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The Simultaneous Lot-sizing and Scheduling Problem in Process Industries Using Hybrid MTS-MTO Production Systems: An Exploratory Case Study

Master's thesis in Global Manufacturing Management
Supervisor: Marco Semini and Swapnil Bhalla
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Trondheim, November 10th, 2020

Ali Akbari

Abstract

Recent market changes in terms of an increase in product variety and demand uncertainty have tremendously complicated production planning in process industries, and in response to this, many manufacturing companies in process industries have been forced to adopt hybrid MTS-MTO production planning systems. To address this complication, several production planning and scheduling approaches have been proposed by researchers. Among these, the simultaneous lot-sizing and scheduling (L&S) problem as one of the most promising approaches has attracted a considerable amount of attention not only from academia but also from many companies in process industries. Over the last two decades, several mixed-integer linear programming (MILP) models have been proposed by researchers for addressing L&S problems.

With the latest advancements in modern commercial optimization solvers, researchers have been able to propose complex mathematical models that are more capable of capturing real-world properties. However, these models have primarily been suggested for process industries with MTS production systems, and the implementation of L&S models in process industries using hybrid MTS-MTO production systems has been almost neglected by the literature.

This master's thesis attempts to fill this gap in the literature and propose an L&S model to process industries using hybrid MTS-MTO production systems. In doing so, a mineral water bottling company, within process industries that uses a hybrid MTS-MTO production system is chosen to be studied. The choice of the company enables the research to investigate and observe challenges of production planning inside process industries, and later to test the applicability of the developed L&S model addressing these challenges in the chosen company.

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List of Acronyms and Abbreviations

APICS	American production and inventory control society
ATO	Assemble-to-order
ATSP	Asymmetric traveling salesman problem
BOM	Bill of materials
CODP	Customer order decoupling point
CLSD	Capacitated lot-sizing problem with sequence-dependent setups
CSLP	Continuous setup lot-sizing problem
DLSP	Discrete lot-sizing and scheduling problem
ELSP	Economic lot-scheduling problem
EOQ	Economic order quantity
EPQ	Economic production quantity
ERP	Enterprise resource planning
ETO	Engineer-to-order
GLSP	General lot-sizing and scheduling problem
L&S	Simultaneous lot-sizing and scheduling
MILP	Mixed-integer linear programming
MPS	Master production scheduling
MRP	Material requirements planning
MTO	Make-to-order
MTS	Make-to-stock
NOK	Norwegian kroner
OPP	Order penetration point
PLSP	Proportional lot-sizing and scheduling problem
PPC	Production planning and control
SME	Small and medium-sized enterprises

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1 Introduction

This chapter introduces this master's thesis. First, the context motivating the research is investigated, and then the experienced problems justifying the rationale and the purpose of doing this study are discussed. Later, the chapter defines the scope of the research and in the end, it explains the structure used for outlining the thesis.

1.1 Background and Motivation

Process industries are industries that add value to products through mixing, separating, forming, and/or performing chemical reactions (Blackstone et al., 2005). Examples of such industries include food and beverages, steel, chemicals, pharmaceuticals, petroleum, and textile industries.

In process industries, products that are produced are typically high volume and high variety with volatile demand. Production machines are large, often highly automated, and expensive. Setups in changing between different products in production lines are complex, time-consuming, and costly and often these setups are sequence-dependent, meaning the setup operations are dependent on the production sequence (King, 2009). Owing to these production process characteristics, process industries were typically used to be known as industries producing make-to-stock (MTS) products (Spenhoff et al., 2016). MTS products are less expensive and standard products with a low variety that because of their predictable nature of demand are produced in high volumes to stock allowing demand to be met directly from inventory (Vollmann et al., 2005).

Recently, as a result of recent changes in the market and production technology that has led to increasing product variety, demand variability, and consequently more uncertainty, some companies in process industries have been forced to implement more flexible production approaches (Vollmann et al., 2005, Kiliç, 2011). However, due to the aforementioned production characteristics, the implementation of highly flexible production approaches is not impossible for these industries (Pochet, 2001), therefore, alongside producing MTS products, they are propelled into dedicating some part of their production to producing make-to-order (MTO) products. MTO products are more expensive and customized products with a high variety that are produced in lower volumes as a response to the actual customer order without being kept in stock (Soman et al., 2004, Vollmann et al., 2005). This trend has led to the rise of hybrid MTS-MTO production systems accommodating both MTS and MTO products in process industries (Soman et al., 2004).

1.2 Problem Description

The discussed conflict in process industries, between production process characteristics that limit flexibility and market characteristics that require flexibility, has created significant problems and challenges for production planning and scheduling tasks in these industries (Spenhoff et al., 2016). To address these problems in an efficient manner, several production planning approaches have been invented and proposed by researchers (Kiliç, 2011).

The simultaneous lot-sizing and scheduling (L&S) problem is one of the most effective production planning approaches in process industries that has attracted a considerable amount of attention not only from academia but also from many companies (Copil et al., 2017). Lot-sizing and scheduling are two of the most vital but challenging tasks in production planning. Lot-sizing decides on the quantity and timing of the production during a finite planning horizon, while scheduling attempts to determine the sequence in which different lots should be produced (Almada-Lobo et al., 2015). Classically, these two tasks are performed individually and separately during the production planning procedure. However, a new research trend in the literature emphasizes the importance of integrating these two tasks in process industries through the implementation of the simultaneous lot-sizing and scheduling (L&S) problem (Clark et al., 2011).

Over the last two decades, several mixed-integer linear programming (MILP) models have been proposed by researchers for addressing L&S problems. With the latest advancements in modern commercial optimization solvers, researchers have been able to propose complex mathematical models that are more capable of capturing real-world properties (Almada-Lobo et al., 2015). However, these models have primarily been suggested for MTS process industries, and the implementation of L&S models within hybrid MTS-MTO process industries has been almost neglected by the literature (Copil et al., 2017).

This master's thesis attempts to fill this gap in the literature. In doing so, a mineral water bottling company that uses a hybrid MTS-MTO production system and suffers from typical production planning problems associated with process industries is chosen so that this thesis can better observe and study these production planning problems and develop a solution to address them.

1.3 Research Objective and Tasks

As explained, the overall objective of this master's thesis is to address production planning and scheduling problems of process industries using hybrid MTS-MTO production systems by developing an L&S model for these environments. To achieve this objective the following tasks are recognized to be accomplished:

Research Task 1: *To evaluate different production planning and scheduling approaches in process industries.*

Research Task 2: *To map the case company and identify the problems associated with the current production planning and scheduling practice.*

Research Task 3: *To develop a production planning and scheduling solution for the case company.*

Research Task 4: *Discuss the applicability and impact of the developed solution on the production planning and scheduling practice of the case company.*

1.4 Research Scope

Even though there are companies in process industries producing only MTS products, in this master's thesis, only those producing both product types and implement hybrid MTS-MTO production systems are studied.

Also, as it will be discussed later in section 3.1, production plans are made in three main levels namely, long-term, medium-term, and short-term levels each varies in purpose, timespan, and level of detail (Stevenson, 2012). However, the scope of this research is limited to only solving problems of short to medium-term operational planning.

Further, in discussing the L&S model, as the solution for solving these problems, the thesis pays more attention to the modeling perspective rather than the solution approach. This means that the thesis more focuses on building the model according to the needs of the chosen company, discussing its potentials, and solving a restricted version of it rather than proposing a fully operational solution for the company.

1.5 Research Outline

The following chapter explains the research methodology and research methods adopted throughout this master's thesis. Chapter 3 studies the theoretical background that provides the required knowledge for conducting this research while chapter 4 studies the chosen case company that motivates the research and helps better understand the problems of process industries using hybrid MTS-MTO systems. Chapter 5 attempts to solve the recognized problems by developing a solution for the production planning problems of process industries using hybrid MTS-MTO systems. Chapter 6, as the final chapter, concludes the research by discussing the contributions and limitations of this master's thesis and the possible future research works that can be pursued after this thesis.

2 Methodology

In this chapter, the research methodology and research method conducted to accomplish the research objective of this master's thesis are explained.

While the research method can be defined as the technique for data collection and analysis, the research methodology is the justification of employing a specific method to address a research phenomenon (Croom, 2010). Research methods can adopt quantitative or qualitative approaches. A quantitative approach uses mathematical tools for investigating the data gathered. A qualitative approach, on the other hand, uses interpretation and perception for addressing the problem (Croom, 2010). In this thesis, a combination of these two approaches is applied to tackle production planning problems using a mathematical optimization model.

This research work is composed of a theoretical and an empirical part in which two research methods are employed: literature study and case study.

2.1 Literature Study

The literature study aims to uncover the state-of-the-art theoretical knowledge which is built upon a particular research topic. It helps to better define the scope of the research and its objectives and to see whether the chosen topic has been investigated so far (Rajasekar et al., 2006).

The literature study in this thesis was conducted to grasp the latest scientific findings of process industries, problems they are facing, and production planning approaches to tackle these problems as well as identifying potential research gaps to be filled. This study also, throughout the thesis contributed to accomplishing research tasks 1 and 3.

2.1.1 Data Collection

To obtain the relevant sources in the literature, primarily two searching techniques were used: keyword search and snowball sampling techniques. Throughout the study as the research further progressed, several main keywords and their equivalent terms in the literature were identified that helped to explore the chosen field of study and narrowing down the research scope. Below are the main keywords used during the search.

- Production planning and control (PPC)
- Hybrid MTS-MTO production systems
- Characteristics of process industries
- Production planning and scheduling in process industries
- The economic lot-scheduling problem (ELSP)
- Simultaneous lot-sizing and scheduling (L&S) problem

These sets of keywords were searched within three academic databases of Web of Science, Scopus, and Google Scholar in which the choice of articles was subjected to engineering, management, business, and decision science areas. Preliminary search involved scanning the titles and abstracts for checking the relevance of the articles found. After the preliminary search, the relevant articles were thoroughly read, summarized, and saved inside EndNote's reference library to be used later for developing the theoretical part of the thesis. During this process, the preference was given to peer-reviewed papers in order to ensure the validity and reliability of the research work.

In addition to the keyword search, the other frequently used searching technique during the study was snowball sampling. In this technique, once the relevant article is decided upon, papers cited by this article and the ones citing this article are analyzed. The backward and forward snowballing is often used to limit the scope of the research (Jalali et al., 2012). Besides these two main searching methods, in a few cases, some of the key textbooks of operations management studied during the master's degree program were also used to find relevant material.

2.2 Case Study

The second research method adopted in this thesis was the case study. The case study provides a realistic and industrial insight into the chosen research topic, by allowing the theory to be implemented, tested, and compared in practice. Therefore, it is considered a valuable method for generating novel theory (Voss et al., 2002). Due to recent technological developments and market changes, it has gained even more importance in operations management (Voss et al., 2002).

The case company studied in this thesis was Snåsavann AS, a mineral water bottling company with a typical manufacturing and planning environment of process industries which implements a hybrid MTS-MTO production system. The choice of the company enabled the research to investigate and observe challenges of production planning inside process industries, and later to test the applicability of the developed solution addressing these challenges. This study contributed to satisfying research tasks 2 and 4.

2.2.1 Data Collection

Data collection in the case study was mainly conducted through the use of semi-structured interviews in multiple sessions. The reason for choosing this type of data collection was motivated by several reasons: It allows the researcher to investigate different aspects of the topic at hand and to evaluate the pros and cons in doing so. It is suitable to be used for different participants. Due to the exploratory nature of the study, strictly following a set of questions is not required, thus facilitating more interactions with the participant (Bryman, 2012, Matthews and Ross, 2010).

Most data required for conducting the master's thesis was acquired in fall 2019 in a 5-day visit at the company when taking the course TPK4530. The observations made were later documented and presented to the management to be approved before leaving the company. Since then, further visits to the company and physical meetings with management were not possible due to the outbreak of the COVID-19 pandemic and, therefore all following communications were established by the means of emails, phone calls, and online meetings.

Before submitting the thesis, the final version of the work was formally presented to the top management to ensure its validity and prevent the use of confidential information. The signed approval of the company is attached as an appendix to the end of the thesis.

3 Theory

In this chapter, to have a good grasp on the research topic at hand, relevant theoretical knowledge laid in the literature is presented. First, the production planning and control systems employed in manufacturing environments and the most recent trend evolving them are investigated. Then the characteristics of process industries in comparison to discrete manufacturing industries are explored, and then different production planning and scheduling approaches specifically designed for these industries are studied. Finally, the simultaneous lot-sizing and scheduling problem and its proposed MILP models, as the most promising planning approach in process industries are discussed in detail.

3.1 Production Planning and Control (PPC) System

Manufacturing is about supplying the demand at the right time in the most profitable way. In doing so, manufacturing firms must constantly assess the capacity or capability of their organizations to satisfy the market's demand and maintain a proper balance between this realized capacity and the expected demand in a certain period. To maintain this balance and to execute production effectively and efficiently, a hierarchical planning system called the production planning and control (PPC) system is used (Arnold et al., 2008). The PPC system involves tasks and decisions trying to "... manage efficiently the flow of material, the utilization of people and equipment, and to respond to customer requirements by utilizing the capacity of our suppliers, that of our internal facilities, and (in some cases) that of our customers to meet customer demand." (Vollmann et al., 2005)

In this production planning and control (PPC) system, the planning part formalizes what is going to happen to the business in the future, while the control part monitors operations activities and handles any deviations from the plan (Slack et al., 2007). In other words, the PPC system provides production managers with a structure upon which they can devise effective plans (Romsdal, 2014). These plans are usually made in three main levels of long-term planning, medium-term planning, and short-term planning, each varies in purpose, timespan, and level of detail (Stevenson, 2012, Arnold et al., 2008).

Long-term Planning Long-term planning is the least-detailed planning level among all levels of the PPC system in which the general direction of the firm for the next two years and over is indicated. Strategic decisions like system design, determining the type of product to be produced, targeting a new market, building a new production facility, or buying new equipment are examples of long-term plans that are made by senior managers in the company. These plans are often reviewed every 6-12 months (Fleischmann et al., 2008, Arnold et al., 2008).

Medium-term Planning Based upon the established objectives and constraints of the long-term planning level, in the medium-term planning level, tactical decisions regarding output rates, general employment levels, inventory levels, backorders, and subcontracting are made by production planners that usually cover a planning horizon of 2-12 months. In this level, plans are more detailed compared to the previous level and they are supposed to be reviewed every month or quarter. The master production scheduling (MPS) as the heart of the PPC system (Stevenson, 2012), and the material requirements planning (MRP) are performed at this level (Fleischmann et al., 2008).

Short-term Planning This level is the last and most detailed level of the PPC planning hierarchy which ends up with producing the actual output. It establishes operational decisions such as scheduling or sequencing job orders, scheduling workers, equipment, and facilities by taking into consideration the limitations set by the previous planning levels. The planning horizon could be from days to a few weeks and these plans are constantly reviewed every day (Stevenson, 2012, Arnold et al., 2008).

3.1.1 Basic Delivery Strategies in PPC Systems

All processes executed throughout the material transformation flow from the point of origin to the point of consumption can be divided into two categories; push or pull processes. Push processes are done in anticipation of the customer order based on the forecast, while pull processes are done in response to actual customer orders. There is a boundary separating push and pull activities in the product structure which is called the customer order decoupling point (CODP) – also referred to as order penetration point (OPP). Those activities that are done before CODP are push-activities and those done after this point are pull-activities (Chopra and Meindl, 2010, Olhager, 2003).

Based on the position of CODP in the value chain, the PPC system can take four basic delivery strategies or approaches, each dictating different objectives regarding production efficiency, customer service, and inventory management (Olhager, 2003, Stevenson et al., 2005). These four basic PPC approaches are as follows:

Make-to-stock (MTS) In this approach, CODP is placed downstream in the value chain and at the finished goods inventory. It has the shortest order fulfillment time since demand is met from the finished goods inventory and all production activities are done based on the forecast and before receiving the actual customer order (Stevenson, 2012).

Assemble-to-order (ATO) In this approach, CODP is placed at the inventory of standard and modular parts. After receiving the order, parts are assembled together according to customer specifications and delivered to the customer (Stevenson, 2012).

Make-to-order (MTO) In this approach, CODP is placed at the fabrication and procurement stage. Pre-designed products are only produced after receiving the customer order. The degree of product customization and delivery times in this approach are more than those of the ATO strategy (Stevenson, 2012).

Engineer-to-order (ETO) In this approach, CODP is placed upstream in the value chain at the design and engineering stage. It has the highest level of product customization and the longest delivery times since all production activities are started after receiving the customer order (Stevenson, 2012).

Figure 3.1 depicts these four strategies and their corresponding CODP placement. Forecast-driven production activities are presented by dotted lines and customer-order-driven activities are presented by straight lines.

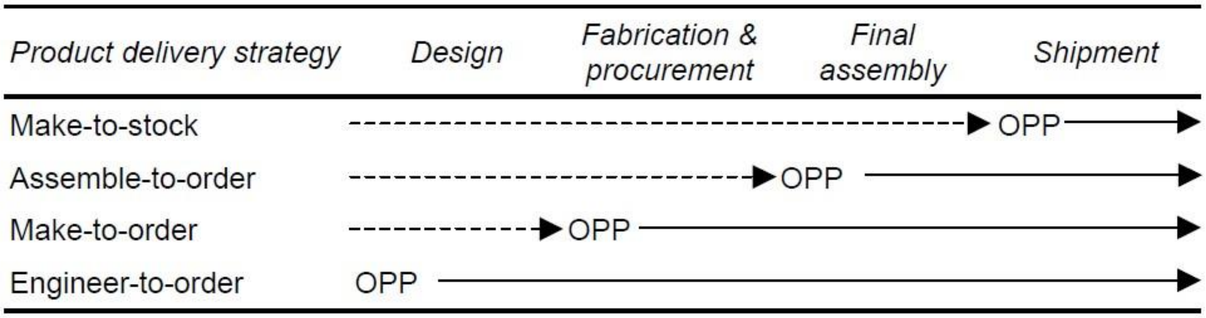


Figure 3.1: Four delivery strategies in the PPC systems (Olhager, 2003)

3.1.2 Hybrid MTS-MTO Strategies

In order to study hybrid MTS-MTO production systems, it is important to first discuss the characteristics of pure MTS and pure MTO production systems.

In MTS production systems, production activities are executed to meet the forecasted demand and the focus is on producing less expensive standard products in high volumes with low variety (Vollmann et al., 2005). The competitive priorities to achieve are higher utilization and fill rates. The main operations issues to deal with are forecasting, lot-sizing, and inventory management, and the performance measures to follow are product-oriented like line item fill rate and average inventory levels (Vollmann et al., 1997, Silver et al., 1998, Soman et al., 2004)

On the other hand, in MTO systems, production activities are executed to meet the actual customer demand and the focus is on producing more expensive customized products with high variety and often in low volumes (Soman et al., 2004, Vollmann et al., 2005). The competitive priorities to achieve are shorter delivery lead times. The main operations issues to deal with, are service level consistency, order acceptance, and capacity planning, and the performance measures to follow are order oriented like average response time or average order delay (Vollmann et al., 1997, Kingsman et al., 1996, Silver et al., 1998, Soman et al., 2004)

Table 3.1 sums up the characteristics of pure MTS and MTO production systems.

Characteristic	MTS	MTO
Products	Low variety, producer specified, less expensive products	High variety, customer specific, more expensive products
Planning focus	Forecasting and planning to meet demand	Order execution
Performance measures	Product focussed (line item fill rate, inventory levels)	Order focussed (response time, order delay)
Competitive priority	Higher fill rates	Shorter delivery lead time
Operations issues	Inventory planning, lot size determination, demand forecasting	Capacity planning, order acceptance/rejection, due adherence

Table 3.1: The key characteristics of the MTS and MTO systems (Romsdal, 2014)

In recent years, technological advances that improve manufacturing flexibility have enabled manufacturing companies to produce products with different characteristics within the same production facility. As a result, PPC systems that combine different strategies such as hybrid MTS-MTO production systems have been employed (Iravani et al., 2012).

Such hybrid MTS-MTO systems should help companies to distinguish between MTS and MTO products and carefully plan them accordingly on shared resources (Van Donk, 2001, Beemsterboer et al., 2016). However, it needs to be noted that planning in these contexts is rather complicated since there are distinctive challenges in hybrid MTS-MTO PPC systems requiring different decisions to be taken compared to traditional pure MTS and pure MTO systems (Soman et al., 2004).

While MTS PPC systems focus on preventing stockouts and performance measures are often cost-based like lowering the inventory holding costs, MTO PPC systems focus on producing products before a fixed due date, and performance measures are often time-based like reducing the timespan (Beemsterboer et al., 2016, Beemsterboer et al., 2017a). Therefore, complex trade-offs must be made between different needs of MTS and MTO products regarding inventory levels, machine utilization, number of setups, and production lead-times (Soman et al., 2004, Romsdal et al., 2013). For instance, in order to incorporate the uncertainty of MTO products in a hybrid MTS-MTO system, the inventory for MTS products should be increased for maintaining the same service level. Allocating no inventory for MTO products due to uncertainty results in increasing the number of setups and consequently decreasing machine utilization, which again leads to increasing production lead-time in the system. Therefore, to hedge against this increased production lead-time, the safety stocks for MTS products, or as Bemelmans (1986) calls it, the capacity-oriented inventory should be increased.

Although hybrid MTS-MTO production systems become more popular in practice every day, most attention of the literature is towards production planning and control in either pure MTS or pure MTO production systems and research on hybrid MTS-MTO PPC systems are scarce (Soman et al., 2004, Iravani et al., 2012, Beemsterboer et al., 2016, Beemsterboer et al., 2017b, Romsdal et al., 2013).

Soman et al. (2004) review the literature in this area and classify the conducted research based on issues they address within three main levels of hybrid MTS-MTO PPC systems, namely long-term, medium-term, and short-term planning levels. By acknowledging the contributions made in the hybrid MTS-MTO literature, they state that majority of the papers do not address the specific characteristics of the process industries – as a type of manufacturing environments in which hybrid MTS-MTO PPC systems are quite prevalent (Soman et al., 2004), and stress the need for some analytical decision aids that can solve short-term operational decisions such as production scheduling and sequencing. In a follow-up study, Soman et al. (2006) evaluate some existing scheduling and sequencing methods that are designed for pure MTS production systems and try to implement them in hybrid MTS-MTO systems by incorporating the uncertainty of MTO products into the methods. They conclude that methods that might work well in pure MTS systems are not necessarily suitable for hybrid MTS-MTO production systems. In another study, Romsdal et al. (2013) discuss a number of challenges in the tactical and operational decision levels of hybrid MTS-MTO systems and emphasize the importance of scheduling and sequencing methods suitable for process industries.

Since this thesis is going to develop an analytical decision model for short-term scheduling hybrid MTS-MTO production systems, it is noteworthy to separately restate the two critical issues mentioned in these papers:

1. This scheduling model must address the complications of the hybrid MTS-MTO production system. Meaning that it must recognize the interactions between MTS and MTO products in a shared limited capacity by considering the trade-off between the inventory holding costs and the setup costs in the system.
2. This scheduling method must address the specific characteristics of the process industries since hybrid MTS-MTO PPC systems are common in these types of industries.

In the next chapter the process industries and their characteristics are discussed to see how these might affect the short-term production scheduling.

3.2 Process Industries

Manufacturing environments can be categorized into two types of discrete manufacturing industries (or assembly operations as King (2009) call them) and process manufacturing industries (in short, process industries) (Abdulmalek et al., 2006). Discrete manufacturing industries produce discrete materials which can be counted as individual items and maintain their solid form without having to contain them, while prosses industries deal with non-discrete materials such as liquids, gases, pulps, and powders that will expand, evaporate, or dry out without putting them into containers (Abdulmalek et al., 2006).

Even though process industries as mentioned, deal with non-discrete materials, not all of them necessarily deliver non-discrete finished products at the end. In many process industries, there is a point within the process in which non-discrete materials turn into discrete materials (Abdulmalek et al., 2006). This point which Pool et al. (2011) call it the discretization point, separates continuous production from discrete production. Therefore, while discrete manufacturing industries employ only discrete production, process manufacturing industries can employ both continuous production and discrete production (Noroozi, 2017). According to this, process manufacturing industries are mainly defined and distinguished from discrete manufacturing industries based on the employed production process rather than the nature of the finished product (Abdulmalek et al., 2006, Noroozi, 2017).

Here it is important to mention that, in referring to process manufacturing industries there is a misconception that allows using the two terms of process manufacturing and process flow production interchangeably, although they do not actually have the same meaning (Abdulmalek et al., 2006). The American Production and Inventory Control Society (APICS) defines process manufacturing as “production that adds value to materials by mixing, separating, forming, and/or performing chemical reactions. It may be done in either batch or continuous mode.” while it defines process flow production as “A production approach with minimal interruption in the actual processing in any one production run or between runs of similar products. Queue time is virtually eliminated by integrating the movement of the product into the actual operation of the resource performing the work.” (Blackstone et al., 2005). This means that all process industries use process manufacturing, but they do not always use process flow production (or continuous production) throughout the production (Abdulmalek et al., 2006). Examples of process industries include food and beverages, steel, chemicals, pharmaceuticals, petroleum, and textile industries.

3.2.1 Distinguishing Characteristics of Process Industries

There are some notable characteristics in process industries that differentiate them from discrete manufacturing industries. Products produced are typically high volume and high variety with volatile demand. The set of production equipment used in these industries is large, often highly automated, and expensive with fixed installations. Usually, the equipment is identified as the bottleneck in the production process. Product changeovers and setups are complex, time-consuming, and costly and often these setups are sequence-dependent, meaning the setup operations are dependent on the production sequence (King, 2009). Table 3.2 compares discrete manufacturing industries and process industries in terms of these general characteristics.

Characteristic	Discrete manufacturing	Process industries
Products	High volume, often low variety	High volume, often high variety
Production equipment	Small, flexible with low-capacity utilization	Large, inflexible with high-capacity utilization, capital intensive and highly
Throughout	Limited by labor	Limited by equipment
Product changeovers	Relatively simple, time- and labor- consuming	Relatively complex, time-, labor-, and material-consuming
Cost of stopping and restarting production	Relatively low	Relatively high

Table 3.2: Characteristics of discrete manufacturing and process industries

3.2.2 New trend and the Emerging Problems

Due to the nature of their production process, process industries were typically used to be known as industries producing high-volume low-variety products utilizing pure MTS systems (Spenhoff et al., 2016). Highly automated, expensive production equipment and long setup times in process industries, dictate high utilization and line item fill rate and allow for minimum interruptions during the production, therefore, manufacturers tend to avoid producing in small lots in the past (Abdulmalek et al., 2006).

However, recent changes in the market trends coupled with fierce competition in the business have led to increasing product variety, demand variability, and consequently, more uncertainty in these industries (Spenhoff et al., 2016). This has made manufacturers use planning systems that can address this increased uncertainty and provide more flexibility (Kiliç, 2011). On the other hand, some of the key characteristics of process industries prevent the use of highly responsible and flexible production planning systems such as pure MTO systems (Pochet, 2001). Therefore, manufacturers are propelled into shifting only part of their production from MTS to MTO and adopting hybrid MTS-MTO production systems (Soman et al., 2004).

As described, while market trends require more flexibility, production process characteristics of process industries limit flexibility. This newly emerged conflict has created serious problems for PPC tasks in these environments (Spenhoff et al., 2016). Below are some of the observed challenges in process industries that may arise from this conflict:

- While there is a higher risk of stockouts for some products due to the growing product variety, the total level of inventory tends to grow faster than the inventory turnover (Packowski, 2013).
- Due to high demand uncertainty, the short-term planning horizon cannot be frozen. Therefore, upon the arrival of new and unplanned orders, frequent rescheduling and

firefighting might occur on the shop floor resulting in deviations between the production targets and the actual outputs (Glenday and Sather, 2018).

- Large production equipment with fixed installation limits layout reconfigurations (Abdulmalek et al., 2006).
- Long and costly setups do not allow for rapid changeovers in the production line making the production of multiple products quite challenging on a shared resource (Spenhoff et al., 2016).
- Sequence dependency of setups adds considerable difficulty to tasks related to production scheduling (Spenhoff et al., 2016).

3.2.3 Production Planning and Scheduling in Process Industries

Production planning and scheduling practice in process industries are complicated (Wilson, 2018), and an efficient PPC system that properly addresses the aforementioned challenges in these industries can play a vital role in a company's competitiveness (Kiliç, 2011). However, despite the realized importance, most research within PPC literature is devoted to discrete manufacturing industries, and process industries have not received much attention (Noroozi and Wikner, 2016).

Production planning and scheduling tasks in process industries mainly revolve around the systematic allocation of resources like facilities and equipment to different operations and establishing the timing of those operations (Kiliç, 2011). Most research contributions regarding production scheduling in process industries belong to two main research lines. The first line of research investigates the economic lot-scheduling problem (ELSP) (Rogers, 1958) which is considered as the multi-product and capacitated version of the economic order quantity (EOQ) problem. The aim of the ELSP is to find a cyclical production pattern that can be repeated over time in an infinite planning horizon and minimizes the sum of setup and inventory holding costs. The generated cyclic schedule determines the cycle time (the time until the next production run) and the production time per lot for each product (Elmaghraby, 1978). This way the sequence of products to be produced and their contributing lot sizes are worked out. Three main approaches are developed for ELSP namely, common cycle approach, basic/extended basic period approach, and time-varying lot size approach. For a more detailed overview concerning the ELSP, its extensions, and associated solution methods the interested reader is referred to Kai Chan et al. (2013) and Santander-Mercado and Jubiz-Diaz (2016).

The second line of research investigates the simultaneous lot-sizing and scheduling (L&S) problem considered as the counterpart of the ELSP that utilizes finite, periodic, and time-varying planning horizons instead of generating cyclic schedules (Kiliç, 2011). By increasing product variety, finding feasible cyclic production schedules in the ELSP becomes extremely difficult (Brander, 2005, Elmaghraby, 1978). In this case, L&S problem can be used to achieve optimal production schedules that minimize the sum of holding and setup costs in the planning horizon (Kiliç, 2011). The generated schedules simultaneously decide on the sequence of production as well as the lot size for different products in each period (Copil et al., 2017). Many mathematical optimization models have been proposed to solve L&S problems, with the most well-known being the discrete lot-sizing and scheduling problem (DLSP), the continuous setup lot-sizing problem (CSLP), the proportional lot-sizing and scheduling problem (PLSP), the general lot-sizing and scheduling problem (GLSP), and the capacitated lot-sizing problem with sequence-dependent setups (CLSD) (Kiliç, 2011, Copil et al., 2017).

Solving both of the two above problems, the ELSP and the L&S, is challenging since they are classified as NP-hard optimization problems (Beck and Glock, 2020, Gallego and Shaw, 1997). In NP-hard problems, exact analytical methods can achieve an optimal solution but only for the restricted versions of the problem. However, to solve the large versions of the problem, mainly heuristic and meta-heuristic methods are used that can achieve a "good" solution with an acceptable optimization gap in a reasonable time (Brander, 2005, Elmaghraby, 1978).

3.3 Simultaneous Lot-sizing and Scheduling (L&S)

Lot-sizing and scheduling are two of the most vital but challenging tasks in production planning. Lot-sizing decides on the quantity and timing of the production during a finite planning horizon, while scheduling, which is also referred to as sequencing in the L&S literature, attempts to determine the sequence in which different lots should be produced (Almada-Lobo et al., 2015).

Classically, these two tasks are carried out separately and hierarchically in different planning levels of the PPC system. However, a new trend in the production planning and control literature emphasizes the importance of integrating these two problems in many manufacturing environments (Clark et al., 2011), and especially in process industries (Copil et al., 2017). There are two reasons for integrating lot-sizing and scheduling problems: Firstly, the integration of these two problems results in the generation of more cost-efficient production plans than the ones generated by addressing the two problems in a hierarchical manner and different planning levels of the PPC system (Guimarães et al., 2014).

Secondly, in manufacturing environments in which the production capacity is tight, for example in process industries due to capital intensity of production equipment, multiple items compete with each other to be produced on a shared machine. This eventually creates scheduling overlaps, meaning that the production-run for one item starts before completing the production quantity of another item (Davis, 1990), and therefore, the machine needs to produce multiple items at the same time, which is not possible (Elmaghraby, 1978). In this situation, lot sizes need to be modified in order to avoid scheduling overlaps and accommodate the production of all products (Brander, 2005), however, lot-sizing models that pay no attention to scheduling and determine the lot size for different products individually without taking into account their relation to other products, such as the economic order quantity (EOQ) or its extension the economic production quantity (EPQ) cannot be used (Axsäter, 2000). Thus in order to create implementable and feasible production plans, it is necessary to have an integrated approach addressing lot-sizing and scheduling problems simultaneously (Almada-Lobo et al., 2015).

The simultaneous lot-sizing and scheduling (L&S) problem is of short to medium scope since it generates plans covering planning horizons of from a few weeks to several months, and therefore, it is placed between the master production scheduling (MPS) and the detailed operational scheduling (Fleischmann and Meyr, 2003).

3.3.1 Modeling Features

Recently, L&S has attracted a considerable amount of attention not only from academia but also from many companies in the industry (Copil et al., 2017). Different mixed-integer linear programming (MILP) models have been suggested by researchers for addressing L&S problems over the last two decades. With the latest advancements in modern optimization solvers regarding their hardware and computational efficiency, researchers have been able to propose more complex and realistic mathematical models for different variants of the L&S problem (Almada-Lobo et al., 2015).

The complexity of different L&S variants depends on the ability of the model to incorporate the features of real-world production systems (Karimi et al., 2003). The following are certain modeling features affecting the complexity of L&S models and better help classifying them.

Planning Horizon The planning horizon is the time period on which the model makes decisions regarding lot-sizing and scheduling. In L&S models, real-world decisions, and events that occur continuously are translated into decisions and events happening on a discrete time scale (Almada-Lobo et al., 2015). According to this discrete representation of the planning horizon, L&S models can be classified into big bucket and small bucket models. In big bucket models, the planning horizon is divided into a small number of long time periods (also known as macro-periods) often representing an interval of a week or a month. In small bucket models, on the other hand, the planning horizon is divided into a large number of short time periods (also known as micro-periods) that represent time intervals equal to days, shifts, or hours (Guimarães et al., 2014). While in big bucket models, the time period is long enough to perform multiple setups and produce multiple products, in small bucket models, the time period is just enough to perform only one setup and produce a maximum of two products (Karimi et al., 2003, Almada-Lobo et al., 2015).

Number of Production Stages and Production Machines L&S models may feature single-stage or multi-stage and single-machine or parallel machine/line production systems. In single-stage production systems, raw materials are directly transformed into finished products with no intermediate buffer of sub-assemblies. Products have independent demand which means that demand for products is calculated from customer orders or forecasts. In multi-stage production systems, raw materials after passing several processing stages turn into finished products. Here the output of one stage is the input for the following stage, and that is why products have dependent demand meaning that the product demands in each stage depend on the product demands of the following stage. Multi-stage L&S models are much more difficult to solve compared to single-stage models (Karimi et al., 2003). Also, several different or identical production machines might be used with different capacity and output rates that can add to the complexity of the modeling (Copil et al., 2017).

Number of Products L&S models can also be designed for planning production systems with one finished product or systems with multiple finished products. The former requires models that plan for one product, while the latter requires more complex models that can plan for various products (Karimi et al., 2003).

Capacity When no restriction is set on resources or capacities of the production system, the model is considered to be incapacitated, and when capacity restrictions are included, the model is called capacitated. Solving capacitated models is much more difficult and time-consuming since capacity restrictions increase the number of constraints in the model (Karimi et al., 2003).

Deterioration of Products Perishability of products adds more complexity to the problem since the model has to be able to trace inventory holding times throughout the planning horizon (Almada-Lobo et al., 2015).

Demand L&S models can be distinguished according to the type of demand they are modeling. If the demand does not change and it is constant it is called static, while if its value changes throughout the planning horizon it is dynamic. In case the value of demand is known in advance, regardless of being static or dynamic, it is said to be deterministic, but when the demand value is not known and it varies based on some probabilities, it is said to be probabilistic. Independent demand also as mentioned earlier means that the demand for products is directly connected to customer orders or forecasts and does not depend on other products' demand. Instead, dependent demand means that the demand for component parts depends on the demand for parent products on the next level. Models addressing dynamic, probabilistic, and/or dependent demands are more difficult to solve than models with static, deterministic, and/or independent demands (Karimi et al., 2003).

Setup Features Changing between different types of products require operations such as machine adjustment or cleansing. Setup operations incur considerable cost to the system and therefore, correctly modeling their different features considerably affects the outcome of L&S models. These setup features are as follows:

1. Setup carryover: Sometimes if the production stops and the machine idles, the setup state of the machine must be preserved and carried over from the current period to the next one to reduce setup time and cost (Almada-Lobo et al., 2015). Figure 3.2 demonstrates the production plan of a machine producing different types of bottled waters. As it is depicted, the configuration of the machine to still water 0.5L is carried from period 2 to period 3.

2. Setup crossover: This feature allows the machine to start and stop the production anywhere in between the planning horizon, and not only within the boundaries of the discrete time period. Under this condition, the setup operation overlaps the boundary of the current period and continuous to the next period, while without considering this feature setup operation must be performed entirely within the time period and cannot continue to the next period. In industries with significantly large setup times implementing this feature might be necessary to properly generate a production plan (Almada-Lobo et al., 2015). Figure 3.2 shows the setup crossover from period 1 to period 2.

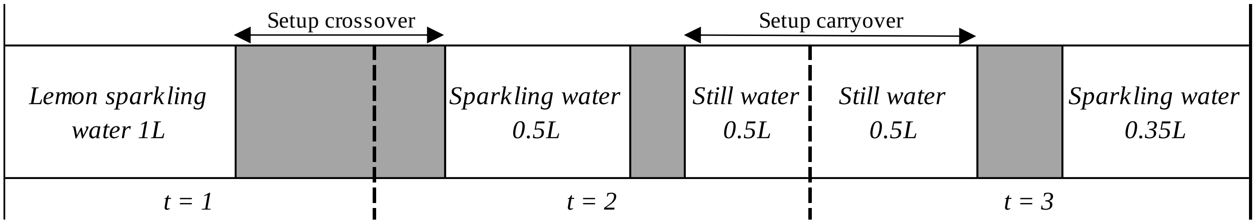


Figure 3.2: Setup carryover and setup crossover

3. Non-triangular setups: In most manufacturing environments, in changing from one product to another, there is no need to use the third product as a shortcut product. In these circumstances, it is said that setups obey the triangular inequality. However, in certain industries, instead of directly changing from one product to another, it is more cost-efficient to produce a third shortcut product in between those two products. This is because the shortcut product acts as a cleanser absorbing the contamination caused by the first product, prepares the machine for producing the other product, and therefore, reduces the overall setup time. This shortcut product results in the presence of non-triangular setups. The model to incorporate this situation needs to allow the production of each product more than once per period (Clark et al., 2014). Figure 3.3 demonstrates the production plan of a machine producing five different products with the presence of non-triangular setups. Product D is the shortcut or cleansing product that cleanses the machine after producing products A and C for producing the next product.

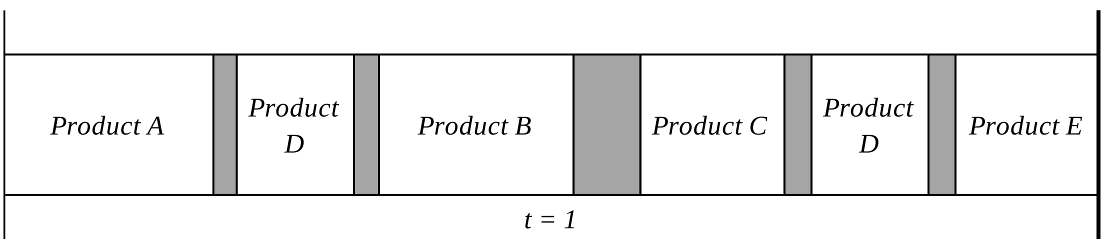


Figure 3.3: Shortcut product D which results in the presence of non-triangular setups

4. Setup families: In some manufacturing environments products can be grouped into different families according to their processing and setup needs. Changeovers between products within the same family are much less costly than changeovers between products from different families. The changeovers between products of the same family are called minor setups and changeovers between products from different families are called major setups (Karimi et al., 2003, Almada-Lobo et al., 2015). Günther et al. (2006) suggest a block planning approach to model the concept of setup families in L&S models in a way that each block is considered as a family in which the production sequence is predefined and does not change due to processing needs. Therefore, the changeovers only happen between the blocks or families and by incurring major setups.

Inventory Shortage The type of inventory shortage is another feature affecting the complexity of the model. In case the shortage is allowed, the current period's demand can be satisfied in future periods by incurring a backlogging cost to the system, and ff the shortage is not allowed, the unsatisfied demand is lost by incurring a lost-sales cost to the system. This is done by introducing a shortage cost to the objective function of the model (Karimi et al., 2003).

3.3.2 Basic L&S Model Variants

Numerous L&S model variants have been suggested by researchers so far. However, there are only five main basic models upon which other extensions incorporating more realistic features have been developed (Copil et al., 2017). These five basic models are as follows:

1. The discrete lot-sizing and scheduling problem (DLSP) by Fleischmann (1990)
2. The continuous setup lot-sizing problem (CSLP) by Karmarkar and Schrage (1985)
3. The proportional lot-sizing and scheduling problem (PLSP) by Drexl and Haase (1995)
4. The general lot-sizing and scheduling problem (GLSP) by Fleischmann and Meyr (1997)
5. The capacitated lot-sizing problem with sequence-dependent setups (CLSD) by Haase (1996)

Among these five models, the DLSP and CSLP are designed for sequence-independent setup costs and do not take into account sequence-dependent setup costs. The other three models namely, PLSP, GLSP, and CLSD all support sequence-dependent setup costs (Copil et al., 2017). Moreover, the PLSP allows for the production of a maximum of two different products per period, while the GLSP and CLSD have no restriction in this regard (Copil et al., 2017). As discussed earlier in section 3.2.2, high product variety and sequence-dependent setups are two of the key characteristics of process industries that can cause challenges for production planning. Therefore, for the purpose of this study, the GLSP and CLSD are considered to be the superior models compared to the other three, since they are the only ones able to incorporate these two characteristics of process industries.

The CLSD as a big bucket model and the GLSP as a small bucket model, are also the two most well-known and studied models of each bucket type (Almada-Lobo et al., 2015). In these models, demand is considered to be deterministic and has to be met by the end of each period, hence inventory shortage is not allowed. Also, both basic models of CLSD and GLSP are presented for a single-stage production environment. Below are their basic mathematical formulations with shared indices and parameters that are adopted from Almada-Lobo et al. (2015):

Sets and indices

i, j products, $i, j = 1, \ldots, N$

t time periods, $t = 1, \ldots, T$

Data

d_{it} demand of product *i* in period *t* (units)

h_{it} holding cost of one unit of product *i* in period *t*

cap_t machine capacity in period *t* (time)

p_i processing time of product *i*

b_{it} upper bound on production quantity of product *i* in period *t*

m_i minimum lot sizes of product *i*

st_{ij} time required to perform a changeover from product *i* to product *j*

sc_{ij} cost incurred when performing a changeover from product *i* to product *j*

$\bar{s}_i$ start-up cost for product *i*

Variables

I_{it} stock of product *i* at the end of period *t*

X_{it} quantity of product *i* to be produced in period *t*

Capacitated Lot sizing with sequence-dependent setups (CLSD)

In order to develop the basic form of the CLSD, the following additional decision variables need to be introduced:

Z_{it}^b (=1) if the machine is set up for product *i* at the beginning of period *t*

Z_{it}^e (=1) if the machine is set up for product *i* at the end of period *t*

T_{ijt} (=1) if a changeover from product *i* to product *j* is performed in period *t*

The MILP formulation for the basic CLSD reads:

Objective function:

$$Min \sum_{i,t} h_{it} \,.\, I_{it} + \sum_{t,i,j} sc_{ij} \,.\, T_{ijt} + \sum_{i,t} \bar{s}_i \,.\, Z_{it}^b \qquad (1)$$

Subject to.:

$$I_{i,t-1} + X_{it} - d_{it} = I_{it} \qquad \forall\, i,t, \qquad (2)$$

$$\sum_{i} p_i \,.\, X_{it} + \sum_{i,j} st_{ij} \,.\, T_{ijt} \leq cap_t \qquad \forall\, t, \qquad (3)$$

$$X_{it} \leq b_{it} \,.\, \left(\sum_{j} T_{jit} + Z_{it}^b\right) \qquad \forall\, i,t, \qquad (4)$$

$$\sum_{i} Z_{it}^b = 1 \qquad \forall\, t, \qquad (5)$$

$$\sum_{i} Z_{it}^e = 1 \qquad \forall\, t, \qquad (6)$$

$$Z_{it}^b + \sum_{j} T_{jit} = \sum_{j} T_{ijt} + Z_{it}^e \qquad \forall\, i,t, \qquad (7)$$

$$\{(i,j) \,:\, T_{ijt} > 0\} \text{ does not include disconnected subtours} \qquad \forall\, t. \qquad (8)$$

$$X, I \geq 0, \qquad Z, T \in \{0,1\} \qquad (9)$$

The objective function (1) minimizes the sum of holding, setup, and startup costs. Since production costs are assumed to be product and time-independent, they are not included in the objective function. Constraints (2) check the balancing of inventory, demand, and production. Constraints (3) make sure that processing times plus setup times do not exceed the available capacity. Due to constraints (4) production can only take place if a setup is conducted in the same period or the product is the first to be produced in that period. Constraints (5) and (6) assure that there is at least one product set up in the machine at the beginning or end of each period. Constraints (7) define machine configuration according to the conducted setup operations for each product.

To better explain Constraints (7) let us consider there are three products needed to be modeled in one period, therefore, to check product 1 the corresponding equation for constraints (7) can be stated as follows:

$$Z_{11}^b + T_{111} + T_{211} + T_{311} = T_{111} + T_{121} + T_{131} + Z_{11}^e$$

Now according to the abovementioned equation, if no setup is conducted at a period, the configuration of the machine at the end of that period is the same as the beginning of that period, meaning that machine configuration is set up for product 1 for the entire period. Hence, $Z_{11}^{b} = Z_{11}^{e} = 1$ and all the other input (T_{jit}) and output (T_{ijt}) setups are equal to zero and thus the equation is satisfied. However, if at least one setup operation is conducted during that period, for each product three possible cases might occur; i) Input setups are greater than output setups. This for the above example means that product 1 is at the end of the period and the machine configuration after changing from, for instance, product 3 remains on product 1 until the end of the period. Hence, $T_{311} = Z_{11}^{e} = 1$ and all the other terms are equal to zero and thus the equation is satisfied. ii) output setups are greater than input setups. This again for the above example means that product 1 is at the beginning of the period and the machine configuration remains on product 1 until it changes to, for instance, product 2 in that period. Hence, $Z_{11}^{b} = T_{121} = 1$ and all the other terms are equal to zero and thus the equation is satisfied. iii) input setups are equal to output setups. For the mentioned example this means that product 1 is in the middle of the period with the product before (for instance product 3) and after it (for instance product 2). Hence, $T_{311} = T_{121} = 1$ and all the other terms are equal to zero and thus the equation is satisfied.

While constraints (9) define the domain of variables, constraints (8) ensure that connected subtours are included but disconnected subtours are excluded from the solution. The part of a lot-sizing and scheduling model with sequence-dependent setups, which determines the optimal production sequence is addressed using the asymmetric traveling salesman problem (ATSP) in a way that the optimal sequence is seen just as the shortest possible path in ATSP. Connected subtours are sequences that are part of the optimal sequence generated by the model while disconnected subtours are not part of the optimal sequence (Guimarães et al., 2014). For example, consider the production plan needs to be decided for five different products and let the optimal sequence be 2-4-1-3-5. However, the CLSD without constraints (8) might generate two irrelevant separated sequences such as 2-3-5 and 4-1 which are irrelevant to the optimal solution. In order to avoid this, constraints (8) ensure that subtours or sequences are connected, and the model generates the optimal sequence. Therefore, without constraints (8) the model is incomplete. In chapter 5, the appropriate equations that can define constraints (8) are discussed. For further information about ATSP in lot-sizing and scheduling problems with sequence-dependent setups and approaches for eliminating disconnected subtours the interested reader is referred to Guimarães et al. (2014), Clark et al. (2014), and Taccari (2016).

General Lot-sizing and Scheduling Problem (GLSP)

In order to develop the basic form of the GLSP, the following additional decision variables need to be introduced:

Q_{is} quantity of product *i* produced in micro-period *s*,

Y_{is} (=1) if the machine is set up for product *i* in micro-period *s*,

Z_{ijs} (=1) if a changeover from product *i* to product *j* is performed at the beginning of micro-period *s*

Since the GLSP is a small bucket model, macro-period t is divided into several micro-periods s. Therefore, the set of micro-periods can be defined as $A_t = \{f_t, \dots, l_t\}$.

The MILP formulation for the basic GLSP reads:

Objective function:

$$Min \sum_{i,t} h_{it} \,.\, I_{it} + \sum_{i,j,s} sc_{ij} \,.\, Z_{ijs} \tag{10}$$

Subject to:

$$I_{i,t-1} + \sum_{s \in A_t} Q_{is} - d_{it} = I_{it} \qquad \forall\, i, t, \tag{11}$$

$$\sum_{i,s \in A_t} p_{it} \,.\, Q_{it} + \sum_{i,j,s \in A_t} st_{ij} \,.\, Z_{ijs} \leq cap_t \qquad \forall\, t, \tag{12}$$

$$Q_{is} \leq b_{it} \,.\, Y_{is} \qquad \forall\, i, t, s \in A_t, \tag{13}$$

$$\sum_{i} Y_{is} = 1 \qquad \forall\, s, \tag{14}$$

$$Z_{ijs} \geq Y_{i,s-1} \,.\, Y_{js} - 1 \qquad \forall\, i, j, s, \tag{15}$$

$$Q_{is} \geq m_i \,.\, \left(Y_{is} - Y_{i,s-1}\right) \qquad \forall\, i, s. \tag{16}$$

$$Q, I, Z \geq 0, \qquad Y \in \{0, 1\} \tag{17}$$

Similar to the CLSD in the GLSP also, the objective function (10) minimizes the sum of holding, setup, and startup costs. Constraints (11) check the balancing of inventory, demand, and production. Constraints (12) make sure that processing times plus setup times do not exceed the available capacity. While constraints (13) make sure of the correct machine configuration in each micro-period, and constraints (14) make sure there is only one setup state in each micro-period. The changeovers within micro-periods are defined by constraints (15). Constraints (16) introduce minimum lot sizes so that the phantom slots or micro-periods with no production are prevented.

3.3.3 The Gap in the Literature

In recent years, there has been an increasing interest in L&S models to address lot-sizing and scheduling problems, and more complicated and realistic models as extensions of the five basic variants have been designed. However, these models have primarily been suggested for pure MTS process industries, and the implementation of L&S models within hybrid MTS-MTO process industries has been almost neglected by the literature (Copil et al., 2017).

4 Case; Snåsavann AS

In this chapter, the case company, Snåsavann AS is introduced, mapped, and analyzed. First, a brief description of the company and its business is presented, and then, different characteristics of the planning environment in terms of product, market, and manufacturing process are explored. In the end, the production planning and scheduling tasks currently practiced at the company as well as the associated problems and challenges of the company are investigated.

4.1 Introduction to the Case Company

Snåsavann AS is a newly established Norwegian mineral water bottling company that started its business in 2011. The company fully owns the right for extraction of the groundwater source called Snåsa, which is one of the ten natural mineral water sources within Norway with the capacity of supplying one billion liters of water per year. The headquarters and production facility are placed in close proximity to the water source 180 km north of Trondheim.

High-quality water, recyclable bottles with award-winning designs, and a strong emphasis on customization are the main factors giving the company a competitive edge in business. According to the classification of (Commission, 20.5.2003), with a turnover of approximately 1 million euros and a staff headcount of 12 employees in 2019, Snåsavann AS can be placed among Norwegian small and medium-sized enterprises (SMEs) within the food and beverage process industry.

4.2 Mapping of the Planning Environment

As Jonsson and Mattsson (2003) argue, mapping the planning environment is vital for achieving a better understanding of the company and its planning system. To do so different characteristics of Snåsavann AS in terms of product, market, and manufacturing process are explored. Later using the integrated framework of Buer et al. (2018) an overview of the planning environment of Snåsavann AS is provided.

Product Characteristics Snåsavann AS produces plastic and glass water bottles filled with still water, sparkling water, and flavored sparkling water in five sizes of 0.35L, 0.5L, 0.65L, 1L, and 5L. The company uses two strategies of MTS and MTO for delivering its products. While MTS products account for the majority of the products, MTO products have a higher profit margin. For the purpose of this thesis, however, only one of the production lines and its corresponding products are studied. This line at the moment produces 16 stock-keeping units (SKUs) all with plastic bottles and in sizes of 0.35L, 0.5L, 0.65L, and 1L. 13 of them are standard-design MTS products in three different product families and three of them are custom-made MTO products in two product families. MTO products are customized based on their labeling design, the color of caps, and the type of water.

The bill of materials has a low level of complexity with only a few components namely, bottle, cap, label, and the beverage which constitute the final product utilizing a few routings. Due to the simplicity of the BOM and routing, the product data accuracy (Jonsson and Mattsson, 2003) is high, despite the fact that the data is manually checked using Excel sheets. However, the level of process planning for each product as the determination of various production operations and their sequences (Jonsson and Mattsson, 2003), cannot be considered as high.

Market Characteristics While the customers of MTS products are mainly a handful of large retailers**,** MTO products have many small customers including gyms, newspapers, clinics, and cafeterias. The company is currently experiencing substantial growth in demand and the number of customers is increasing. The demand is volatile in general with an observed seasonality during the year. The ordering size can range from only a mere dozen bottles per year to approximately half a million bottles per year for different customers.

The growing market share coupled with offering customized products leads to high demand uncertainty making forecasting even for MTS products quite challenging. Snåsavann AS is not currently implementing a systematic forecasting approach, and the production requirements for MTS products are realized based on the company's safety stock policy keeping track of annual figures and previous recent orders. As for the procurement requirements also, the company simply communicates its calculated needs to the suppliers in a form of tacit agreements instead of making formal agreements with regular deliveries through the use of integrated inventory solutions. By defining the production lead time (P) as the time from the start of production of the first component to the end of production of the finished product, and the delivery lead time (D) as the time required by the customer to deliver the product (Jonsson and Mattsson, 2003), the P/D ratio for both MTS and MTO products in Snåsavann AS is less than one.

Manufacturing Process Characteristics Snåsavann AS employs a product-oriented flow shop layout with three production lines of both U shape and I shape. However, as mentioned earlier this thesis studies only one of the production lines which is the only line producing a mix of MTS and MTO products and therefore, is the most challenging line in terms of efficient planning. Using large, fixed, and semi-automated production equipment with long sequence-dependent setups, the manufacturing environment of Snåsavann AS is considered as a typical process industry.

Due to high product variety and volatile demand, the fluctuations in production capacity requirements are high. However, the company's capacity flexibility, as the ability to adjust to the production capacity (Rossi and Lödding, 2012), and the load flexibility, as the flexibility of adapting to the available capacity (Rossi and Lödding, 2012), is also considered high.

From a manufacturing process perspective, products are perceived homogenous since they have more or less the same processing needs (Jonsson and Mattsson, 2003) with few possible routings, thus the flow complexity is at a low level (Rossi and Lödding, 2012). Production is carried out in lots with hourly throughput times; for MTO products, the lot sizes are equal to received orders while for MTS products, lot sizes are often larger to satisfy several weeks of demand. Components are processed in a one-piece-flow, meaning that they are transported to the next station as soon as they are processed (Rossi and Lödding, 2012).

Since the bottles are filled with natural mineral water extracted directly from the nearby source, no significant processing is done on the water itself and water tanks are almost always filled and ready to feed the process. Therefore, the production process initiates by first blowing the bottles, followed by filling the bottles with water, capping, labeling, and then it ends with packing the finished products as illustrated in figure 4.1. Since these processes occur continuously and in series, for production planning and scheduling purposes the production line is often considered as one unit. The CODP placement for MTS products is at the finished goods inventory while for MTO products it is at the start of the production process.

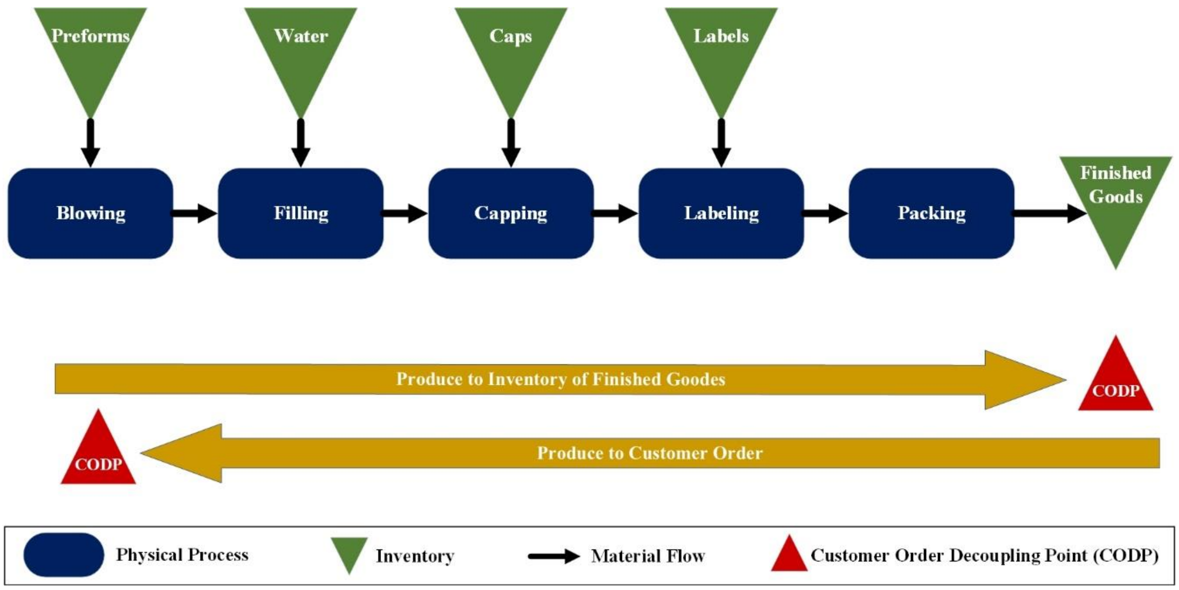


Figure 4.1: Production process at Snåsavann AS

Figure 4.2 gives an overview of the company's planning environment by devising its different characteristics. As planning for MTS and MTO products is different, the associated characteristics of MTS products are presented with red color, and for MTO products they are presented with blue color.

	Variable	Values			
Product characteristics	CODP placement	ETO	MTO 🔵	ATO	MTS 🔴
	Customization level	Fully customized	Some customization allowed 🔵	None 🔴	
	Product variety	High	Medium 🔵	Low 🔴	
	BOM complexity	More than 5 levels	3-5 levels	1-2 levels and several items	🔵 1-2 levels and few items 🔴
	Product data accuracy	Low	Medium	High 🔵🔴	
	Process planning level	None	Partial process planning 🔵🔴	Fully designed process	
Market Characteristics	P/D ratio	<1 🔵🔴	1	>1	
	Demand type	Customer order allocation 🔵	Calculated requirements 🔴	Forecast	
	Source of demand	Customer order 🔵		Stock replenishment order 🔴	
	Volume/frequency	Few large customer orders per year	Several customer orders with large quantities per year 🔴	Large number of customer orders with medium quantities per year 🔵	Frequent call-offs based on delivery 🔵 schedules
	Customer demand frequency	Unique	Block-wise or sporadic 🔵	Regular 🔴	Steady (continuous)
	Time distributed demand	Annual figure 🔵🔴		Time Distributed	
	Demand characteristics	Dependent		Independent 🔵🔴	
	Type of procurement ordering	Order by order procurement 🔵🔴		Order releases from a delivery agreement	
	Inventory accuracy	Low	Medium 🔵🔴	High	
Manufacturing process characteristics	Manufacturing mix	Mixed products		Homogenous products 🔵🔴	
	Shop floor layout	Fixed position	Functional	Cell	Product 🔵🔴
	Type of production	Single unit production	Small series	Serial production 🔵🔴	Mass production
	Throughput time	Months	Weeks	Days	Hours 🔵🔴
	Number of major operations	High	Medium	Low 🔵🔴	
	Batch size	Equal to customer order quantities 🔵	Small, equal to one week of demand	Medium, equal to a few weeks of demand 🔴	Large, equal to a month's demand or more
	Frequency of production order repetition	Non-repetitive production	Production with infrequent repetition	Production with frequent repetition 🔵🔴	
	Capacity requirement fluctuations	High 🔵🔴	Medium	Low	
	Planning points	High	Medium	Low 🔵🔴	
	Setup times	Low	Medium	High 🔵🔴	
	Sequencing dependency	None	Low	Medium	High 🔵🔴
	Part flow	🔵 One-piece-flow 🔴	Overlapped	Lot-wise	Bulk (batch)
	Material flow complexity	High	Medium	Low 🔵🔴	
	Capacity flexibility	High 🔵🔴	Medium	Low	
	Load flexibility	High 🔵🔴	Medium	Low	

Figure 4.2: Profiling of Snåsavann AS planning environment (adapted from Buer et al. (2018))

4.3 Current Production Planning and Scheduling Practice

Production planning at Snåsavann AS is carried out within two planning levels namely medium-term planning and short-term planning. Although in a few months' time the company will be implementing an ERP system, at the time of writing this thesis it uses Excel datasheets as its main planning tool. Medium-term planning is mostly used for non-manufacturing functions like accounting and raw material procurement. Based on yearly contracts and previous annual figures, a rough estimation for the next few months is made so that it can be used as an input for short-term planning. This way the demand for MTS products is worked out for shorter often weekly periods. At this level also, the order acceptance/rejection policy for MTO products is decided. Meaning that for each product the company decides the minimum delivery time, so that if the sales department agrees with the customer at that time the order is accepted, otherwise it is rejected.

Production planning and scheduling tasks are mainly focused on the short-term planning level in which weekly production orders are transformed into a schedule consisting of the sequence of the production orders, lot-size, and the starting time for each order. In other words, short-term production planning and scheduling tasks are intended for answering:

1. What to produce
2. How much to produce
3. When to produce

Every week the sales department sends a list of approved orders with fixed due dates to the production department. Looking at the inventory on hand, the production planner decides whether the order for MTS products can be satisfied from the inventory of finished goods or he needs to release a production order to fill the inventory. For MTO products, however, since no finished goods inventory is held, the production planner anyway releases a production order equivalent to the quantity of the received order. Now the first question, *"what to produce"* is answered and besides, the second question is also partially addressed.

To answer the next question *"How much to produce"*, for each MTS product the cycle time, which is the time until the first next production-run for that same product (Elmaghraby, 1978) is roughly estimated. The estimation is according to the last few weeks' demand patterns and the planner's experience. The lot-size or production quantity for MTS products is therefore calculated by adding the known demand for the current week to the forecasted demand throughout the cycle time. For MTO products as mentioned earlier, the production quantity is equal to the received order size.

Finally, *"when to produce"* is answered by sequencing the orders backward based on their due dates. In doing so products with similar processing needs are grouped in the same product family and they are normally produced together to reduce the total setup time.

These production planning and scheduling tasks are done manually today at Snåsavann AS. Even though some rules of thumb have been created by the production department throughout recent years, the adopted production planning system by the company is in fact a trial and error method.

Employing the current planning system, the company admits to experiencing several problems that can affect the efficiency of the production in periods of high demand. Some of the observed problems associated with the current planning system are as follows.

- The schedules made do not follow any regularity or consistency that can help the company in purchasing raw materials and scheduling workers and equipment.
- The calculation of cycle times is a rather crude approximation, and they often tend to significantly change during time.
- Due to sudden changes in the customer order, frequent readjustments of the production plan need to be done by the production department. Therefore, the actual outputs may not meet weekly production targets.
- Even though products within the same product family must be sequenced in a way to be produced together, the generated schedules sometimes do not comply with the preferred sequence.

5 Solution Development

In chapter 3, the scientific literature study showed that a crucial conflict has emerged between new market trends and manufacturing process characteristics of process industries. While new market trends require production flexibility, manufacturing process characteristics limit flexibility, and this makes production planning tasks quite challenging in process industries (Spenhoff et al., 2016). Besides, many companies in process industries to accommodate the increased product variety and demand uncertainty, have implemented hybrid MTS-MTO production systems.

Furthermore, it was discussed that among different suggested approaches from academia to address production planning in process industries, L&S models have shown great potential in recent years, since these models facilitate production planning of a larger number of different products (Brander, 2005, Copil et al., 2017). However, L&S models have not been studied much in hybrid MTS-MTO process industries and most of the literature's attention has been focused on pure MTS systems (Copil et al., 2017).

Later in chapter 4, a case company from process industries with typical manufacturing characteristics of such industries that are run under a hybrid MTS-MTO production system was studied. After mapping the planning environment and investigating the current production planning procedures, it was concluded that this case also suffers from several production planning problems that are found in the literature. However, to resolve these problems it is needed to develop a solution for addressing production planning in process industries with hybrid MTS-MTO production systems. Hence in this chapter, it is attempted to discuss the use of L&S models in hybrid MTS-MTO production environments.

5.1 Production Planning in Hybrid MTS-MTO Process Industries

Production planning in hybrid MTS-MTO process industries is not straightforward, since the decisions need to be taken for MTS products are very much different from those made for MTO products (Soman et al., 2004). In producing MTS products, the primary objective is to prevent stockouts while reducing the inventory holding costs, while in producing MTO products, the objective is to meet orders before the prespecified due dates. Some manufacturing characteristics of process industries such as capital-intensive production equipment, enforce the increase of machine utilization and line item fill rates by producing MTS products, but, on the flip side, due to demand uncertainty in MTO products, it is necessary to reserve capacity in planning periods so that there is enough capacity to meet MTO orders on time. This reserved capacity for MTO products might lead to stockouts for MTS products, and therefore, to prevent this, in periods of low demand for MTO products, the inventory of MTS products should be increased (Beemsterboer et al., 2016, Soman et al., 2004, Soman et al., 2006).

In order to properly make such decisions in hybrid MTS-MTO process industries, it is important to answer questions like when and how much capacity for MTO products should be reserved? How dates for MTO products should be set? how much inventory for MTS products should be kept?

After considering the findings from the literature and the empirical observations made from the case study, this thesis proposes a solution to use the L&S problem for tackling the production planning challenges of hybrid MTS-MTO process industries. This solution can be explained as follows:

In case the aggregate demand for MTO products can be considered as rather constant during short-term planning periods, for example during several weeks or a few months, by distributing the aggregate demand throughout the planning horizon, it is possible to reserve enough capacity for producing MTO products and dedicate the remaining capacity to MTS products in each period. In this manner, the already existing L&S models that are designed for MTS production environments can be utilized in hybrid MTS-MTO environments. However, another twist in hybrid MTS-MTO environments is that there is a tendency to accumulate different orders of MTO products and produce them together so that the number of setups is minimized. Therefore, when the first order for a certain MTO product is received, the production planner does not execute the production for that product, instead, he/she delays the production until the last possible period in which, the first order needs to be delivered and accumulate other similar MTO orders to produce them together on that period. The duration of this delivery time for each MTO product is decided beforehand through the company's order acceptance/rejection policy. The decisions regarding the order acceptance/rejection policy are taken at previous levels of the PPC system and thus are known when conducting the short-term operational production planning.

The implementation of this solution is discussed in more detail on the model further in this chapter, but first, the appropriate L&S model has to be selected and then adapted according to the manufacturing needs of the case company.

5.2 L&S model Utilized in a Hybrid MTS-MTO Production System

The L&S problem is considered an NP-hard problem, and as described in section 3.2.3, the large versions of the problem must be solved using heuristic and meta-heuristic methods such as genetic algorithm, particle swarm optimization, simulated annealing, and tabu search (Beck and Glock, 2020). However, due to time limitations, proposing the production planning solution for a large-scale problem is out of the scope of this research. Therefore, this thesis using exact methods attempts to propose the solution based on a restricted version of the problem with a much smaller number of decision variables.

So far it was discussed that among the five basic L&S model variants, CLSD and GLSP are superior to the others for the purpose of this study since they can be used in environments with sequence-dependent setups and a high variety of products. The GLSP is a small bucket model. In small bucket models, macro-periods are divided into several micro-periods, and in each of these micro-periods, the setup states are decided by binary variables. Therefore, even for a restricted version of a problem, small bucket models employ significantly more decision variables compared to big bucket models, and this makes solving small bucket models extremely hard or impossible using standard optimization solvers (Günther, 2014). For this reason, it is decided to build the solution based on the CLSD which is a big bucket model.

5.2.1 The L&S Model Adaptation

The basic CLSD model needs to be adapted according to the manufacturing requirements of Snåsavann AS. Therefore, looking at the modeling features discussed in section 3.3.1, the assumptions of the adapted CLSD model can be stated as follows:

1. The model is designed for a single-stage single-machine production system.
2. The model accommodates several different MTS and MTO products.
3. Since the products' expiry time is so long, they are not considered as perishable.
4. The demand for MTS products is static and deterministic. Although the demand for MTO products is not known in advance, the aggregate demand is constant during periods.
5. Backlogging is not allowed, and demand must be met by the end of each period.
6. The problem is capacitated, and capacity constraints are given.
7. Production rates are constant.
8. Production setups are sequence-dependent.
9. Setup states are carried over to the next period, meaning that the machine configuration is preserved at the end of each period and also over idle periods, and then it is carried over to the next period.

Since the basic CLSD model assumes a complete loss of setup states between periods, to introduce setup carryover, $Z_{it}^{e} = Z_{i,t+1}^{b}$ and $\bar{s}_i = 0$ are imposed to the model (Almada-Lobo et al., 2007).

Next, to eliminate disconnected subtours, as discussed in section 3.3.2, constraints (8) are replaced by the following constraints as proposed by Guimarães et al. (2014):

$$\sum_{j} T_{ijt} \leq 1 \qquad \forall\, i, t, \qquad (18)$$

$$\sum_{j} T_{jit} \leq 1 \qquad \forall\, i, t, \qquad (19)$$

$$\sum_{i \in S, j \notin S} T_{ijt} + \sum_{i \in S} Z_{i,t+1} \geq \sum_{j} T_{jkt} \qquad \forall\, t, k \in S, S \subseteq N. \qquad (20)$$

Where *N* is the set of all products and *S* is the set of all disconnected subtours. If a disconnected subtour *S* occurs, the left-hand side of the constraints (20) equals 0 while the right-hand side is at least 1, and this violates the inequality and therefore, the disconnected subtour is eliminated from the solution.

By incorporating the same common variables, indices, and parameters defined earlier in section 3.3.2, the MILP formulation of the final adapted CLSD reads:

Objective function:

$$Min \sum_{i,t} h_{it} \,.\, I_{it} + \sum_{t,i,j} sc_{ij} \,.\, T_{ijt} + \sum_{i,t} \bar{s}_i \,.\, Z_{it}^b \tag{21}$$

Subject to.:

$$I_{i,t-1} + X_{it} - d_{it} = I_{it} \qquad \forall\, i, t, \tag{22}$$

$$\sum_{i} p_i \,.\, X_{it} + \sum_{i,j} st_{ij} \,.\, T_{ijt} \leq cap_t \qquad \forall\, t, \tag{23}$$

$$X_{it} \leq b_{it} \,.\, \left(\sum_{j} T_{jit} + Z_{it}^b \right) \qquad \forall\, i, t, \tag{24}$$

$$\sum_{i} Z_{it}^b = 1 \qquad \forall\, t, \tag{25}$$

$$\sum_{i} Z_{it}^e = 1 \qquad \forall\, t, \tag{26}$$

$$Z_{it}^b + \sum_{j} T_{jit} = \sum_{j} T_{ijt} + Z_{it}^e \qquad \forall\, i, t, \tag{27}$$

$$Z_{it}^e = Z_{i,t+1}^b \,, \qquad \bar{s}_i = 0 \qquad \forall\, i, t, \tag{28}$$

$$\sum_{j} T_{ijt} \leq 1 \qquad \forall\, i, t, \tag{29}$$

$$\sum_{j} T_{jit} \leq 1 \qquad \forall\, i, t, \tag{30}$$

$$\sum_{i \in S, j \notin S} T_{ijt} + \sum_{i \in S} Z_{i,t+1} \geq \sum_{j} T_{jkt} \qquad \forall\, t, k \in S, S \subseteq N. \tag{31}$$

$$X, I \geq 0, \qquad Z, T \in \{0, 1\} \tag{32}$$

5.2.2 Solution Approach

As described, due to the time limitation, a restricted version of the problem with a smaller number of decision variables is studied in this master's thesis. Hence, even though Snåsavann AS produces 16 different products, only two MTS products and one MTO product are planned during two periods (weeks), which makes the problem have 42 decision variables and suitable to be solved with Microsoft Excel's add-in, Solver. Figure 5.1 illustrates a snapshot of the problem solved in the Excel spreadsheet. Yellow cells represent the 42 decision variables that need to be decided based on the input parameters that are added in blue cells. The value of the objective function (21), as the final planning cost, is shown in the red cell, and constraints (22) to (32) are written inside green cells.

Lot-size

X(ij)	X11	X21	X31	X12	X22	X32
	8070	3500	0	9330	0	2500

Inventory

I(it)	I11	I21	I31	I12	I22	I32
	670	0	0	0	0	0

Changeover

T(ijt)	t=1	i=1	i=2	i=3	t=2	i=1	i=2	i=3
	j=1	0	1	0	j=1	0	0	0
	j=2	0	0	0	j=2	0	0	0
	j=3	0	0	0	j=3	1	0	0

Start of Production

Zb(it)	Zb11	Zb21	Zb31	Zb12	Zb22	Zb32
	0	1	0	1	0	0

End of Production

Ze(it)	Ze11	Ze21	Ze31	Ze12	Ze22	Ze32
	1	0	0	0	0	1

Demand

d(it)	d11	d21	d31	d12	d22	d32
	7500	4000	0	10000	0	2500

Holding Cost

h(it)	h11	h21	h31	h12	h22	h32
	0.2	0.25	999999	0.2	0.25	0.3

Capacity

cap(t)	cap1	cap2
	135000	135000

Processing Time

p(i)	X1	X2	X3
	10	12	15

Max Lot-size

b(it)	b11	b21	b31	b12	b22	b32
	10000	10000	10000	10000	10000	10000

Min Lot-size

m(i)	m1	m2	m3
	50	100	10

Setup Time

st(ij)	1	2	3
X1		1800	4200
X2	1800		4200
X3	4200	4200	

Setup Cost

sc(ij)	1	2	3
1		4500	10500
2	4500		10500
3	10500	10500	

Startup Cost

s(i)	X1	X2	X3
	0	0	0

Beginning Inventory

I(i0)	I10	I20	I30
	100	500	0

Objecive Function

Min Z= **NOK 15,134**

Subject to

			RHS
	0	=	0
	0	=	0
	0	=	0
	0	=	0
	0	=	0
	0	=	0
	124500	<=	135000
	135000	<=	135000
	-1930	<=	0
	-6500	<=	0
	0	<=	0
	-670	<=	0
	0	<=	0
	-7500	<=	0
	1	=	1
	1	=	1
	1	=	1
	1	=	1
	0	=	0
	0	=	0
	0	=	0
	0	=	0
	0	=	0
	0	=	0
*	0	<=	1
*	1	<=	1
*	0	<=	1
*	1	<=	1
*	0	<=	1
*	0	<=	1
*	1	<=	1
*	0	<=	1
*	0	<=	1
*	0	<=	1
*	0	<=	1
*	1	<=	1
*	0	=	0
*	0	=	0
*	0	=	0
*	0	>=	0
*	1	>=	0
*	1	>=	0
*	1	>=	0

Figure 5.1: The L&S problem solved in Excel

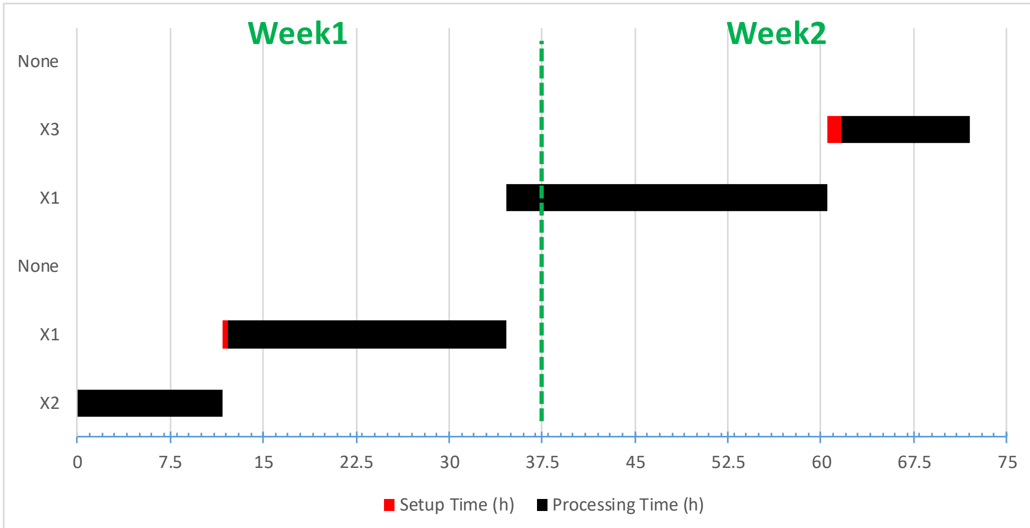
Both MTS and MTO products are accommodated in the model using the following manner: At the beginning of week one, the forecasted demands of two MTS products (product1 and product 2) are known in weeks one and two (*d11=7500, d21=4000, d12=1000, d22=0*), and the first week's demand for the MTO product (product 3) is also received (*d31*). Although the second week's demand for the MTO products is not known yet in week one, the aggregate demand for the MTO product is constant across every two weeks and this amount is estimated to be 2500 (*d31+d32=2500*). The delivery lead time of the MTO product is decided before to be two weeks. During these two weeks, all received MTO orders are accumulated to be produced together in week two in order to minimize the total setup cost. Since no inventory is kept for the MTO product before the start of production, a very high holding cost must be incurred to the model in the week (*h31=999999*).

Even though in this example of the problem the input values of parameters are just assumptions, they are selected in a way that the main point of the model is conveyed properly. For instance, setup times are selected so that they are sequence-dependent ($st_{12} \neq st_{32}$). Besides, since the two MTS products and the MTO product belong to two different product families, minor setups ($st_{12}, st_{21} = 1800$) and major setups ($st_{13}, st_{23}, st_{31}, st_{32} = 4200$) are decided for them. Setup costs are defined as the product of setup times and the production cost per minute.

The final solution for the lot size and inventory of products are shown in their corresponding yellow cells. However, the optimal sequence of production which is decided by binary variables can be read as follows. The production in week one starts with product 2 ($Z_{21}^{b} = 1$), continues with product 1 ($T_{211} = 1$), and also ends with product 1 ($Z_{11}^{e} = 1$). Similarly, in week two, the production again starts with product 1 ($Z_{12}^{b} = 1$), continues with product 3 ($T_{132} = 1$) and also ends with product 3 ($Z_{32}^{e} = 1$). Therefore, the generated production sequence during the two weeks is 2-1-3.

To facilitate the comprehension of the solution, a dynamic dashboard (displayed in figure 5.2) is created that shows the details of the generated production plan. Note that in the dashboard the sequence is demonstrated with X1, X2, and X3.

Period	Week1			Week2		
Sequence	X2	X1	None	X1	X3	None
Lot size	3500	8070	0	9330	2500	0
Setup Time (h)	0.00	0.50	0.00	0.00	1.17	0.00
Processing Time (h)	11.67	22.42	0.00	25.92	10.42	0.00
Processing Time (days)	1.56	2.99	0.00	3.46	1.39	0.00



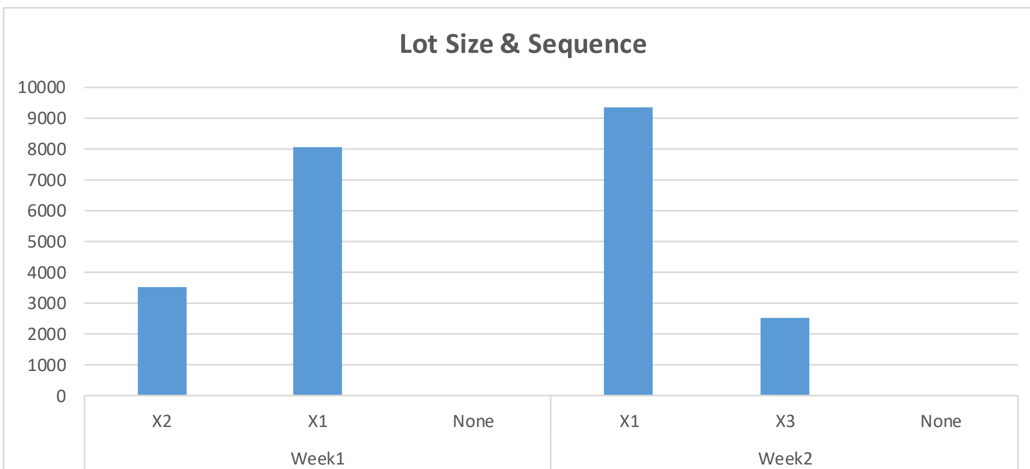


Figure 5.2: The dynamic dashboard showing the generated production plan

5.2.3 Potentials of the Developed L&S Model

As seen the L&S model is able to generate optimal production plans determining the lot size for different products and the sequence of production. Further, in order to assess the applicability of the model and its impact on the production planning of process industries using hybrid MTS-MTO systems, it is necessary to once again discuss the four observed production planning problems at the case company and to check the capability of the L&S model in solving those problems.

The four observed production planning of the case company and the impact of the developed L&S model on these problems are listed below.

1. It was explained that the presence of long sequence-dependent setups complicates the generation of cost-efficient schedules, and the case company sometimes cannot execute the production according to the preferred sequence of products. The L&S model eliminates this complication for the company since it generates optimal plans that account for sequence-dependent setups.

2. Another problem was that providing the volatile nature of the demand and due to receiving sudden changes in orders, the case company has to frequently conduct replanning, and in periods of high demand, this results in missing weekly production targets and therefore in some cases backlogging of orders. However as shown in the previous section, through the use of the L&S model, the company will be able to accommodate this uncertainty in the production plan, reserve weekly capacity for MTO orders, and then allocate the rest for MTS products. In this way, the company can plan the production of MTS products for several weeks in advance and ensure that MTS orders are met. In the case of receiving sudden order changes or unplanned MTO orders also, the reserved weekly capacity can be utilized.

3. The other observed problem was that, with the current production planning and scheduling the case company has to estimate for each product the time between two consecutive production-runs or as Elmaghraby (1978) calls it, cycle times so that it can calculate the demand during this period and launch the production accordingly. These calculations, nevertheless, are not often accurate enough as cycle times and demand requirements can significantly change in different seasons and again. This problem also will be addressed by implementing the L&S model since the company will be able to plan for several weeks ahead and update these weekly plans frequently as changes in demand patterns are realized and therefore avoid backlogging.

4. The last problem was the inability of the current generated schedules to follow any regularity or consistency that can help the company to plan for different resources such as raw materials, workers, and machines. The L&S problem and the proposed model do not address this problem. Even though the schedules made using the L&S model are optimal, they do not necessarily follow a regular pattern and are not consistent through different periods. Therefore, this can be considered as a limitation of using such models. The other production planning and scheduling approaches that attempt to find cyclical production patterns such as the ELSP or the product wheel concept proposed by Wilson and Ali (2014) can achieve this regularity and consistency.

6 Discussion and Conclusion

In previous chapters, production planning and scheduling problems in process industries were recognized and studied, and later a planning solution as the form of an L&S model was proposed to address some of the problems of the studied case. This final chapter presents the accomplishment of the research tasks set to help reach the overall objective of the research that is addressing production planning and scheduling problems of process industries using hybrid MTS-MTO production systems by developing an L&S model. It then concludes the work by discussing the contributions and limitations of this master's thesis, and also the further research that can be built upon it.

6.1 Achievement of the Research Tasks

Research Task 1: *To evaluate different production planning and scheduling approaches in process industries.*

During the literature study in section 3.2.3, it was discussed that there are mainly two research lines addressing the production planning and scheduling in process industries (Kiliç, 2011). The first one which deals with the economic lot-scheduling problem (ELSP), attempts to find cyclical production patterns that can be repeated over time in an infinite planning horizon. However, a shortcoming of the ELSP is that by increasing product variety, finding feasible cyclic production schedules becomes extremely difficult (Brander, 2005, Elmaghraby, 1978). To address this shortcoming, the second line of research which studies the simultaneous lot-sizing and scheduling (L&S) problem, utilizes finite, periodic, and time-varying planning horizons to generate optimal production schedules that determine the sequence of production and the lot size of different products in each period (Copil et al., 2017). Later in section 3.3.2, it was mentioned that the L&S problem has attracted great attention both from academia and the industry, and to solve this problem several MILP models have been suggested by researchers. Among five main basic variants of L&S models, the basic CLSD and GLSP were recognized as the two more promising and most-well known models since they incorporate sequence-dependent setups and more product variety (Almada-Lobo et al., 2015). In section 3.3.3, a gap in the literature was localized as all proposed L&S models address production planning in MTS production systems and none of them are implemented in process industries that use hybrid MTS-MTO production systems (Copil et al., 2017).

Research Task 2: *To map the case company and identify the problems associated with the current production planning and scheduling practice.*

This task was accomplished in chapter 4. First, in section 4.2, the planning environment of the company in terms of its product, market, and manufacturing process characteristics were explored. Then in section 4.3, the current production planning and scheduling tasks carried out at the company and the problems associated with them were discussed.

Research Task 3: *To develop a production planning and scheduling solution for the case company.*

The development of a planning solution for the case company was covered throughout chapter 5. First, it was discussed how the L&S model can accommodate both MTS and MTO products and plan for both of them. Then after selecting the CLSD and GLSP as the two most promising L&S models to be implemented in hybrid MTS-MTO production environments with high product variety and sequence-dependent setups, it was needed to be decided that based on which of these two the solution should be developed. Later it was explained that solving the GLSP model would be out of the scope of this research due to the number of variables that would be used in this model, hence the CLSD model was selected. In section 5.2.1, the basic variant of the CLSD was adapted to the needs of the company, and then in the next section, a restricted version of this adapted model was solved using MS Excel' Solver.

Research Task 4: *Discuss the applicability and impact of the developed solution on the production planning and scheduling practice of the case company.*

This task was achieved in section 5.2.3 where the ability and limitations of the developed model were discussed in detail. These findings were then presented to the case company in order to be affirmed and validated. Based on the company's feedback the model shows great potential to address the current problems of production planning and scheduling. The feedback of the company is attached as an appendix to the end of the thesis.

6.2 Limitations and Future Research

Even though the developed L&S model as the proposed solution of this thesis is capable of generating optimal production plans, the application of such models without an in-depth understanding of mathematical optimization and the Operations Research field can be difficult in practice (Semini, 2011). Besides, the schedules made using the developed L&S model do not necessarily follow a regular pattern. This regularity and consistency in generated schedules might sometimes be desirable for companies to help them plan for different resources such as raw materials, workers, and machines. This can be achieved using the other production planning and scheduling approaches that attempt to find cyclical production patterns such as the ELSP or the product wheel concept proposed by Wilson and Ali (2014). However, these approaches themselves, have serious limitations in incorporating a large number of different product types. Lastly, as discussed, due to time limitations, proposing the production planning solution for a large-scale problem was out of the scope of this research. Therefore, the thesis, using exact methods proposed the solution based on a restricted version of the problem with a much smaller number of decision variables. For future work, the large version of the problem can be solved using heuristic and meta-heuristic methods such as genetic algorithm, particle swarm optimization, simulated annealing, and tabu search (Beck and Glock, 2020) so that the model can act as a fully operational solution for the company.

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Appendix
Feedback from the Case Company

Feedback on Master's Thesis

The master's thesis written by Ali Akbari offers a valuable oversight of the operations, and current capabilities of Snåsavann AS. Hidden areas of improvement are examined in the thesis. They will be taken into consideration for future expansion. The given explanations about the developed production planning solution are greatly useful for implementing it in practice.

The developed planning solution along with mapping of the planning environment will help improve the production planning process at Snåsavann AS. We see the potential of the suggested solution and look forward to applying it to our company.

Further, the data used in the thesis does not compromise the contracts we have with our customers and suppliers regarding confidentiality.

Snåsavann AS is pleased with the results and the collaboration with the student taking the Global Manufacturing Management (GMM) Msc program at NTNU. His contributions help us in seeing the planning process in a more systamitic way and better understanding the areas of improvement. Because of that, we would like to continue collaborating with GMM in the future.

CEO/CTO/COO

COO

Signature

Patrick Aronli

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