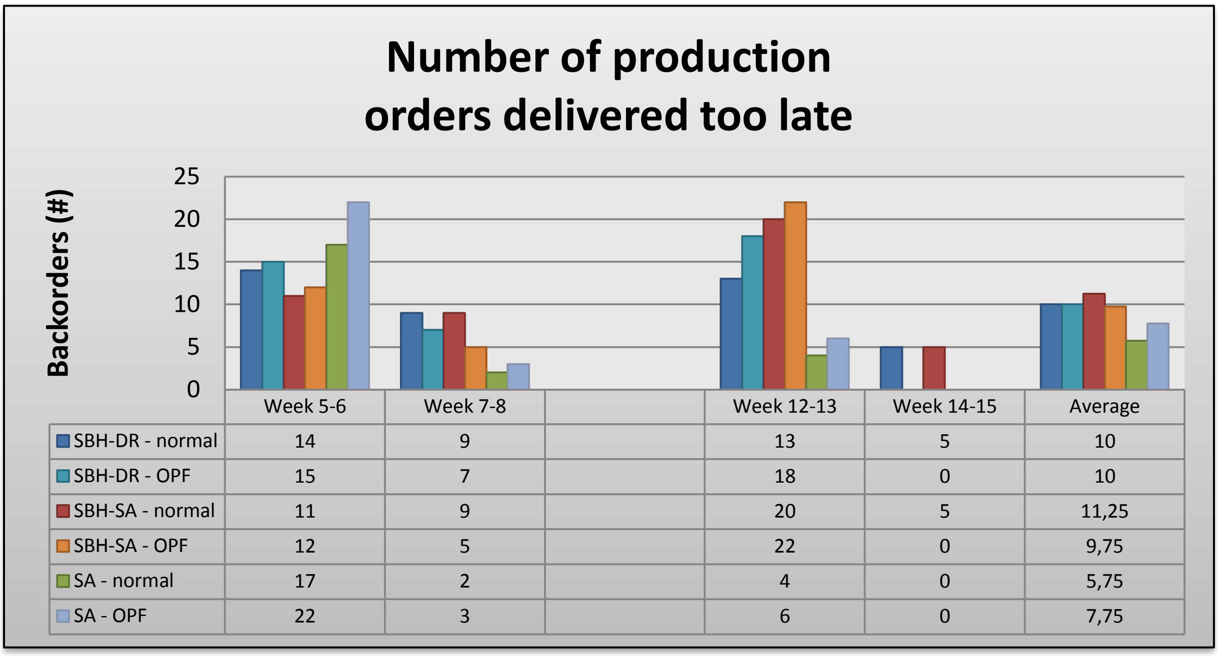
This research performs several experiments to assess the three alternatives to determine if the goals can be achieved and if the proposed schedules are feasible. As a sample for our experiments we use two types of data sets. The first data set contains the finished production orders of weeks where the service level was far below the desired level and the second data set contains the finished production orders of weeks where the service level was on or above the desired level. We select data sets of performing and underperforming weeks to determine the value of the alternatives. To make a decent comparison we select four samples of 2 weeks. Samples one and two (week 5-6 & week 7-8) consist of production orders that resulted in a service level below 65% and sample three and four (week 12-13 & week 14-15) consist of production orders that resulted in a service level above 85%. The samples, unfortunately, differ in terms of workload for each machine and number of production orders. Furthermore, the samples only capture the production orders that are processed at the Installation department and fall under the responsibility of Installation. Therefore, the samples exclude production orders that are taken over from other departments. These orders generally consist of only one processing step. For each of the samples, the alternative approaches construct a production schedule based on the production orders of the respective weeks.

The samples we select contain the set of production orders that have been completed during those weeks and are used as input for the solution models. Based on the buffer classes we determine the can-start time, corresponding with a buffer ratio of 0 (the theoretical desired moment of order release). Production orders, as they are used now, can be very large. To model the one piece flow principle we divide a production order in several sub orders with the size of at most one reel or at most 24 hours of processing time. The model simulates the production facility as it was at March 2014, meaning that the model uses the machines, capacity, and restrictions as they were then.

Performance assessment

The first performance indicator we assess is the number of backorders on a set of production orders since it is the determining factor for calculating the most important objective of this research, the service level. The term backorders refers to the number of production orders that complete after their delivery date. Figure 5.1 shows the performance on the number of backorders per time period per solution approach. All alternatives have two variants. The ''normal'' variant uses the data as they are currently used, and the ''OPF'' variant uses the data that implements the one piece flow ideology.

In terms of the number of backorders, the SA-normal approach outperforms the other solution approaches in the weeks 7 to 15, with on average 5.75 orders that were delivered too late. In weeks 5-6, SBH-SA-normal results the fewest number of backorders. The SBH-SA-normal approach yields on average the highest number of backorders. Even though all companies want to minimise its number of backorders, backorders alone do not give a good representation of the performance of the production cell. For example, one out of one orders that is delivered too late is significantly worse than one out of one hundred orders. The OPF variants contain on average 1.6 times as many jobs than the normal variants. Taking that into consideration, we conclude that the SA-OPF approach yields the best performance with an average of 7.75 backorders. Figure 5.1 depicts the performance of all alternatives on the different time periods.



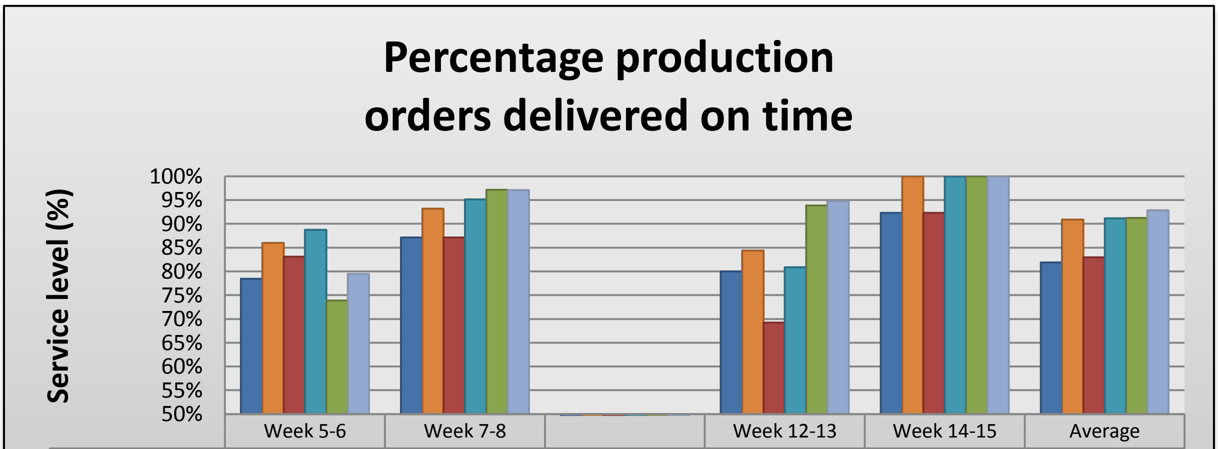
	Week 5-6	Week 7-8		Week 12-13	Week 14-15	Average
SBH-DR - normal	14	9		13	5	10
SBH-DR - OPF	15	7		18	0	10
SBH-SA - normal	11	9		20	5	11,25
SBH-SA - OPF	12	5		22	0	9,75
SA - normal	17	2		4	0	5,75
SA - OPF	22	3		6	0	7,75

Figure 5.1: Number of backorders per scheduling approach

As said, the number of backorders on its own does not completely provide a good performance indication because the number of scheduled production orders differs (per time period and between different approaches). Therefore, we assess the service level of the time periods as well. We calculate the service level with formula 5.1.

$$Service\ level = \frac{\#\ production\ orders - \#\ backorders}{\#\ production\ orders} \qquad (5.1)$$

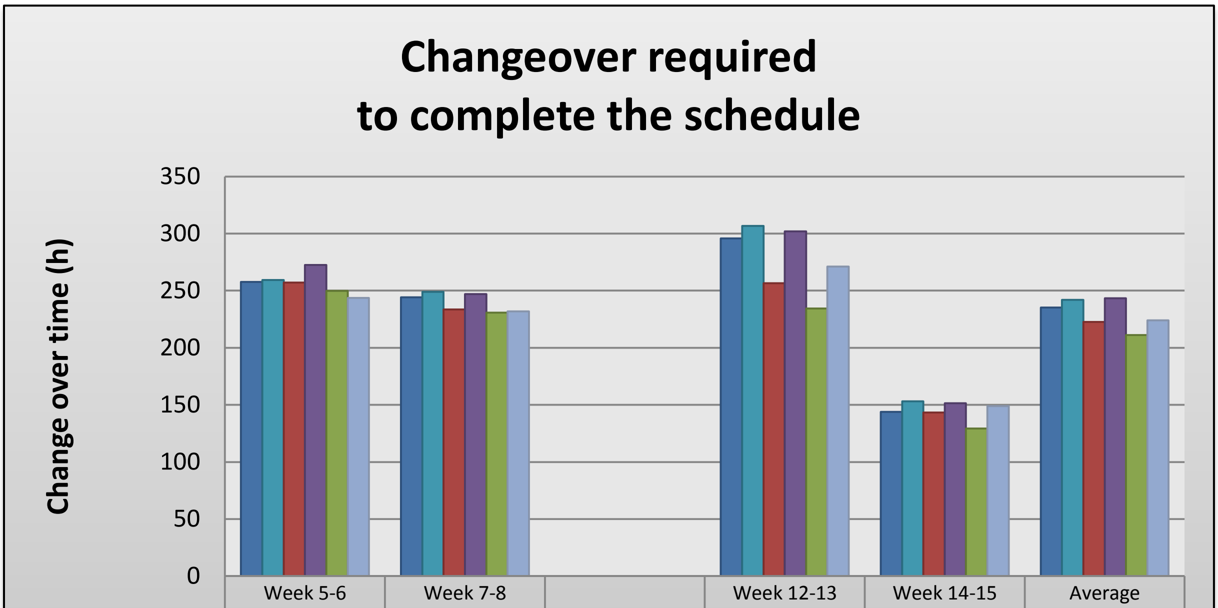
As Figure 5.2 shows, the SA-OPF approach yields on average the highest service level with a service level of 79% in weeks 5-6, 97% in weeks 7-8, 95% in weeks 12-13, and 100% in weeks 14-15, whereas the SBH-DR-normal approach yields the lowest service level. The models indicate that, in weeks with a relatively bad service level performance, the braiding machines are the primary bottleneck. In weeks 14-15 we see that four models achieve 100%, and is the best performing data set which corresponds with the actual performance of the well-performing data set (85%). The set of production orders used in these weeks mainly consisted of production orders with few processing steps and only a few that required braiding. Therefore, we conclude that the performance on the service level is highly dependent on the (widely varying) set of production orders. When comparing the service level graph with the graph of the number of backorders we conclude that indeed, a lower number of backorders not necessarily results in a higher service level. SA-normal has in weeks 5-6 17 backorders that results in a service level of 74%. SA-OPF however, has in weeks 7-8 22 backorders but achieves a service level of 79%. Compared to the other alternatives, the SA-OPF approach does not always provide the best performance, but the variation when performing multiple experiments is limited while the performances of the other approaches fluctuate highly. For most of the experiments, the one piece flow variant outperforms the original variant (large production orders) on service level, even though the number of backorders is higher. When analysing the results we notice that, for the "normal" variants, operations are completed too late because another operation, with a lower ''can start'' date, is processed on this machine if this machine is available before first mentioned operation can start. Obviously, this occurs at the OPF approaches as well. However, the impact at the OPF variants is significantly less because the processing times of production orders is significantly less. At the normal approaches we encounter production orders that block a machine for a week, whereas at the OPF this is reduced to ±24 hours.



	Week 5-6	Week 7-8		Week 12-13	Week 14-15	Average
SBH-DR - normal	78%	87%		80%	92%	82%
SBH-DR - OPF	86%	93%		84%	100%	91%
SBH-SA - normal	83%	87%		69%	92%	83%
SBH-SA - OPF	89%	95%		81%	100%	91%
SA - normal	74%	97%		94%	100%	91%
SA - OPF	79%	97%		95%	100%	93%

Figure 5.2: Average service level per scheduling approach

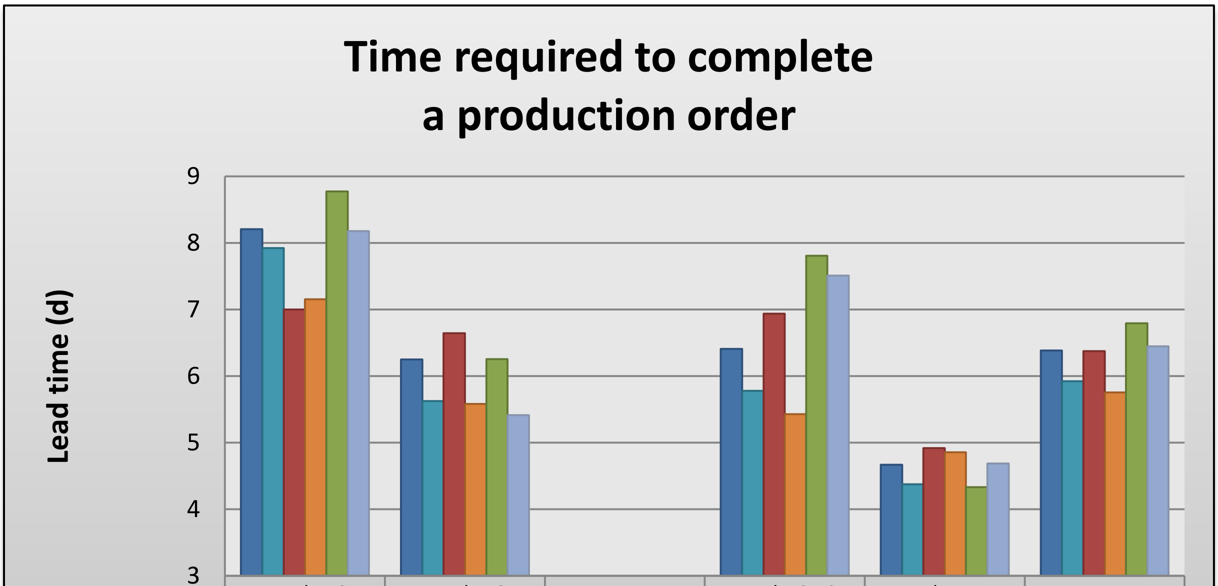
The total changeover time provides an indication on the costs and efficiency of the solution approaches. In Chapter 3, we elaborated on the different types of changeovers for each of the machines. Recall that the production sequence has the biggest impact on the total changeover times at the sheathing machines because, as opposed to cold processes, material changes requires a significant changeover and can be avoided by producing products within a product family subsequently. The changeover of a machine costs material, human resources, and, besides the direct costs, changeover time is lost processing time. We decide to use changeover time rather than number of changeovers since a changeover, minor or major, is required every time a reel is processed. Figure 5.3 shows the total required changeover time per solution approach per time period. The solution approaches incorporating the one piece flow principle require on average the highest changeover time. The number of production orders, and therefore the probability of larger changeovers, at the one piece flow variants is significantly higher than for the normal approaches. When we analyse the production schedules, we conclude that the SBH-SA-OPF and SA-OPF reduce the number of changeovers compared to their normal counterparts. This is the result of the secundairy objective that stimulates simulated annealing to cluster production orders within a product family to reduce the total changeover time. The highest improvement is achieved at the sheething processes, where the changeover time required to produce products with different characteristics is significant.



	Week 5-6	Week 7-8		Week 12-13	Week 14-15	Average
SBH-DR - normal	258	244		296	144	235
SBH-DR - OPF	260	249		307	153	242
SBH-SA - normal	257	234		257	143	223
SBH-SA - OPF	273	247		302	152	243
SA - normal	250	231		235	129	211
SA - OPF	244	232		271	149	224

Figure 5.3: Total changeover time per scheduling approach

Recall from the objective as stated in Chapter 1, that one of the objectives of this research is to provide a scheduling approach that reduces the lead time of products. The lead time is the total time required to produce a product. When discussing the different solution approaches, we decided to exclude the insulation processes from the models. However, to start production at stranding, the insulated cores have to be available. This way we allow TKF to produce insulated cores with reasonable efficiency and avoid that the need to schedule the insulation processes as efficient as possible negatively affects the overall production schedule. To be able to compare the lead time resulting from the experiments with the current situation, we decide to add two days to the lead time. Another unscheduled production process is the final inspection of products to verify its quality. Currently, TKF aims to inspect all completed products within 24 hours after arrival, so for the lead time calculation we assume this is achievable. Figure 5.4 depicts the average product lead time per time period. The short lead time in weeks 14-15 is a result of, as said, the limited number of processes per production order. Most production orders only required two or three processing steps with short production time resulting in an average lead time of 4.3 days, which is achieved by the SA-normal alternative. Furthermore, the approaches using one piece flow manufacturing yield a lower average product lead time than when using the normal approach. This complies with the statements from Chapter 2, when discussing the advantages of one piece flow manufacturing. The SBH-SA-OPF variant performs best on lead time. On all machines, the operations with the earliest due date are processed first, regardless the impact on service level or changeover times. The SBH-SA and SA approaches aim to optimize multiple objectives, and therefore it occurs that a job is not processed immediately after arrival but has to wait in a queue, increasing the product lead time. In essence this is unwanted but if it benefits the service level however, and the increase in lead time is marginal, it is still an improved solution.



	Week 5-6	Week 7-8		Week 12-13	Week 14-15	Average
SBH-DR - normal	8,2	6,3		6,4	4,7	6,4
SBH-DR - OPF	7,9	5,6		5,8	4,4	5,9
SBH-SA - normal	7,0	6,6		6,9	4,9	6,4
SBH-SA - OPF	7,2	5,6		5,4	4,9	5,8
SA - normal	8,8	6,3		7,8	4,3	6,8
SA - OPF	8,2	5,4		7,5	4,7	6,4

Figure 5.4: Average product lead time per time period

5.2 Sensitivity analysis

This section provides the sensitivity analysis on the slack factor that captures the time required for changeovers, breakdowns, and other (unexpected) losses. At TKF, the slack factor is currently 30% and the higher we set the slack factor, the less capacity available for actual production. To incorporate the slack factor in the models, we divide the production time of an operation by the decreasing factor. As mentioned in Section 4.2, the decreasing factor is ''1 - slack factor''. Recall from the discussion of the solution approaches in Chapter 4 that the model uses the actual changeover time required when changing from one product family to another. Therefore, the capacity available in the models is estimated to be lower than the actual capacity. To evaluate the impact of the slack factor, we analyse the impact of the decreasing factor on the service level. We decide to use the SBH-DR-normal and SBH-SA-normal approach as test environment because of respectively their bad and good performance as seen in Section 5.1.

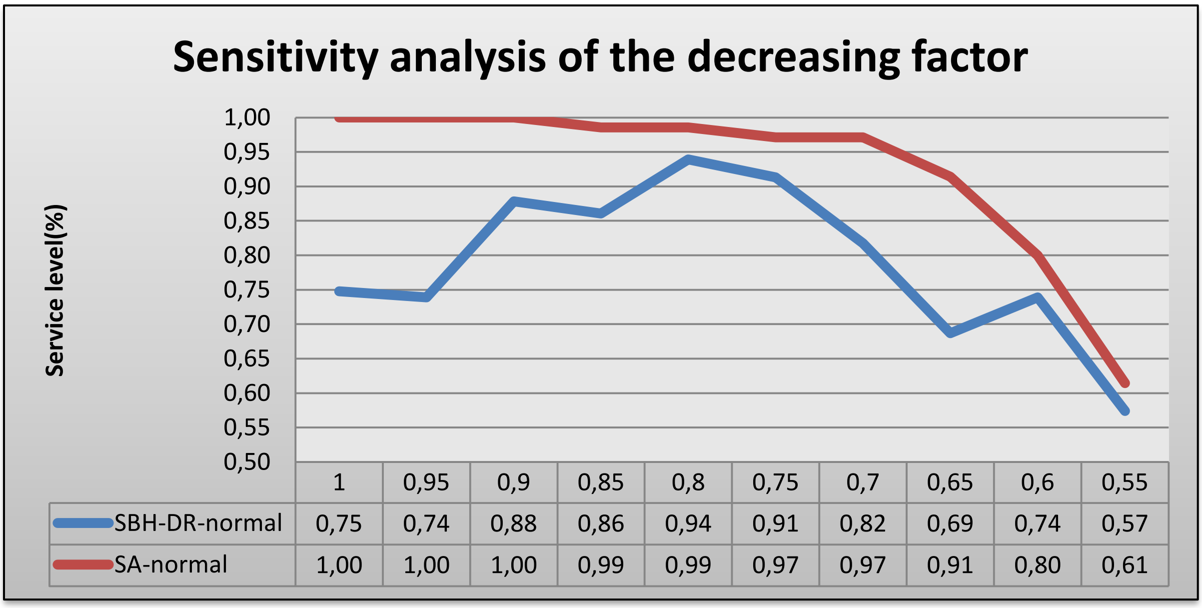
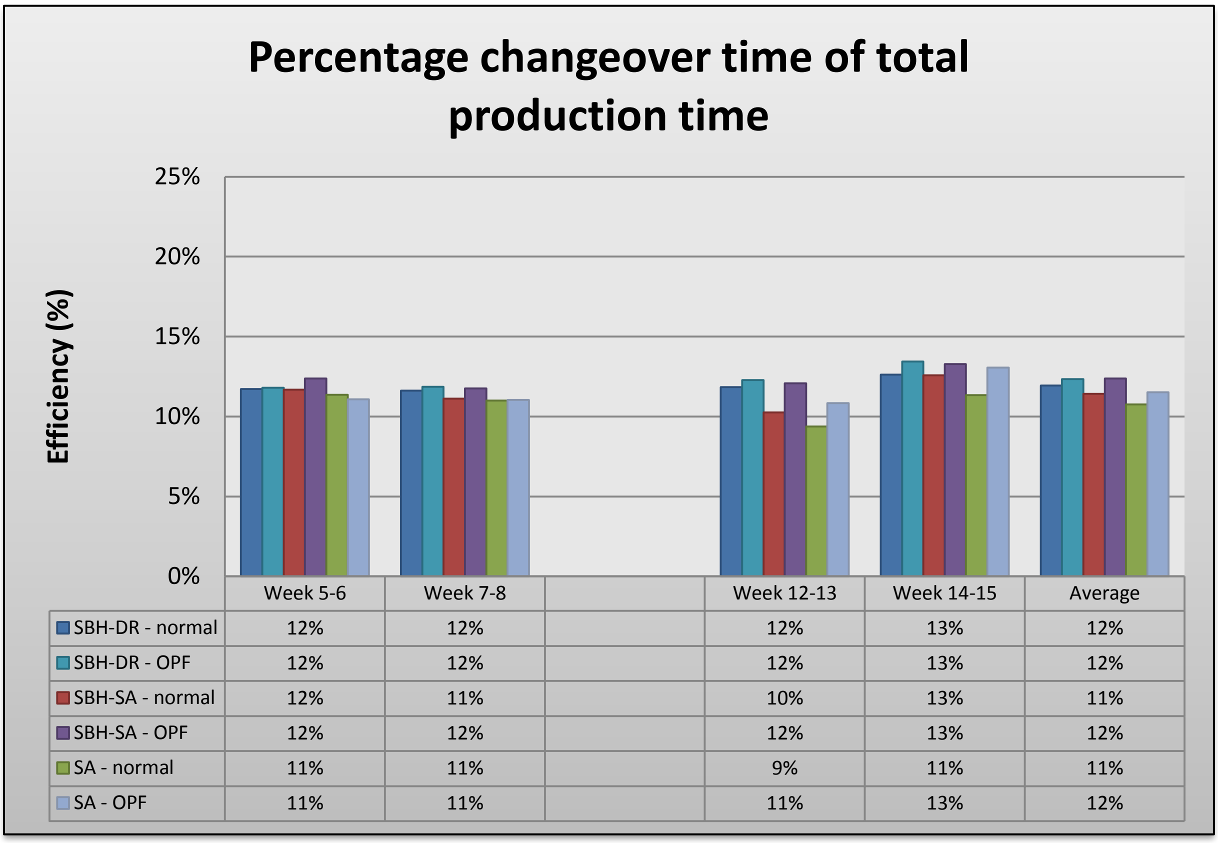


Figure 5.5: Sensitivity analysis of the slack factor

We expect that a lower decreasing factor, and therefore higher processing times, results in a higher service level. The sensitivity analysis shows that the SBH-DR-normal schedules the production orders to its optimum (94%) with a decreasing factor of 0.8 and a slack factor of 0.2. The SBH-EDD schedules operations based on the Extended Jackson rule which sorts the operations based on the due date values and schedules the first available operation first. After analysing the production schedules of the SBH-DR-normal approach we conclude that the model schedules operations differently when the decreasing factor changes. Changing the decreasing factor changes the due date and availability of a production order. Therefore, the model is selects different operations to be scheduled first which can have a positive result. On the other hand, the SA-normal model creates neighbour solutions and selects the best neighbour. Regardless the decreasing factor, the model evaluates most possible sequences. An increase of the decreasing factor results in a higher likelihood of meeting the due date because the processing times are reduced, i.e. less processing time is required to complete the schedule.

As mentioned, the models incorporate both changeover times as well as the decreasing factor. To determine a more reliable and realistic decreasing factor, we calculate the percentage of time the model used for changeovers. The total time is the sum of the production times and the sum of the changeover times. Figure 5.6 shows the percentage of time the models used for changeover times, which was on average 12%.

When combining the information from Figures 5.5 and 5.6, we conclude that using a decreasing factor of 0.82 (=0.70+0.12) for the models corresponds best with the actual situation and yields the best performance when using a dispatching rule to construct the production schedule.



	Week 5-6	Week 7-8		Week 12-13	Week 14-15	Average
SBH-DR - normal	12%	12%		12%	13%	12%
SBH-DR - OPF	12%	12%		12%	13%	12%
SBH-SA - normal	12%	11%		10%	13%	11%
SBH-SA - OPF	12%	12%		12%	13%	12%
SA - normal	11%	11%		9%	11%	11%
SA - OPF	11%	11%		11%	13%	12%

Figure 5.6: Percentage of time used for changeovers

5.3 Conclusion

This chapter provided the results of this research in order to provide an answer to the stated research question: “*Which of the developed planning approaches suits best to the situation of TKF?”.* We evaluated the performance of the solution approaches by analysing their performance on several performance indicators. We performed four experiments per solution approach to analyse their performance. The experiments contained the data of time periods with extreme performances; one time period performed well under the desired service level, and the second time period performed well above the desired service level. The SA-OPF approach is overall the best performing alternative on service level, number of back orders as well as total changeover times. For the two data sets, the SA-OPF approach achieved an average service level of 93%. SA-OPF does not always outperform all approaches, but overall it provides a reliable and stable service level while the performances of the other approaches are subject to large variations. For all time periods, alternatives incorporating the one piece flow principle outperform the alternatives that do not incorporate the one piece flow principle even though the number of backorders is higher. The number of production orders increases with a factor 1.6 after implementing the one piece flow principle, so the service level improves as long as the increase of number of backorders is less than the aforementioned factor.

The increasing numbers of production orders result in a significant increase of total changeover time as well. At stranding for example, for every production order the machine operator needs to replace the input reel which takes up to 90 minutes. Compared with the normal production strategy, the one piece flow approaches require up to 6% more changeover time. Looking at the sheathing processes, the SBH-SA and SA approaches reduce the number of changeovers compared to their dispatching rule counterparts. This is the result of the secondary objective of the simulated annealing algorithm, which is to minimise the changeover time. The model clusters orders with similar product families, if the due date objective allows it, to reduce the changeover time and results in a more practically applicable solution. On the contrary, SBH-DR-OPF and SBH-DR-normal schedule operations based on their due date. Therefore, the result is a poor performance on total changeover time because the sheathing processes require a substantial larger changeover time to process all operations. Besides the higher required changeover times, the SBH-DR schedules will not be accepted because of the impractical consequences.

The total changeover time is not the only factor influencing the efficiency of the schedule. The total idle time provides an indication of the time the machine is available for processing, but not utilised. We decide to exclude the idle time analysis from this research because some machines are designed to have overcapacity. Besides the overcapacity of machines, TKF does not have the workforce to operate all machines simultaneously. On average, Installation has manpower to operate 10 machines simultaneously, while 15 operators are required to operate all machines. The results of our research show that the bottleneck machines have low idle time, while other machines are not utilised at all. Appendix H provides an analysis of production schedules of the bottleneck machines resulting from the shifting bottleneck heuristic. As said, the selected bottleneck highly depends on the diversity of production orders.

Besides being a *reliable* supplier, TKF wants to differentiate from its customers by offering customers a *short lead time* on production orders. SBH-DR-OPF and SBH-SA-OPF divides large production orders in to several small production orders, reducing the maximum production time per production order from 142 hours to 24 hours. The implementation of one piece flow reduces the average lead time with 11% with respect to their normal counterpart.

To answer the research question as stated at the beginning of this section, we conclude that the SA-OPF approach suits best to the situation at TKF due to its excellent performance on service level, changeover time, and lead time. Furthermore, the running time to solve the JSSP is significantly smaller compared to the SBH-SA alternatives. The SA-OPF provides solutions within one hour, while SBH-SA-OPF runs over 4 hours. The latter is not desirable for TKF.

6 Conclusions and recommendations

In Section 1.2, we formulated four research questions to which the answers result in the solution to the research objectives. Each of the previous chapter provided an answer to one of the research questions. In Chapter 2, we performed a literature study to identify possible solution methodologies and approaches. In Chapter 3, we analysed the current production and production planning situation to identify restrictions and limitations. In Chapter 4, we designed the solution approaches whereby we formulated the objective functions, model structures, and practical extensions. Finally, in Chapter 5, we analysed the performance of the solution approaches.

This chapter provides the answer to the main research question. We start, in Section 6.1, with the conclusions of this research. Next, we discuss the recommendations to TKF in Section 6.2, and finally, Section 6.3 discusses the limitations of this research and proposes suggestions for further research.

6.1 Conclusions

The main problem, as stated at the start of this report, was an unstructured, non-standardised scheduling process that highly depends on the intuition and experience of the production planner. The lack of a scheduling process results in an underperforming production department in terms of throughput, lead times, and on-time delivery. To differentiate from competitors, TKF decided to focus more on custom and innovative solutions rather than bulk production. Therefore, the product mix is changing from high volume & low variety to low volume & high variety, making the scheduling process more complex. Besides offering unique cables, TKF puts the emphasis on short delivery times and therefore a short product lead time is a prerequisite. When offering short delivery times, it is critical to meet the agreed delivery date to be seen as a reliable supplier. Because the current scheduling approach is merely a manual and intuitive approach, which schedules production orders for the upcoming 24 production hours, it is difficult, if not impossible, for the production planner to take long term consequences into account. A schedule for a day may look ideal, but may result in inefficiencies or problems in the long run. Furthermore, the short scheduling horizon forces the production planner to solve problems ad-hoc and disables the ability to cluster production orders with similar characteristics to reduce changeover times. Due to the aforementioned reasons, TKF currently does not meet the desired service level. Therefore, we formulated the following main research question:

"How can TKF improve its production scheduling approach such that it results in an increase of service level and throughput and a decrease of product lead times at the Installation production department?".

In Chapter 2 we characterised the production environment at TKF as a job shop environment. Furthermore, we concluded that the scheduling activities are on the offline and online operational level. This implicates that the scheduling horizon of the solution approaches is at most several weeks. The offline and online operational level encompasses actual scheduling activities. Based on the production environment characterisation and hierarchical level of the problem we performed a literature study to identify the best solution approaches. After the literature study, we concluded that several algorithms and heuristics were suitable, after some adjustments, to be adapted at TKF.

In Chapter 3, we analysed the current production and production scheduling processes to gather the information required to design solution approaches. The analysis resulted in information we implemented in the solution approaches, such as machine capabilities, product families, changeover times, and reel capacity. The analysis also taught us that the sizes of the production orders result in complications. The large sizes result in blocking of machines, reducing the flexibility of the production environment. For example, when a rush or rework order requires immediate processing, it has to wait for the current production order to finish. Due to the large size of the production order, the time until the machine is available can be substantial and has an adverse effect on the product flow, lead time, and possibly the service level towards the customer. Therefore, we decided to implement one piece flow scheduling in the solution models. One piece flow means that each production order consists of a maximum of one reel after stranding (the bottleneck machine regarding reel sizes). Furthermore, the processing time on the most time consuming machine (braiding) needs to around 24 hours. The theoretical advantages of one piece flow are an increase in flexibility, reduction of the work in progress, higher service level, and the remaining of the seven lean wastes. We refer to Section 2.4.2 for more information on this subject.

This research defines three solution approaches in Chapter 4:

1) *Shifting bottleneck heuristic that uses the Extended Jackson rule for single and parallel machine scheduling*
2) *Shifting bottleneck heuristic that uses the simulated annealing algorithm for single and parallel machine scheduling*
3) *Simulated annealing algorithm that uses the Extended Jackson rule to formulate the initial solution*

As the names of alternative one and two suggest, these solution approaches focus on the bottleneck machines of the scheduling problem, where the machine that results in the highest lateness per operation is considered bottleneck. All three approaches use product families to calculate the changeover time required between two consecutive production orders. The changeover time required between two product families is based on actual OEE data and estimates from operators at TKF. Furthermore, we decide to exclude the insulation processes from the scheduling approaches due to the high changeover costs between products and the overcapacity compared to the subsequent processes.

Chapter 5 discussed the performance of the proposed scheduling approaches. For the performance indicators ‘’service level’’ and “total changeover time’’ we conclude that ***‘’Simulated annealing with one piece flow’’*** outperforms the other approaches in both the good performing and poor performing experiments. The number of backorders increases after the implementation of one piece flow manufacturing. The service level however, improves as long as the growth of the number of backorders is less than the growth of the number of production orders. The implementation of one piece flow results in a higher service level compared to the current approach. However, the total changeover time required to achieve this improvement increases with 6%. Finally, we conclude that the lead time of products can be reduced with 7% if TKF changes to one piece flow manufacturing.

6.2 Recommendations

To achieve a structured and standardised production scheduling approach TKF needs to change their production approach. Producing according to the one piece flow principle will greatly increase the service level towards customers, improve the flexibility of the production environment, and reduce product lead times and all kinds of waste. Once the production methodology is adapted, we recommend using the simulated annealing algorithm with the one piece flow manufacturing approach because it generates good solutions as shown in Chapter 5.

To implement one piece flow scheduling, we recommend decoupling the insulation processes from the scheduling problem otherwise the efficiency will be unacceptable. We recommend to schedule the insulation processes with a Kanban strategy, or similar, to enable efficient production. The insulation of all conductors on Kanban is not feasible (due to high storage costs and space restrictions), but the most frequently used conductors in any case. From the Kanban, conductors can be used for stranding whenever they are required. The most important criterion to have success with one piece flow scheduling is reliability. One piece flow is only beneficial once the production environment is able to produce high quality products, i.e. with a low number of defects. Therefore we advise TKF to (keep focussing) focus on quality and process issues.

Third, we recommend TKF investigating in reducing the changeover times at the stranding and sheathing processes, because one piece flow manufacturing results in a significant increase in changeovers. After analysing the production orders we used to create the data sets for performance evaluation, we noticed that the buffer classes of production orders are not always representative for the number of processes. We recommend TKF to re-assess the buffer classes such that the recommended model, as well as NaVision, provides correct information.

Simulated annealing with one piece flow uses production data of two weeks. As said in Chapter 1, a short scheduling horizon is not desirable. Currently, a reliable and accurate forecast for the upcoming two weeks is lacking. We recommend organising a process that enables the sales department to provide a reliable and accurate forecast to the production planner such that the production planner can utilise the tool provided by this research.

Last, we recommend TKF to incorporate changeovers in the ERP system. This enables the production planner to see the implications of a certain schedule. Furthermore, the manual input for the tool is reduced significantly. We advise to define and allocate product families to production orders or products. Product families do not give a 100% accurate description of the product characteristics but they result in a good approximation of the actual changeovers required.

6.3 Limitations and further research

The first limitation of the solution approaches is the input they require, such as production speeds, quantities, and delivery dates. The input does not incorporate all uncertainties of the production environment such as significant machine breakdowns, rework needed on certain processes, or defect products. For the latter, the production planner creates a new production order. Rework orders are processed on the first available and suitable machine to keep the flow intact. Furthermore, we limited the model design to the most common production orders and product flows due to complexity reason, so it is possible that some extraordinary production orders are excluded. Regarding products that require processing at another department, we reserve two production days per processing step. Experience has shown did not always prove to be sufficient. This parameter requires updating when the latter is the case. Furthermore, the definition of the ‘’one piece’’ used for one piece manufacturing is subject for discussion. Future will show whether the current definition is acceptable or that the definition has to be revised.

Considering future research, the design of producing insulated cores on Kanban, or a similar system that decouples insulation from the scheduling problem, needs to be investigated. Furthermore, one piece flow scheduling results in an increase of changeovers at the several processes, so improvements to this matter will have a significant impact. To benefit the most of one piece flow scheduling, we need to identify optimal lot sizes for inventory products as well. We also noticed that the processing times (which are used as input for this model), changeover times and buffer classes do not always comply with the actual (practical) situation. For the accuracy of this model, or any scheduling approach, it is important to have the correct parameters and variables. As mentioned when discussing the recommendations, a forecast for the near future helps improving the service level because the scheduling horizon can be expanded.

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Appendices

This section provides the appendices of this research. The subjects in the appendices are found not relevant enough to insert in the main text or merely serve an informative purpose.

Appendix A: Example shifting bottleneck heuristic

To exemplify the working of the shifting bottleneck heuristic, we provide a simple example. Table A.1 shows the jobs, the machines it needs to be processed on and their corresponding processing times.

Jobs	Machine	Processing times
1	1,2,3	$p_{11} = 10$, $p_{21} = 8$, $p_{31} = 4$
2	2,1,4,3	$p_{22} = 8$, $p_{12} = 3$, $p_{42} = 5$, $p_{32} = 6$
3	1,2,4	$p_{13} = 4$, $p_{23} = 7$, $p_{43} = 3$

Table A.1: Job characteristics

The shifting bottleneck heuristic starts with the disjunctive graph representation, as is depicted in Figure A.1. Based on the disjunctive graph, the release and due dates of operations are determined. Each node depicts one of the operations from table A.1. The times on the arcs denote the processing time of the operation.

Iteration 1

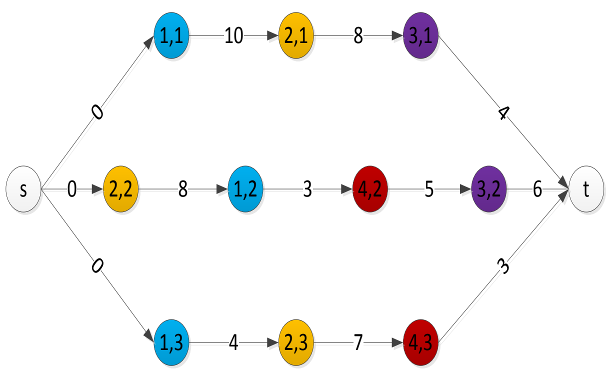

Figure A.1: Disjunctive graph belonging to the example

Machine 1

Job	1	2	3
r1j	0	8	0
p1j	10	3	4
d1j	10	11	12
	Optimal schedule	**1,2,3**	**L_{max} (1) = 5**

Table A.2: Scheduling machine 1

Based on the disjunctive graph, we calculate the release and due date. Table A.2 shows the data for machine 1 required to create a schedule. Based on the data we determine that sequence 1→2→3 provides the best schedule, with a lateness of 5. The same exercise is repeated for machines 2 to 4. Machine 1 yields the highest lateness and is labelled bottleneck (1).

After determining the first bottleneck machine, the disjunctive graph is updated with the schedule of the selected bottleneck machine. As Figure A.2 shows, the arcs belonging to the schedule of iteration one are included in the disjunctive graph. These arcs influence the release and due dates of the other operations.

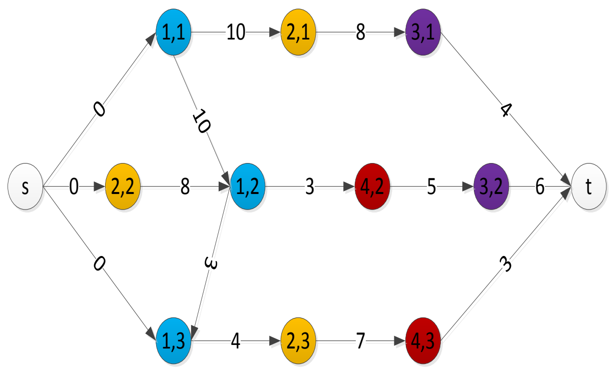

Figure A.2: Disjunctive graph after bottleneck selection

Iteration 2

Based on the updated disjunctive graph, we repeat the scheduling step as in iteration 1. We calculate the release and due dates of operations and aim to schedule these to optimality.

Machine 2

Job	1	2	3
r_{2j}	10	0	17
p_{2j}	8	8	7
d_{2j}	23	10	14
	Optimal schedule	2,1,3	L_{max} (2) = 1

Table A.3: Scheduling machine 2

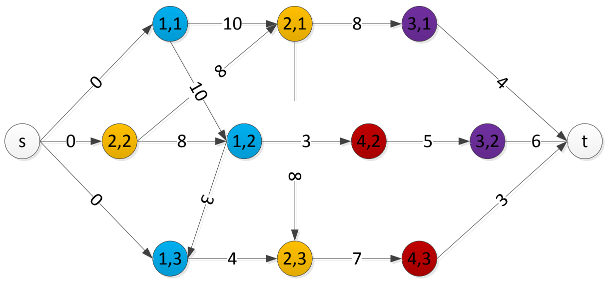

Figure A.3 Graph after iteration 2

After scheduling machine 2 to 4, machine 2 yields the highest maximum lateness and is now considered bottleneck (2). Therefore we fix the schedule that resulted in the minimum maximum lateness; 2→1→3 with a maximum lateness of 1. After updating the disjunctive graph we get Figure A.3.

Reoptimisation

At the reoptimisation stage the heuristic aims to reschedule the previous bottleneck machines. In this example we start with reoptimising machine 1. First we remove the arcs belonging to the sequence of machine one (graph A.4), after which we perform the scheduling exercise of machine 1.

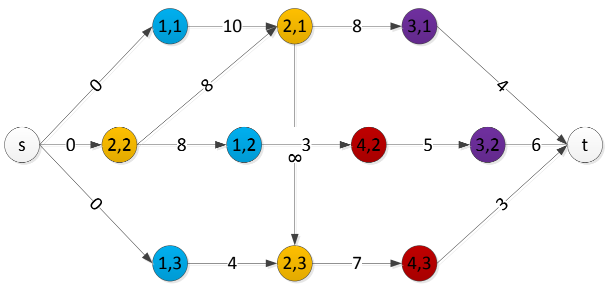

Figure A.4: Reoptimsation iteration 2

Machine 1

Job	1	2	3
r_{1j}	0	8	0
p_{1j}	10	3	4
d_{1j}	10	14	14
	Optimal schedule	1,2,3	L_{max} (1) = 3

Table A.4: Reoptimsation machine 1

Final schedule

Repeating the scheduling and reoptimisation steps ultimately result in the schedule depicted in Figure A.5. In the third iteration we select machine 3 as the bottleneck. Reoptimising machine 1 and 2 does not yield a different result. Finally machine 4 is selected bottleneck. Reoptimising machine 1 to 3 does not yield a different result. Figure A.5 depicts the optimal production schedule for the example scheduling problem.

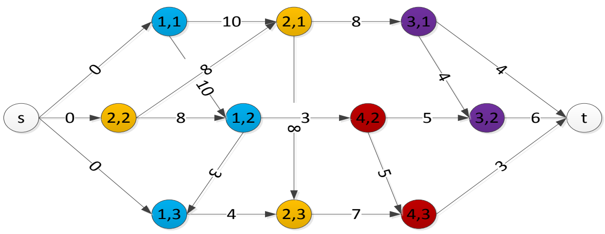

Figure A.5: Final schedule example shifting bottleneck heuristic

Appendix B: Single machine scheduling algorithm

As said in Chapter 2, to include single machine scheduling in to a model, it needs an algorithm. Algorithm 2 shows how the model solves the single machine scheduling problems. First it sorts all operations in descending order based on their due date. Next, the model finds the first available operation to schedule on this machine, and assigns this operation to this machine after which the steps are repeated until all operations are assigned

Algorithm 2: Single machine scheduling

Step 1: Sort operations in descending order based on their due date
Do for all operations
  If $d_j < d_{j+1}$ *then*
    $d_j = d_j$
    $d_{j+1} = d_{j+1}$
  Else
    $d_j = temp$
    $d_j = d_{j+1}$
    $d_{j+1} = temp$
  End if
Step 2: find first available job:
Do for all operations
  If $r_j \leq$ *machine availability*
    Schedule operation O_{ij}
  Else if r_j *is minimum of all* r_j
    Schedule operation O_{ij}
  Else
    Go to next operation
  End if
  Stop

Appendix C: Parallel machine scheduling algorithm

As said in Chapter 2, to include parallel machine scheduling in to a model, it needs an algorithm. Algorithm 3 shows how the model solves the parallel machine scheduling problems. First it sorts all operations in descending order based on their due date. Next, the algorithm selects the first available machine to schedule the operation on. After a machine is selected, the model finds the first available operation with the lowest due date and assigns this operation to the selected machine after which the steps are repeated until all operations are assigned to a machine.

Algorithm 3: Parallel machine scheduling

Step 1: Sort operations in descending order based on their due date
Do for all operations
    If $d_j < d_{j+1}$ *then*
        $d_j = d_j$
        $d_{j+1} = d_{j+1}$
    Else
        $d_j = temp$
        $d_j = d_{j+1}$
        $d_{j+1} = temp$
    End if
Step 2: find first available machine:
Do for all machines
Selected machine = machine (1)
    If machine availability (i) ≤ machine availability (i+1)
        Selected machine = machine (1)
    Else
        Selected machine = machine (2)
    Else
        Go to next machine
    End if
Step 3: find first available job:
Do for all operations
    If $r_j \leq$ *machine availability*
        Schedule operation O_{ij}
    Else if r_j *is minimum of all* r_j
        Schedule operation O_{ij}
    Else
        Go to next operation
    End if
    Stop

Appendix D: Changeover time calculation

As said in Chapter 2, to include sequence dependent changeover times in to a model, it needs an algorithm. Algorithm 4 shows how the model calculates sequent dependent changeover time. As mentioned in Chapter 4, the models use product families to calculate the changeover required between two subsequent operations. Table D.1 shows an example of a changeover matrix, in this case the changeover matrix of EI MANTELLIJN 5, that is used to determine the changeover time between two families. Algorithm 4 determines the product families of operations O_{ij} and O_{ij-1} and finds the changeover time in the changeover matrix.

Algorithm 4: Changeover time calculation

If operation i is the first operation to be scheduled then
Changeover time = 0
Else If product family of operation i = product family of operation i – 1 then
Changeover time = $s_{family,family}$
Else if product family of operation i ≠product family of operation i – 1 then
Changeover time = $s_{family,family}$
End if

EI MANTELLIJN 5	Type A	Type B	Type C	Type D	Type E	Type F	Type G	Type H	Type I	Type J	Type K	Type L	
Type A	0,5	1	1	0,5	1	1	3,5	3,5	3,5	3,5	3,5	3,5	Type A = MBZH mantelen kleur GRIJS
Type B	1	0,5	1	1	0,5	1	3,5	3,5	3,5	3,5	3,5	3,5	Type B = MBZH mantelen kleur ZWART
Type C	1	1	0,5	1	1	0,5	3,5	3,5	3,5	3,5	3,5	3,5	Type C = MBZH mantelen kleur ORANJE
Type D	0,5	1	1	0,5	1	1	3,5	3,5	3,5	3,5	3,5	3,5	Type D = MBZH vullen/mantelen kleur GRIJS
Type E	1	0,5	1	1	0,5	1	3,5	3,5	3,5	3,5	3,5	3,5	Type E = MBZH vullen/mantelen kleur ZWART
Type F	1	1	0,5	1	1	0,5	3,5	3,5	3,5	3,5	3,5	3,5	Type F = MBZH vullen/mantelen kleur ORANJE
Type G	3,5	3,5	3,5	3,5	3,5	3,5	0,5	1	1	0,5	1	1	Type G = PVC mantelen kleur GRIJS
Type H	3,5	3,5	3,5	3,5	3,5	3,5	1	0,5	1	1	0,5	1	Type H = PVC mantelen kleur ZWART
Type I	3,5	3,5	3,5	3,5	3,5	3,5	1	1	0,5	1	1	0,5	Type I = PVC mantelen kleur ORANJE
Type J	3,5	3,5	3,5	3,5	3,5	3,5	0,5	1	1	0,5	1	1	Type J = PVC vullen/mantelen kleur GRIJS
Type K	3,5	3,5	3,5	3,5	3,5	3,5	1	0,5	1	1	0,5	1	Type K = PVC vullen/mantelen kleur ZWART
Type L	3,5	3,5	3,5	3,5	3,5	3,5	1	1	0,5	1	1	0,5	Type L = PVC vullen/mantelen kleur ORANJE

Figure D.1: Changeover matrix of Mantellijn 5

Appendix E: Parameter settings SA

Simulated annealing contains several parameters that require initialisation. The settings of these parameters determine the quality of the solution and the computational time of the model. With several tests and experiments we define the settings of the parameters

The first parameter we initialise is the start temperature. Ideally, the start temperature has to be large enough to result in an acceptance probability of nearly 1. By performing several experiments we determined the maximum deterioration of the objective function. With the maximum deterioration we calculate the acceptance ratio. The formula we used to construct Figure E.1 is:

$$P(c) = e^{\frac{\text{Max deterioration}}{c_{\text{start}}}} \tag{E.1}$$

The start temperature, combined with the decreasing factor and the termination temperature, determine the running time of the model. To be able to deliver a model that practically delivers a schedule within a reasonable time; we select a start temperature of 575 which corresponds with an acceptance ratio of 85.5%.

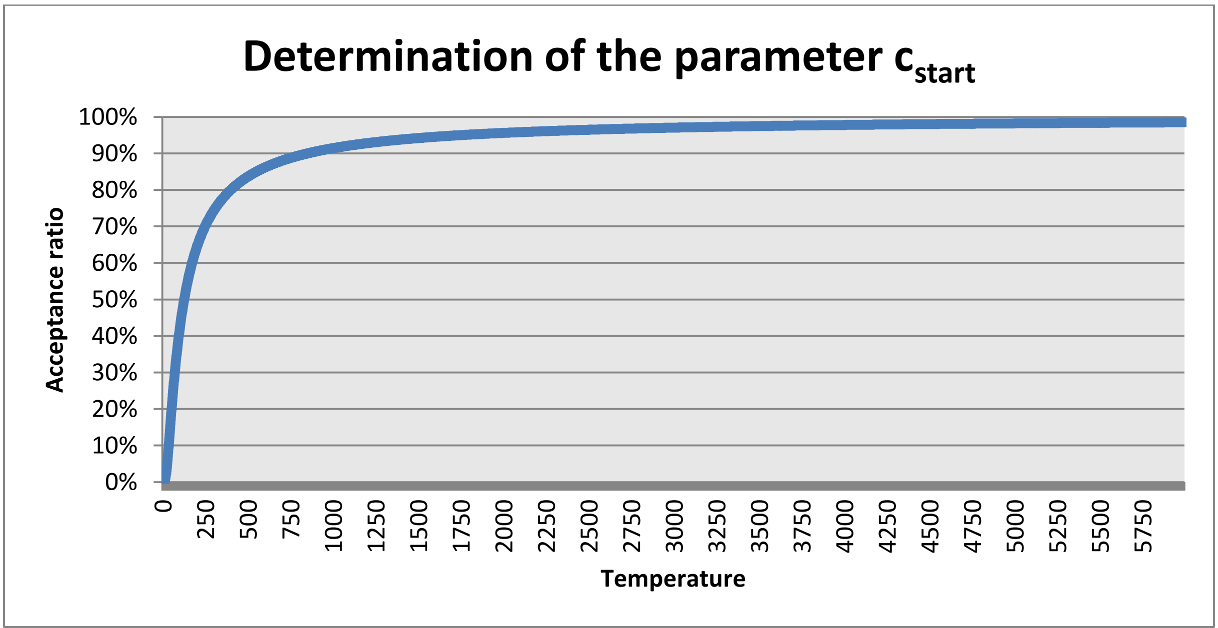

Figure E.1: Acceptance ratio Simulated Annealing

To determine the stop temperature we repeat the acceptance ratio calculation, but with a small deterioration because we want the model to reject deteriorations when the algorithm reaches its end. We select a termination temperature of 0.25 because this results in an acceptance ratio of less than 1% in case of a deterioration of 1 on the objective value. The decreasing factor determines how quick the temperature decreases. For this research we select a decreasing factor of 0.975 and is the best result of several tests with various values.

Appendix F: Example production schedule

Below we attached the production schedule for one of the braiding machines, the ''EI VLECHTER 24-6''. We choose to show this production schedule, because it is the result of one of the two parallel machine scheduling problems. The group ''EI VLECHTER 24-6'' contains 3 separate machines. The schedule below shows the sequence of the production orders on each of the machines. This schedule is the outcome of the SBH-SA-normal approach. Several operations finish after their due date, while others are processed first even if their due date is higher and is the result of simulated annealing for the parallel machine scheduling.

	EI VLECHTER 24-6	Omschrijving 1	Omschrijving 2	Lengte	Start time	Processing Time	Completion Time	Due Date	Setup Tijden
I VLECHTER 24-6-1	306683-1	SW VO-YMeKas EMC	4 x 2,5 mm2	3050	54	44	99	163	0
EI VLECHTER 24-6-2	306583-1	SW VO-YMeKas EMC	2 x 2,5 mm2	13100	42	199	241	375	0,5
EI VLECHTER 24-6-3	306685-1	SW VO-YMeKas EMC	4 x 6 mm2	5000	62	62	125	253	0,5
EI VLECHTER 24-6-1	306606-1	SW VO-YMeKas EMC	2 x 1,5 mm2	12000	99	178	277	349	0,5
EI VLECHTER 24-6-3	306688-1	SW VO-YMeKas EMC	7 x 1,5 mm2	3500	125	47	172	250	0,5
EI VLECHTER 24-6-3	306681-1	SW VO-YMeKas EMC	2 x 6 mm2	3000	173	42	215	391	0,5
EI VLECHTER 24-6-3	306672-1	SW VO-YMeKas EMC	2 x 1,5 mm2	3100	216	46	262	247	0,5
EI VLECHTER 24-6-2	306605-1	SW VO-YMeKas EMC	4 x 1,5 mm2	12000	242	184	426	401	0,5
EI VLECHTER 24-6-3	306684-1	SW VO-YMeKas EMC	4 x 2,5 mm2	3000	262	44	306	325	0,5
EI VLECHTER 24-6-1	306689-1	SW VO-YMeKas EMC	7 x 1,5 mm2	3500	278	47	325	302	0,5
EI VLECHTER 24-6-3	306690-1	SW VO-YMeKas EMC	7 x 1,5 mm2	1500	306	20	327	400	0,5
EI VLECHTER 24-6-1	306607-1	SW VO-YMeKas EMC	2 x 1,5 mm2	12000	325	178	503	465	0,5
EI VLECHTER 24-6-3	306603-1	SW VO-YMeKas EMC	4 x 1,5 mm2	12000	327	184	511	473	0,5
EI VLECHTER 24-6-2	306686-1	SW VO-YMeKas EMC	4 x 6 mm2	5000	426	62	489	460	0,5
EI VLECHTER 24-6-2	306473-1	SW VO-YMeKas EMC	4 x 6 mm2	10000	489	125	614	640	0,5

FigureF.1: Example production schedule of the parallel scheduling problem of EI VLECHTER 24-6

Appendix G: Idle times

As said in Chapter 4, the idle time is the cumulative difference between the completion time of operation O_{ij} and the start time of operation $O_{i,j+1}$. The shifting bottleneck heuristic aims to identify and optimise the bottleneck machine, i.e. the machine that yields the highest maximum lateness. The expectation is that the first machine labelled bottleneck machine is the most critical machine in the process. We assessed the production schedules of weeks 5-6 with the SBH-SA-OPF approach. The SBH-SA-OPF labelled the EI VLECHTER 24-6 as the most critical machine. As expected, the idle time of this machine is limited, in this case 0. EI MANTELLIJN 6 has an idle time of 102 hours. Analysing the production schedule of this machine and we find that on three occasions that last over 24 hours, this process is waiting on EI VLECHTER 24-6 to complete its operation. This is a great example of the shifting bottleneck heuristic; the schedule of the most important machine is fixed, after which the rest is scheduled. In other words, the schedule of the most important machine determines the schedule on the other machines.

Bottleneck machine	Machine name	Idle time (h)
1	EI VLECHTER 24-6	0
2	EI MANTELLIJN 6	102
3	EI ARMEERLIJN 1	0
4	EI DRUMTWISTER 3	292
5	EI SAMENSLAGLIJN 3	99
6	EI MANTELLIJN 5	186
7	EI VLECHTER 36-1	121
8	EI MANTELLIJN 4	411
9	EI VLECHTER 24-4	270

Table G.1: Performance on idle time

Appendix H: Changeover times - One piece flow vs current approach

To exemplify the impact of one piece flow we provide the production schedule of EI MANTELLIJN 5. We compare the one piece flow performance with the currently used approach. The tables show that the difference in changeover time is limited. As the tables show, the one piece flow approach divides production orders in to smaller sub-orders. It occurs that one sub-order is processed multiple days before another sub-order because it is beneficial for the outcome of scheduling problem. It is possible an extra changeover is required to realise this. On general this occurs for production orders that require braiding to level the workload at this process (green shaded).

One Piece Flow

EI MANTELLIJN 5	Artikelnummer	Omschrijving 1	Omschrijving 2	Start time	Processing Time	Completion Time	Setup Tijden
308581-1	28526	BMqK 0,6/0,6 kV BLAUW	1 X 2,5 CuSnrss	168,0	0,6	168,6	0,0
311261-1	8990	Z1G-YMz1Kasmbzh 0,6/1 kV	4 X 10 rs + as10	291,7	2,9	294,5	1,0
310701-1	8621	XLET-HF 0,6/1 kV	4 x 6 mm2	295,0	4,8	299,8	0,5
310316-1	11848	XLPE/SWA/HFFR 0,6/1 kV	2 x 2,5 rm	300,3	0,5	300,8	0,5
311579-1	25222	XLET-HF [moederkabel]	5 G 1,5 rm	367,3	10,0	377,3	1,0
311579-2	25222	XLET-HF [moederkabel]	5 G 1,5 rm	386,2	3,8	390,0	0,5
310776-1	40222	DK-AXQ-AL-M 0,6/1kV	4 x 16 Alrm	391,0	3,5	394,5	1,0
311304-1	103318	Instalflex mbzh 0,6/1 kV	5 G 16 rss	395,5	0,6	396,1	1,0
310491-1	28479	YMz1Kmbzh 0,6/1 kV	1 X 25 rs	397,1	0,7	397,8	1,0
311063-2	16021	MarineLine YZp 0,6/1 kV	3 x 4 mm2	446,5	2,6	449,0	1,0
311216-1	16026	MarineLine YZp 0,6/1 kV	4 x 6 mm2	491,4	6,0	497,4	1,0
311063-3	16021	MarineLine YZp 0,6/1 kV	3 x 4 mm2	498,4	0,8	499,2	1,0
311063-1	16021	MarineLine YZp 0,6/1 kV	3 x 4 mm2	499,7	2,6	502,3	0,5
311712-1	8986	YMz1Kmbzh 0,6/1 kV	5 G 6 rm	502,8	4,0	506,7	0,5
310475-4	26101	MarineLine YOZp FR 0,6/1 kV	2 x 1,5 mm2	543,0	1,5	544,5	0,5
310475-1	26101	MarineLine YOZp FR 0,6/1 kV	2 x 1,5 mm2	547,2	1,5	548,7	0,5
310475-2	26101	MarineLine YOZp FR 0,6/1 kV	2 x 1,5 mm2	549,2	1,5	550,7	0,5
310914-1	27180	MarineLine YOZp X-FR 0,6/1 kV	3 G 1,5 mm2	551,7	1,9	553,6	1,0
311580-1	25222	XLET-HF [moederkabel]	5 G 1,5 rm	554,6	10,0	564,6	1,0

311580-2	25222	XLET-HF [moederkabel]	5 G 1,5 rm	565,1	3,8	568,9	0,5
310475-6	26101	MarineLine YOZp FR 0,6/1 kV	2 x 1,5 mm2	569,9	0,1	570,0	1,0
311747-1	8621	XLET-HF 0,6/1 kV	4 x 6 mm2	606,5	4,8	611,3	0,5
310475-5	26101	MarineLine YOZp FR 0,6/1 kV	2 x 1,5 mm2	611,8	1,5	613,3	0,5
310475-3	26101	MarineLine YOZp FR 0,6/1 kV	2 x 1,5 mm2	613,8	1,5	615,3	0,5
312062-2	16033	MarineLine YZp 0,6/1 kV	3 x 16 mm2	688,9	4,0	692,8	1,0
312062-1	16033	MarineLine YZp 0,6/1 kV	3 x 16 mm2	693,3	4,0	697,3	0,5
						Total	**18,5**

Table H.1: Changeover times achieved by SBH-SA-OPF in weeks 5-6

Current approach

EI MANTELLIJN 5	Artikelnummer	Omschrijving 1	Omschrijving 2	Start datum	Processing Time	Completion Time	Setup Tijden
310701-1	8621	XLET-HF 0,6/1 kV	4 x 6 mm2	246,5	4,8	251,3	0,0
308581-1	28526	BMqK 0,6/0,6 kV BLAUW	1 X 2,5 CuSnrss	252,3	0,6	253,0	1,0
311304-1	103318	Instalflex mbzh 0,6/1 kV	5 G 16 rss	265,9	0,6	266,5	1,0
311579-1	25222	XLET-HF [moederkabel]	5 G 1,5 rm	351,4	13,8	365,1	2,0
311261-1	8990	Z1G-YMz1Kasmbzh 0,6/1 kV	4 X 10 rs + as10	366,1	2,9	369,0	1,0
310776-1	40222	DK-AXQ-AL-M 0,6/1kV	4 x 16 Alrm	378,7	3,5	382,2	0,5
310316-1	11848	XLPE/SWA/HFFR 0,6/1 kV	2 x 2,5 rm	382,7	0,5	383,1	0,5
310491-1	28479	YMz1Kmbzh 0,6/1 kV	1 X 25 rs	383,6	0,7	384,3	0,5
310914-1	27180	MarineLine YOZp X-FR 0,6/1 kV	3 G 1,5 mm2	407,0	1,9	408,9	0,5
311712-1	8986	YMz1Kmbzh 0,6/1 kV	5 G 6 rm	462,1	4,0	466,0	1,0
311063-1	16021	MarineLine YZp 0,6/1 kV	3 x 4 mm2	466,5	6,0	472,5	1,5
311216-1	16026	MarineLine YZp 0,6/1 kV	4 x 6 mm2	491,4	6,0	497,4	1,0
311580-1	25222	XLET-HF [moederkabel]	5 G 1,5 rm	556,4	13,8	570,1	1,0
310475-1	26101	MarineLine YOZp FR 0,6/1 kV	2 x 1,5 mm2	605,9	8,2	614,1	3,0
311747-1	8621	XLET-HF 0,6/1 kV	4 x 6 mm2	621,1	4,8	625,9	0,5
312062-1	16033	MarineLine YZp 0,6/1 kV	3 x 16 mm2	688,4	7,9	696,3	2,0
						Total	**17,0**

Table H.2: Changeover times achieved by SBH-SA-NORMAL in weeks 5-6

Appendix I: Main modules used in the tools

Appendix I shows the main module of the scheduling tool called ''Shifting Bottleneck Heuristic'' and the bottleneck improvement module. The module ''Shifting Bottleneck Heuristic'' is the heart of the scheduling tool and calls all necessary sub-modules. The main module uses the structure of the shifting bottleneck heuristic as explained in Chapter 2 and Appendix A. Module ''BottleneckRescheduling'' is used as rescheduling procedure. The most important practical modification concerns the sheathing processes. As processes, applying the inner sheath and outer sheath are two separate processes but are processed on the same sheathing machine.

```
'Main module
Sub Shifting Bottleneck Heuristic()
'  Alle sheets schoonmaken voor nieuwe schedule
Call Module4.Clearsheets
'Define machines
Machine (1) = "EI DRUMTWISTER 3"
Machine (2) = "EI SAMENSLAGLIJN 3"
Machine (3) = "EI MANTELLIJN 4"
Machine (4) = "EI MANTELLIJN 5"
Machine (5) = "EI MANTELLIJN 6"
Machine (6) = "EI ARMEERLIJN 1"
Machine (7) = "EI VLECHTER 24-4"
Machine (8) = "EI VLECHTER 24-6"
Machine (9) = "EI VLECHTER 36-1"
Machine (10) = "EI VLECHTER 36-2"
Machine (11) = "EI MANTELLIJN 4"
Machine (12) = "EI MANTELLIJN 5"
Machine (13) = "EI MANTELLIJN 6"
'  Data van alle productieorders en overige parameters inlezen
Call Module1.Initialisation
'  Itereren totdat alle machines bottleneck gelabeled zijn
For i = 1 To 10
'  Release en due dates berekenen
        Call Module1.DisjunctiveGraph
'  Op deze sheet de heuristiek printen
        sheet = i & "e bottleneck bepaling"
'  Schedulen van de machines en bottleneck bepaling
        Call Module1.Scheduling(sheet, i)
'  Reschedulen van de bottleneck machines die voor iteratie i bepaald zijn
        Call Module3.BottleneckImprovement(i)
'  Volgende iteratie
Next i
'  Productieprogramma printen en KPIs berekenen
Call Createfinalschedule
End Sub
```

```
' Reschedule module voor vorige bottleneck machines
Sub BottleneckRescheduling(ByVal iteratie As Integer)
' Voor alle iteraties de bottleneck reschedulen. Beginnen bij de eerst gekozen bottleneck
For i = 1 To iteratie - 1
' P bepaalt de plek op de sheet waar de data weergegeven wordt
P = PasteSpot(Bottlenecknumber(i))
' Bijbehorende bottleneck zoeken
number1 = Bottlenecknumber(i)
number2 = 0
' Als de bottleneckmachine binnenmantelen of buitenmantelen is,
' is automatisch de tegenpool ook bottleneck
If Bottlenecknumber(i) > 2 And Bottlenecknumber(i) < 6 Then
        number2 = Bottlenecknumber(i) + 8
ElseIf Bottlenecknumber(i) > 10 Then
        number2 = Bottlenecknumber(i) - 8
End If
' Het vastzetten van de bottleneck schedule in de disjunctive graph uitzetten
BottleneckMachine(number1) = False
BottleneckMachine(number2) = False
' Calculate release en due dates
Call Module1.DisjunctiveGraph
' Bottleneck machine optimaliseren
Call Module1.BottleneckScheduling(Bottlenecknumber(i), P, iteratie)
' Het vastzetten van de bottleneck schedule in de disjunctive graph aanzetten
BottleneckMachine(number1) = True
BottleneckMachine(number2) = True
' Naar volgende bottleneck gaan
Next i
End Sub
```