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Optimization of Production Scheduling at IKEA Industry Hultsfred

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Optimization of Production Scheduling at IKEA Industry Hultsfred

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Optimization of Production Scheduling at IKEA Industry Hultsfred

Mattias Anemyr

June 2020

Sammanfattning

En av IKEA Industries fabriker ligger i Hultsfred, Småland. IKEA Industry Hultsfred tillverkar IKEA:s garderobssortiment PAX. Under 2018 producerade fabriken i Hultsfred över 2.8 miljoner garderober som förser IKEA:s varuhus i norra och östra Europa, samt Nederländerna med garderober. IKEA Industry Hultsfred producerar samtliga delar till garderoben förutom baksidan. En av komponenterna på garderoben är socklarna (eng. Plinths). Denna komponent produceras på en egen produktionslina i fabriken.

En fabrik i Portugal och en fabrik i Tyskland, som också producerar garderober till IKEA har blivit intresserade av att börja köpa socklar av IKEA Industry Hultsfred. Detta innebär att fabriken i Hultsfred måste öka sina produktionsvolymen för att förse fabrikerna i Portugal och Tyskland med socklar.

Detta arbete omfattar att konstruera och utveckla en optimeringsmodell som har samma egenskaper som sockelproduktionen på IKEA Industry Hultsfred. Detta innebär exempelvis att optimeringsmodellen behöver ta hänsyn till produktionssekvensen, ställtiden beror på vilken produkt som tillverkats i maskinen innan. Arbetet omfattar också att utvärdera hur mycket tid (i form av skift) som behövs för att hinna tillverka socklarna till sig själva, Portugal och Tyskland, under olika omständigheter.

Avslutningsvis omfattar arbetet även att väga ställtider mot lagernivåer. Det vill säga, hur lagernivåerna förändras om optimeringsmodellen fokuserar på att minimera ställtiden, och vise versa. Resultatet visar att lägre lagernivåer och ställtider kan uppnås över en sjudagarsperiod genom att förändra produktionsplaneringen jämfört med hur produktionsplaneringen den ser ut idag. Resultatet visar även att två skift per dag under 16 dagar är tillräckligt för att möta den uppskattade efterfrågan från Hultsfred, Portugal och Tyskland, denna lösning visar att medellagernivåerna i slutet av varje dag varierar mellan 338 och 329 pallar, och ställtiden varierar mellan 184 och 262 minuter, beroende på om ställtiden eller lagernivåerna prioriteras. Vid ett scenario där den uppskattade efterfrågan ökar med 15% visar resultatet att det behövs två skift under 12 dagar, och 3 skift under 4 dagar för att möta efterfrågan. I denna lösning varierar de genomsnittliga lagernivåerna vid slutet av varje dag mellan 350 och 320 pallar, och ställtiden mellan 210 och 325 minuter. Avslutningsvis visar resultatet att det även är möjligt att producera den uppskattade efterfrågan till Hultsfred, Portugal och Tyskland på bara tio dagar, om produktionen är igång dygnet runt.

Abstract

IKEA Industry has factories in several locations where one location is in Hultsfred, Småland. IKEA Industry Hultsfred produces IKEA:s wardrobe collection PAX. In 2018, 2.8 million wardrobes were manufactured in Hultsfred. The factory supplies northern and eastern Europe, and the Netherlands with wardrobes. IKEA Industry Hultsfred manufactures all components on the wardrobe except the back. One of the components is the plinth (sv. Sockel). This component is produced on its own production line in the factory.

One factory in Portugal and one factory in Germany, which also produce wardrobes to IKEA, is interested in buying plinths from IKEA Industry Hultsfred. This entails that the factory in Hultsfred needs to increase its production volumes to meet the demand from the factories in Germany and Portugal with plinths.

This thesis covers the subject of constructing and developing an optimization model which has the same characteristics as the plinth production at IKEA Industry Hultsfred. This means that the optimization model must consider production sequence; the setup time is different depending on which products that have been produced in the machine earlier. The thesis also covers to investigate how much time that is necessary to produce the plinths to Hultsfred, Portugal, and Germany under different circumstances.

This thesis also balances inventory levels and setup time. I.e., how the inventory levels are changed if more emphasis is put into minimizing setup time, and the other way around. The results show that lower inventory levels and setup times are achievable over seven days if the production planning technique is changed. The results also show that two shifts per day during 16 days are enough time to meet the expected demand from Hultsfred, Portugal, and Germany. This solution shows that the average number of pallets at the end of each day ranges between 329 and 338 pallets, and the setup time is varying between 184 and 262 minutes, depending on if setup time or inventory levels are minimized. When the expected demand is increased by 15 %, two shifts during 12 days are needed, and three shifts for four days in order to meet the expected demand. The average number of pallets in inventory at the end of each day is ranging between 350 and 320 pallets, and the setup time between 210 and 325 minutes when the expected demand has increased by 15 %. Finally, the results show that it is possible to produce the demand for Hultsfred, Portugal, and Germany in 10 days when the production is running 24/7.

Keywords: Capacitated Lot Sizing Problem with Sequence Dependent Setup Times (SLSP-SDST), Production Scheduling, Weighted Sum Method

Förord

Detta examensarbete har utförts under våren 2020 som avslutning på civilingenjörsutbildningen Kommunikation, Transport och Samhälle (KTS) med inriktning kvantitativ logistik.

Först och främst vill jag tacka Klas Franzén och Anette Strand på IKEA Industry Hultsfred som gav mig möjligheten att skriva examensarbetet på IKEA. Jag vill också rikta ett stort tack till alla andra på IKEA Industry Hultsfred för hjälpen med att förstå produktionen och svarat på dumma frågor. Jag vill även tacka min handledare Stefan Engevall som även han stått ut med dumma frågor, knackig engelska och givit värdefull input till arbetet! Också ett stort tack till examiner Tobias Andersson Granberg och opponenter Gustav Sedvallson och Simon Istgren som givit bra synpunkter på arbetet.

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Norrköping, 17 juni 2020



Mattias Anemyr

Acronyms

APS Advanced Planning and Scheduling

CLSP Capacitated Lot-Sizing Problem

CLSP-SDSC Lot-Sizing Problem with Sequence Dependent Setup Cost

CLSP-SDSCST Lot-Sizing Problem with Sequence Dependent Setup Cost and Setup Times

DLSP Discrete Lot-Sizing Problem

ERP Enterprise Resource Planning

IKEA Ingvar Kamprad, Elmtaryd, Agunnaryd

MIP Mixed Integer Programming

MRP Material Requirements Planning

MTS Make To Stock

TSP Travelling Salesman Problem

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Chapter 1

Introduction

This chapter describes the problem background, aim, purpose and research questions. At the end of this chapter the delimitations for this thesis are presented and also an outline for this report.

1.1 Background

Every minute passed; eleven IKEA wardrobes are produced. That's the situation at IKEA Industry Hultsfred which produces IKEA wardrobes. IKEA Industry Hultsfred supplies the IKEA warehouses in the Nordic market, Netherlands and eastern Europe with wardrobes. The wardrobes consist of three different components. The first component is the frame, which consists of top, bottom, sides and back. The other two components are shelves and plinths. This thesis will only cover the production of plinths for the wardrobes. IKEA Industry Hultsfred produces twelve different kinds of plinths in varying lengths and foils (colors).

IKEA Industry Hultsfred have been asked by two other factories if they are willing to sell plinths to them. One factory, located in Pacos, Portugal, which belongs to the IKEA Industry organization, is interested in buying a yearly total of 2 million plinths, ranging between all different foils and lengths. Another factory located in Bürstadt, Germany, which does not belong to the IKEA Industry organization, is interested in buying 8 million plinths every year, also with varying foils and lengths. These two factories are producing the same wardrobes as in Hultsfred, which means that no additional lengths or foils needs to be produced ¹.

To avoid unnecessary risks, it is of great importance to investigate the possibilities of increasing the production of plinths and investigate how the inventory volumes would change, before accepting the offer to start selling plinths. IKEA Industry Hultsfred is now interested in analyzing the current production capacity, investigate how much production time that is necessary in order to satisfy the increased demand, and evaluate which inventory levels an increased demand might lead to. IKEA Industry Hultsfred does not use any specific software to plan the plinth production. Therefore it will be evaluated if putting more emphasis into minimizing setup times or inventory levels will have any impact on the total setup time or inventory levels and indicate which of those that could be more important to consider when doing the plinth production planning .

¹Klas Franzén, Managing director. Interview, 27th of January 2020

1.2 Aim, Objective and Research Questions

1.2.1 Aim

The aim of this thesis is to create an optimization model which takes sequence-dependent setup times into consideration. The optimization model aims to map the characteristics of the plinth production at IKEA Industry Hultsfred. Further, the aim is to use the optimization model to find a relation between inventory levels and setup times in the production planning at IKEA Industry Hultsfred.

1.2.2 Purpose

The purpose of this thesis is for IKEA Industry Hultsfred to get an indication of how a different production planning technique could affect the setup time and inventory levels. Further, the purpose is to investigate how much production time that is necessary to increase the production of plinths, and how the inventory levels and setup time relates to each other if the production volume increases.

1.2.3 Research questions

All the following research questions and related results are based on an optimization model which is presented in Section 3.2.8.

Q1 and *Q2* relates to the production volumes without considering the demand for Germany or Portugal.

Q1 - How do the inventory levels and setup times depend on and relate to each other over a seven day period at IKEA Industry Hultsfred?

Q2 - How do the inventory levels and setup times depend on and relate to each other over a seven day period at IKEA Industry Hultsfred when the available time for production is decreased?

Q3 and *Q4* are formulated with taking the demand for the factories in Germany and Portugal into consideration.

Q3 - How much production time is necessary at the plinth production to increase the production volumes to meet the estimated demand from the factories in Germany and Portugal, while also supplying the demand for IKEA Industry Hultsfred?

Q4 - How do the inventory levels and setup times depend on and relate to each other when IKEA Industry Hultsfred has increased their production to meet the estimated demand from the factories in Germany and Portugal, while also supplying the demand for IKEA Industry Hultsfred?

According to site manager Klas Franzén at IKEA Industry Hultsfred, there is a possibility of a 15 % demand increase from Germany and Portugal. *Q5* and *Q6* are formulated with this demand increase taken into consideration.

Q5 - How much production time is necessary at the plinth production to increase the production volumes and meet a 15 % increase in the estimated demand from the factories in Germany and Portugal, while also supplying the demand for IKEA Industry Hultsfred?

Q6 - How do the inventory levels and setup times depend on and relate to each other when IKEA Industry Hultsfred has increased their production volume to meet a 15

% increase in the estimated demand from the factories in Germany and Portugal, while also supplying the demand for IKEA Industry Hultsfred?

Q7 and *Q8* are formulated to evaluate how short lead time IKEA Industry Hultsfred can offer Germany and Portugal.

Q7 - How much production time is necessary at the plinth production to have time to first produce the order to Portugal, and then the order to Germany in the shortest time possible, while also supplying the demand for IKEA Industry Hultsfred?

Q8 - How do the inventory levels and setup times depend on and relate to each other when IKEA Industry Hultsfred has to finish the orders to Portugal and Germany in the shortest time possible, while also supplying the demand for IKEA Industry Hultsfred?

1.3 Delimitations

Figure 1.1 shows a simplified image of the production. The red dotted line is the system border. This means that this thesis will include the production line where the plinths are produced. The thesis also covers the inventory where the finished plinths are stored. The packaging line is partly involved in the thesis since the demand of plinths is determined by the packaging volumes.

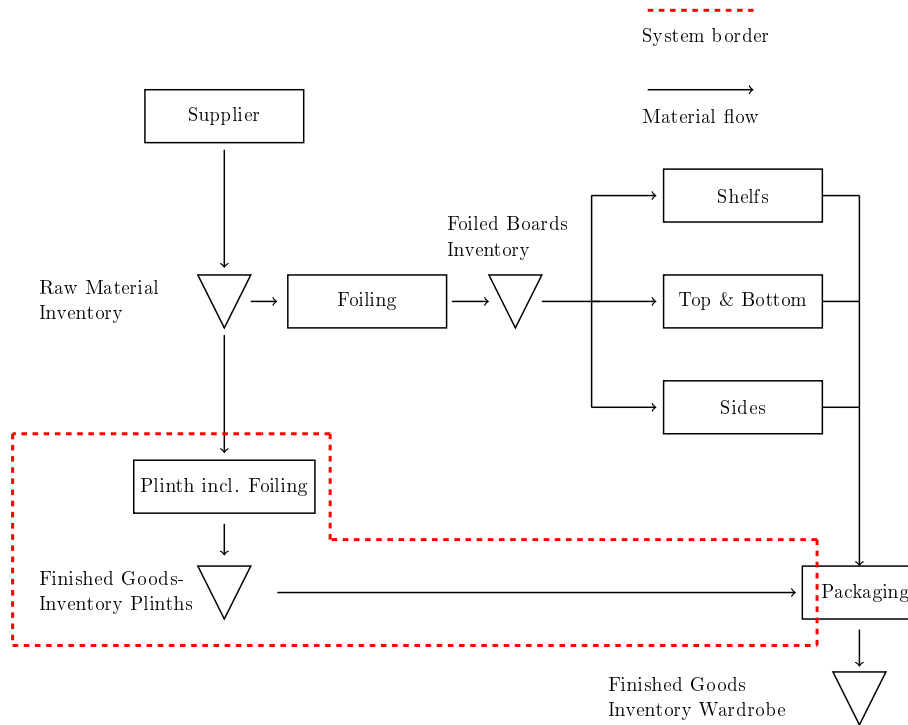


Figure 1.1: Simplified overview of the plinth production.

Increasing the production capacity will also increase the costs of operators since more man-hours need to be spent for the production of plinths. Changes in production also leads to additional purchasing costs, for example raw material. This thesis will not consider any economic evaluation such as: which price the plinths should be sold for, or if it is profitable to increase production and start selling to the other two factories.

In reality it is possible to adjust the production planning on a day to day basis if new

customer orders have been placed. This thesis will not consider day to day changes but only weekly or monthly production planning. That is: In practice a change in the demand might occur at Wednesday and the production planning is changed accordingly for that day. This scenario will not be considered in this project.

1.4 Outline

Chapter 2 presents a general methodology and which method that is used in this thesis. Chapter 3 describes the relevant theory of production planning and optimization. In chapter 4 is IKEA as an organization presented, and chapter 5 describes IKEA Industry Hultsfred and its production in great detail. Chapter 6 presents the optimization model and its extensions. In chapter 7 is the results presented, and chapter 8 presents a relevant discussion of the obtained results. Lastly, chapter 9 concludes the report and answers the research questions.

Chapter 2

Method

This chapter covers different research methodologies, for example: quantitative and qualitative methods. This chapter also describes the methods used, and how they are applied in this thesis.

2.1 Methodology

This section describes different general research methodologies and how they can be used in a study.

2.1.1 Quantitative, Qualitative and Mixed Methods

Three approaches can be used when conducting research: qualitative methods, quantitative methods, and mixed methods (Creswell and Creswell, 2018). For explaining properties with numerical values, quantitative methods can be useful. Weight and length are two examples of quantitative terms (Hartman, 2004). Hartman (2004) divides the quantitative research method into three different phases: (1) planning, (2) data collection, and (3) analysis. The planning phase (1) is about formulating a valid hypothesis, which later can be backed up by other scientific literature. In the data collection-phase (2), it is essential to collect the data in a way that has been described earlier in the research. This is important for gaining validity and reliability of the research. The analysis phase (3) is divided into two separate parts. The first part is to describe and organize the collected data. In the second part statistical methods can be used to test a hypothesis or to produce a result (Hartman, 2004).

It is not possible to measure or explain everything with quantitative methods. An alternative or complement to quantitative methods is qualitative methods. A qualitative method is something that is described or classified in non-numerical terms. Qualitative studies are often used to gain more profound knowledge in a specific research area, event, or situation (Björklund and Paulsson, 2003).

The third research method which can be used is the mixed method. A mixed method is a combination of quantitative and qualitative methods. The advantage with this is that both quantitative and qualitative data can be used within the same study (Creswell and Creswell, 2018; Björklund and Paulsson, 2003).

The study's objective is the primary factor that decides if the study is quantitative or qualitative.

Björklund and Paulsson (2003) states that mathematical models and surveys fit better for quantitative studies, while interviews and observations are well suited in qualitative studies. However, the way the interview and observations are conducted is the factor deciding if the data gathered is suitable for a quantitative or qualitative approach (Björklund and Paulsson, 2003).

2.1.2 Explorative, Descriptive, Explanative and Normative studies

The existing knowledge in a research area is important in deciding which type of study that should be conducted. Björklund and Paulsson (2003) lists four common types of studies which are dependant on how much previous knowledge that exists in the area:

1. **Explorative** - This is often used when there is no or little previous research in the studied area. The aim is to gain basic knowledge in the research area.
2. **Descriptive** - This is used when there are some research and understanding in the area. The aim is to describe, but not explain the relations in the research area.
3. **Explanative** - This is used when more in-depth knowledge and understanding are desired. The aim is to both describe and explain a topic in the researched area.
4. **Normative** - This is used when research and understanding exist in the area. The aim is to give guidance and propose actions.

2.1.3 Reliability, Validity and Objectivity

The reliability of a research instrument is high if the results are consistent over time and if the results of a study can be reproduced under the same methodology (Nahid, 2003). Kirk and Miller (1986) identifies three different types of reliability in quantitative research: (1) To which degree a measurement stays the same when repeated, (2) the stability for a measurement over time, and (3) the similarity between measurements over a given time period.

The validity of a measurement is the degree to which the tool measures what it is supposed to, or claims to measure (Nahid, 2003). That is if the research represents the reality it claims to describe. One method to increase the validity of a research is by using triangulation (Björklund and Paulsson, 2003). Triangulation is when several research methods are used to study the same phenomenon.

According to Björklund and Paulsson (2003), reliability and validity can be described by using dartboards. High reliability is when the darts hit the same area. High validity is at the center of the board. High validity and reliability appear when the darts are hitting the center of the board. Figure 2.1 visualizes this:

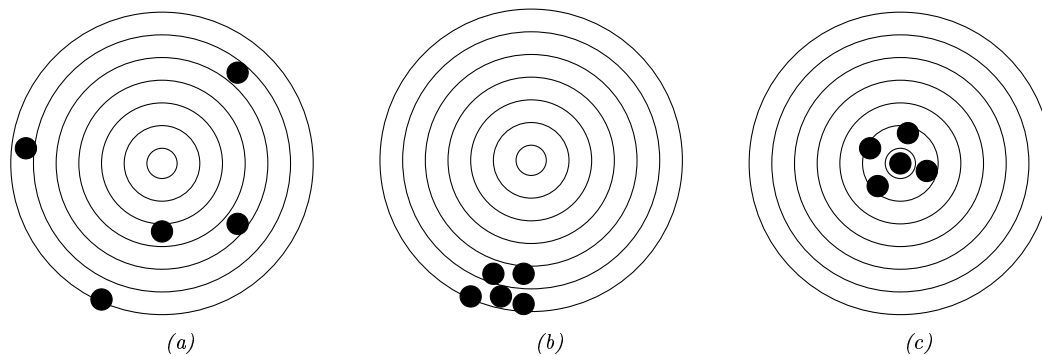


Figure 2.1: Figure 2.1a shows low reliability and validity. Figure 2.1b shows high reliability but low validity. Figure 2.1c shows high reliability and validity. Inspiration from Björklund and Paulsson (2003) p.60.

Objectivity is to which degree the author of a research lacks bias, judgment, or prejudice. Objectivity can be increased by clearly stating and motivating the different choices made during the study, which gives the reader the possibility to have an opinion on the research (Björklund and Paulsson, 2003).

2.2 Data Collection

Several data collection methods exist which can be used to collect data in a study. Sections 2.2.1 to 2.2.3 describe some of the most common data collection methods according to Denscombe (2014) and Björklund and Paulsson (2003).

2.2.1 Literature Review

The primary purpose of a literature review is to gain knowledge of a research area and review what other researchers already have accomplished within the area. Via the newly gained information, a researcher can get guidance on how their study can be conducted (Hartman, 2004; Bell, 2014). The literature review is also used to set up the theory chapter, which describes the relevant general and specific theories used in the study. The theory chapter should also include clear explanations of the terms used (Hartman, 2004).

To reach high academic quality in a study, it is of importance to use sources of high quality, for example, peer-reviewed articles. Other scientists in the relevant field have reviewed a peer-reviewed article, which improves the credibility and quality of the research (Kelly, Sadeghieh, and Adeli, 2014). To determine if a journal or an article has been peer-reviewed International Scientific Indexing (ISI) or Ulrichsweb can be used (Indexing, 2020; Ulrichsweb, 2020).

2.2.2 Interviews

A researcher can do interviews via personal meetings, telephone, email or text messages. Björklund and Paulsson (2003) and Denscombe (2014) distinguishes between three types of interviews:

1. **Structured** – In this type of interview the questions are decided before the interview, and they are asked in a particular order.
2. **Semi-structured** – In this type of interview the topic is decided before the interview starts. The questions arise during the interview, and the upcoming questions are based on the respondents answers to previous questions.

3. **Unstructured** – This type of interview is more like a conversation where the questions are defined during the interview.

An interview is a suitable tool to collect data if the topic is complex and if a detailed understanding of how things work is needed. An interview is also useful to gain privileged information, where one or several key persons can give valuable insights based on their experience or position. One or several persons can be present at an interview (Denscombe, 2014). The number of questions asked during an interview depends heavily on the scope of the interview. Broader scope tends to have more questions (Björklund and Paulsson, 2003). It is essential to avoid leading questions independent of which type of interview that is conducted. A leading question can affect the respondent to answer the question in a particular way which can result in false information (Denscombe, 2014). The goal of an interview is to gain knowledge in the research area and to collect information which can be used in the study (Björklund and Paulsson, 2003).

2.2.3 Observations

Zikmund, Babin, and Griffin (2009) describe observations as a systematic process of recording the behavior of people, objects and occurrences as they are witnessed. A wide variety of objects can be observed, ranging from the time required to perform a work task, finished goods inventory levels to facial expressions of workers when doing a task. According to Zikmund, Babin, and Griffin (2009) observations can be made in two ways: visible observation or hidden observation. When the observer's presence is known, it is called visible observation. If the studied subjects are unaware that they are being observed, it is called hidden observation. One advantage with hidden observation is that the respondents work as usual and minimizes their errors compared to visible observation. The data is recorded when the behavior or action takes place. Simple tools such as pen, paper and stopwatch timer can be used when conducting an observation (Björklund and Paulsson, 2003).

2.3 Research Procedure

Lekvall and Wahlbin (2007) present the Wahlbinian U, that aims to visualize the necessary steps and activities concerned in a study. The aim of the Wahlbinian U is also to show how the different activities are related. The research procedure for this thesis is based on the Wahlbinian U.

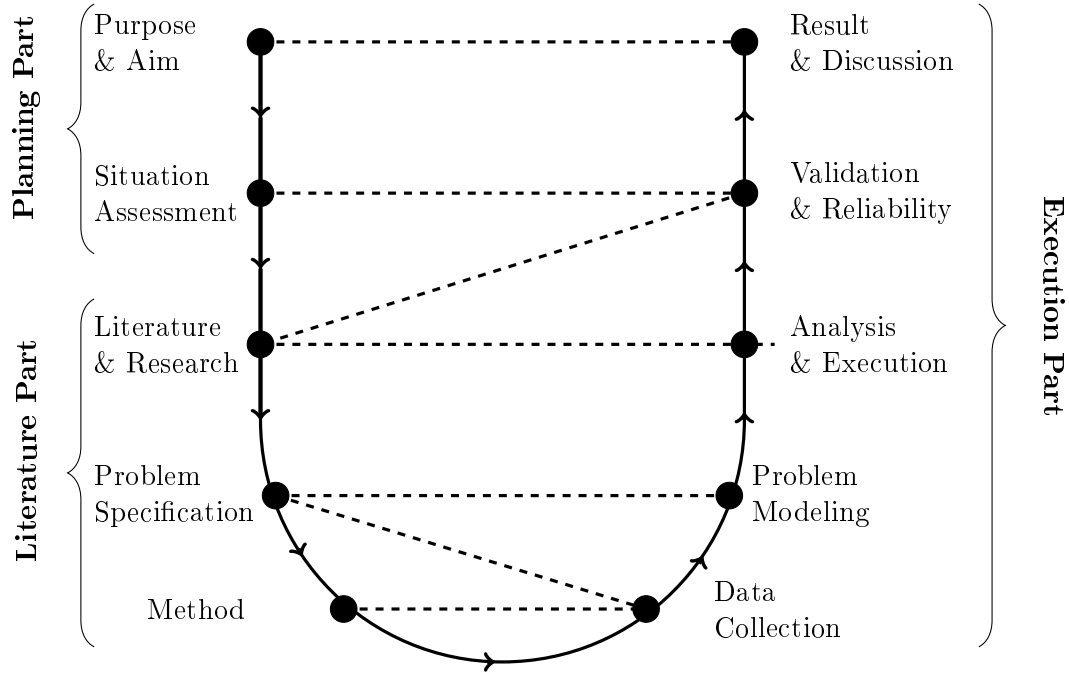


Figure 2.2: The Wahlbinian U adapted for this thesis. With inspiration from Lekvall and Wahlbin (2007, p.183).

Figure 2.2 shows that the Wahlbinian U is divided into three steps that all are explained in sections 2.3.1 to 2.3.3.

2.3.1 Planning Part

IKEA Industry Hultsfred were interested in investigating the possibilities to produce higher volumes of plinths. A higher production volume needs a changed production plan in terms of batch sizes and setup sequence etcetera, to maximize the production volumes. An increase in production volumes also affects other factors, such as inventory levels. Henceforth, eight research questions were formulated, which all cover production planning and inventory level aspects. Delimitations were introduced after the research questions had been formulated. Delimitations were made in cooperation with the supervisor at IKEA Industry Hultsfred and the academic supervisor. The delimitations were also made to decrease the magnitude of the thesis since not everything can be investigated or solved.

The situation assessment included an analysis of the situation today with respect to production planning (how much to produce, at which times and in which sequence), inventory levels and setup times. The situation assessment led to two individual branches in this thesis:

- **Branch 1:** The situation over seven days with the same demand as today.
- **Branch 2:** The situation where IKEA Industry Hultsfred delivers plinths to Portugal and Germany and have increased production volumes.

This thesis uses a mixed research method. Mainly quantitative methods have been used since much of the results and analysis are based on numerical values. However, to gain knowledge of the system, qualitative methods have been used, such as interviews and observations. The thesis type is also a mix between explanative and normative study. A lot of research exist within the production scheduling and inventory fields, while more in-depth knowledge was needed to adopt and extend current research. Finally, the goal was to give guidance on which aspects that are important when doing the production

planning, and also give an indication of how large inventory levels that could arise when IKEA Industry Hultsfred start to sell plinths.

2.3.2 Literature Part

From the situation assessment, initial purpose and aim, it was possible to conduct a literature review. The literature review included: production and scheduling optimization and production planning methods in general. Additionally, literature regarding how to collect data has been studied since data collection is a crucial part of this thesis.

For the production scheduling problem a few initial searches were made at Google Scholar with the keywords “Scheduling” and “Production”. The top ten relevant articles were sorted by title, irrelevant articles that did not cover production planning or scheduling problems were removed. The abstracts were read for the remaining articles. The articles by Liouane et al. (2007), Driscoll and Emmons (1977) and Tang and Liu (2007) mentioned optimization or Mixed Integer Programming (MIP). Henceforth, the keyword “Optimization” was added to the search. MIP was not added to the search since this could narrow the search scope down too early in the search process. The article by Maccarthy and Liu (1993) was found by applying the same sorting process as in the previous step. Maccarthy and Liu (1993) mention that the scheduling problem to be solved needs to be classified. Therefore “Classification” was added to the keywords.

The search with the following keywords: "Scheduling", "Production", "Optimization" and "Classification" gave 300 000 hits. However, only the ten first articles were sorted out and then out of these articles, the ones whose title or abstract did not mention classification of production scheduling or optimization models were removed. Two relevant articles regarding classification of scheduling problems were found and read, Harjunkoski et al. (2014) and Méndes et al. (2006). The classification framework in Méndes et al. (2006) was used to classify the plinth production at IKEA Industry Hultsfred. This classification was chosen due to its straightforward approach. The classification of the plinth production can be found in Appendix A.1, while the reader is referred to Méndes et al. (2006) for more details.

The result of the classification was that more keywords were found which were used to find an optimization model that have the same characteristics as the plinth production at IKEA Industry Hultsfred. The following keywords were found via the classification: “Single Stage”, “Multi-Product”, “Sequence-dependent”, “Setup cost”, “Scheduling problem”. The first ten hits were sorted by the same procedure as mentioned above, and the following articles were found: Almada-lobo et al. (2007), Salomon et al. (1997) and Fleischmann (1994). The model by Almada-lobo et al. (2007) was chosen since this model has the same characteristics as the plinth production at IKEA Industry Hultsfred and the article provides an exact mathematical formulation. The search process is summarized in Table 2.1 with information about which search engine used, which keywords, how many hits per search and the relevant articles found.

Table 2.1: The keywords used in the search process for optimization model.

No.	Search Engine	Keywords Used	Hits	Relevant Articles
1	Google Scholar	Scheduling, Production	2 430 000	<ul style="list-style-type: none"> ► Liouane et al. (2007) ► Driscoll and Emmons (1977) ► Tang and Liu (2007)
2	Google Scholar	Scheduling Production Optimization	1 140 000	<ul style="list-style-type: none"> ► Maccarthy and Liu (1993)
3	Google Scholar	Scheduling, Production, Optimization, Classification	300 000	<ul style="list-style-type: none"> ► Harjunkski et al. (2014) ► Méndes et al. (2006)
4	Unisearch	Scheduling, Production, Optimization, Classification	412	<ul style="list-style-type: none"> ► Wörbelaue, Meyr, and Almada-Lobo (2019)
5	Google Scholar	Multi-Product, Sequence-dependent, Setup Cost, Scheduling, Problem	1850	<ul style="list-style-type: none"> ► Fleischmann (1994) ► Salomon et al. (1997) ► Almada-lobo et al. (2007)

Primarily peer-reviewed articles and books have been used as literature throughout the thesis. The articles have been found at Google Scholar or Linköping University library (Unisearch). After the literature review, the problem formulation and the research questions could be described in greater detail. The production planning problem was identified as a Capacitated lot-sizing Problem with Sequence Dependent Setup Times.

2.3.3 Execution Part

IKEA Industry Hultsfred provided data regarding the demand at the factory in Hultsfred. Demand data ranging from days to months was available. Production schedules (what to produce and how much) was also available. The yearly demand for the factories in Portugal and Germany is 2 million plinths and 8 million plinths, respectively. The monthly variations in how many plinths, which length and which foil were not known for Portugal and Germany. The demand for Germany and Portugal was generated by using demand data from IKEA Industry Hultsfred.

1. The average three-week demand for IKEA Industry Hultsfred was calculated.
2. The average three-week demand was multiplied with a factor so that the yearly demand is 2 million for Portugal and 8 million for Germany.

Appendix C displays the calculations in detail. The lead-time from received order to that the plinths are in Germany and Portugal is three weeks; more information about this is found in Chapter 7. The calculated demand is used to generate results.

Interviews were another data collection approach used. An initial semi-structured interview was held with Klas Franzén, managing director, on the fifteenth of January. This interview was about the requirements on the results for the thesis. A semi-structured interview was also held with supply chain manager Annette Strand on the eleventh of February. This interview discussed the demand and production order data. During the second of March

to the sixth of March unstructured interviews was held with the line-operators at the plinth production. Fidan Breznica, production leader, was interviewed via an unstructured interview on the third of March. This interview was about the data collection of the plinth line.

Cycle times were collected via a time-study, while other data such as setup times and stop times were already available. More details about the time study can be found in Section 3.3.1. Stop times include all time that is spend on other activity than actual production of plinths. The operators at the production were aware of the time-study. In other words, a visible observation. The time study for the cycle times was conducted during five days between the second of March to the sixth of March.

After the data collection phase, the optimization model by Almada-lobo et al. (2007) was implemented and modified. An optimization approach to solve the problem was chosen for several reasons. The first reason is that earlier research had developed a model which suited the characteristics of the plinth production well. This led to that more time could be spent on extending the model to fit the production at IKEA Industry Hultsfred even better, and also spend more time on producing results rather than developing a new model. A second reason is that the demand is known and that the stop times are assumed to be equal every day. If for example, the demand had large daily variations and also the stop times, a discrete simulation approach might have been better. However, this was not the case, and the purpose of this thesis was not to evaluate how the stop times affect the production, henceforth, an optimization approach was used. One final reason is that an optimization model produces good and reliable solutions.

Minimum production quantities and adding weighting factors to the objective function is two extensions that were implemented in the optimization model. Section 6.1.3 explains all the extensions in detail. The expected output from the model is to evaluate how setup times and inventory levels affect each other. The weighting factors adjust this in the objective function, see Section 3.2.5.

Average stop times were extracted in Excel with the data provided by IKEA Industry Hultsfred. The collected data was also processed in Excel to calculate cycle times for the different plinth lengths. These data was used as input to the optimization model. Section 5.2.2 explains the data processing in depth.

Five different scenarios were optimized:

- Optimization over seven days with demand only from IKEA Industry Hultsfred. Production time corresponds to one shift per day.
- Optimization over seven days with demand only from IKEA Industry Hultsfred. Lower available production time on the seventh day.
- Optimization over 16 days with demand from the factories in Germany and Portugal.
- Optimization over 16 days with a 15% increase in demand from the factories in Germany and Portugal compared to the previous scenario.
- Optimization over ten days to simulate shorter lead times from the factories in Germany and Portugal.

Chapter 7 explains the scenarios in greater detail.

Each of the scenarios generated three primary results:

- A Pareto front which states how the average inventory levels and setup times affect each other.

- A graph displaying the unused capacity per day. This indicates how much of the available time that is used to produce plinths.
- A graph displaying the inventory development during the planning horizon (seven, ten or sixteen days).

The model was implemented in OPL studio, and the optimization was run on a 3.70 GHz Intel Xeon with 32 GB of random access memory. All optimization was run for 15 minutes and is a balance between time spent and reasonable results.

Further, the results were analyzed and discussed with a focus on interpreting and understanding the results. Lastly, the results were concluded.

Chapter 3

Theory

This chapter describes the relevant theory necessary for obtaining a result and conduct a relevant analysis. The chapter begins with describing the production planning in a supply chain perspective. Relevant general optimization theory is also described and optimization in a production planning perspective. Later is an optimization model described and last in the chapter is the theory about work measurement described. The solution approach in this thesis is based on optimization, and work measurement theory is used when the data have been collected.

3.1 Supply Chain

Stadtler and Kilger (2014) write that a supply chain consists of two or more legally separated organizations which are being linked by material, financial or information flow. The organizations involved in a supply chain could be firms producing parts, components or end products. A supply chain also involves the target group, which is the customer. A supply chain approach is also applied in large companies to coordinate information, financial and material flow between different production sites located in different countries, for example.

Close cooperation between the different organizations in a supply chain is vital to have a good competitive supply chain. The cooperation functions can range from marketing, production, logistics or finance. A good supply chain can, for example: increase the competitive advantage against competitors, improve the efficiency of plants and increase customer satisfaction (Stadtler and Kilger, 2014).

3.1.1 Production Planning

Production planning incorporates a wide range of elements, from everyday activities of staff to meeting delivery times for the customer, etcetera. By an effective production planning operation any form of manufacturing process can be improved to use its full potential (Kiran, 2019). Kiran (2019) states that the brain of the production program is the production planning and control. This program ensures, for example, the availability of material and the right quantities at the right place. The main concerns with production planning can be summarized as

- What facilities are needed?
- How should the facilities be laid out in the space available for production?

- How should they be used to produce the right quantities at the desired rate of production?

Some of the main objectives of production planning and control are: minimize the idle time of machine and workforce, minimize inventory, maximize product quality and customer satisfaction (Kiran, 2019).

3.2 Optimization

Optimization is a branch in applied mathematics where mathematical models and methods are used to find the best solution in different situations (Lundgren, Rönnqvist, and Värbrand, 2008). A general formulation of an optimization problem is:

$$\begin{array}{ll} \min & f(x) \\ \text{subject to} & g_i(x) \leq b_i \quad i = 1, \dots, m \end{array}$$

Where $f(x)$ is the objective function which depends on the variables $x = (x_1, \dots, x_n)^T$. $g_1(x), \dots, g_m(x)$ are functions which depend of x and b_1, \dots, b_m are given constants. A solution that minimizes $f(x)$ is an optimal solution (Lundgren, Rönnqvist, and Värbrand, 2008).

3.2.1 Mathematical Programming

The area where theory and practice of optimization are joined is known as mathematical programming (Antoniou and Lu, 2007). Several branches of mathematical programming exist according to Antoniou and Lu (2007). Some of the most used are linear, integer and dynamic programming.

Linear programming is used when the optimization problem is formulated with linear constraints and a linear objective function. Integer programming is used when some or all variables in a problem are set to equal integer values (Lundgren, Rönnqvist, and Värbrand, 2008). Dynamic programming is often used when a series of decisions must be made in sequence and where decisions are affected by decisions made earlier (Antoniou and Lu, 2007). Mixed Integer Programming (MIP) is the term used when a problem has both continuous and integer variables. A MIP optimization problem is generally hard to solve, which means that it can be challenging to obtain an optimal solution. Some MIP problems are in practice unsolvable, depending on the MIP formulation and problem instances. Instead, other optimization techniques can be used, such as heuristics (Garey and Johnson, 1979).

3.2.2 Optimization in Production Planning Context

Today many businesses use planning systems such as Enterprise Resource Planning (ERP), Advanced Planning and Scheduling (APS) and/or Materials Requirement Planning (MRP). These systems have one thing in common; they are unusable or unable to handle considerable complexity of the underlying capacitated planning problems (Pochet and Wolsey, 2006). It may be possible to improve capacity planning problems by using optimization according to Wang and Liu (2013) and Pochet and Wolsey (2006). One known example where optimization was used to reduce costs, improve customer satisfaction and improve production capacity is the Kellogg Company. The company is the world's largest cereal manufacturer and estimates to save \$34-40 million per year by switching from ERP and MRP to a custom software which uses optimization (Brown et al., 2001).

3.2.3 The Lot-Sizing and Scheduling Problem

The lot-sizing and scheduling problem originates from the 1950:s by the work of Manne (1958) and has over the years been refined and developed into two branches, Discrete Lot-Sizing and Scheduling Problem (DLSP) and Capacitated Lot-Sizing and Scheduling Problem (CLSP). DLSP is also called small window approach or small-time bucket approach (Pochet and Wolsey, 2006; Gupta and Magnusson, 2005). In DLSP, the planning horizon is split into smaller segments where only one product can be produced per period. CLSP is, on the contrary, called large time window or big-bucket approach. CLSP allows for longer periods where several products can be produced in each period (Pochet and Wolsey, 2006; Gupta and Magnusson, 2005).

Numerous extensions exist, both of the DLSP and CLSP. One extension is Capacitated Lot-Sizing and Scheduling Problem with Sequence Dependent Setup Cost (CLSP-SDSC). Sequence-dependent means that the cost of setup is different depending on in which order the products are produced. To clarify, say that three products are to be produced, A, B, and C, and the machine is initially setup for product A. Setup cost between the different products are displayed in Table 3.1.

Table 3.1: Cost for setup in example problem.

Change (From \rightarrow To)	Cost
A \rightarrow B	10
A \rightarrow C	5
B \rightarrow A	12
B \rightarrow C	15
C \rightarrow A	10
C \rightarrow B	5

Setup from A to B and then to C gives a cost of $10 + 15 = 25$ cost units. If the sequence dependence is taken into consideration, it is possible to reduce the cost. Setup from A to C and then to B gives a cost of $5 + 5 = 10$ cost units.

Another extension is Capacitated Lot-Sizing and Scheduling Problem with Sequence Dependent Setup Cost and Setup Times (CLSP-SDSCST). This extension was first presented by Gupta and Magnusson (2005) who formulated the problem as a MIP. The complexity of the model increases when positive setup times are included. It has been shown that this problem is NP-Complete, hence very hard to solve to optimality for larger problem instances (Trigeiro, Thomas, and McClain, 1989). Almada-lobo et al. (2007) have proposed an alternative formulation to Gupta and Magnusson (2005) which reduces the number of binary variables significantly. This also reduces the complexity and calculation time of the problem.

3.2.4 Optimization Process

When applying optimization to real-life applications, the optimization model must represent reality as good as possible in order to achieve an applicable output from the optimization procedure (Lundgren, Rönnqvist, and Värbrand, 2008). Lundgren, Rönnqvist, and Värbrand (2008) divide the process of constructing an optimization model into several steps.

- The real problem is often large and complex, and it is often necessary to narrow down the problem by introducing limitations and simplifications, which results in a simplified problem.

- The simplified problem is then described and formulated in a mathematical formulation, in terms of an objective function, variables and constraints.
- The mathematical formulation of the problem is solved. The result is verified and validated to reassure that the model gives an appropriate output that relates to the original problem.

3.2.5 Weighted Sum Method and Pareto Front

Many real-life optimization problems often involve more than one objective where the objectives generally are in conflict. All the objectives cannot be minimized or maximized simultaneously and therefore a compromise between the objectives is often necessary (Jubril, 2012). Assume that f_1 and f_2 are two objective functions and λ_1, λ_2 are weighting coefficients for objective functions f_1 and f_2 . The weighted sum method states that these two objective functions can be combined into one objective function with help of the weighting coefficients.

$$F(x) = \lambda_1 \cdot f_1 + \lambda_2 \cdot f_2 \quad (3.1)$$

Where

$$\sum_{i=1}^2 \lambda_i = 1 \quad (3.2)$$

One challenge with this method is how to select the weighting coefficients since the solution depends on the weighting of the coefficients. There is no guideline on how to select the weights in order to obtain the best solution.

One method is that the decision-maker values one objective higher than the other, and therefore sets the corresponding weight coefficients to a higher value than the other objective. Another approach is to vary the coefficients with equal step size and solve the problem several times with different values on the coefficients (Bruke and Kendall, 2014; Yang, 2014). It is possible to plot the solutions for all the different values of the coefficients. Figure 3.1 shows an example of this.

Figure 3.1a shows the Pareto front of a bi-objective problem. All the optimal solutions to the problem lie on this front. It is impossible to improve f_2 without worsening f_1 , and the other way around. The black dots are Pareto points, and the dashed line is the Pareto front. The figures serve an illustrative purpose, and the Pareto points are not necessarily always evenly distributed over the front.

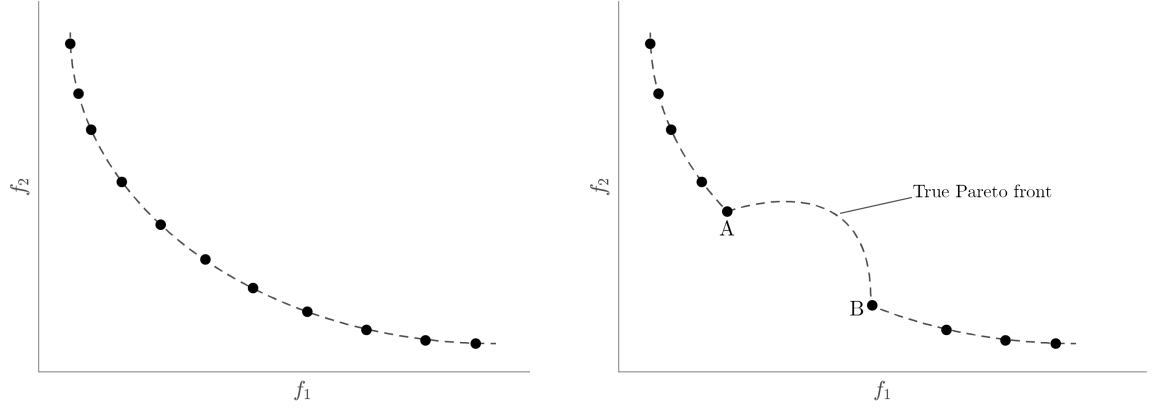
It is only possible to generate an optimal Pareto front if the front is convex when using the weighted sum method. The weighted sum method can not find any Pareto solutions in non-convex regions. Figure 3.1b shows that weighted sum method can find point A and B , but can not decide any points on the non-convex area.

3.2.6 Triangle Inequality

Triangle inequality states that the sum of two side's lengths in a triangle always is at least the length of the third side. Mathematically, the triangle inequality is defined as:

$$Z \leq X + Y \quad (3.3)$$

Where Z, X and Y are visualized in Figure 3.2.



(a) All convex Pareto front

(b) Pareto front with non-convex parts

Figure 3.1: The result of weighted sum method on different Pareto fronts.

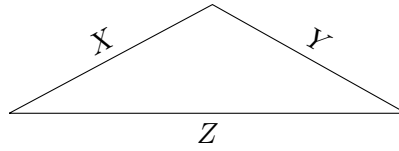
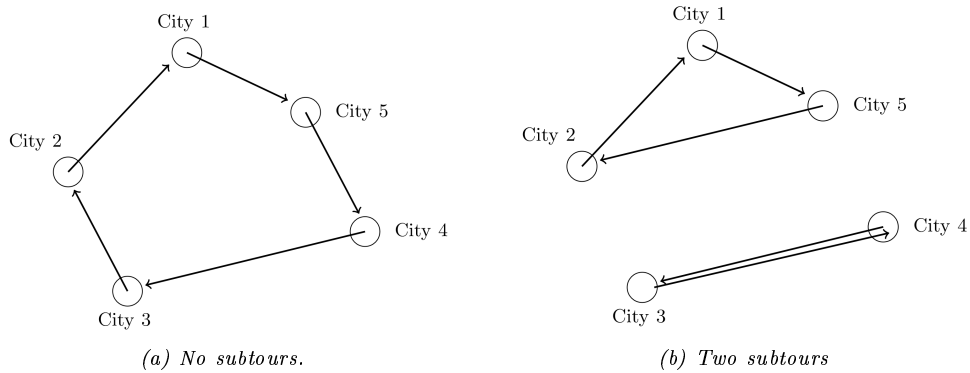


Figure 3.2: Triangle to demonstrate the triangle inequality.

3.2.7 Subtour Elimination

Subtour is a phrase that is often used in routing problems, such as the Travelling Salesman Problem (TSP). TSP aims to find the shortest total distance travelled between cities or the cheapest route, depending on the problem formulation. A subtour is a solution to the TSP where the salesman returns to starting position without visiting all cities. This can be avoided by adding subtour elimination constraints (Lundgren, Rönnqvist, and Värbrand, 2008). Figure 3.3 shows a graph with and without subtours.



(a) No subtours.

(b) Two subtours

Figure 3.3: Graphs with subtours and without subtours

3.2.8 CLSP - SDSCST Optimization Model

The following optimization model is a Capacitated Lot-Sizing and Scheduling Problem with Sequence Dependent Setup Cost and Setup Times (CLSP-SDSCST) presented by Almada-lobo et al. (2007). The model assumes that no backlogging is allowed, i.e. that all demand must be met at all periods and can not be delivered in another period. The

demand is satisfied either by production or from inventory carried from previous periods. Shortages of any kind (inventory or raw material, etc.) are not allowed either.

Let T be the number of time periods of equal length. The index set for all time periods is denominated $t = 1, \dots, T$. The number of products are N . X_{it} is the production quantity of product i in period t . The capacity of the machine in period t is denoted as Cap_t and is expressed in time units. The processing time for one unit of product i is denoted as p_i and is also expressed in time units. d_{it} is the demand for product i in period t . An upper bound for production quantity is denoted M_{it} and is calculated:

$$M_{it} = \min \left\{ \frac{Cap_t}{p_i}, \sum_{u=t}^T d_{iu} \right\} \quad (3.4)$$

Variable T_{ijt} is used to capture a setup from product i to product j in period t . It is defined as:

$$T_{ijt} = \begin{cases} 1 & \text{If setup occurs from product } i \text{ to product } j \text{ in period } t, \\ 0 & \text{Otherwise} \end{cases}$$

Moreover, let I_{it} be the inventory level of product i in the end of period t . The inventory holding cost for carrying one unit of inventory from one period to the next is defined as h_i for product i . The setup cost from product i to product j is denoted as C_{ij} , where $C_{ij} \geq 0$ and $C_{ii} = \infty$ to prevent setup from a product to itself. S_{ij} is the time units required to setup from product i to j , $S_{ij} \geq 0$. It is also assumed that the triangle inequality holds with respect to setup times and to cost, $C_{ik} \leq C_{ij} + C_{jk}$ and $S_{ik} \leq S_{ij} + S_{jk}$ for all products i, j, k .

To model so that a setup can occur in one period where no products are produced and so that a setup can be carried over from one period to another, the following binary variable is needed:

$$\alpha_{it} = \begin{cases} 1 & \text{If the machine is setup for product } i \text{ at the beginning of period } t, \\ 0 & \text{Otherwise} \end{cases}$$

Lastly, an auxiliary variable, V_{it} is introduced. This variable represents the machine state throughout any product sequence. The following model is presented by Almada-lobo et al. (2007). Note that constraint (3.6b) is incorrect. See section 6.1.3 for the correct reformulation of the constraint.

The objective function (3.5) aims to minimize the setup costs and inventory carrying cost over all periods.

$$\text{Minimize } \sum_{t=1}^T \sum_{i=1}^N \sum_{j=1}^N C_{ij} T_{ijt} + \sum_{t=1}^T \sum_{i=1}^N h_i I_{it} \quad (3.5)$$

$$\text{subject to } I_{it} = I_{i,t-1} + X_{it} - d_{it} \quad \forall i, t, \quad (3.6a)$$

$$\sum_{i=1}^N X_{it} p_i + \sum_{i=1}^N \sum_{j=1}^N \sum_{t=1}^T T_{ijt} S_{ij} \leq Cap_t \quad \forall t \quad (3.6b)$$

$$X_{it} \leq M_{it} \left(\sum_{j=1}^N T_{jit} + \alpha_{it} \right) \quad \forall i, t, \quad (3.6c)$$

$$\sum_{i=1}^N \alpha_{it} = 1 \quad \forall t, \quad (3.6d)$$

$$\alpha_{it} + \sum_{j=1}^N T_{jit} = \alpha_{i,(t+1)} + \sum_{j=1}^N T_{ijt} \quad \forall i, t, \quad (3.6e)$$

$$V_{jt} \geq V_{it} + N \cdot T_{ijt} - (N - 1) - N \cdot \alpha_{i,t} \quad \forall i \neq j, t, \quad (3.6f)$$

$$X_{it}, I_{it}, \alpha_{it}, V_{ij} \geq 0 \quad \forall i, t, j \quad (3.6g)$$

$$T_{ijt} \in \{0, 1\} \quad \forall i, t, j \quad (3.6h)$$

Constraint (3.6a) is the inventory balance constraint which ensures that the demand is met via production or inventory. Constraint (3.6b) ensures that the total production and setup times does not exceed the capacity available. Constraint (3.6c) guarantees that a product can not be produced if the machine is not setup for it. Constraints (3.6d) to (3.6f) determine the sequence of the products and keep track of the machine state throughout time periods. (3.6d) ensures that the machine is setup for only one product at the beginning of a period. Constraint (3.6e) ensures a balanced network flow of the setups and carries the setup state over time periods. Constraints (3.6g) and (3.6h) define the bounds for the variables. α_{it} does not need to be a binary variable if the machine is setup for a product in the first time period, for the remaining time periods α_{it} is forced to integrality due to constraints (3.6d) and (3.6e). It is possible to let the model choose initial setup state by setting a binary condition on the α_{it} variable.

The setups can be explained using a graph. Assume that nodes correspond to products and arc (i, j) corresponds to a setup from product i to j . The set $\{(i, j) \mid T_{ijt} = 1\}$ corresponds to a set of disjoint path and cycles. Constraints (3.6a) to (3.6e) and (3.6g) to (3.6h) ensures that each solution have at most one path, but could have many subtours. (3.6f) ensures that only one single component is linked to α_{it} and hence, gives a feasible solution.

3.2.9 Applications of CLSP-SDSCST

Earlier research has adopted the CLSP-SDSCST in process industries and chemical industries (Ramya et al., 2019). The capacity is often well defined in process industries, and the capacity can not be expanded using overtime or additional shifts. Additionally, the setup times between products are often long and capital intensive (Smith-Daniels and Ritzman, 1988). In chemical industries, it is often necessary to clear remaining residue in the machine before starting a new production batch, which increases the setup times (Selen and Heuts, 1990).

Gupta and Magnusson (2005) adopted the CLSP-SDSCST in a sandpaper producer. The sandpaper has different roughness. The manufacturer uses different glue, depending on which roughness of the sandpaper that is produced. The machine needs to be cleaned after each different type of glue. The cleaning process takes time, which leads to high setup times. Gupta and Magnusson (2005) showed that it is possible to reduce setup-times via the use of CLSP-SDSCST.

Almada-lobo et al. (2007) adopted the CLSP-SDSCST in the glass container industry. This process consists of two steps, the furnace, which produces glass, and the molding machine,

which shapes the glass. The setups depend on which product is made in the molding machine. The furnace is still on during the setup, which wastes a tremendous amount of energy and is the main production cost. By considering product sequence, it was possible to minimize the cost (Almada-lobo et al., 2007).

There is little research of the CLSP-SDSCST in the discrete manufacturing industries. The discrete manufacturing industry is one who can stop or pause the manufacturing at any time. Examples are industries which produce automobile parts, furniture industry and smartphone manufacturers. However, Gnani et al. (2003) studied supply chain performance by considering sequence dependence in multiple plants within the supply chain. If an integrated production planning model was used throughout the whole supply chain, the total costs were reduced by 15 %.

3.3 Work Measurement

Work measurement aims to determine how long time it should take to perform a job. There are several reasons why a work measurement study is performed. Some of them are, according to Barnes (1949):

- Determine time standards and establishing piece-work rates
- Assistance when making improvements in production
- Production planning purposes

Incorrect times can, for example, lead to an under or over-estimation of production capacity, which results in higher costs in production (Olhager, 2013). Olhager (2013) and Reid and Sanders (2013) state that different methods exist which can be applied when conducting a work measurement study, where time study is one commonly used method and is described in detail in the upcoming subsection.

3.3.1 Time Study

Barnes (1949) defines time study as the analysis of a job with the purpose to determine the time it should take for a qualified worker, working at a normal pace, to finish the job using a definite and prescribed method. Stopwatch or video is often used to monitor and capture the times needed for the study. The steps to perform a time study can be broken down into the following (Reid and Sanders, 2013; Olhager, 2013):

1. Choose what to study. Example: A production line.
2. Tell the line-operator that a time study is going to be performed.
3. Divide the production line into smaller segments. Example: Drilling is one and sawing is another.
4. Calculate the number of cycles that need to be observed. Equation 3.7 can be used.
5. Time the worker, note the time and continue until all observations have been made.

$$n \geq \left[\left(\frac{z}{a} \right) \left(\frac{s}{x} \right) \right]^2 \quad (3.7)$$

Table 3.2 explains the different notations used in equation 3.7.

Table 3.2: Description of notations used in equation 3.7.

Notation	Description
n	Number of observations needed
z	Number of normal standard deviations needed for desired confidence
a	Desired accuracy or precision (sv. Risknivå)
s	Standard deviation of the sample
x	Mean of the sample

To compute equation 3.7 it is necessary to begin with a few observations to determine the standard deviation and sample mean.

An example from Reid and Sanders (2013) is used to demonstrate the use of equation 3.7. Assume that the observation object is the preparation time of a pizza. The sample standard deviation equals 0.01 and the mean of the sample equals 0.012. The confidence level is set to 95 % which corresponds to 1.96 normal standard deviations according to table values. The desired accuracy is set to 5 %. This states that the time to prepare a pizza is to be within 5 % of the true mean 95 % of the times.

These numbers put in Equation 3.7 yields:

$$n \geq \left[\left(\frac{1.96}{0.05} \right) \left(\frac{0.01}{0.012} \right) \right]^2 = 11 \quad (3.8)$$

This concludes that 11 observations or more are needed to get an accuracy of 5 % and a confidence level of 95 %.

Chapter 4

Company Description

This chapter presents IKEA as an organization and involves a comprehensive description of the studied factory in Hultsfred and its plinth production.

4.1 Inter IKEA Group

IKEA was founded in 1943 by Ingvar Kamprad, and it is an international company which primarily sells furniture and interior decoration. The company has 422 stores in more than 50 countries, and in 2018 the company had a turnover of 37.1 billion Euro (Inter IKEA Systems B.V., 2018b; Inter IKEA Systems B.V., 2018a).

The structure of IKEA as an organization is complicated. At the top of the hierarchy is Interogo Foundation which is a Liechtenstein based foundation. Interogo Foundation ultimately owns Inter IKEA Holding B.V which can be separated into three branches (Inter IKEA Systems B.V., 2018b):

- **Franchise** – Consists of IKEA Systems B.V. and its subsidiaries. This branch licenses the IKEA retail system and trademarks to franchises all over the world.
- **Range and Supply** – Consists of IKEA of Sweden AB, IKEA Supply AG, IKEA Communications AB and related businesses. This branch works through the whole supply chain and is responsible for developing and designing IKEA products.
- **IKEA Industry AB** – Produces home furnishing products and develops IKEA capacities in relevant parts of the supply chain, such as distribution and production. IKEA Industry AB produces around 12% of all IKEA products. IKEA Industry has production in 9 countries where Poland is the country with most factories, 12 in total. Examples of other countries where IKEA Industry AB also has production are Russia, Portugal and Sweden. Hultsfred and Älmhult are the two places which produce furniture in Sweden. Älmhult produces kitchen furniture while Hultsfred produces wardrobe furniture (Inter IKEA Systems B.V., 2016; Inter IKEA Systems B.V., 2018b). Figure 4.1 shows a simplified layout over the IKEA organization.

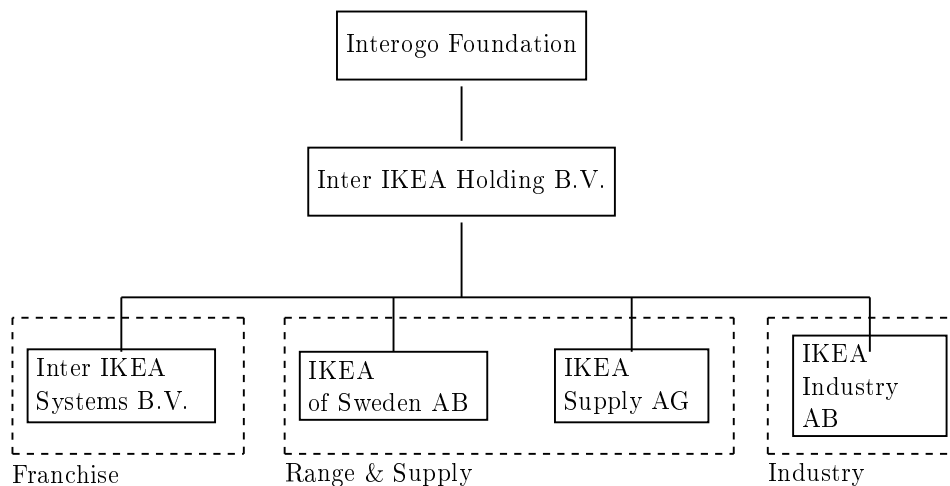


Figure 4.1: Inter IKEA Group.

4.2 IKEA Industry Hultsfred

The top, bottom, sides and plinths of the wardrobes are produced by IKEA Industry Hultsfred. They also produce shelves as previously stated in section 1.1. Figure 4.2 shows these components on an assembled wardrobe.

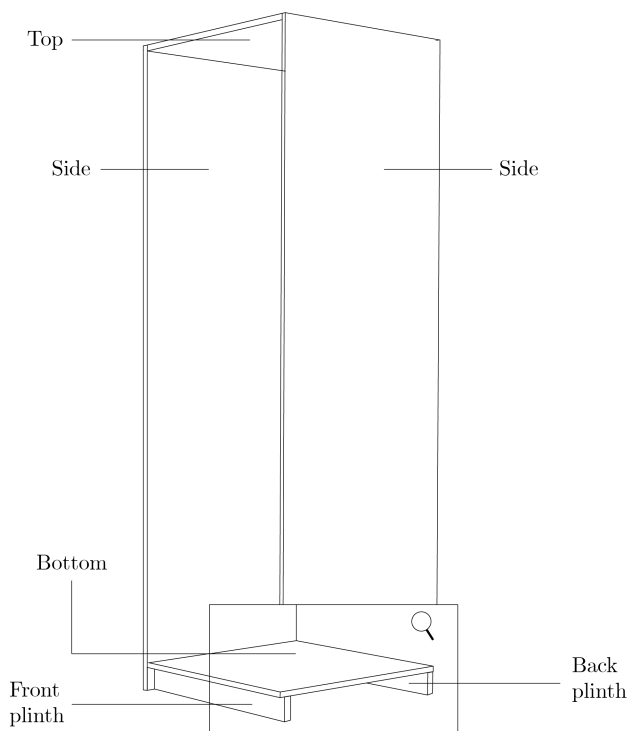


Figure 4.2: Description of the different parts of the wardrobe.

4.2.1 PAX Wardrobe

IKEA has a wardrobe system called PAX, which is the wardrobe system produced by IKEA Industry Hultsfred. The wardrobes come in ten different sizes with a size range from 50 cm to 100 cm in width, 35 cm to 58 cm in depth and 201 cm to 236 cm in height. The wardrobes have three different foils: white, white oak and black/brown (Inter IKEA

Systems B.V, 2020a). The most produced wardrobe is the one with white foil, which stands for 92% of the sales. White oak and black/brown have a sale of 4%, each ¹.

4.2.2 PAX Wardrobe Plinths

The wardrobes have three different foils where the front plinth matches the foil on the rest of the wardrobe. Wardrobes with a depth over 35 cm require two plinths, one foiled at the front and one unfoiled at the back. Wardrobes with a depth of 35 cm only require one foiled plinth at the front. Figure 4.3 shows from left to right: black/brown, white oak, white and unfoiled plinths.



Figure 4.3: Plinths with foils. From left to right: black/brown, white oak, white and unfoiled.

Table 4.1 shows a summary of the dimensions of wardrobes and foils of the different plinths. The first column describes the different widths of the wardrobes, and the second column describes which depths that are available. The third column states how many plinths needed that are needed for the wardrobe. The last column describes the length of the plinth.

Table 4.1: Dimensions for wardrobes.

Width on Wardrobe	Depth on Wardrobe	Number of Plinths Needed	Length on Plinth
100 cm	58 cm	2	961 mm
	35 cm	1	
75 cm	58 cm	2	711 mm
	35 cm	1	
50 cm	58 cm	2	461 mm
	35 cm	1	

Height and thickness of the plinths are 68 mm and 13 mm respectively, independent of length and foil. All plinths are available in white, white oak, black/brown and unfoiled. Each of the wardrobes also come in two different heights, 201 cm or 236 cm, but the number of plinths needed per wardrobe is not affected by the height of the wardrobe.

4.2.3 Production lines

IKEA Industry Hultsfred has six different production lines. The production starts in the first production line. This production line foils the raw-material (particleboards), and the

¹Klas Franzén, Managing director. Interview, 27th of January 2020.

particleboards are then cut to an appropriate length depending on which component the board is reserved for. The foiled boards are stored temporality until they are ordered out from any of the following production lines:

- **Line 2** – Produces top and bottom.
- **Line 3** – Produces sides.
- **Line 4** – Produces shelves.

The production line which produces the plinths is the fifth production line. The plinth production line does not order its material from the foiled particleboards inventory. Instead, this production line orders raw-material directly from the raw-material inventory. After the completion of all components, they are sent to a temporary inventory or to the packaging line, which is the sixth production line. After packaging, the parcels are sent to the finished goods inventory and awaits delivery to an IKEA-warehouse or IKEA-distribution centre. The next subsection presents a thorough description of the plinth production line.

4.2.4 System Description of the Plinth Production

The plinth production starts with the raw-material. The plinth production line receives the raw-material from the raw material inventory on an automated vehicle. The raw-material consists of particleboards, and the line-operators orders it to the production line. The particleboards can have three different lengths, depending on what length the plinth has.

A robot unloads layers from the pallet of particleboards and lifts them onto the plinth production line. It is not possible to buffer particleboards at the robot. Consequently, the production of the planned length must continue until all the particleboards are depleted before another length of plinth can be produced.

After the robot, the particleboard is sawn horizontally into three equal pieces. The board then passes a gritting station. The gritting smoothens the board and is required to achieve a good result when the foil is applied. The next step is foiling. A machine applies glue to the board and then foil. The glue is required for the foil to stick to the boards. IKEA Industry Hultsfred also produces unfoiled boards. The unfoiled boards take the same route as the foiled board but do not get any glue or foil applied.

The board is sawed vertically after the foiling station. If plinths of 50 cm are produced, the outcome is that each board results in five plinths. A board is from now on referred to as plinth. The plinths have now the correct length, which corresponds to 461, 711 or 961 mm depending on which length of plinth produced. 461, 711 and 961 mm are hereinafter referred to as 50 cm, 75 cm and 100 cm throughout this thesis.

Two holes at each end of the plinth are drilled after the second sawing. The holes are at the same place, independent on foil or length. After the drilling station, the plinths are moved onto pallets by another robot. A line operator moves the pallets from the production line by using a forklift. The line operator moves the pallet when it is fully loaded. A pallet of plinths is also moved when all the raw-material for the specific plinth is depleted. The inventory is placed only a few meters from the assembly line. Figure 4.4 shows the production layout described.

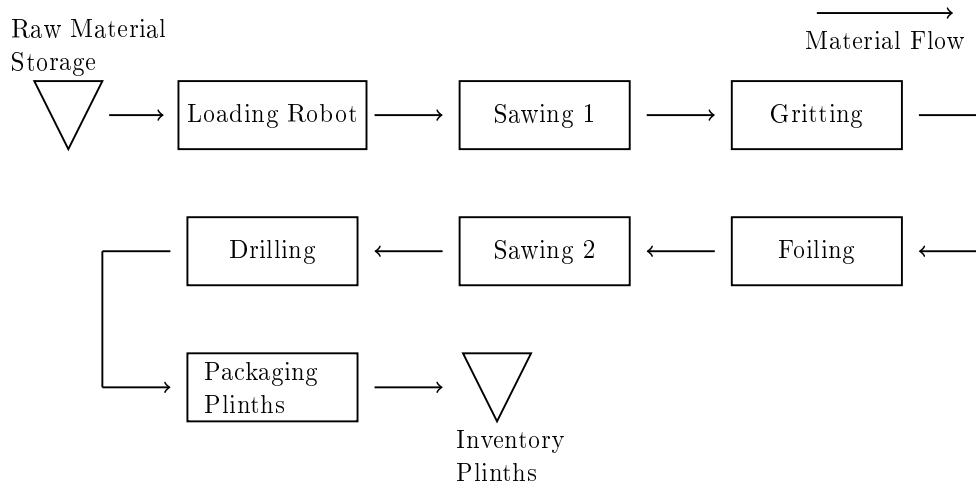


Figure 4.4: Simplified view of the plinth production.

4.2.5 Shift and Schedule

All the production lines except the plinth production line run 24/7 and the production personnel have a five-shift schedule. The plinth production is running one shift six times a week, and two shifts on one day of the week due to schedule structures. One shift at the plinth production is eight hours, and each shift has a lunch break of 30 minutes. The production is shut down during lunch. The plinth production line always has two operators that are in control of the production line, if needed it is possible to introduce additional shifts and increase the production to meet changes in the demand ².

4.2.6 Raw-Material

The raw-material that is used to produce the plinths is delivered on pallets. These pallets with raw-material are from now on referred to as stacks. Each stack consists of 44 layers of particleboards where each layer has five individually sawn particleboards. The length of the raw-material depends on which plinth length that is produced. Table 4.2 displays the length of the particleboard for each plinth length.

Table 4.2: Length of the particleboards.

Plinth length	Length of one particleboard (meter)
100 cm	1.980
75 cm	2.190
50 cm	2.365

The number of plinths that can be produced from a stack is also different dependent on plinth length. Table 4.3 shows how many finished plinths it is possible to produce from one stack of raw-material.

Table 4.3: Number of plinths per stack.

Plinth length	Number of plinths per stack
100 cm	1320 plinths
75 cm	1980 plinths
50 cm	3300 plinths

²Klas Franzén, Managing director. Interview, 27th of January 2020.

Chapter 5

Situation Assessment

This section contains details on how the production planning is conducted today. This section also describes the data from the time-study that has been made and the result of the conducted time-study.

5.1 Production Planning Overview

IKEA Industry Hultsfred uses a Make To Stock (MTS) strategy for the production. The central organization at IKEA delivers the prognosis for a whole year with an update every Monday. The production rate in the factory is decided by production lines one to four. That is, not the plinth production. The master production schedule is frozen for the first eight weeks in the planning horizon where only minor changes are made.

A software is used to plan the production sequence and the number of wardrobes to be produced on production lines one to four. The same sequence is used when the plinth production is planned. This sequence is not necessarily optimal for the plinth production in terms of setup times or inventory levels. Column one to three in Table 5.1 is decided by the software. The number of foiled plinths needed is shown in column four which is also decided by the software. However, the number of unfoiled plinths to be produced has to be decided manually by knowing if the specific wardrobe requires an unfoiled plinth or not¹. If the wardrobe requires both a foiled and an unfoiled plinth depends on the depth of the wardrobe, see Section 4.2.2.

Table 5.1: A part of a plinth production plan.

Nr.	Plinth length (cm)	Color	Plinth Need
1	50	White	3168
2	50	Unfoiled	3168
3	75	Black/Brown	1056
4	75	Unfoiled	1056
5	100	White	1584
6	50	White	3168
7	50	Unfoiled	3168

For the example presented in Table 5.1, 3168 white foiled plinths with a length of 50 cm are produced first. Secondly, 3186 unfoiled 50 cm plinths are produced and so forth. Although

¹Annete Strand, Supply Chain Manager, Interview 11th of February 2020

the production sequence is the same, the plinth production is not synchronized with the rest of the production lines. The plinth production can at times be days ahead, compared to the other production lines. For instance, the plinth production can produce 1000 white 50 cm plinths on Monday, while the packaging line needs those plinths first on Friday the same week. However, the production sequence can be changed. If the production sequence is changed depends on two things. The first is when the demand for the plinths are needed. If the plinth production is days ahead and already has fulfilled the demand for the upcoming days, it is possible to swap. The second factor is depending on the operator. Not all operators swap the production sequence; hence, the changes are not consistent throughout all days. In the example in Table 5.1, it is possible to swap Nr. 7 with Nr. 3 and Nr. 6 with Nr. 4, if the demand for the upcoming days already have been produced. This results in two fewer setups and thereby saved setup time.

5.2 Production Overview

This section presents the collected data at IKEA Industry Hultsfred. Some of the data has been collected via time-studies while some data is based on interviews with the line-operators, and some data is from the database at IKEA Industry Hultsfred.

5.2.1 Stop Times for Plinth Production

Historical data over stop times in the production was available in the internal data system at IKEA Industry Hultsfred. The operators report the stop times. The stop times includes lunch-breaks, unscheduled stops and other scheduled stops. A typical shift is 480 minutes with a break of 30 minutes each shift. Henceforth, only shifts with a length of 480 minutes and where the scheduled stops were 30 minutes was taken into consideration when sorting the data. Therefore, shifts with staff meetings or other scheduled stops were removed since these occurrences are unusual and do not represent a typical shift. The historical data over stop times has been selected from 2019-01-12 to 2020-03-04 to reassure that the data used is still valid since no significant changes have been made in the production process during this period.

One shift including startup and shutdown procedure, other unscheduled stops and 30 minutes lunch break has an average stop time of 155 minutes. The total available time for production during one shift is, therefore, $480 - 155 = 325$ minutes. If two shifts are conducted after each other, one startup and shutdown procedure can be removed. For instance, one shift begins at 06:00 with a startup procedure, and the shift ends 14:00. If another shift begins at 14:00 and ends 22:00, there is no need for a startup procedure at 14:00, since there is a handover between the two shifts. However, a shutdown procedure at 22:00 is required.

If the startup and shutdown procedure is removed the average total stop time is reduced to 140 minutes. Hence, the available production time for two shifts is $480 \cdot 2 - 155 - 140 = 665$ minutes. If three shifts are conducted per day, the start and shutdown procedure is removed entirely since the production is always running. The total time available for production is $480 \cdot 3 - 140 \cdot 3 = 1020$ minutes.

The result is summarized in Table 5.2.

5.2.2 Cycle Times

The cycle times have been calculated by measuring the total time it takes to fill one pallet of plinths, and the total time to fill one pallet of plinths has then been divided with the

Table 5.2: Stop times per shift based on historical data.

No. Shifts per day	Total shift time (minutes)	Average Stop Time (minutes)	Available Time for Production (minutes)
1	480	155	$480 - 155 = 325$
2	960	295	$960 - 295 = 665$
3	1440	420	$1440 - 420 = 1020$

number of plinths per pallet.

This measurement and calculation has been conducted for all lengths. The cycle times only depend on length, not on foil or unfoiled. Hence, white plinths of length 100 cm have the same cycle time as unfoiled plinths of length 100 cm. Four initial measurements were conducted and used to calculate the total number of measurements needed. A confidence level of 95 % was used and a risk level of four percent, which was based on the example in Olhager (2013). The collected data can be found in Appendix B. Table 5.3 shows the result of the time study.

Table 5.3: Result of the time study.

Length of Plinth	Total number of measure- ments	Mean time to fill one pallet (seconds)
100 cm	11	495.75
75 cm	5	552.50
50 cm	5	620.75

The cycle time per plinth is calculated by dividing the total time to fill one pallet with the total number of plinths per pallet. Table 5.4 shows the cycle time for each plinth length.

Table 5.4: Cycle times for the different plinths.

Length of Plinth	Mean time to fill one pallet (seconds)	Number of plinths per pallet	Cycle time per plinth (seconds)
100 cm	495.75	550	0.90
75 cm	552.50	850	0.65
50 cm	620.75	1100	0.56

5.2.3 Setup Times

No time study regarding the setup times has been conducted in this thesis. The setup times used are based on the reported numbers from the operators ². The setup times are as follows:

- **Change of length:** Is when the production is changed from one length of plinth to another. Ex. from 50 cm to 100 cm. A foil change can be done at the same time as the change of length, no additional time is required for the foil change. This procedure takes on average 16 minutes.

²Production personnel, Interview 3rd of March 2020

- **Foil change:** Change from foiled to unfoiled, the opposite or from one foil to another foil. This procedure takes on average 10 minutes.

5.3 Production Scheduling Example

The following section presents an illustrative example of how the production is conducted over seven days, with one shift per day (325 minutes of available production time). The demand is based on a prognosis from IKEA Industry Hultsfred and the demand is a week in March. Table 5.5 shows the demand for seven days for the different plinths. The initial inventory level is assumed to be zero. Full stacks are used for the specific plinth type. To clarify, it is possible to produce 1320 pieces of 100 cm plinths from one stack, but 1320 plinths will always be produced even if the demand is only 1056 plinths. As a result, there will be an excess of plinths since more plinths are produced than the demand.

The inventory levels are inspected at the beginning of each week, and the production is adjusted for the upcoming week, depending on the inventory levels. However, this adjustment is not shown in the example since the example only considers one week. Producing times, setup times and cycle times used in the example are found in section 5.2.1 to 5.2.3.

The demand over the seven days is assumed to be as shown in Table 5.5.

Table 5.5: The demand for each day in the example.

Plinth Type	Demand per Day						
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
100 cm white	0	5280	4224	5280	0	8976	6336
100 cm white oak	0	0	0	0	0	0	0
100 cm black/brown	0	0	0	0	4752	0	0
100 cm unfoiled	0	5280	4224	5280	4752	8976	6336
75 cm white	0	0	4224	4224	0	0	0
75 cm white oak	0	0	0	0	0	0	0
75 cm black/brown	0	0	0	0	2112	0	0
75 cm unfoiled	0	0	4224	4224	0	0	0
50 cm white	10560	4224	1056	0	1056	0	0
50 cm white oak	0	0	0	0	0	0	0
50 cm black/brown	0	0	0	0	0	0	0
50 cm unfoiled	10560	4224	1056	0	1056	0	0

Table 5.6 shows the full production planning schedule over the seven shift period. Column one shows the plinth length and foil. The second column shows the demand for the next day. The demand for the next day is assumed to be immediately needed at the beginning of the next day and must, therefore, be completed at least one day before. The time to produce the demand is shown in column three, while the fourth shows how many plinths that are produced. Column five shows the production time for the plinths. Column six shows total time spent on setup and column seven the inventory at the end of the day.

Table 5.6: How the production is conducted over the seven days.

Plinth Type	Plinth Demand Upcoming Day	Production Time Demand (Minutes)	No. Plinths Produced	Actual Production Time (Minutes)	Setup Time (Minutes)	Inventory (Pallets)
Shift 1						
50 cm unfoiled	10560	98.2	13200	122.8	16	3
50 cm white	10560	98.2	13200	122.8	10	3
Sum Shift 1	21120	196.4	26400	245.5	26	6
Shift 2						
50 cm white	4224	39.3	3300	30.7	0	2
50 cm unfoiled	4224	39,2832	3300	30.7	10	2
100 cm white	5280	79.2	5280	79.2	16	0
100 cm unfoiled	5280	79.2	9240	139.0	10	8
Sum Shift 2	19008	237.0	21120	279.1	36	12
Shift 3						
100 cm unfoiled	4224	63.4	1320	19.9	0	2
100 cm white	4224	63.4	5280	79.2	10	2
75 cm white	4224	46.5	7920	87.1	16	5
75 cm unfoiled	4224	46.5	7920	87.1	10	5
50 cm white	1056	9.8	0	0	0	1
50 cm unfoiled	1056	9.8	0	0	0	1
Sum Shift 3	19008	239.3	22440	273.2	36	16
Shift 4						
75 cm unfoiled	4224	46.5	1980	21.8	0	2
75 cm white	4224	46.5	1980	21.8	10	2
100 cm white	5280	79.2	5280	79.2	16	2
100 cm unfoiled	5280	79.2	10560	158.4	10	12
50 cm white	0	0	0	0	0	1
50 cm unfoiled	0	0	0	0	0	1
Sum Shift 4	19008	251.3	19800	281.2	36	20
Shift 5						
100 cm unfoiled	4752	71.3	3960	59.4	0	11
100 cm black/brown	4752	71.3	5940	89.1	10	3
75 cm black/brown	2112	23.2	3960	43.6	16	3
50 cm white	1056	9.8	3300	30.7	16	3
50 cm unfoiled	1056	9.8	3300	30.7	10	3
75 cm unfoiled	0	0	0	0	0	2
75 cm white	0	0	0	0	0	2
100 cm white	0	0	0	0	0	2
Sum Shift 5	13728	185.4	20460	253.4	52	15
Shift 6						
100 cm white	8976	134.6	7920	119.0	16	0
100 cm unfoiled	8976	134.6	9240	138.6	10	11
100 cm black/brown	0	0	0	0	0	3
75 cm black/brown	0	0	0	0	0	3
50 cm white	0	0	0	0	0	3
50 cm unfoiled	0	0	0	0	0	3
75 cm unfoiled	0	0	0	0	0	2
75 cm white	0	0	0	0	0	2
Sum Shift 6	19008	269.3	17160	254.4	26	27
Shift 7						
100 cm unfoiled	6336	95.0	1320	19.8	0	2
100 cm white	6336	95.0	6600	99.0	10	1
50 cm white	0	0	0	0	0	3
50 cm unfoiled	0	0	0	0	0	3
75 cm unfoiled	0	0	0	0	0	2
75 cm white	0	0	0	0	0	2
75 cm black/brown	0	0	0	0	0	3
100 cm black/brown	0	0	0	0	0	3
Sum Shift 7	12672	190.1	7920	118.8	10	19

Only limited data on how the production is conducted in practise was available. Therefore,

the example presented in Table 5.6 is based on observations made at IKEA Industry Hultsfred. The following observations were used in the example:

The line operators only take the demand in the upcoming day into consideration. If there is a demand of 50 cm plinths on day two and day three, all the demand is produced on the first day. The line operators do not examine the demand on day four or five or any other upcoming day. Low emphasis is put into minimizing inventory levels, and the plinth production continues to produce plinths as long as the inventory space is available.

Notice that the presented production schedule only is an illustrative example of how the production planning could be done over seven days. In practice, there are always eight shifts per seven days, but not in the example. This will, however, not have an impact since the presented example is only illustrative of how the production planning could be done, based on observations at IKEA Industry Hultsfred. This example will later be used in Chapter 7 to illustrate the advantage of using optimization in a production planning context.

Chapter 6

Mathematical Formulation

Earlier chapters have described the advantage of using optimization for production planning purposes. Section 3.2.8 presented an optimization model by Almada-lobo et al. (2007). This chapter maps the characteristics of the optimization model by Almada-lobo et al. (2007) to the plinth production at IKEA Industry Hultsfred, and presents necessary extensions to the model. This chapter also covers the selected optimization software and verification of the implementation of the model as proposed by Almada-lobo et al. (2007). Full verification of the model with its extensions is found in Section 7.1.

6.1 Optimization Model Characteristics

The chosen optimization model must map the production at IKEA Industry Hultsfred to achieve a relevant result. The optimization model by Almada-lobo et al. (2007) presented in Section 3.2.8 maps the plinth production at IKEA Industry Hultsfred well, specifically on the following characteristics:

- The model considers sequence dependence. This is an important aspect since the setup time between plinths with the same length is different compared to plinths with different length and setup times between foiled and unfoiled plinths also differ.
- The model by Almada-lobo et al. (2007) is a large bucket model which means that several setups can be processed in each period. Hence, several products can be produced in one period. One of the delimitations of this thesis is only to conduct aggregate planning. It is assumed that one time period in the model corresponds to one day of production. Therefore, it is necessary to have a model where several products can be produced in each period.
- It is possible to setup for a product at one time period, even if the product is not produced in that period. This minimizes setup times for the succeeding time period. This also brings the model closer to reality since the operators at IKEA Industry Hultsfred occasionally sets up the machine at the end of some shifts to prepare for the next shift.

6.1.1 Software

The software used to implement the optimization model is CPLEX Studio by IBM. It is based on Optimization Programming Language (OPL) which is an algebraic language well suited for implementing mathematical formulations. CPLEX is also one of the leading solvers for solving MIP problems (Mittelman, 2019; Duque, Arbelaez, and Díaz,

2019).

6.1.2 Verification of the Implementation

It is of great importance that the optimization model is implemented correctly and outputs a feasible and correct result. The formulation presented in Section 3.2.8 was implemented in CPLEX Studio with data from Almada-lobo et al. (2007). Thus, it is possible to compare the solutions from Almada-lobo et al. (2007) and draw a conclusion of whether the solution is correct or not.

The following data is used. $Cap_t = 100$ for every t and $p_i = 1$ for every i . $s_{ij} = 5$ for $i \neq j$ and zero otherwise. Initial inventory levels are zero, and the machine is setup for product three at the beginning of time period one. The other input data is shown in Table 6.1.

Table 6.1: Input data for the example problem.

	d_{it}			c_{ij}			h_i
	t=1	t=2	t=3	j=1	j=2	j=3	
i=1	15	5	10	0	3	3	10
i=2	20	35	20	4	0	3	15
i=3	0	110	40	5	5	0	20

The result of the test data is shown as a Gantt chart in Figure 6.1. By comparing this solution to Almada-lobo et al. (2007) it is possible to draw the conclusion that the result of this implementation is the same as in Almada-lobo et al. (2007). Hence, this is an indication that the implementation is correct.

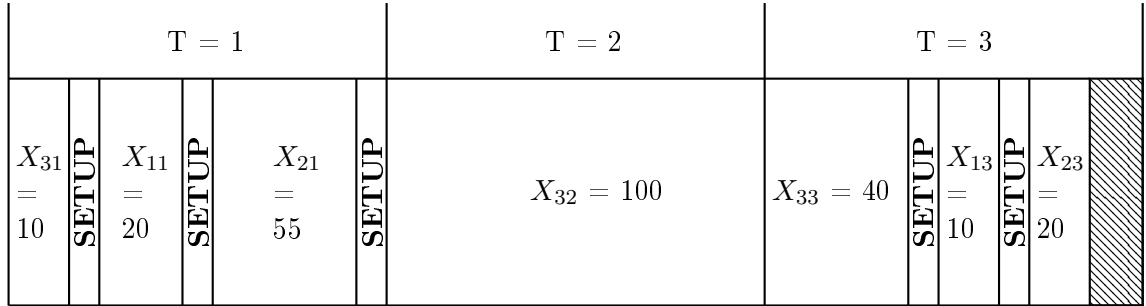


Figure 6.1: Gantt Chart of the optimal solution for the test data.

Three setups occur in the first time period. At the end of the first-period setup is made for product three, which means that no setup needs to be made in the second period. From period two to three, it is also visible that the setup state can be carried over from one time period to the next since no setup is made at the beginning of the third period. All available capacity is used in the first two periods but not in the third. This is visualized with the diagonal lines at the end of the third period in Figure 6.1.

6.1.3 Model Extensions and Corrections

The model presented in Section 3.2.8 has many similar characteristics to the production at IKEA Industry Hultsfred. However, it is possible to extend the model to match the characteristics of the plinth production at IKEA Industry Hultsfred even better.

- **Initial setup state:** If an initial setup state is given for the machine, the integrality condition of the α_{it} variable can be removed and slightly reduce the complexity of

the model (Almada-lobo et al., 2007). An initial state is formulated as a constraint:

$$\alpha_{i,0} = 1 \quad (6.1)$$

Where i can be a randomly chosen or deliberately chosen product.

- **Initial inventory levels:** It is assumed that the inventory levels in the beginning of the first period is zero, for all products. This yields:

$$I_{i,0} = 0 \quad \forall i \quad (6.2)$$

- **Reformulation of the capacity constraint:** The capacity constraint (3.6b) has three sums in the second term on the left-hand side. This is incorrect according to previous research (Gupta and Magnusson, 2005; Gopalakrishnan, 2000; Haase and Kimms, 2000; Trigeiro, Thomas, and McClain, 1989). The correct formulation of the capacity constraint is the following:

$$\sum_{i=1}^N X_{it} p_i + \sum_{i=1}^N \sum_{j=1}^N T_{ijt} S_{ij} \leq Cap_t \quad \forall t \quad (6.3)$$

- **Production Quantities:** One stack of raw-material, i.e. the particleboards, at IKEA Industry Hultsfred can only be used to produce one specific plinth length, and one stack of raw-material needs to be fully emptied before the next plinth length can be produced. An example: One stack of raw-material for 50 cm plinths can only produce 3300 pieces. Hence, the number of 50 cm plinths to be produced must equal a multiple of 3300. The corresponding number for 75 cm plinths is 1980 pieces and 1320 pieces for 100 cm plinths, as previous presented in Table 4.3 in Section 4.2.6. Table 6.2 shows an example of production quantities for one stack of raw-material for 50 cm plinths.

Table 6.2: Example of production quantities for 50 cm plinths.

Plinth length and foil	Number produced
50 cm white	1000
50 cm white oak	500
50 cm black/brown	500
50 cm unfoiled	1300
Total produced	3300

In Table 6.2 the multiple is one, since $3300 \cdot 1 = 3300$. Another example of production quantities is given in Table 6.3.

Table 6.3: Another example of production quantities for 50 cm plinths.

Plinth length and foil	Number produced
50 cm white	4000
50 cm white oak	1000
50 cm unfoiled	1600
Total produced	6600

In Table 6.3 the multiple is two since, $3300 \cdot 2 = 6600$. The idea is the same for plinths of 75 cm and 100 cm with the difference that the number of plinths that can be produced from one stack of raw-material is different.

The plinths are produced in three different lengths, and they are divided into three sets. Plinths of length 100 cm in set S_a , and plinths of length 75 cm and plinths of length 50 cm in set S_b and S_c , respectively.

$$\begin{aligned} S_a &= \{100 \text{ cm white}, 100 \text{ cm white oak}, 100 \text{ cm black/brown}, 100 \text{ cm unfoiled}\} \\ S_b &= \{75 \text{ cm white}, 75 \text{ cm white oak}, 75 \text{ cm black/brown}, 75 \text{ cm unfoiled}\} \\ S_c &= \{50 \text{ cm white}, 50 \text{ cm white oak}, 50 \text{ cm black/brown}, 50 \text{ cm unfoiled}\} \end{aligned}$$

The production quantities from one stack of raw-material is defined by the variable n_k and have the following values:

$n_a = 1320$ for 100 cm plinths.

$n_b = 1980$ for 75 cm plinths.

$n_c = 3300$ for 50 cm plinths.

The variable Y_{it} is also introduced. Y_{it} is the number of multiples of raw-material for product i that is needed in period t . $Y_{it} \in \mathbb{Z}_{\geq 0}$

$$\sum_{i \in S_k} X_{it} = n_k \cdot Y_{it} \quad \forall i \in t, k = a, b, c \quad (6.4)$$

Constraint (6.4) ensures that the production quantity for each length equals multiples of plinths that can be produced from the raw-material.

- **Objective function:** The objective function is adjusted to:

$$\text{Minimize } (1 - \lambda) \sum_{t=1}^T \sum_{i=1}^N \sum_{j=1}^N S_{ij} T_{ijt} + \lambda \sum_{t=1}^T \left(\sum_{i \in a} \frac{I_{it}}{550} + \sum_{i \in b} \frac{I_{it}}{850} + \sum_{i \in c} \frac{I_{it}}{1100} \right)$$

Which aims to minimize the total time spent on setup and the total inventory levels. λ is a weighting factor associated with the weighted sum method, see Section 3.2.5. The cost for inventory, h_i is removed since no data regarding inventory cost were available. Instead the inventory space is considered.

For the inventory levels, the number of pallets is considered and not the number of individual plinths. The number of plinths is divided by the number of plinths on one pallet to consider inventory space. 550 is the number of finished plinths per pallet for plinths with a length of 100 cm. The corresponding number for plinths of 75 cm and 50 cm is 850 and 1100. The sets S_a, S_b, S_c are the same as earlier:

$$\begin{aligned} S_a &= \{100 \text{ cm white}, 100 \text{ cm white oak}, 100 \text{ cm black/brown}, 100 \text{ cm unfoiled}\} \\ S_b &= \{75 \text{ cm white}, 75 \text{ cm white oak}, 75 \text{ cm black/brown}, 75 \text{ cm unfoiled}\} \\ S_c &= \{50 \text{ cm white}, 50 \text{ cm white oak}, 50 \text{ cm black/brown}, 50 \text{ cm unfoiled}\} \end{aligned}$$

6.1.4 Input Data

The model has the following input which needs to be specified:

- **Number of periods (T):** The number of periods on the planning horizon needs to be specified. Since the complexity increases with more periods it is necessary to find a good ratio between computational time and desired output. The number of periods used are specified for each scenario, see Chapter 7.

- **Products (N):** The number of products is twelve, and does not change.
- **Initial setup state (α_{it}):** α_{it} is set to a continuous variable, and an initial setup state is needed to have a valid model. α_{it} is set to α_{10} , which says that the machine is setup for product 1 in the first period. The product is set to 100 cm white plinths.
- **Demand (d_{it}):** The demand for each product in each period is a required input. It is expressed in the number of plinths.
- **Setup times (S_{ij}):** Setup times between all products is a necessary input. It is entered in minutes.
- **Production Quantities (n_k):** The number of plinths that is possible to produce from one stack raw-material depends on the length, which is summarized in Table 4.3 in Section 4.2.6.
- **Available Production Time (Cap_t):** Is given in minutes per period.
- **Processing time for one plinth (p_i):** This is given in minutes and is different depending on plinth length. See Table 5.4.

6.1.5 Extended model and Improved Model

The extended model is made by adding the extensions in Section 6.1.3 to the presented model by (Almada-lobo et al., 2007) in Section 3.2.8.

$$\text{Minimize } (1 - \lambda) \sum_{t=1}^T \sum_{i=1}^N \sum_{j=1}^N S_{ij} T_{ijt} + \lambda \sum_{t=1}^T \left(\sum_{i \in a} \frac{I_{it}}{550} + \sum_{i \in b} \frac{I_{it}}{850} + \sum_{i \in c} \frac{I_{it}}{1100} \right) \quad (6.5)$$

$$\text{subject to } I_{it} = I_{i,t-1} + X_{it} - d_{it} \quad \forall i, t, \quad (6.6a)$$

$$\sum_{i=1}^N X_{it} p_i + \sum_{i=1}^N \sum_{j=1}^N T_{ijt} S_{ij} \leq Cap_t \quad \forall t, \quad (6.6b)$$

$$X_{it} \leq M_{it} \left(\sum_{j=1}^N T_{jit} + \alpha_{it} \right) \quad \forall i, t, \quad (6.6c)$$

$$\sum_{i=1}^N \alpha_{it} = 1 \quad \forall t, \quad (6.6d)$$

$$\alpha_{it} + \sum_{j=1}^N T_{jit} = \alpha_{i,(t+1)} + \sum_{j=1}^N T_{ijt} \quad \forall i, t, \quad (6.6e)$$

$$V_{jt} \geq V_{it} + N \cdot T_{ijt} - (N - 1) - N \cdot \alpha_{i,t} \quad \forall i \neq j, t, \quad (6.6f)$$

$$I_{i,0} = 0 \quad \forall i, \quad (6.6g)$$

$$\alpha_{1,0} = 1 \quad (6.6h)$$

$$\sum_{i \in S_k}^N X_{it} = n_k \cdot Y_{it} \quad \forall i \in t, k = a, b, c \quad (6.6i)$$

$$Y_{it} \in \mathbb{Z}_{\geq 0} \quad \forall i, t \quad (6.6j)$$

$$X_{it}, I_{it}, \alpha_{it}, V_{ij} \geq 0 \quad \forall i, t, j, \quad (6.6k)$$

$$T_{ijt} \in \{0, 1\} \quad \forall i, t, j, \quad (6.6l)$$

$$(6.6m)$$

Constraint (6.6a) is the inventory balance constraint and (6.6b) is the capacity constraint. Constraint (6.6c) guarantees that a product can not be produced if the machine is not setup for it and constraints (6.6d) to (6.6f) determine the sequence of the products and keep track of the machine state throughout time periods. Constraint (6.6g) states that the initial inventory in the first period is zero. Constraint (6.6h) states that the machine is setup for product one in the first period. Constraint (6.6i) defines the multiple of raw-material. Constraint (6.6j),(6.6k) and (6.6l) defines the bounds for the variables.

Chapter 7

Result and Analysis

Five different scenarios has been optimized and analyzed, and are presented below. These scenarios are chosen due to several reasons. The first two are selected to show an indication of how inventory levels and setup times could be improved over seven days, with only a different production planning method. The third and fourth scenario are given by IKEA Industry Hultsfred to evaluate if it is possible to produce more plinths, and which inventory levels and setup times that would give. The last scenario is a "what-if" scenario which could prove useful for IKEA Industry Hultsfred to indicate which lead-time that can be offered to the factories in Germany and Portugal.

- **Scenario 1:** Section 5.3 described how the production is conducted in practice for seven days. Scenario 1 presents an optimal solution to the same problem as in Section 5.3.

The purpose for this scenario is to show the potential of using an optimization model to conduct the production planning, and show how large differences in setup time and inventory levels such a model could generate, compared to the example in Section 5.3.

Further, the purpose is to show how the inventory levels and setup times depend on each other and how they affect the capacity utilization. This is visualized via a Pareto front, amount of unused capacity and the development of inventory levels. The Pareto front and the other solutions were generated by using the weighted sum method, see Section 3.2.5.

- **Scenario 2:** This scenario uses the same demand data as in Scenario 1, but lower available time for production. In this scenario, 325 minutes are available from the first day to the sixth, and none on the seventh day. The purpose of this scenario is to show that a seven-day demand can be produced in six days. The purpose is also to show how inventory levels and setup times depend on each other, i.e., how setup times are changed when more emphasis is put into minimizing setup times, and the other way around. The emphasis which decides how inventory levels and setup times are balanced is adjusted by using the weighted sum method, see Section 3.2.5. The result is a Pareto front, a figure over the inventory development over the seven days and a figure over the amount of unused capacity. The figure over the unused capacity is used to analyze the unused time and evaluate which solutions that give the most or least amount of unused capacity.
- **Scenario 3:** In this scenario, orders for the factories in Germany and Portugal are taken into account. The lead time is, according to IKEA Industry Hultsfred, three

weeks (21 days) and therefore a longer planning horizon of 16 days is used in this optimization scenario. The transportation is assumed to take six days to Portugal, and four to Germany, therefore, the planning horizon is shorter than 21 days. The purpose of this scenario is to show how the inventory levels and setup times depend on each other; this is made by changing the λ parameter, see Section 3.2.5. The purpose is also to see how much capacity needed to produce the demand for the factories in Germany and Portugal. The result is presented in a Pareto front for the different λ , a figure over the unused capacity for each day and an inventory development graph. The figure over unused capacity is used to evaluate which solutions give the most unused capacity, and when the most unused capacity occurs. The inventory development graph is used to visualize how the inventory changes over the 16 days.

- **Scenario 4:** According to IKEA Industry Hultsfred, the demand from Germany and Portugal could vary by a 15% increase. Except for the increased demand, this scenario is the same as Scenario 3. The same figures as the previous scenario are presented.
- **Scenario 5:** This scenario considers a shorter lead-time to the factories in Portugal and Germany. The orders are to be finished as soon as possible after received order. This is more a "what-if" scenario to see how large quantities IKEA Industry Hultsfred can produce during a short amount of time. The weighted sum method is used in this scenario to evaluate how inventory levels and setup times affect each other. A Pareto front, unused capacity, and inventory development graphs are displayed.

7.1 Scenario 1 - Solution over seven days

This subsection presents the optimal solution for the same problem as presented in Section 5.3.

The problem was solved with the λ parameter varying from 0.0 to 1.0 with a step size of 0.05 to display how the balance between inventory level and setup times changes. The chosen step size was a compromise between computational time and the number of solutions desired. A smaller step size results in more optimization runs, which affects the total computational time. More emphasis is put on minimizing the total inventory when λ is large. A small λ aims to minimize the total time spent on setup while putting less emphasis on minimizing the inventory levels.

Figure 7.1 shows the different solutions with varying λ values. The x-axis shows the total time spent on setup, while the y-axis represents the average number of pallets in inventory at the end of each day. The λ values for each of the solutions are found in Figure 7.1. The black dot in Figure 7.1 also displays the solution from Section 5.3. The position of the black dot shows that neither inventory nor setup times are optimized today since the dot is not on the Pareto front.

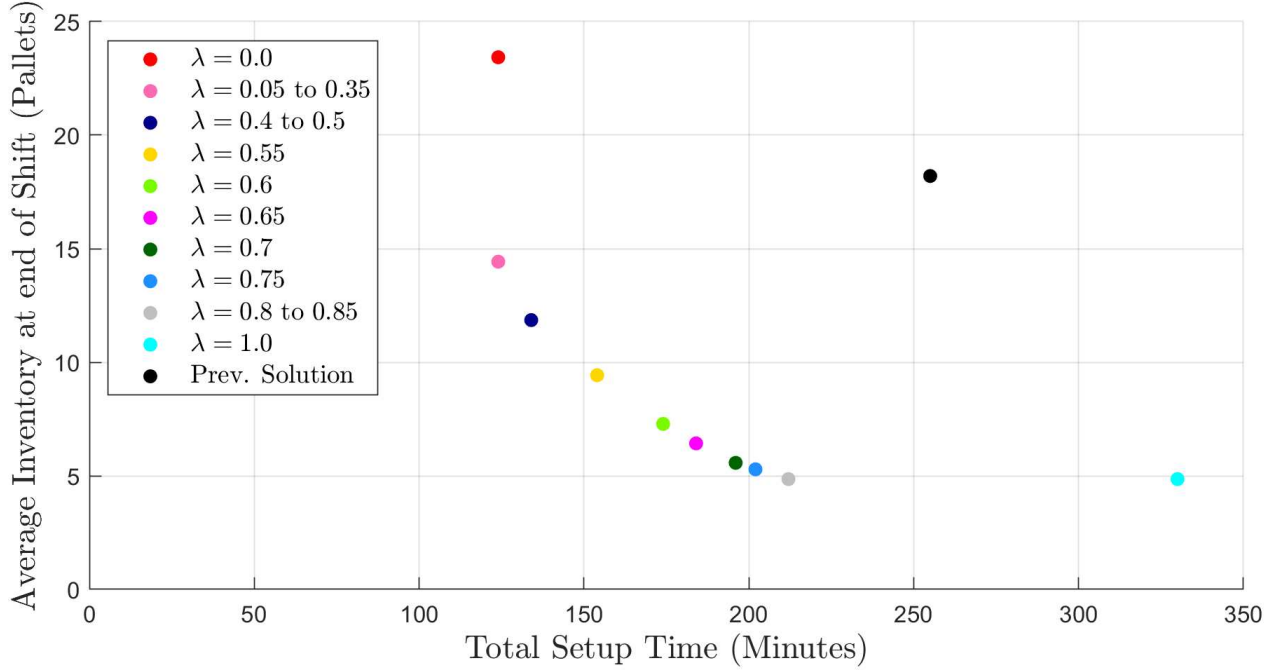


Figure 7.1: Optimal solutions for different λ values.

Figure 7.1 shows optimal solutions for the different λ values. $\lambda = 0.0$ outputs the same setup time as $\lambda = 0.05$. However, the inventory levels are higher for $\lambda = 0.0$, and this could be considered a worse solution with no advantage in either setup times or inventory levels, compared than when $\lambda = 0.05$. The same principle goes for when $\lambda = 1.0$, which outputs the same inventory levels as $\lambda = 0.8$, but with higher setup times. Hence, more time is spent on setup with no improvement in inventory. All the instances of λ were solved to optimum.

Figure 7.2 shows the unused capacity per day and for each λ .

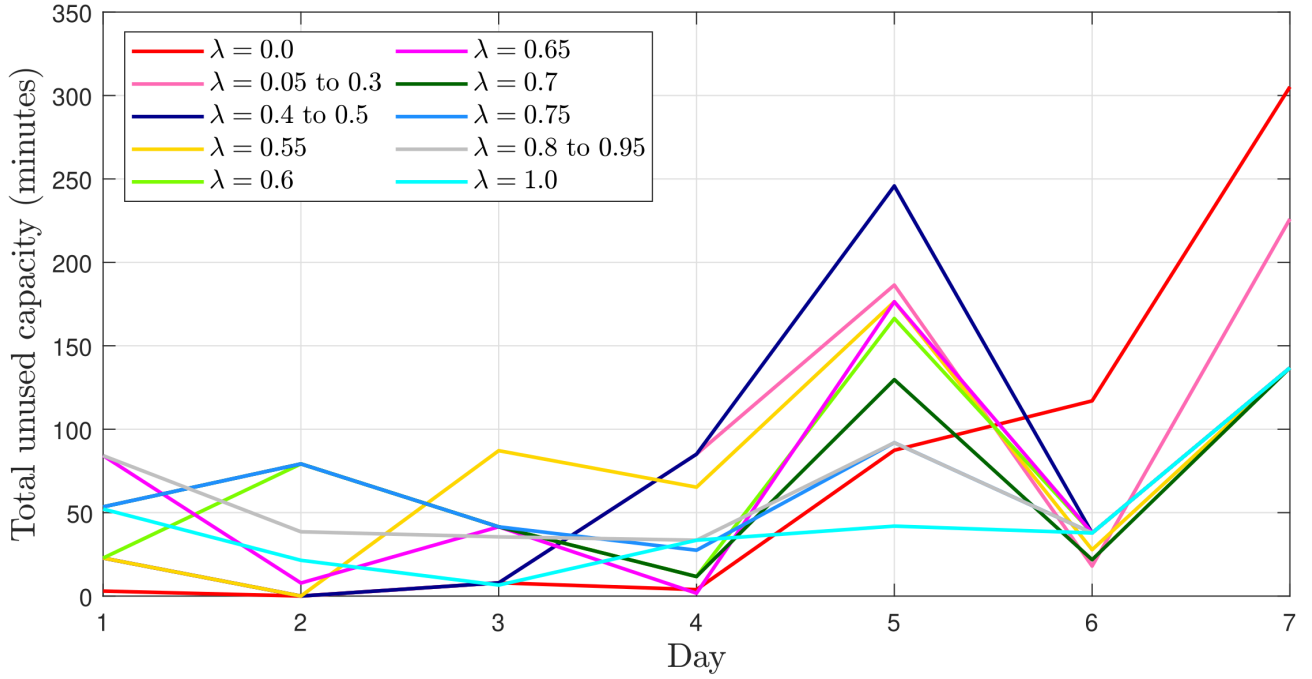


Figure 7.2: Amount of unused capacity for different λ values.

The largest amount of unused capacity occurs on day seven when $\lambda = 0.0$, and the total unused time is over 300 minutes. Day one to four and day six have the lowest unused capacity independent of λ . The unused capacity is increasing on the last day for all λ . This is because the model does not produce more than necessary, and there is no need to carry inventory over to the next day since day seven is the last day of the planning horizon. The increase of unused capacity in day seven could also depend on that the demand on day six and seven consists of the same products. The model produces more on day six to avoid setup times on day seven. This could also explain why much capacity is utilized on day six.

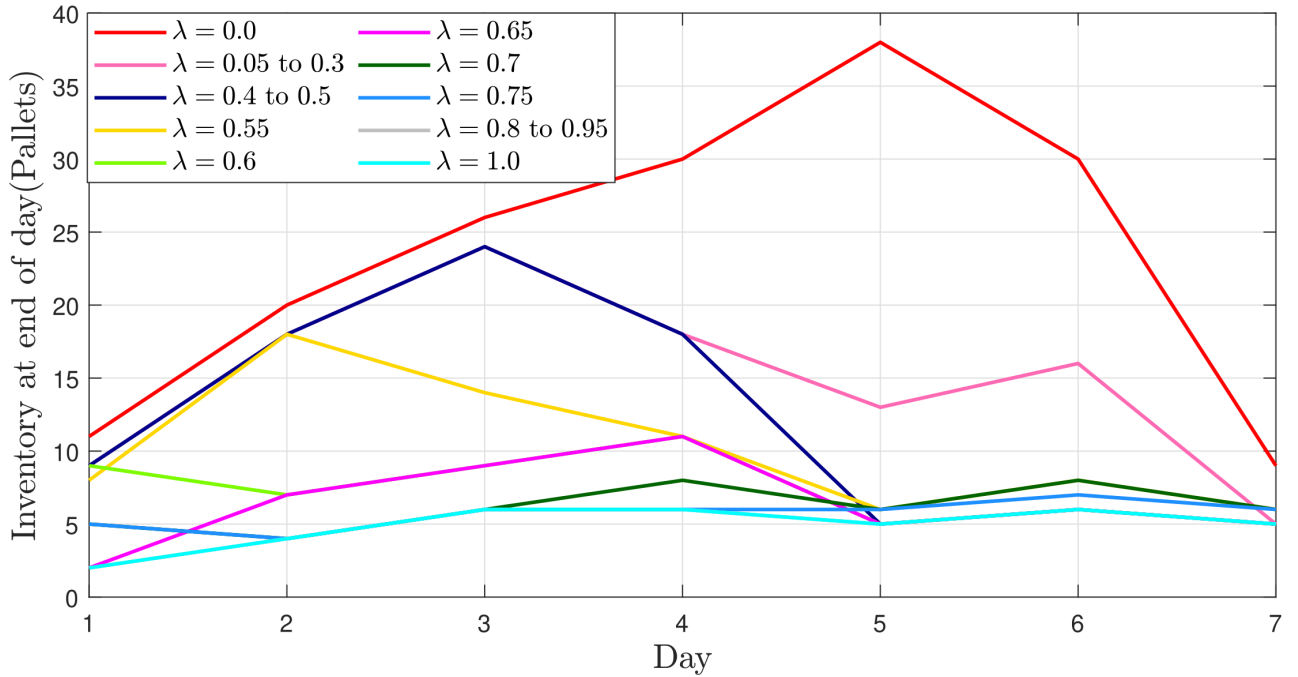
When $\lambda = 0.0$ only the setup time is considered in the objective function. The natural thought is that the most unused capacity would be when $\lambda = 0.0$ since less time is spent on setups. By looking at Figure 7.2 it can be seen that this is not the case. $\lambda = 0.0$ has the most unused capacity on day six and seven. $\lambda = 0.0$ has a total unused capacity of 487 minutes over the 7-days, while $\lambda = 0.05$ has 546 minutes of unused capacity. The difference between these two solutions is 59 minutes. The answer to this is found by looking at the inventory levels at the end of day seven. The inventory level at the end of day seven when $\lambda = 0.0$ and $\lambda = 0.05$ is summarized in Table 7.1. The plinth lengths that have an ending inventory of zero are not displayed in the table.

Table 7.1: Number of plinths in inventory at the end of day seven.

Plinth type	$\lambda = 0.0$			$\lambda = 0.05$		
	No. Plinths	No. Pallets	Production time (Minutes)	No. Plinths	No. Pallets	Production time (Minutes)
100 cm white	0	0	0	264	1	4.0
100 cm unfoiled	4224	8	63.4	0	0	0
75 cm white	0	0	0	792	1	8.7
75 cm unfoiled	792	1	8.7	0	0	0
50 cm white	264	1	2.4	2508	3	23.3
50 cm unfoiled	2244	3	20.1	0	0	0
Sum	7524	13	95.4	3564	5	36.0

Figure 7.1 and Figure 7.3 shows that the ending inventory level is higher for $\lambda = 0.0$ than for $\lambda = 0.05$. By comparing the production time for $\lambda = 0.0$ and $\lambda = 0.05$ it can be seen that $\lambda = 0.0$ accomplishes production for around 60 more minutes than $\lambda = 0.05$. The demand is fulfilled for both solutions, so the answer to why $\lambda = 0.0$ has less unused capacity is due to overproduction. $\lambda = 0.0$ produces more plinths than the demand for the seven days. This is because the objective function only considers the number of setups, not the total time spent on production. Especially when $\lambda = 0.0$ no inventory levels are considered in the objective function, there is nothing that says that overproduction should not occur.

Figure 7.3 shows the inventory levels over the seven days. The starting inventory levels are zero.

Figure 7.3: Inventory levels for different λ values.

When the aim is to minimize the setup time ($\lambda = 0.0$), the highest simultaneous inventory level reached is 38 pallets. The solution when $\lambda = 0.0$ is somewhat unnecessary since it

is possible to reach the same setup time but lower inventory levels when $\lambda = 0.05$. The highest simultaneous inventory level when $\lambda = 0.05$ occurs on day three and is 24 pallets. When much emphasis is put on minimizing the inventory levels ($\lambda = 1.0$ and $\lambda = 0.8$), the highest inventory level reached is 6 pallets. This inventory level is reached on day three.

Figure 7.3 shows that the inventory levels are as expected, i.e., higher when λ is smaller, and lower when λ is larger.

Table 7.2 shows in detail how the production is conducted when setup time and inventory levels are weighted equally ($\lambda = 0.5$). Column one shows the plinth length and foil. The second column shows the demand for the next day. Recall that the demand for the next day is assumed to be needed at the beginning of the next day and must, therefore, be completed at least one day before. The time to produce the demand is shown in column three, while the fourth column shows how many plinths that are produced. Column five shows the production time for the plinths. Column six shows total time spent on setup and column seven the inventory at the end of the day. Also, recall that the inventory space is measured in pallets, this means that one pallet in inventory could be full or only hold a few plinths.

Table 7.2: How the production is conducted over the seven days.

Plinth Type	Plinth Demand Upcoming Day	Production Time Demand (Minutes)	Produced	Actual Production Time (minutes)	Setup Time (Minutes)	Inventory
Period 1						
50 cm white	10560	98.2	16896	157.1	0	6
50 cm unfoiled	10560	98.2	12804	119.1	10	3
Sum Period 1	21120	196.4	29700	276.2	10	9
Period 2						
50 cm unfoiled	4224	39.2	6600	61.4	0	5
100 cm unfoiled	5280	79.2	10296	154.0	16	10
100 cm white	5280	79.2	5544	83.0	10	1
50 cm white	4224	39.2	0	0	0	2
Sum Period 2	19008	237.0	22440	299.0	26	18
Period 3						
100 cm white	4224	63.4	9240	138.6	0	10
75 cm unfoiled	4224	46.5	8448	92.9	16	5
75 cm white	4224	46.5	5412	59.5	10	2
100 cm unfoiled	4224	63.4	0	0	0	2
50 cm white	1056	9.8	0	0	0	1
50 cm unfoiled	1056	9.8	0	0	0	4
Sum Period 3	19008	239.3	23100	291.0	26	24
Period 4						
75 cm white	4224	46.5	3036	33.4	0	0
75 cm black/brown	0	0	2904	31.9	10	4
100 cm black/brown	0	0	4752	71.3	16	9
100 cm unfoiled	5280	79.2	4488	67.3	10	0
75 cm unfoiled	4224	46.5	0	0	0	0
100 cm white	5280	79.2	0	0	0	0
50 cm unfoiled	0	0	0	0	0	4
50 cm white	0	0	0	0	0	1
Sum Period 4	19008	251.3	15180	203.9	26	18
Period 5						
100 cm unfoiled	4752	71.2	5280	79.2	0	1
100 cm black/brown	4752	71.2	0	0	0	0
75 cm black/brown	2112	23.2	0	0	0	1
50 cm white	1056	9.8	0	0	0	0
50 cm unfoiled	1056	9.8	0	0	0	3
Sum Period 5	13728	185.4	5280	79.2	0	5
Period 6						
100 cm unfoiled	8976	134.6	9504	142.6	0	2
100 cm white	8976	134.6	8976	134.6	10	0
50 cm unfoiled	0	0	0	0	0	3
75 cm black/brown	0	0	0	0	0	1
Sum Period 6	19008	269.3	18480	277.2	10	6
Period 7						
100 cm white	6336	95.0	6600	99.0	0	1
100 cm unfoiled	6336	95.0	5280	79.2	10	0
50 cm unfoiled	0	0	0	0	0	3
75 cm black/brown	0	0	0	0	0	1
Sum Period 7	12672	190.1	11880	178.2	10	5

Table 7.2 shows that 50 cm white and 50 cm unfoiled plinths are produced in period one. These plinths are produced in period one since there is a demand for them in period to.

The production quantity is higher than the demand in period two. The higher production quantity is because there is a demand of 50 cm white and unfoiled plinths in period three, four, and five.

The production in period two begins with 50 cm unfoiled. This setup state is the same as at the end of period one, hence, no setup needed. All 50 cm white and unfoiled plinths are produced in the first two periods, even though they are also demanded in period four and six.

The production quantities in period three and four are higher than the demand for period four and five (i.e., when the plinths are demanded). The reason for this is low production quantities in period five and avoided setups in this period. The machine keeps the setup state for 100 cm unfoiled plinths from period four to period six.

The number of plinths produced per length must equal a multiple of stacks of raw-material. This criterion is implemented in the model via the help of one constraint, see Section 6.1.3. It is possible to validate if the model considers this by looking at Table 7.2. In period four there are 3036 pieces of 75 cm white and 2904 pieces of 75 cm black/brown plinths produced. $3036 + 2904 = 5940$. It is possible to produce 1980 plinths from one stack of raw-material for plinths with a length of 75 cm, which means that 3 whole stacks were used to produce the 5940 plinths ($1980 \cdot 3 = 5940$). This is the desired result, and this confirms that the model considers the multiple of stacks of raw-material.

Since the production quantities have to equal a multiple of stacks for the raw-material, there will be unused plinths at the end of the planning horizon. At the end of period seven, there are five pallets in inventory. However, in practice, the demand will continue after period seven, which means that these 5 pallets that are in inventory most likely will be used in the future.

By the description above and via the help of Table 7.2, it can be seen that the model gives sufficient and expected results and could henceforth be considered validated.

7.2 Scenario 2 - Lower Available Production Time over Seven Days

It is possible to adjust the time available for production and have less unused capacity. The planning horizon is still seven days, and the optimization has seven periods. However, one shift is removed on day seven so that the available time is 325 minutes on day one to day six, and 0 minutes on day seven.

Figure 7.4 shows the Pareto front for the solution with no available time for production on day seven.

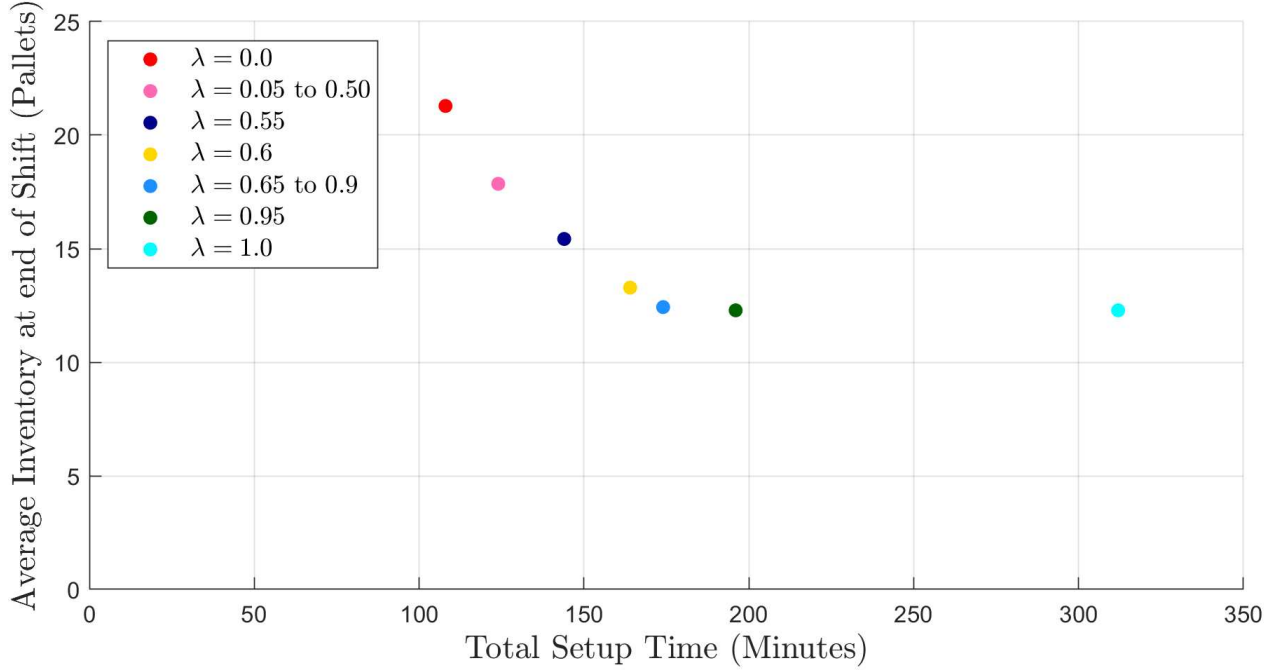


Figure 7.4: Pareto front for the seven days with no production on day seven.

Figure 7.4 shows no surprises regarding the results. $\lambda = 0.0$ has the lowest setup time and highest inventory levels, which is fair since all emphasis is put into minimizing setup time. $\lambda = 0.65$ to $\lambda = 1.0$ have the same inventory level of 13 pallets. However, the setup time is increasing with an increasing λ value. This is because less emphasis is put into minimizing the setup time and more into minimizing the inventory levels. However, the inventory level is never lower than 13 pallets independent of λ . Since optimal solutions were obtained for all λ , it can be concluded that 13 pallets is the lowest inventory level that can be reached.

Figure 7.5 shows the unused time for different λ . Figure 7.5 shows that the total amount of unused capacity is lower for all λ compared to the solution in Scenario 1.

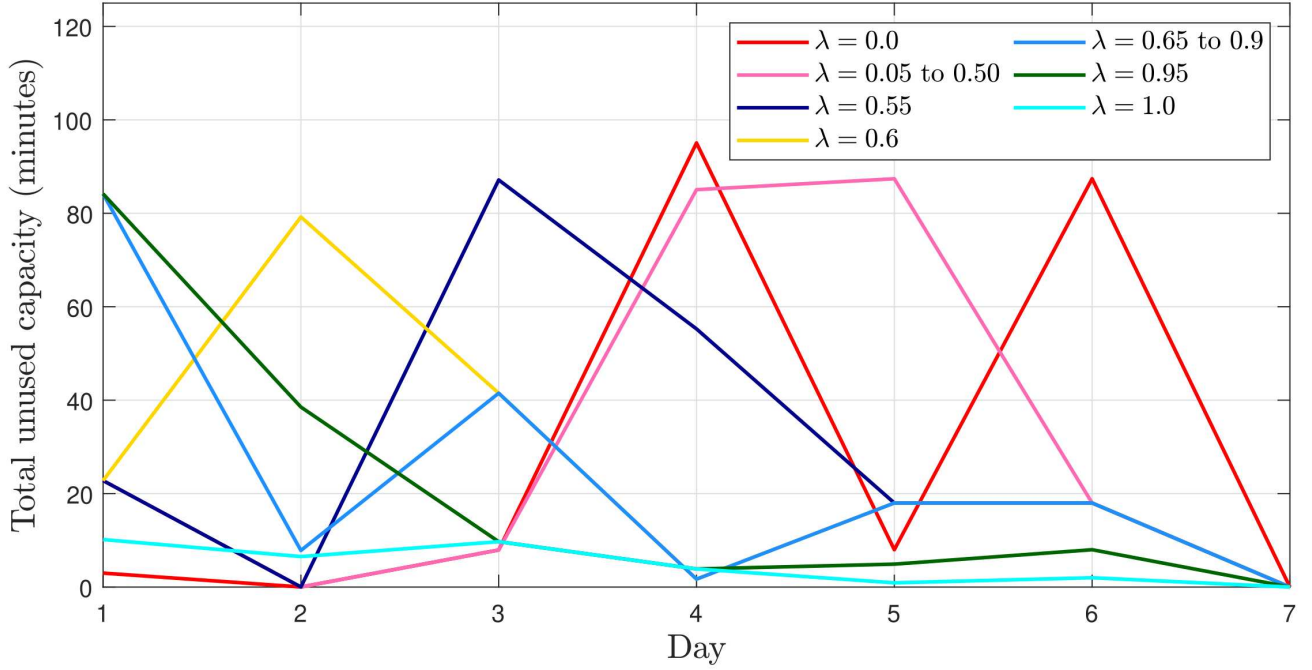


Figure 7.5: Unused capacity when the available time is lower.

$\lambda = 1.0$ uses most of the available capacity compared to all the other λ , the highest amount of unused capacity occurs in day three and is less than 10 minutes. The highest amount of unused capacity is on day four when $\lambda = 0.0$ and is around 90 minutes. This can be compared to the Scenario 1, where the highest number of unused capacity was over 300 minutes. How the inventory levels are changing when lower capacity is available is shown in Figure 7.6.

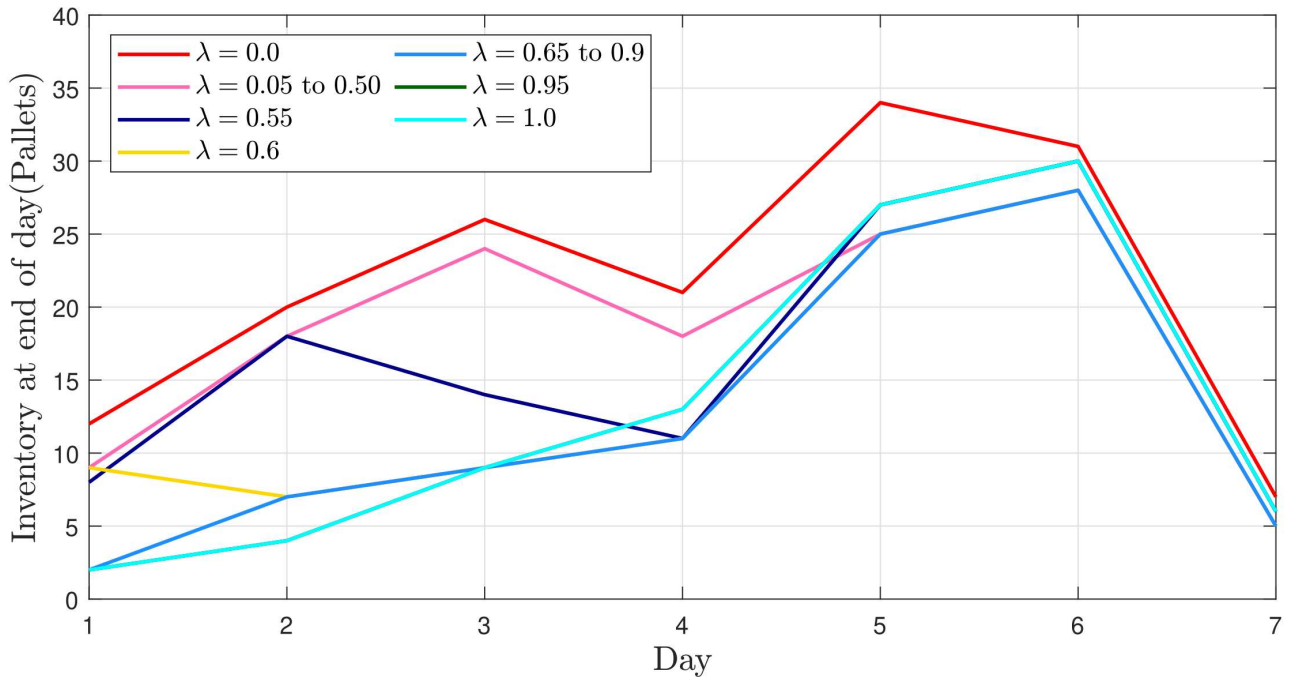


Figure 7.6: Inventory levels when the available time is lower.

Figure 7.6 shows that the maximum inventory level is 34 pallets on day five, when $\lambda = 0.0$. 34 pallets in inventory is a lower maximum level in comparison with Scenario 1, when production occurs on day seven. However, the number of pallets in inventory on day four to day seven is higher compared to the solution in Scenario 1. The inventory levels are higher because the demand on day seven must be met from inventory since no production occurs on day seven. The result is that the production volumes increases in the preceding days and more inventory is carried over from one day to another.

The highest inventory level when $\lambda = 0.5$ is 28 pallets. The corresponding inventory level was 6 pallets when production occurred on day seven. Henceforth, the least number of pallets in inventory simultaneously changed from 6 to 28 pallets compared to when production took place on the seventh day.

7.3 Scenario 3 - Solution Over 16 days

IKEA Industry Hultsfred has been asked if they could produce plinths to two other factories, in Germany and Portugal. The factory in Germany has a yearly demand of around 8 million plinths with varying foils and lengths. The factory in Portugal has a yearly demand of 2 million plinths, also with varying foils and lengths. The orders should be at the factories in Germany and Portugal three weeks (21 days) after received order. The transportation to Germany is assumed to take four days and to Portugal six days (DHL, 2020; DSV, 2020). Details on how the demand is generated and calculated can be found in Appendix C. The demand for the factory in Hultsfred is from a prognosis from IKEA Industry Hultsfred. The demand is from 16 following days in March.

It is assumed that IKEA Industry Hultsfred receives the order from Portugal and Germany on day one of the planning horizon, and the production also starts on day one. One day of safety lead time is also assumed to protect against unscheduled stops or other unexpected occurrences. As a consequence of the delivery time and safety time the completion time for Portugal is set to day 14 and for Germany day 16 of the planning horizon. The planning horizon is set to 16 days to capture the demand and production for both Portugal and Germany.

Table 7.3 shows the total demand and total producing time for all plinths over the 16 days, including Germany, Portugal and Hultsfred.

Table 7.3: Average demand for the three factories.

Factory	Demand for plinth length			Total production time (minutes)
	100 cm	75 cm	50 cm	
Portugal	53 350	29 750	37 400	1500.0
Germany	209 000	113 050	152 900	5800.1
Hultsfred	102 960	51 464	76 032	2817.6
Total	365 310	194 264	266 332	10 117.7

If the production line accomplishes two shifts per day, 665 minutes of time is available each day, which can be used for production and setups during the 16 days. $665 \cdot 16 = 10\,640$ minutes. This will give $10\,640 - 1500.0 - 5800.1 - 2817.6 = 552.3$ minutes for setups during the 16 days. The numbers used in the calculations are found in Table 7.3. The total production time is calculated by multiplying the cycle time for each plinth with the total demand for that plinth length. 552.3 minutes might sound like much time to spend

on setups. However, if only one shift is removed only $552.3 - 325 = 227.3$ minutes are available for setups. This is not enough available time for setups for CPLEX to find a feasible solution for any λ .

The optimization model is hard to solve to optimum for many periods (days), and an optimal solution for the 16 days is therefore not possible to get within a reasonable amount of time, or it might not be possible to find a solution at all. In the following sections the step size for λ is set to 0.1 which will give eleven different solutions, from $\lambda = 0.0$ to $\lambda = 1.0$. The optimization has run with a time limit of 15 minutes for each λ . The step size and time limit for the optimization is a balance between time spent and reasonable results.

Figure 7.7 shows the Pareto front for the 16 days with the average inventory levels on the y-axis and the setup time on the x-axis for the different λ .

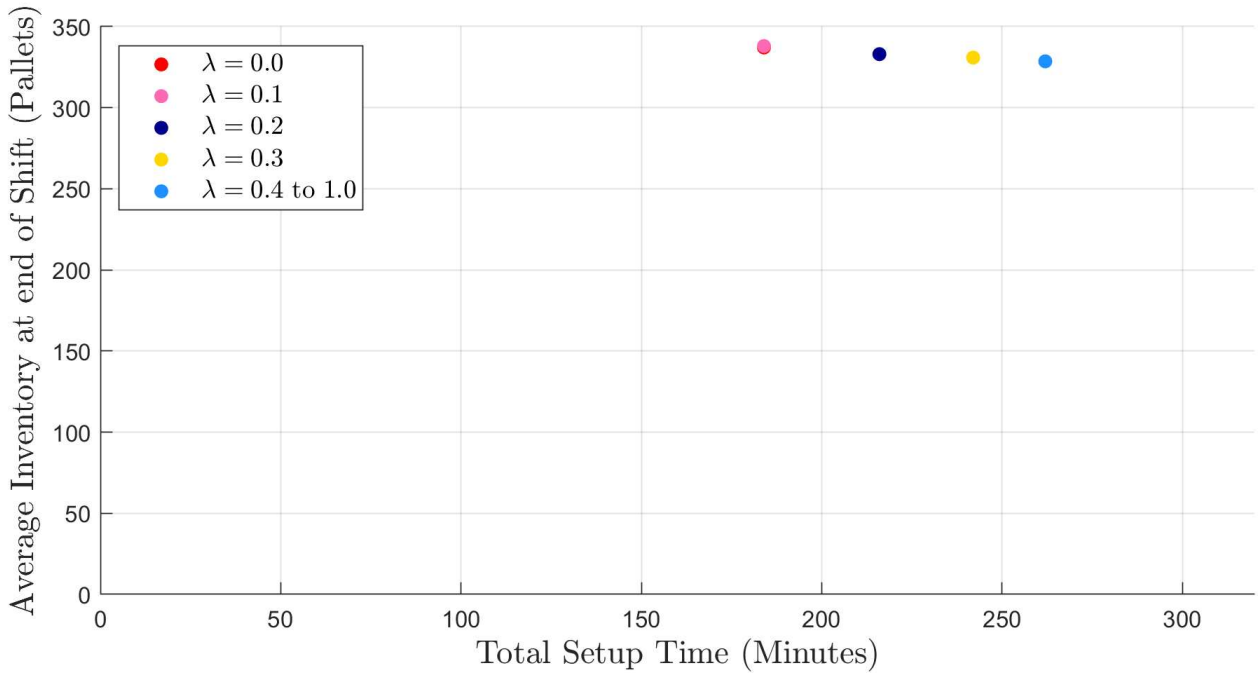


Figure 7.7: Solutions for different λ values over the 16 days

In order to achieve as good solutions as possible (small optimality-gap), CPLEX "Warm-Start" feature was used. The optimization began with running $\lambda = 0.0$ for 15 minutes. This solution was then used when solving $\lambda = 0.1$, which gives CPLEX an initial solution and improves the solution for $\lambda = 0.1$. The same approach was used throughout the whole optimization process. I.e., the solution for $\lambda = 0.1$ is used in solving $\lambda = 0.2$ and so forth. If CPLEX does not find a feasible solution from the previous solution, CPLEX tries to repair the solution and make it feasible in the current problem. If the repair fails, CPLEX will start from scratch.

Figure 7.7 shows the result for all λ . The expected result is a convex Pareto front. However, the result in Figure 7.7 shows a close to linear front but slightly concave front. Since $\lambda = 0.4$ to $\lambda = 1.0$ outputs the same solution, many data points are in the same place, and few points remain that could form a Pareto front. Another factor for the non-convex front is that no optimal solution is found for any λ . The optimality gap for all λ is displayed in Table 7.4.

Table 7.4: Optimality-gap for the solutions in Figure 7.7.

λ	Optimality-gap (%)
0.0	16.44
0.1	3.81
0.2	4.13
0.3	3.56
0.4	3.76
0.5	2.82
0.6	1.87
0.7	2.0
0.8	1.6
0.9	1.33
1.0	2.23

The solution with the smallest optimality-gap occurs when $\lambda = 0.9$, and the gap is 1.33%. The largest optimality-gap happens when $\lambda = 0.0$ with a gap of 16.44 %.

$\lambda = 0.1$ gives lower inventory levels than $\lambda = 0.0$ while the setup time is the same; the same has occurred for the 7-days in Figure 7.1. The lowest average inventory level is reached when the aim is to consider only inventory levels and not setup time ($\lambda = 1.0$). The average inventory level at the end of each day when $\lambda = 0.4$ to $\lambda = 1.0$ is 328 pallets, with a total setup time of 262 minutes. $\lambda = 0.2$ gives lower setup time but higher inventory levels than if $\lambda = 0.3$, which is an expected result since more emphasis is put on minimizing setup times when λ is smaller.

Figure 7.8 shows the unused capacity during the 16 days.

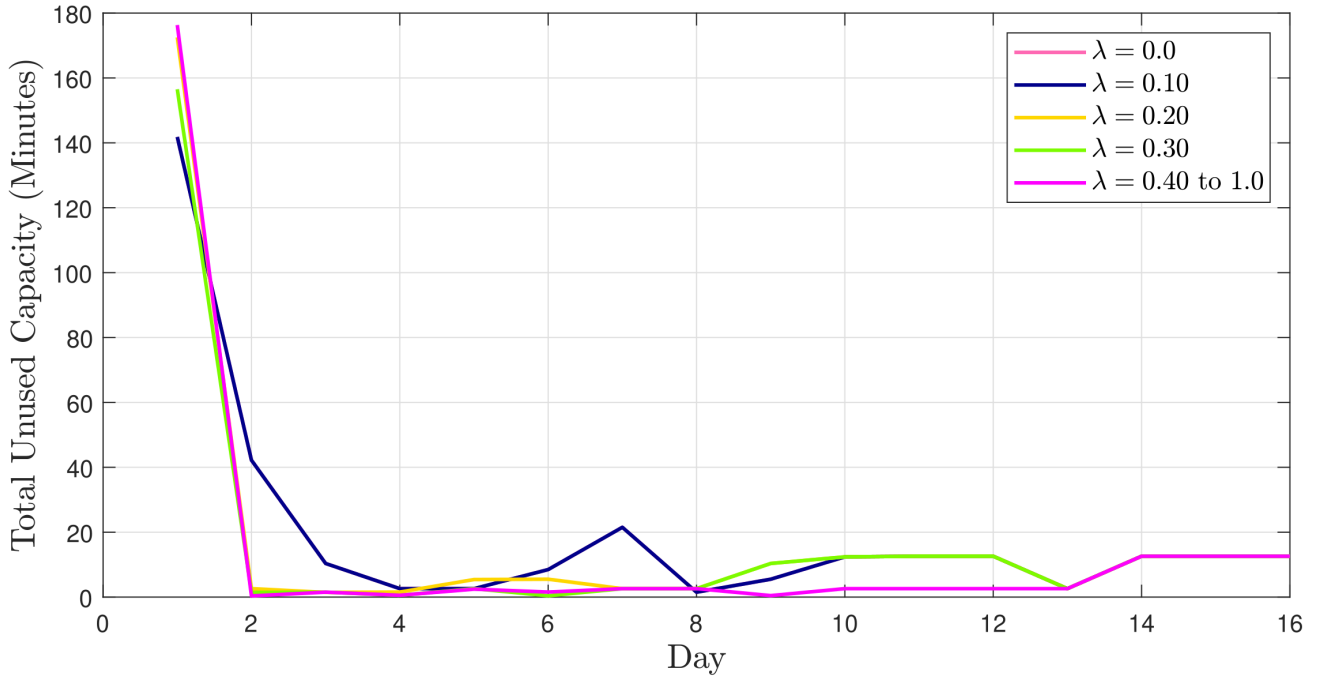


Figure 7.8: Unused capacity for the 16 days.

From Figure 7.8, it can be seen that there is not much change in the unused capacity

regardless of λ . All λ have much unused capacity on the first day, ranging from 178 minutes for $\lambda = 0.4$ to $\lambda = 1.0$ to 140 minutes for $\lambda = 0.1$. From day four to day sixteen, less than 20 minutes of capacity is available for any λ . All λ utilize the same amount of time from day 13 to 16. Notice that $\lambda = 0.0$ is not shown in the graph. This is because it has the same amount of unused capacity as $\lambda = 0.1$. The order to Portugal has a deadline on day 14 and the order to Germany on day 16. These are two large orders, and Figure 7.8, can be interpreted as that the production for these orders begin on the second day and continue for the rest of the planning horizon.

Figure 7.8 also shows that it is possible to remove around 140 minutes on the first day, and still have a feasible solution for all λ . This was not done in the optimization since no shift have a length of 140 minutes and only shifts of full length is considered in the optimization.

Figure 7.9 shows the inventory development over the 16 days.

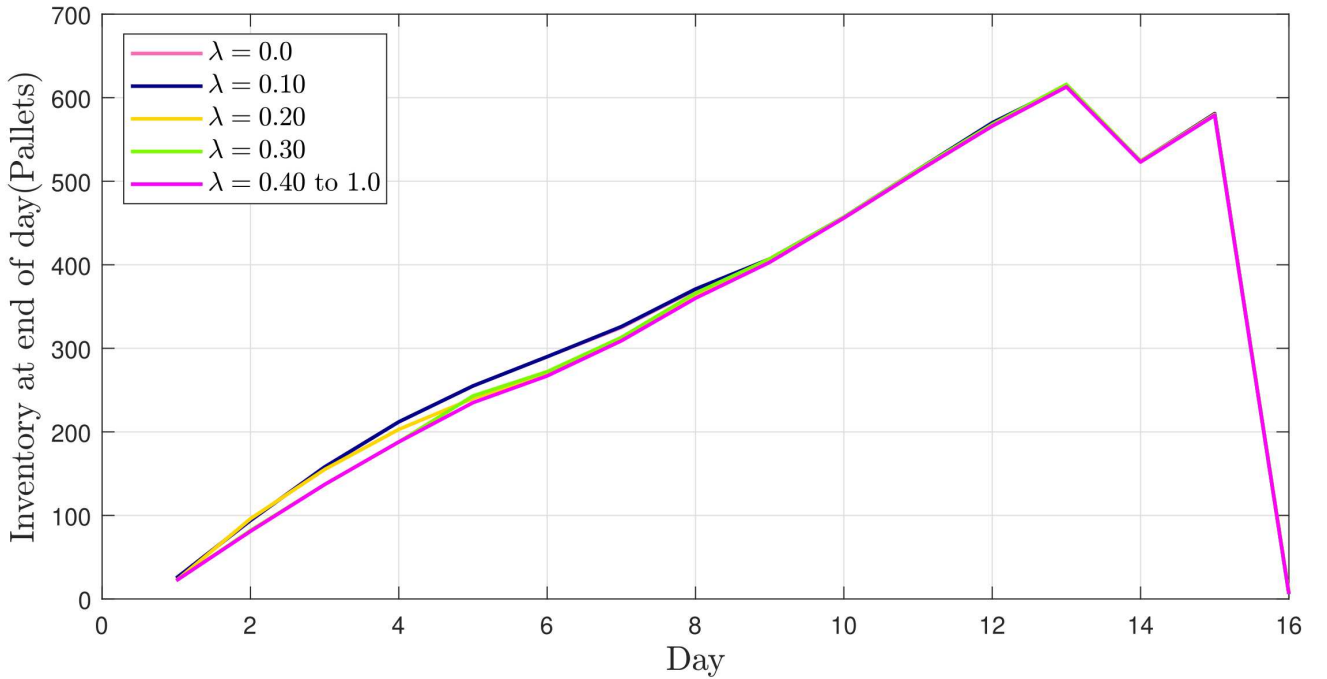


Figure 7.9: Inventory levels over the 16 days.

There are no significant, differences in the inventory levels between the different λ . The inventory levels are increasing from day one to day 13. The inventory level is increasing to meet the demand from the factories in Portugal and Germany. The inventory levels are decreasing on day 14 because the order to Portugal is shipped on this day. The inventory levels are then increasing on day 15 and decreasing on day 16. The production is increasing on day 15 to meet Germany's demand, which is being shipped on day 16, and that is why the inventory levels are decreasing massively on day 16.

$\lambda = 0.4$ to $\lambda = 1.0$ has the lowest inventory levels from day one to day nine, which is an expected result since the emphasis is put on minimizing inventory levels. From day nine and onward there is no or minimal differences in the inventory levels. The $\lambda = 0.0$ and $\lambda = 0.1$ are again almost identical. However, there are small differences in some of the days where $\lambda = 0.1$ has 1 or 2 more pallets in inventory than $\lambda = 0.0$.

7.4 Scenario 4 - Solutions when the Demand is Increased

This section presents solutions for when the factories in Germany and Portugal have increased their demand with 15% compared to the previous case, while the demand for IKEA Industry Hultsfred is unchanged. The orders are completed on day 14 for the factory in Portugal and on day 16 for Germany. IKEA Industry Hultsfred still receives the orders on day 1, and the planning horizon is 16 days. The demand for Hultsfred is unchanged from Scenario 3.

Table 7.5 shows the total demand and total production time.

Table 7.5: Demand for the three factories with a 15% increase in demand.

Factory	Demand for plinth length			Total production time (minutes)
	100 cm	75 cm	50 cm	
Portugal	62 150	36 550	47 300	1771.1
Germany	240 900	130 900	177 100	6700.1
Hultsfred	102 960	51 464	76 032	2817.6
Total	406 010	218 914	300 432	11 288.8

Table 7.5 shows that the time needed for production has increased compared to Scenario 3. Table 7.5 also shows that more than two shifts per day are needed to produce the increased volumes of plinths ($665 \cdot 16 - 11288.8 = -648.8$ minutes). The capacity is set to two shifts (670 minutes) the first 12 days and is increased to three shifts for the last four days (1020 minutes). This gives: $670 \cdot 12 + 1020 \cdot 4 = 12\,120$ minutes available for production and setup. By using the production time presented in Table 7.5 can it be seen that the time available for setup is: $12\,120 - 1771.1 - 6700.1 - 2817.6 = 831.3$ minutes. CPLEX can not find a feasible solution if the available time is reduced by one shift ($831.3 - 325 = 506.3$ minutes).

Figure 7.10 shows the Pareto front for when the demand has increased with 15%.

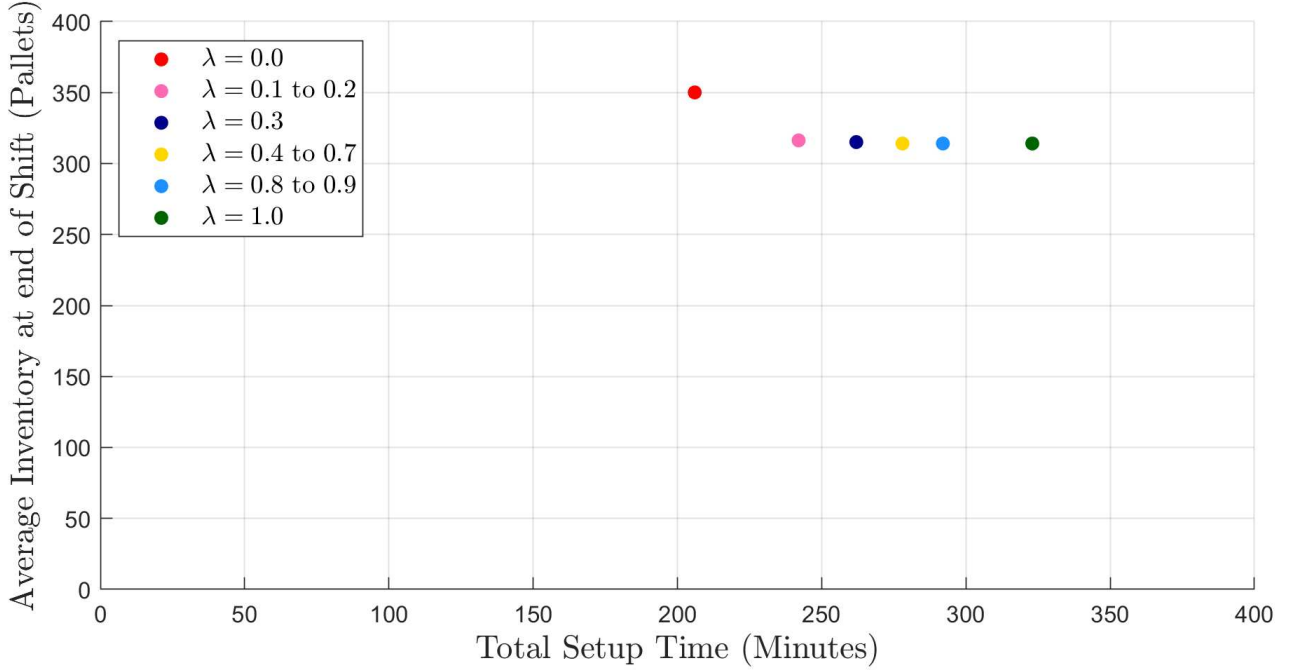


Figure 7.10: Pareto front for the solution when the demand has increased with 15 percent.

CPLEX did not find an optimal solution for any λ . The smallest optimality-gap occurred when $\lambda = 1.0$, with a value of 1.39 %. The solution with the largest optimality gap is when $\lambda = 0.0$ with a gap of 32.43 %. The optimality-gap for all λ is displayed in Table 7.6.

Table 7.6: Optimality-gap for the solutions in Figure 7.10.

λ	Optimality-gap (%)
0.0	32.43
0.1	9.28
0.2	5.73
0.3	4.39
0.4	3.40
0.5	3.85
0.6	2.79
0.7	3.38
0.8	2.31
0.9	2.80
1.0	1.39

The highest inventory level is when $\lambda = 0.0$ and the lowest is when $\lambda = 0.4$ to $\lambda = 1.0$. The highest total setup time occurred when $\lambda = 1.0$. These are expected results since low emphasis is put on minimizing the inventory levels for low λ . $\lambda = 0.4$ to $\lambda = 1.0$ all give the same inventory level but different setup times, higher λ value leads to higher setup time. Higher λ value puts less effort into minimizing the setup times and more into minimizing inventory levels. However, the inventory levels are not getting lower than 314 pallets for $\lambda = 0.4$ to $\lambda = 1.0$. This indicates that the inventory levels can not get any lower than 314 pallets. The largest difference in setup time and inventory levels is between $\lambda = 0.0$ and $\lambda = 0.1$ to $\lambda = 0.2$. The difference in setup time is 38 minutes, and the average inventory

level is a difference of 34 pallets. The large difference in inventory levels and setup time between these solutions could depend on two factors.

1) $\lambda = 0.0$ has a large optimality-gap, and the solution may be far from optimal, which would mean that the solution has higher inventory levels and setup time than optimal. However, as seen in the previous scenarios, the inventory levels are always high for $\lambda = 0.0$ since no emphasis is put into minimizing inventory levels.

As seen in Section 7.1 overproduction is made when $\lambda = 0.0$, and this could be the case also in this solution. I.e., more plinths are produced than the demand, which leads to high inventory levels at the end of the last day. Altogether, the possibility that a solution with lower optimality-gap would get lower inventory levels is rather small. Additionally, the setup time is lower than for $\lambda = 0.1$. In previous solutions in Scenario 1,2 and 3 the setup time for $\lambda = 0.0$ and $\lambda = 0.1$ is always the same.

2) The second factor is that the solution for $\lambda = 0.1$ to $\lambda = 0.2$ could improve. As mentioned earlier, the setup time for $\lambda = 0.0$ and $\lambda = 0.1$ has been the same in previous scenarios. Hence, if the optimization was run longer time than 15 minutes, it might be possible to reduce the optimality-gap for $\lambda = 0.1$ and provide a solution closer to $\lambda = 0.0$.

Figure 7.11 shows the amount of unused capacity in minutes over the 16 days with a 15% increase in total demand from the factories in Germany and Portugal.

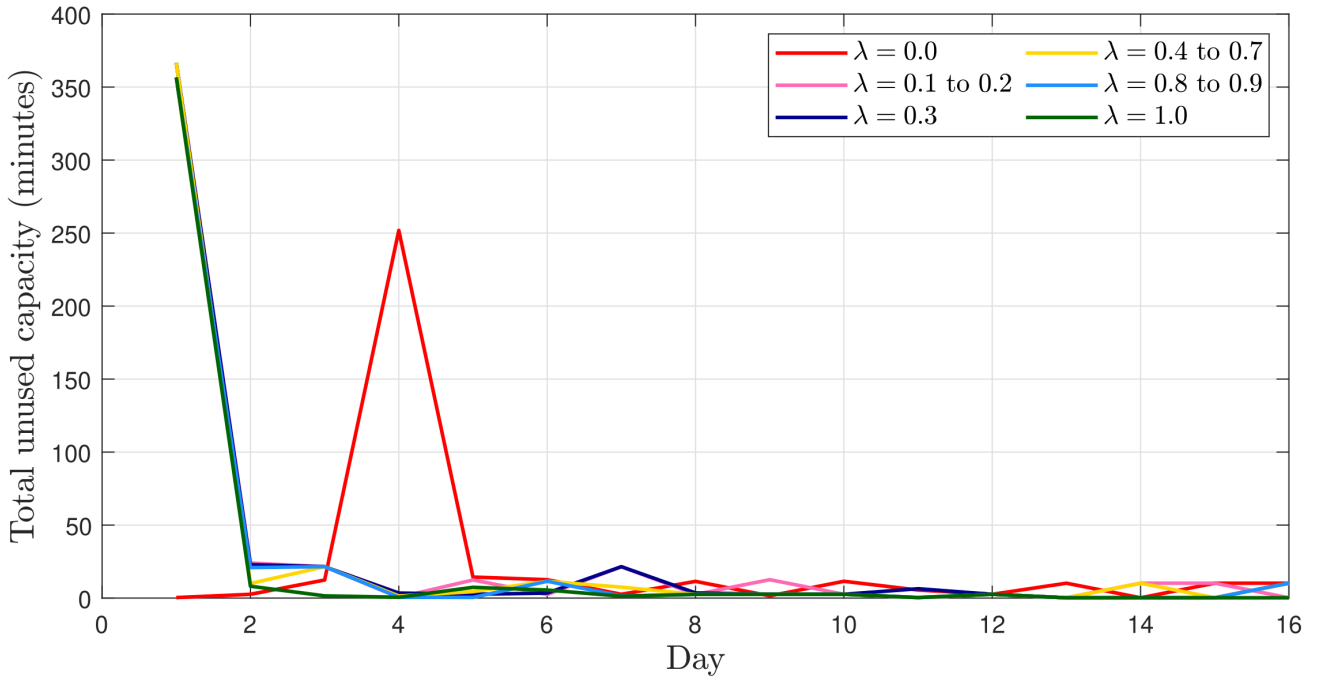


Figure 7.11: Unused capacity over 16 days when the demand has increased by 15%.

Figure 7.11 shows that the unused capacity on day one is ranging from 353 minutes when $\lambda = 0.9$, to almost zero minutes when $\lambda = 0.0$. On day five to day ten, almost all capacity is utilized, independent of λ value. This is due to that the order to Portugal and Germany has a deadline on day 14 and 16. Therefore, all capacity must be used in order to satisfy the demand for these orders.

All λ except $\lambda = 0.0$ have over 350 minutes of unused capacity on the first day, and this corresponds to more than one shift of unused capacity since one shift is 325 minutes.

However, if one shift is removed on the first day in the model, CPLEX can not find a solution to the problem. This shift could, however, be manually be removed without changing the model. $\lambda = 0.0$ has almost zero unused capacity on day one, while this solution instead has 250 minutes of unused capacity on day four. The model formulation does not state on which day the unused capacity should be put, so instead of having much unused capacity on the first day, the solution $\lambda = 0.0$ puts the unused capacity on day four.

$\lambda = 0.0$ should have the most unused capacity since less time is spent on setups. This is not the case, according to Figure 7.11. This is due to overproduction, and more plinths are produced than are demanded, see Section 7.1. This is because $\lambda = 0.0$ only considers setup times and the capacity limit. It is possible to spend 10 minutes on setups, and spend the rest of the unused capacity on production, even if the production quantities are unnecessary.

Figure 7.12 shows inventory development over the 16 days with a 15% increase in total demand from the factories in Germany and Portugal.

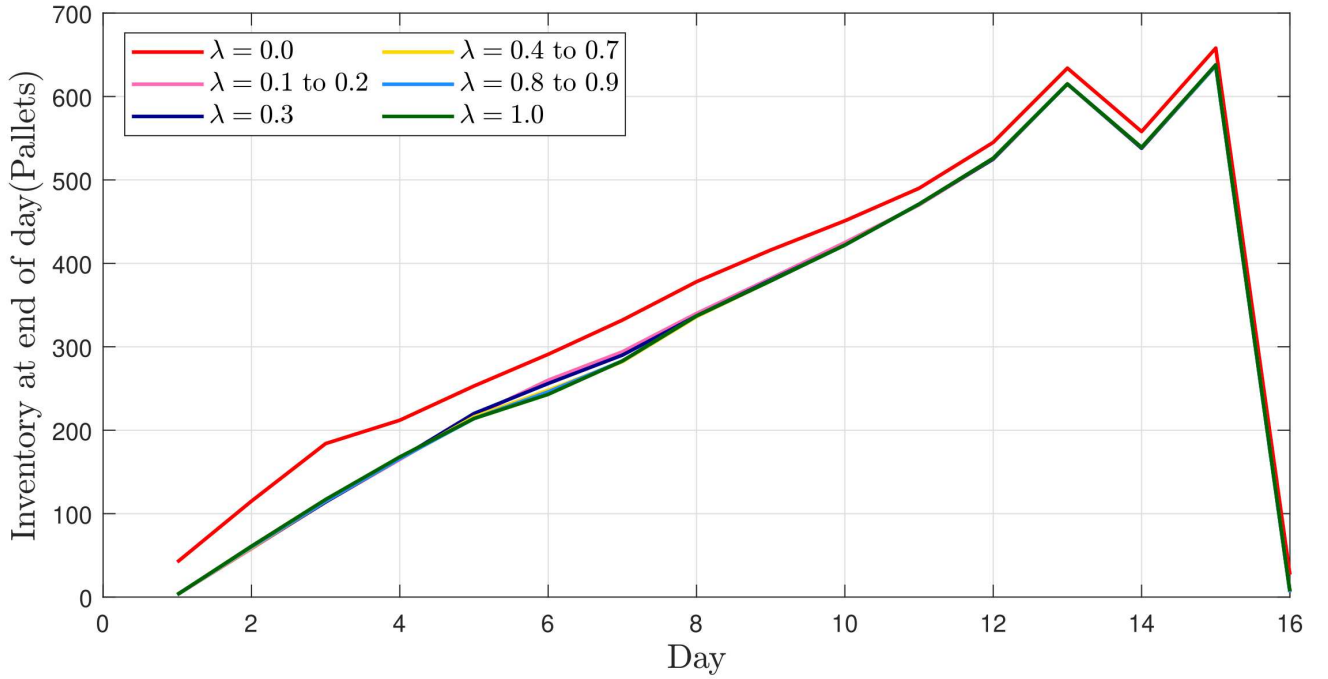


Figure 7.12: Inventory development when the demand has increased with 15 percent.

The appearance of the curve is similar to the result in Section 7.3. The highest inventory level is 658 pallets on day 15, and this arises when $\lambda = 0.0$. $\lambda = 0.0$ has overall higher inventory levels during day 1 to 15 compared to the other λ . This is due to that inventory levels are not taken into consideration. The difference in inventory levels between all other lambdas are minor. The highest inventory level when $\lambda = 0.4$ to $\lambda = 0.7$ is 637 pallets on day 15.

The delivery to Portugal has a deadline on day 14, which is why the figure shows decreasing inventory levels on this day. The order to Germany has a deadline on day 16, which is the reason why the inventory levels are decreasing heavily on this day. $\lambda = 0.1$ to $\lambda = 1.0$ have 6 or 7 pallets in inventory on day seven, which is due to that an even multiple of raw-material must be produced. $\lambda = 0.0$ however, has 27 pallets in inventory on day

16. This together with the total amount of unused capacity in Figure 7.11 shows that overproduction probably occurs for this λ , as in previous scenarios.

7.5 Solution when Lead Times are as Short as Possible

This section presents the result if the factories in Germany and Portugal are offered shorter lead times. There can be many reasons why the factories in Germany and Portugal might need their order on a shorter notice, ex: rapidly increasing demand. This scenario is also interesting for IKEA Industry Hultsfred since it is an indication of how large quantities that can be produced in a short amount of time. It is assumed that the factory in Portugal is sending their order on day one and Germany on day two on the planning horizon, assuming that the Portugal order is to be finished first. Table 7.7 displays the demand for each of the factories. The demand for Hultsfred is unchanged compared to Scenario 3.

Table 7.7: Average three-week demand for Portugal, Germany and Hultsfred

Factory	Demand for plinth length			Total production time (minutes)
	100 cm	75 cm	50 cm	
Portugal	53 350	29 750	37 400	1475.3
Germany	209 000	139 450	152 900	6091.0
Hultsfred (day 1 and 2)	4224	0	19 008	240.1
Hultsfred (day 3 to 10)	51 216	33 792	38 016	1493.5
Total	317 790	202 992	247 324	9299.9

The available time for production is set to 1020 minutes (3 shifts) per day for the first nine days, and 325 minutes (1 shift) on day ten. The total available time for production and setups is therefore, $1020 \cdot 9 + 325 = 9502$ minutes. The total production time need over the ten days is 9299.9 minutes which gives that $9502 - 9299.9 = 205.1$ minutes are available for setups.

IKEA Industry Hultsfred can produce the whole order for Portugal in 2 days. I.e. $1020 \cdot 2 - 1475.3 - 240.1 = 324.6$, and the remaining eight days are required for the German order. The complete demand used in this model can be found in Appendix C, while Table 7.7 displays the total demand and total production time used in the calculations above.

Figure 7.13 shows the Pareto front when the lead-time is shorter.

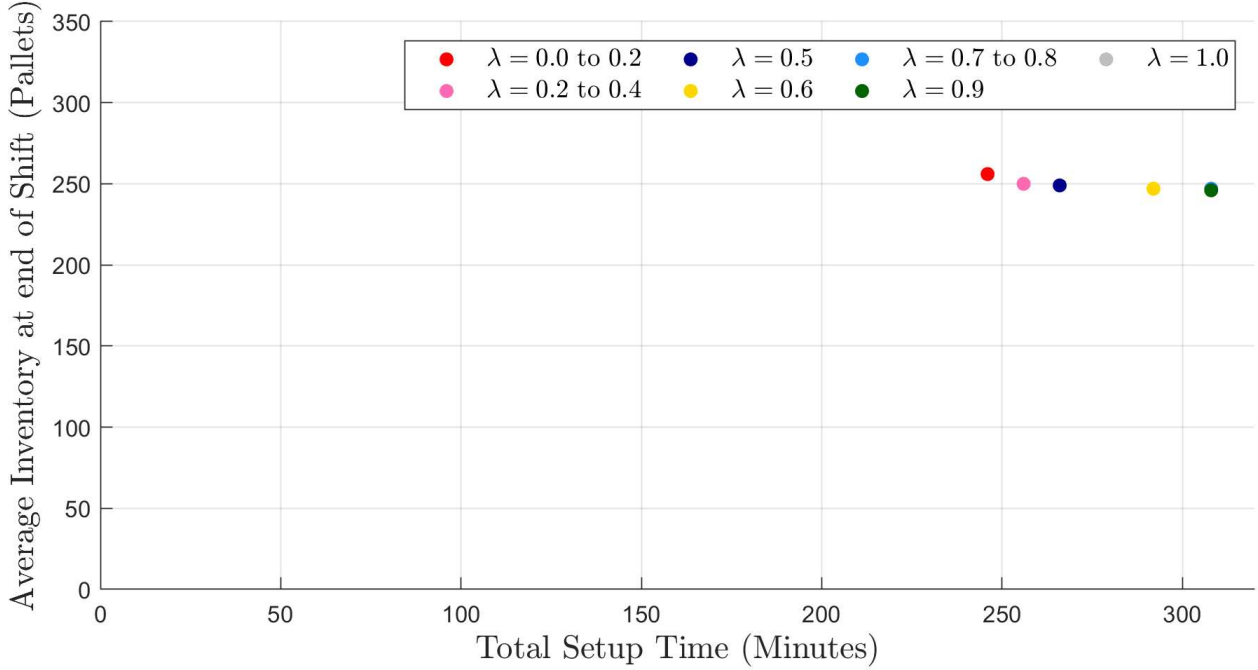


Figure 7.13: The Pareto front for when the lead-time is shorter.

The same technique as before was used, see Scenario 3, using a previous solution to solve the next λ problem. CPLEX did not manage to solve any λ to optimum. Table 7.8 shows the optimality-gap for the different λ .

Table 7.8: Optimality-gap for the solutions in Figure 7.13.

λ	Optimality-gap (%)
0.0	11.69
0.1	5.29
0.2	2.82
0.3	1.91
0.4	1.51
0.5	0.93
0.6	1.08
0.7	0.80
0.8	0.94
0.9	0.25
1.0	0.25

The largest optimality-gap occurred when $\lambda = 0.0$ and the smallest when $\lambda = 0.9$ and $\lambda = 1.0$.

The highest inventory levels are reached when $\lambda = 0.0$ to $\lambda = 0.2$. The average inventory level at the end of each day is 256 pallets, with a total setup time of 246 minutes. This result is expected since no or very low emphasis is put into minimizing the inventory levels. The lowest inventory levels are reached when $\lambda = 0.9$ to $\lambda = 1.0$, with an average inventory level of 246 pallets at the end of each day. However, $\lambda = 1.0$ gives much higher setup time, but the same inventory levels as $\lambda = 0.9$. Hence, $\lambda = 0.9$ could be considered a better solution since the inventory levels are the same, but with a lower setup time.

The reason why $\lambda = 1.0$ has a high setup time is because the machine in the model is setup to a plinth length that is not produced, which adds unnecessary setup time. Even if the setup time is not explicitly considered in the objective function, it is still considered in some sense. For example, the model can only setup one product once each day (ex. 100 cm white), and the time capacity for that day limits the time that can be spent on setups. If more capacity was available per day, the setup times for $\lambda = 1.0$ could be even higher.

Note that, Figure 7.13 does not have the same convex look as achieved in Figure 7.1. This is due to that none of the λ were solved to optimum.

Figure 7.14 shows the unused demand per day and per λ .

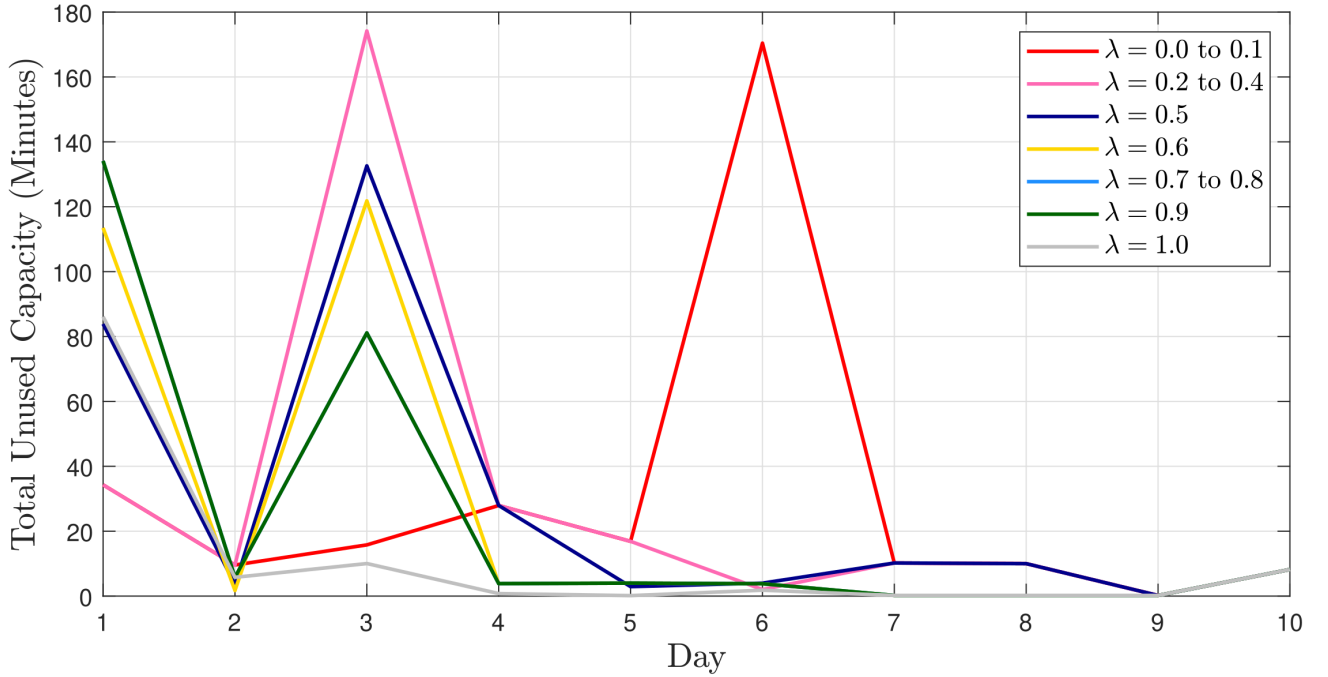


Figure 7.14: Unused capacity in minutes during 10-days

Figure 7.14 shows that $\lambda = 0.0$ to $\lambda = 0.1$ have the most unused capacity. This result is expected since less time is spent on setup, which leads to more unused capacity. The difference in unused capacity over the ten days compared to $\lambda = 0.2$ to $\lambda = 0.4$ is, however, only 10 minutes. The solution with the smallest amount of unused capacity is $\lambda = 1.0$. This solution has around 80 minutes of unused capacity on the first day, and almost all capacity used for the remaining days. There are two reasons for high capacity usage. The first one is that the aim is to minimize inventory levels, and the production is postponed as long as possible. The second reason is that this solution suggests unnecessary setups to products that are not even being produced, as mentioned earlier.

The high capacity usage on the second day is because the deadline for Portugal is on this day. The fact that much capacity is utilized on this day shows that much of the production occurs on the same day as the deadline, which gives lower inventory levels to carry over from the previous day. Many of the λ have much unused capacity on day three. This is due to that the German order has a deadline on day ten, and the production for this order begins on day four. From day four to ten, almost all capacity is used (≤ 30 minutes of unused capacity available) for all λ except $\lambda = 0.0$ to $\lambda = 0.1$ which have a peak of unused

capacity on day six. $\lambda = 0.0$ to $\lambda = 0.1$ have a peak of unused capacity on day six because much capacity has been utilized for the first five days. On day six, the inventory levels are high, and the available time for the remaining four days is enough to be able to produce the correct quantities for the order to Germany.

Note that $\lambda = 0.7$ to $\lambda = 0.8$ have the same amount of unused capacity as $\lambda = 0.9$, therefore $\lambda = 0.7$ to $\lambda = 0.8$ are not visible in Figure 7.14. However, the inventory levels are not consistent over the ten days for $\lambda = 0.7$ to $\lambda = 0.8$ and $\lambda = 0.9$.

Figure 7.15 shows the inventory development during the 10-days.

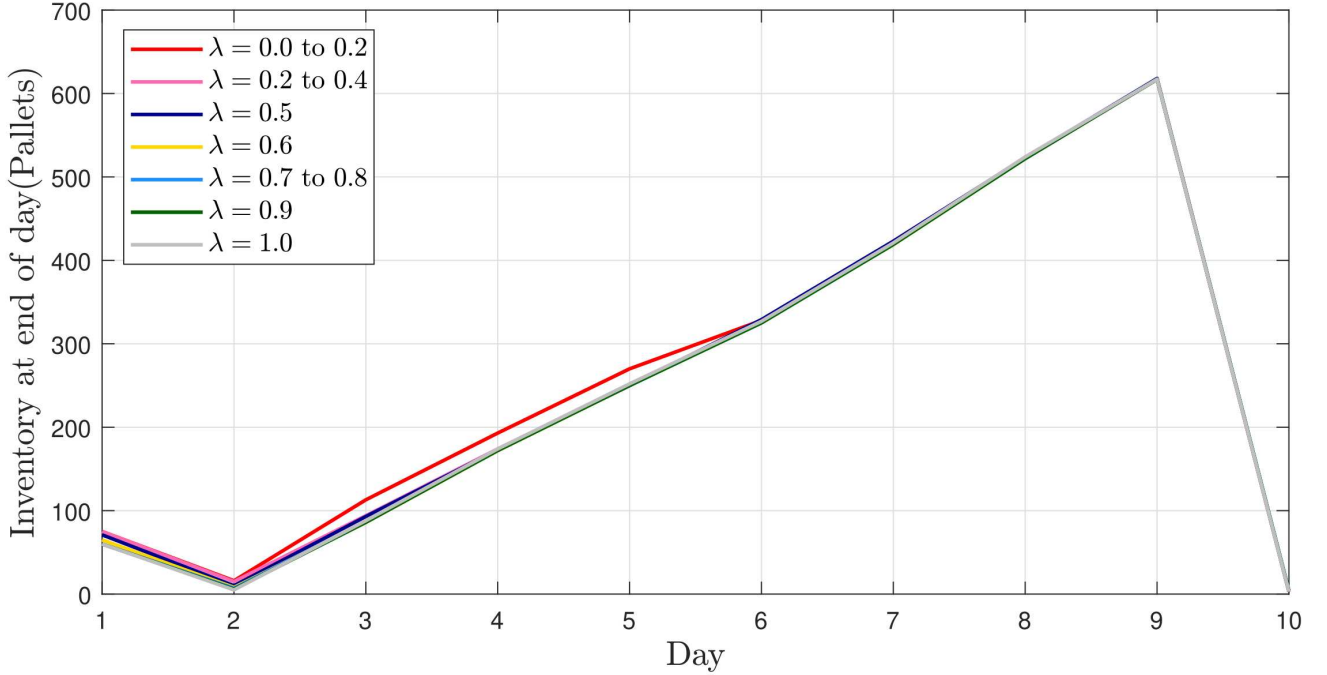


Figure 7.15: Inventory development during the 10-days.

As seen in Figure 7.15, the inventory levels are almost the same independent of λ . The only noticeable difference is from day two to day six. During these days the inventory level for $\lambda = 0.0$ to $\lambda = 0.1$ is around 20 pallets higher than for the rest of the λ . From day six to day ten, there are no significant differences in the inventory levels for any λ . The inventory level is decreasing on day two. This is the same day as the order to Portugal is shipped. From day two to day nine, the inventory levels are increasing. The inventory levels are built up because the order for Germany is to be shipped on day ten. That is also why the inventory levels almost reach zero on the tenth day. Since a whole stack of raw-material needs to be emptied, it is unavoidable to overproduce a few plinths. There are 5 to 6 pallets in inventory on day ten. These will, however, most likely be used to satisfy demand in upcoming days in practice.

7.6 Summary of the Results

This section briefly summarizes the results presented in Section 7.1 to 7.5.

7.6.1 Scenario 1 and 2

The results show that if one shift of 325 minutes is conducted each day for seven days, the lowest average inventory level possible is 5 pallets, with a total setup time of 210 minutes over the seven days. The lowest available setup time achievable over seven days is 130 minutes. This gives an average inventory level of 15 pallets at the end of each day. The highest simultaneously inventory level is 37 pallets when the aim is to minimize only setup time and 6 pallets when the aim is to minimize the inventory levels. Lastly, the result in Scenario 1 shows that it is possible to reduce the number of shifts from seven to six by removing the shift from the seventh day.

One shift of 325 minutes is conducted on day one to six, and none on the seventh day. If all emphasis is put into minimizing inventory levels do the solution show that the maximum average inventory level is 22 pallets with a total setup time of 108 minutes. If the emphasis is put into minimizing inventory level, the lowest achievable average inventory level is 13 pallets at the end of each day, with a total setup time of 174 minutes over seven days.

If the inventory storage is not limited, it is possible to reduce the available production time by 190 minutes. However, if the available time is reduced, there is no room for unscheduled stops. The results also show that the inventory storage space must be able to carry at least 28 pallets simultaneously.

7.6.2 Scenario 3

The order to Portugal is to be finished 14 days after received order and the order to Germany 16 days after received order. This solution shows that it is possible to produce all the demand on 16 days with two shifts per day, which gives a total available production time of 670 minutes per day.

The inventory level is, on average, 338 pallets at the end of each day when the setup time is 186 minutes. If the emphasis is put on minimizing inventory levels, the setup time is 262 minutes, with an average inventory level of 329 pallets at the end of each day.

If wanted, it is possible to reduce the available capacity by around 140 minutes on the first day. The inventory levels are almost identical, independent if setup times or inventory levels are minimized. The highest inventory level is 614 pallets, and therefore the storage space must be able to hold at least 614 pallets.

7.6.3 Scenario 4

The order to Portugal and Germany are still to be finished 14 and 16 days after received order. If the demand has increased with 15%, more production time is necessary. It is possible to produce the orders in 16 days by using two shifts (670 minutes) the first twelve days after receiving the orders, and three shifts (1020 minutes) the last four days. The average inventory level at the end of each day is ranging from 350 pallets to 314 pallets, while the setup time varies from 206 minutes to 276 minutes.

The total inventory capacity needed is ranging from 616 to 662 pallets, depending on if the aim is to minimize inventory levels or setup time. If needed, the first day could be reduced down to one shift (325 minutes). CPLEX could not find any feasible solution if one shift is removed from the first day.

7.6.4 Scenario 5

The last scenario is when the order to Portugal is finished in two days, and the order to Germany in ten days. This is possible to achieve if three shifts of 1020 minutes are

conducted each day during the ten days. The lowest possible setup time is 236 minutes, with a corresponding average inventory level of 256 pallets at the end of each day. When all emphasis is on minimizing inventory levels, the lowest average inventory level is 246 pallets with a total setup time of 309 minutes. The inventory built up for the order to Portugal requires an inventory space of 75 pallets while the order for Germany requires an inventory space of 618 pallets.

It is possible to reduce the available time if needed. If all emphasis is put into minimizing inventory levels, the available time can be reduced by 80 minutes on the first day. If all emphasis is put into minimizing setup time, the available time can be reduced by 170 minutes. This was not implemented since only shifts of full length was considered.

Chapter 8

Discussion

This chapter presents a discussion about the obtained solutions in the previous chapter. It discusses applicability, in reality, model limitations and more. Lastly, further research suggestions are proposed.

8.1 Optimization over seven days

An optimal way to conduct the production planning today was presented in Section 7.1. Independent of λ , the proposed solutions in Section 7.1 are better than the observed actual production that IKEA Industry Hultsfred uses today. By studying the solutions from Section 7.1, a few observations can be discussed.

The model looks at the demand over the whole planning horizon (7 days) and produces the demand for upcoming days several days ahead. For example, Table 7.2 shows that the demand for the 50 cm plinths during the seven days is produced in the first two days. If the machine is setup for 50 cm white plinths, it is better to setup to 50 cm unfoiled and produce all the demand for 50 cm unfoiled at the same time. This saves setup time in succeeding days. The disadvantage is the slightly higher inventory levels that have to be carried over several days. The advantage is less setup time. Another advantage is that the production probably runs smoother on the days when only one plinth length is being produced. There are few or no interruptions due to setups, which gives a better flow in the production. The production rate can also be run at the same pace during the whole day due to the same plinth length.

From the result in Table 7.2, it is also visible that the model rather setup to 100 cm plinths than 75 cm or 50 cm. I.e., the model setup to 100 cm plinths 6 times, 75 cm plinths 4 times and to 50 cm plinths 2 times. This could be due to two reasons. The first is that the demand of 100 cm plinth is the highest and has a demand five out of seven possible days. The other one is that 100 cm plinths in some way gives higher flexibility in time, and it is possible to produce lower quantities. One stack of raw-material for 100 cm give 1320 plinths, the same figure for 50 cm is 3300 plinths. The minimum production time for 100 cm plinths is, therefore, $1320 \cdot 0.015 = 19.8$ minutes and $3300 \cdot 0.0093 = 30.69$ minutes for 50 cm plinths, a difference of almost 11 minutes, where 0.015 and 0.0093 are the cycle times for 100 cm and 50 cm plinths, respectively. Hence, if a setup is made to 50 cm plinths, at least 30.69 minutes must be spent on production, while the same time for 100 cm plinths is only 19.8 minutes.

8.2 Applicability in Reality

Two shifts per day are applied in Scenario 3. Without any details of practical scheduling, this seems like a straightforward approach to implement. One solution to avoid collision and large rearranging with the scheduling in the rest of the factory is always to have two day-shifts on the plinth production. That is, the plinth production starts every day at 06:00 and ends at 23:00 (total available production time 665 minutes). Such approach would also avoid night shifts and potentially save money on labor costs.

In Scenario 4 where the demand has increased with 15% there is a mix between two and three shifts per day. The applicability of this, in reality, can be questioned. One advantage compared to only day-shifts is that the plinth production can run on the same schedule as the rest of the factory. Another advantage with three shifts per day is the lack of startup and shutdown procedures, and more time can be spent on production. One disadvantage is that more workers are needed on the days where three shifts are applied. This can probably be solved by hiring more workers. However, the scenario where the demand is increasing with 15% might only appear once every now and then. Furthermore, such a case might be solvable without hiring more workers.

In Scenario 5, where the lead time is shorter, three shifts per day are applied. This would probably not be any problems and it could fit well with the scheduling in the rest of the factory. The major disadvantage is that more workers are needed to fill the two extra shifts per day, compared to Scenario 1. In the current situation, only one shift is applied per day at the plinth production so that the extra shifts needs more workers.

The scheduling problems that will occur might be fixable via rescheduling or by hiring new workers. However, it is essential to look at the whole supply chain before making any major decisions. Such factor is the supply of raw-material. Since the production volumes will increase heavily, it is crucial that the supply of particleboards can be guaranteed, so that the required volumes of plinths can be produced. Other factors that should be considered is the packaging solution and storage possibilities. The pallets must in some way be wrapped in plastic or other material before being shipped in order to arrive at the destination unharmed. The storage possibilities at IKEA Industry Hultsfred today are limited. A new warehouse is probably needed to fit the pallets that would be sent to Portugal and Germany.

It is important to realize that the optimization model results are only as good as the input data. The cycle times for the plinths have been measured in this thesis and are considered valid and accurate. The most critical uncertainty in the data is the stop times. These times are estimated/measured by the operators at the production line. This self-reported data could have significant uncertainties and be underestimated, I.e., the stop times could in reality be higher than the ones used in this thesis.

8.3 Unused Capacity in the Solutions

The capacity usage is low on some days in some of the solutions. This is mainly due to that the model considers inventory levels. It is better to wait with the production and minimize the inventory levels than produce them and carry inventory. However, this might not be a realistic solution. It is not reasonable to work 70 minutes one day and 480 minutes the other day. This would result in very uneven work weeks with an uneven workload. Nonetheless, unused capacity might not always be a bad thing. This time can, for example, be used to maintain the machines at the production line, small preventive maintenance services, cleaning, and so forth. Preventive services and a higher degree of

cleansing could minimize the unplanned stops in the future.

The days with much excess capacity can be an advantage when planning the operations in the whole factory. The plinth production is today sometimes shut down entirely, and the line-operators are transferred to other production lines. If the schedule presented in this thesis is applied, the line-operators could initially produce plinths, for example, 110 minutes, and then shut down the plinth production, and move to another production line.

Lastly, the unused time can be used as a buffer against unexpected stops. The stop times used in the optimization model is based on an average, which means that the stop times can be both higher and lower than the ones used in the model. Excess capacity can act as a buffer against unexpected stops. The unused capacity on one day might be needed in another day due to a stop time larger than the average 155 minutes used in the optimization model.

8.4 Impact of Limitations

The optimization has several limitations. The limitation with the most substantial impact is the solution time. Since the model is complex, it does take a long time to solve the model to optimum. It is necessary to keep the number of products and periods as low as possible to reduce the model complexity. It might be hard or even impossible to obtain a solution if the degree of complexity is too high.

The complexity is also a problem when generating the results and generating "what-if" scenarios. For example: if the capacity is too tight, no solution is obtained at all. This leads to difficulties in investigating factors such as how an unexpected stop affects the production output.

More extended periods (in terms of time) will reduce the number of periods needed, while shorter periods (in terms of time) means that more periods are needed to cover the same planning horizon. Fewer periods reduces the complexity of the model but will also limit the number of possible setups.

Assume a production planning horizon of four months. If one period in the optimization model covers one month of production planning, the aggregate demand for one month and for one product needs to be produced at the same time if a setup occurs at the beginning of the month. This leads to low flexibility in the production planning, I.e., if one plinth type already has been produced, it is only possible to produce it again earliest in the upcoming month. This approach also leads to substantial inventory levels since at least one month of demand needs to be held in inventory. If a shorter period (e.g. 1 day) is used for a four month period, there is greater flexibility in the model, and it is possible to setup more often and keep inventory levels lower. However, more periods in the optimization model increases the model's complexity, and it could take a long time, or be impossible to obtain even a feasible solution.

8.5 Further Research

Much further research can be conducted regarding the optimization model in general and the case at IKEA Industry Hultsfred. One is to run the optimization for a longer time with more processing power, both for the 10-days and the 16 days. This could lead to better solutions in form of a smaller optimality-gap, which would give more accurate results regarding inventory levels and setup times. Implementation of a longer planning horizon is

another interesting research to investigate how the planning would look like over ex. one month or two. It is also possible to change the delivery dates for Portugal and Germany if a longer planning horizon is used. In the results presented above are the orders received on the same day, this might not be the case in practice.

Further research could also be to implement a heuristic solution. A heuristic could improve the solution time but still output a sufficiently good solution. It could also be possible to introduce more time periods in the heuristic solution and extend the planning-horizon. Such a solution could also be implemented in Java or C++ and give IKEA Industry Hultsfred a production planning software that can be used on a daily or weekly basis. In this thesis, CPLEX is used as solver, which is an expensive software to buy for only optimizing the plinth production. Instead, a heuristic implemented in Java or C++ would only have cost of implementation.

To mention a few other scenarios that could be interesting to investigate from an IKEA Industry Hultsfred perspective:

- Increase the demand further than 15% and test how large quantities that could be produced. This information could be valuable for the future if the demand continues to increase or if, additional, factories would like to buy plinths.
- Lower the stop-times. One such aspect could be to take the lunch breaks in shifts. I.e., instead of shutting down the plinth production for lunch, the operators could go to lunch one at a time without shutting down the production. This could potentially gain an additional 30 minutes of production time per day.
- Introduce costs for the production and the inventory is another interesting scenario to evaluate the economic aspect of the changed production.
- Introduce limited storage space. The inventory level is not in practice unlimited, and if such a constraint is introduced, the result could change. The result would also show how much of the available storage space is occupied at the end of each day.

8.6 Social and Ethical Aspects

One positive effect of the production being placed in Hultsfred is from an environmental perspective. In 2018 only 16.5 % of the electricity usage in Germany came from renewable. In Portugal, that figure was 30.3 %. This can be compared to Sweden which had 54.6 % of renewable energy usage in 2018. Both Germany and Portugal also uses coal for generating electricity compared to Sweden which uses no coal to generate electricity. Coal stands for over 40 % of the energy related emissions of carbon dioxide (International Energy Agency, 2019). Sweden also uses some coal but primarily in the mining and steel industry. Henceforth, not to generate electricity, and the factory in Hultsfred does not use electricity from the coal industry (Ekonomifakta, 2020). Consequently, by producing the plinths in Sweden instead of Germany or Portugal would result in lower environmental impact.

Another advantage with the production being placed in Sweden is that the raw-material supply is near. IKEA Industry Hultsfred uses particleboards as raw-material. The particleboards are produced in the neighbouring factory and there is no transportation between the factories since IKEA Industry Hultsfred has direct access to the particleboards from the neighbouring factory. This means that no emissions regarding transportations of raw-material. The neighbouring factory also has a their supply of raw-material(wood) near the factory, i.e., the Swedish forest, which also leads to lower emissions than if the wood were to be imported, which Germany or Portugal might have done (Sveaskog, 2013).

One additional advantage with placing the production in Hultsfred is the usage of available capacity. Hultsfred has as shown a lot of unused capacity which could be utilized to produce plinths. This is probably a better idea out of an environmental perspective than constructing a new plinth production somewhere else.

One additional advantage with the a production increase is the possibility of hiring new workers. If IKEA Industry Hultsfred starts to sell plinths, it might be necessary to hire new workers to be able to cope with the increased production time. I.e., new employments are available as well as this is a good impact on the unemployment rate.

One downside with the production in Hultsfred instead of in Germany or Portugal is the longer transportations needed for the finished plinths. By looking at the result of Scenario 4, it can be seen that the number of pallets to Germany and Portugal are 662. Assuming that a truck can carry 48 pallets: $\frac{662}{48} = 13.79 = 14$ trucks are needed every three weeks. This is a transportation that does not exist today, and hence will have an impact on emissions.

Chapter 9

Conclusions

This thesis aims to create an optimization model which considers sequence-dependent setup times and find a relation between the setup times and inventory levels. The purpose is to investigate how the optimization model used in this thesis affects the setup time and inventory levels. Further, the purpose is to investigate how much time that is needed to produce an increased demand in plinths and how the inventory levels and setup times relates to each other. All this have been achieved by using the optimization model and its extensions presented in Section 6.1.3. Below are the answer to the research questions:

Q1 - How do the inventory levels and setup times depend on and relate to each other over a seven day period at IKEA Industry Hultsfred?

When all emphasis is put on minimizing inventory levels is the highest reached setup time 330 minutes, and the average inventory level at the end of each day is 5 pallets. If all emphasis is put into minimizing setup time, the average inventory level at the end of each day is 24 pallets, with a setup time of 124 minutes. If equal emphasis is put into minimizing setup time and inventory levels the setup time is 154 minutes, and the average inventory levels 9 pallets. This concludes that the setup time lies in the range between 124 and 154 minutes, and the average inventory level at the end of each day lies between 5 and 24 pallets.

Q2 - How do the inventory levels and setup times depend on and relate to each other over a seven day period at IKEA Industry Hultsfred when the available time for production is decreased?

The results show that if no emphasis is put into minimizing the inventory levels, the setup time is 110 minutes and the average inventory levels at the end of each day is around 23 pallets. If all emphasis is put into minimizing inventory levels, the setup time is 315 minutes, with a corresponding inventory level of 13 pallets. However, if low emphasis is put into minimizing setup time and much emphasis on minimizing inventory levels, the setup time can be reduced to 196 minutes, with an average inventory level of 13 pallets. If setup time and inventory levels are balanced equally, the setup time is 126 minutes with an average inventory level of 17 pallets. This concludes that the setup time lies in the range between 110 and 315 minutes, and the average inventory level at the end of each day lies between 13 and 23 pallets.

Q3 - How much production time is necessary at the plinth production to increase the production volumes to meet the estimated demand from the factories in Germany and Portugal, while also supplying the demand for IKEA Industry Hultsfred?

The results show that two shifts per day over a 16-day period are enough to produce

the demand quantities to Germany and Portugal. Two shifts give a total available production time of 665 minutes per day. When two shifts are conducted each day it is around 180 minutes of total unused capacity over the 16 days.

- Q4 - How do the inventory levels and setup times depend on and relate to each other when IKEA Industry Hultsfred has increased their production to meet the estimated demand from the factories in Germany and Portugal, while also supplying the demand for IKEA Industry Hultsfred?*

The results show that when all emphasis is put into minimizing setup time the average inventory level at the end of each day is 338 pallets with a setup time of 184 minutes. If all emphasis is put into minimizing inventory levels the average inventory level is 329 pallets, with a total setup time of 262 minutes. The difference between these solutions is 9 pallets in inventory and 78 minutes in setup time. This shows that the difference in inventory levels is small and the difference in setup time is slightly more significant. The conclusion of this result is that it is better to minimize the setup time since the differences in inventory levels between the different solutions are small.

- Q5 - How much production time is necessary at the plinth production to increase the production volumes and meet a 15 % increase in the estimated demand from the factories in Germany and Portugal, while also supplying the demand for IKEA Industry Hultsfred?*

In the optimization model, the available capacity was set to two shifts (665 minutes per day) of available capacity on the first twelve days and three shifts (1020 minutes per day) of available capacity on the last four days. It was impossible to obtain a feasible solution within 15 minutes of solution time if the available capacity was lower. Figure 7.11 displays the unused capacity over the 16 day planning horizon. It can be seen that it is possible to remove one shift on the first day and still have enough capacity. Hence, the available time needed for a 15 % increase in plinth volumes are one shift on day 1, two shifts on day 2 to 12, and three shifts from day 12 to day 16.

- Q6 - How do the inventory levels and setup times depend on and relate to each other when IKEA Industry Hultsfred has increased their production volume to meet a 15 % increase in the estimated demand from the factories in Germany and Portugal, while also supplying the demand for IKEA Industry Hultsfred?*

Independent on how the emphasis is balanced there is no, or very little change in the inventory levels. When all emphasis is put into minimizing setup time the average inventory level at the end of each day is 350 pallets, with a setup time of 210 minutes. However, this solution produces more plinths than the demand, and is therefore not practical. The inventory levels are unchanged for all other solutions while the setup time increases when more emphasis is put into minimizing inventory levels (higher λ), the average inventory levels are around 320 pallets at the end of each day. The conclusion from this solution is that it is better to put low emphasis on minimizing inventory levels to achieve a lower setup time, compared to the same inventory levels and more setup time when more emphasis is put into minimizing inventory.

- Q7 - How much production time is necessary at the plinth production to have time to first produce the order to Portugal, and then the order to Germany in the shortest time possible, while also supplying the demand for IKEA Industry Hultsfred?*

Ten days is the shortest time period possible to finish the orders to Portugal and

Germany. Over a production horizon of ten days, three shifts of 1020 minutes are necessary the first nine days, and one shift on the tenth day.

Q8 - How do the inventory levels and setup times depend on and relate to each other when IKEA Industry Hultsfred has to finish the orders to Portugal and Germany in the shortest time possible, while also supplying the demand for IKEA Industry Hultsfred?

The inventory levels have only small changes when the emphasis of setup time or inventory level is adjusted. The average inventory levels at the end of each day are at around 260 pallets when the setup time is 240 minutes. If all emphasis is put into minimizing inventory levels is the setup time 320 minutes with an average inventory level of 240 pallets. If equal emphasis is put into minimizing inventory and setup time is the average inventory level 250 pallets with a setup time of 270 minutes. I.e., it can be concluded that the inventory levels is around 240 to 260 pallets independent on how the emphasis is balanced.

This thesis has implemented an optimization model that maps the characteristics of the plinth production at IKEA Industry Hultsfred. The optimization model has balanced the inventory levels and setup times by using weighting factors in the objective function. The result of the scenarios showed that there are only small changes in the inventory levels, independent if emphasis is put on minimizing inventory levels or setup times. The results have also shown that it is possible to satisfy the demand from Portugal and Germany while also satisfying the demand from IKEA Industry Hultsfred. One final conclusion is that there will be no problems to increase the production volumes and satisfy the demand from Germany and Portugal in terms of available time.

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Appendices

Appendix A

Classification of Plinth Production

Table A.1 shows the classification of the plinth production which is based on the framework from Mendes et al. (2006).

Table A.1: Classification for plinth production.

Category	Selected	Motivation
Process Topology	Single stage and single unit	Only the plinth production is studied which can be considered as a single stage and only one machine is available, hence single unit.
Equipment Assignment	Fixed	The equipment can only be used to produce plinths.
Equipment Connectivity	Full	The connectivity is high since the production is single stage.
Inventory Storage Policy	Non-intermediate storage	There is no need or ability for intermediate storage.
Material Transfer	Instantaneous	No material transfer within the production since there is only one stage.
Unit Design	Variable batch size	The batch size for one length of plinths is variable. It is possible to produce plinths of 50 length with different colors. However, all the raw material must be used, so a lower batch size exists.
Batch Processing Time	Variable unit/batch-size dependent	Each plinth is associated with a cycle time and batch processing time will vary depending on batch size.
Demand Patterns	Due dates Multi product demands	There is a total of twelve different products which must be finished on certain dates.
Changeovers	Sequence dependent and product dependent	The setup times vary depending on which length of plinth that was produced in the machine before. The number of plinths produce do no affect the setups.
Resource Constraints	None (only equipment)	Equipment is the only resource constraints.
Time Constraints	Shifts	The production has a limitation due to only one shift per day of 8 hours.
Costs	Inventory	Only inventory costs will be considered.
Degree of certainty	Deterministic	The demand is deterministic due to known production volumes.

Appendix B

Time-Study Data

This appendix summarizes all the collected data in the time-study. All the time-studies measured the time to fill one pallet of plinths. The following tables display the collected data for each plinth length. Table B.1 shows the collected data for the plinths with a length of 100 cm.

Table B.1: Measurements for plinths with length of 100 cm.

Measurement	Time to fill one pallet of plinths, 100 cm (s)
1	536
2	478
3	480
4	489
5	485
6	486
7	496
8	495
9	492
10	485
11	488

Table B.2 shows the collected data for the plinths with a length of 75 cm.

Table B.2: Measurements for plinths with length of 75 cm.

Measurement	Time to fill one pallet of plinths, 75 cm (s)
1	553
2	544
3	565
4	564
5	550

Finally, Table B.3 shows the collected data for plinths with a length of 50 cm.

Table B.3: Measurements for plinths with length of 50 cm.

Measurement	Time to fill one pallet of plinths, 50 cm (s)
1	630
2	618
3	619
4	619
5	620

Appendix C

Demand Data Generation

This appendix explains how the demand used in the result chapter have been generated. A suitable solution according to the factory manager at IKEA Industry Hultsfred is that Portugal and Germany are ordering quantities for three weeks at a time. Ikea Industry Hultsfred have one planned maintenance week each year, and it is assumed that Germany and Portugal do the same. Henceforth, during one year, there will be 17 deliveries ($17 \cdot 3 = 51$ weeks). The factory in Germany have a yearly demand of around 8 million plinths and Portugal 2 million plinths, all with varying foil and length.

C.1 Demand Data Scenario 3 and 5

The average demand for three weeks for the factories in Portugal and Germany is based on the average three week demand for the factory in Hultsfred. The demand in Hultsfred is based on a prognosis from IKEA. Column one shows the average demand for the three first weeks in March-May 2020. The demand for different plinths is varying from month to month, i.e., some months are there less demand of white oak plinths, therefore three months is selected in order to get a fair demand volume for all plinth types.

The demand for Germany and Portugal has been adjusted so that the yearly demand corresponds to 8 and 2 million plinths, respectively. The demand is displayed in Table C.1.

Table C.1: Average demand over three weeks.

Plinth Type	Average demand over three weeks		
	Hultsfred	Germany	Portugal
100 cm white	84 942	109 678	27 417
100 cm white oak	5214	6733	1683
100 cm black/brown	6996	9034	2259
100 cm unfoiled	63 822	82 407	20 600
75 cm white	38 631	49 881	12 469
75 cm white oak	2727	3522	881
75 cm black/brown	1848	2387	597
75 cm unfoiled	43 209	55 792	13 947
50 cm white	60 588	78 232	19 556
50 cm white oak	2904	3750	938
50 cm black/brown	2508	3239	810
50 cm unfoiled	51 084	65 960	16 489
Sum	364 473	470 615	117 646

$470\,615 \cdot 17 = 8\,000\,455$ which corresponds to the correct yearly demand for Germany. For Portugal: $117\,646 \cdot 17 = 1\,999\,982$ which is also correct. Each plinth length and foil from Table C.1 is rounded to nearest pallet quantity before used in the model. For example:

$$\frac{27\,417}{550} = 49.85 \quad (\text{C.1})$$

550 is the number of plinths per pallet of 100 cm plinths, 27 417 is the demand for 100 cm white plinths for Portugal. 49.85 is 49 and 0.85 pallets, a pallet of 0.85 could be assumed harder to transport and it is probably easier to transport only full pallets. Henceforth, $49.85 \approx 50$ pallets which is:

$$550 \cdot 50 = 27\,500 \quad (\text{C.2})$$

27 500 plinths is produced instead of 27 417.

C.2 Demand Data 15% Increase in Demand (Scenario 4)

Another scenario analyzed is when the demand for each plinth type is increased with 15 %. The figures presented in Table C.1 is simply multiplied with 1.15 and the numbers presented in Table C.2

Table C.2: Average demand over three weeks with 15% increase in demand.

Plinth Type	Average demand over three weeks		
	Hultsfred	Germany	Portugal
100 cm white	84 942	126130	31530
100 cm white oak	5214	7743	1935
100 cm black/brown	6996	10389	2598
100 cm unfoiled	63 822	94768	23690
75 cm white	38 631	57363	14339
75 cm white oak	2727	4050	1013
75 cm black/brown	1848	2745	687
75 cm unfoiled	43 209	64161	16039
50 cm white	60 588	89967	22489
50 cm white oak	2904	4313	1079
50 cm black/brown	2508	3725	932
50 cm unfoiled	51 084	75854	18962
Sum	364 473	541 208	135 293

Also in this case is the plinth volumes rounded up to the nearest pallet.