Make-to-order and make-to-stock in food processing industries

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Make-to-order and make-to-stock in food processing industries

Proefschrift

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door

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Chetan Anil Soman
Groningen, December 2004
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Chapter 1

Prologue

The majority of the research into production/inventory control systems in process industry has mainly consisted of reporting general process characteristics, high-volume production scheduling, and mixed integer linear programming (MILP) formulations for specific problems such as determining recipes (blending problem). However, the control of a production situation characterised by limited capacity, which is highly utilized, and by a combination of make-to-order (MTO) and make-to-stock (MTS) products, which is very common in process industry and more specifically food processing industry, has not been duly addressed in the current literature. The discussion in this prologue deals with how the process industry production control problem has been addressed previously, the specific problem on hand, and the approach that will be used to solve it.

1.1 Introduction

Almost 22% of the total turnover of the Dutch industry is provided by the food industry (CBS Statline, general industrial statistics 2001). The research subject of this thesis is founded in this industry. Since the profit margins in food industry are diminishing, a small decrease in production and inventory costs because of better production control can give a significant increase in profits. In this thesis the combined make-to-order and make-to-stock production strategy is studied.

A thorough look at the production management research literature reveals that a majority of it has been for industries handling discrete units that are fabricated and/or assembled during manufacturing. This research has resulted in numerous successful developments in taxonomies, production and inventory management systems, and implementation strategies for the discrete industries.
The process industries (to which food industries are mostly classified as belonging to), although more automated than discrete industries at the process control level, lag behind discrete industries when it comes to research in overall production planning and control tools. A brief overview of past and current research in the process industry is presented in table 1.1. The literature can be classified under different categories.

The first category reports general characteristics of the industry. There is a great deal of the process industry research that does this. A more exhaustive list of literature in this category can be found in Dennis and Meredith (2000). This literature focuses on process industry uniqueness and compares it to discrete industries and talks about– yield variability, variations in raw material quality, variations in BoM, divergent flows, unit of measure differences, number of packaging, technical constraints of batching and storage possibilities– which are of great importance to process industries. It is also very clear that one of the main areas of attention in process industry is the orientation on the use of capacity.

The second category in the generic classification captures much of the current scheduling practices in process industries. Taylor and Bolander (1997) are advocating and illustrating a technique called process flow scheduling (PFS) from early 1980’s. However, this research has focussed primarily on high volume process flow manufacturers. Nakhla (1995) uses conventional priority rules and techniques for scheduling the flow shop in a food industry. Van Donk and Van Dam (1996) have described a framework for designing a planning and scheduling system, which uses the concepts of process routings and capacity groups to analyze the structure of the scheduling problem.

The third category of the literature deals with the special production control problems posed by typical process industry characteristics such as by-products, co-products, or recipe-flexibility. For a more elaborate and up-to-date review of the production planning approaches in the process industry, please refer to Crama et al. (2001) and Kallrath (2002).

We can also classify the literature based on the problem solving approach used. This is shown in the right column of table 1.1. The typical solution approaches are simulation, mixed integer linear programming (MILP) based optimization, analytical models, artificial intelligence (AI) models, and the combination of two or more of these approaches. Simulation and MILP has been most commonly used. Reklaitis (1995) has a detailed discussion on these various approaches and
1.1. Introduction

Table 1.1: Process industry literature: an overview

<table>
<thead>
<tr>
<th>Generic classification</th>
<th>Classification solution approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Process industry uniqueness-</td>
<td>(a) Simulation based- e.g.</td>
</tr>
<tr>
<td>e.g. Fransoo and Rutten (1994)</td>
<td>Baudet et al. (1995)</td>
</tr>
<tr>
<td>3. Specific production control problems- e.g. Rutten (1995), Baudet et al. (1995)</td>
<td>(c) Analytical models- Queuing theory- e.g. Carr et al. (1993)</td>
</tr>
<tr>
<td></td>
<td>(d) AI-related methods</td>
</tr>
<tr>
<td></td>
<td>(e) Combination of two or more of the above- e.g. Rutten (1995), Van Dam (1995)</td>
</tr>
</tbody>
</table>

related literature.

In the proposed study, we focus on food processing industries in particular. In addition to the fact that food industry accounts for 22% of the total Dutch industrial output, there are others reasons as well–

1. The research in food processing industries has mainly focussed on food engineering issues. In the operations management area, there has been some research on outbound logistics but not much work has been done in the production planning and control area. This research is likely to benefit the industry (consisting of numerous SMEs and a few very big players) in the way they carry out their production control function.

2. It is likely that the food industry in the developing countries will grow rapidly. For example, a study conducted by the Confederation of Indian Industry (CII) and McKinsey & Company, Inc. shows that– a) Food offers what is unquestionably one of the largest opportunities in India today, and b) The food industry will grow threefold to reach US $60 billion, a figure well in excess of the entire Indian manufacturing sector today. The improved and proven knowledge of production control in food processing industry is hence likely to be of immense benefit.

In the next section, we spell out the specific problem that will be addressed in this thesis.
1.2 Research objectives

For many years it was a common policy for food processing companies to produce in large batches to keep production costs low and limit the number of setups. The research literature also focussed on this. However, now industries are experiencing growing logistical demands, growing variety of products and intense competition and as a reaction they are trying to relocate their decoupling point and are moving a part of their production to follow a make-to-order strategy (Van Donk 2001). This has resulted in a production situation characterised by a combination of make-to-order (MTO) and make-to-stock (MTS) in addition to the key existing characteristic of limited and highly utilized capacity. This thesis focuses on the following questions arising because of this situation:

• What products should be made to stock and what products should be made to order?
• What are the main factors to be taken into account for the control of such production situations?
• How can we manage and control such a combined production mode?

The existing theory does not give much of an answer to these questions. The analytical and quantitative tools are not available– to measure the interaction effect between the level of stock and orders; or to give an answer to the question– how much MTO is possible on a limited capacity; if and how the kind of demand or production facilities influence the nature and possibilities of control.

With our research, we plan to attain an improved knowledge on the planning and control in the production environment with limited capacity and combination of MTO and MTS products. The main problem to be solved by planners is finding a balance between the possibilities of buffering (in time and quantity) the uncertainty of orders by finding suitable levels of stocks of MTS products. The solutions to that will be restricted by performance measures on dependability, speed, cost, capacity and utilization, while demand will be uncertain as well as production capacity. So far, little is known on finding this balance. Specific food industry characteristics like limited shelf life of products will also be addressed.

The main research objectives are as follows:

1. To identify the main issues that determine the nature and possibilities for controlling and planning the capacity-oriented combined MTO-MTS production in food processing industries.
2. To develop models for planning and scheduling in combined MTO-MTS production in food processing industries.

3. To use the models developed for improving the way planners in food processing industries do their work.

The research consists of three stages corresponding to these three research objectives: (1) Building a framework for production control in combined MTO-MTS production, (2) Development of analytical and simulation models, and (3) Illustration of the production control framework in a real-life setting.

1.3 Thesis outline

The first research objective is addressed by Chapter 2. It is a state-of-the-art literature survey on the combined MTO-MTS production situation. It discusses the relevance of the surveyed literature in the context of food processing literature and then proposes a comprehensive hierarchical planning framework covering the important decisions in the combined MTO-MTS production situation. This hierarchy is also intended to provide a proper setting for discussing various MTO-MTS issues in the later chapters. Chapters 3, 4, and 5 address the second research objective and are devoted to MTO or MTS decision, medium term capacity coordination, and short term scheduling models, respectively. The third research objective is addressed by an illustrative case study in chapter 6. In each of these chapters the focus is on food processing industries and the presentation is organized as follows:

1. Provide a self-contained exposition of the sub-problem. This allows readers to treat each chapter as a stand-alone piece of research.

2. Discuss algorithmic, computational, and implementation issues, where relevant.

3. Provide a comprehensive list of topics to further probe into.

Chapter 2 provides a literature overview of MTO-MTS literature. The chapter starts by examining the recent trends in many industries and especially food processing industries and how they are forcing food producers to move from pure MTS to combined MTO-MTS production situation. After a detailed overview of the MTO-MTS literature, it is evaluated for its applicability in the context of special product, process, plant, and market characteristics of the food processing firms. Next, various MTO-MTS production decisions are categorized into 3 different types viz. MTO or MTS decision, Production Inventory decisions, and
Operational decisions. These decisions are presented in the form of conceptual hierarchical production planning framework. Though it is just another way of looking at the decision-making and a generic but not an in-depth prescription for structuring the specific levels for all the MTO-MTS situations, it can be used as a starting point for designing or redesigning the planning and scheduling hierarchy structure for a particular situation.

The MTO or MTS decision constitutes the subject of Chapter 3. A simple, quantitative but practical tool that aids in MTO or MTS decision is presented in this chapter. The tool is largely based on a number of well-known theoretical concepts.

Chapter 4, on medium term capacity coordination, is in two parts. Both parts deal with multi-product lot sizing issues under limited capacity. Limited shelf life for products is very common in food processing industry and is considered in the context of lot scheduling problem in the first part of the chapter. A heuristic is suggested for the problem along with an illustrative example to show the superiority of the approach above existing approaches. In the second part, we discuss various ways of incorporating MTO items in economic lot scheduling problem (ELSP). Some guidelines are provided regarding the choice of each of these MTO incorporation.

Operations scheduling forms the subject matter of chapter 5. We first introduce classical dynamic runout scheduling methods in pure MTS situations. Next, we make some adaptation to include MTO products in these models. We then compare and discuss the performance of these methods through a simulation study.

Chapter 6 illustrates the hierarchical planning framework presented in chapter 2 and the insights gathered from chapters 3, 4, and 5 by reporting a real-life case study. Areas of improvements in the framework have been identified and possible decisions aids are suggested. In particular, the short-term batch-scheduling problem requires more attention and we provide a heuristic to solve that problem.

In chapter 7, we summarise the findings of thesis and look back on the assumptions that we made. Other important issues in combined MTO-MTS production situations that fall outside the scope of this thesis are also discussed.
The thesis is a compilation of the following papers that are published or are under review and a recent contribution in the form of chapter 3.


Chapter 2

Combined MTO-MTS food processing

This chapter\(^1\) presents the state-of-the-art literature review of the combined MTO-MTS production situations. A variety of production management issues in the context of food processing companies, where combined MTO-MTS production is quite common, are discussed in detail. The chapter proposes a comprehensive hierarchical planning framework that covers the important production management decisions to serve as a starting point for evaluation and further research on the planning system for MTO-MTS situations.

2.1 Introduction

A majority of the operations management research characterizes production systems as either make-to-order (MTO) or make-to-stock (MTS). The MTO systems offer a high variety of customer specific and typically, more expensive products. The production planning focus is on order execution and the performance measures are order focused, e.g. average response time, average order delay. The competitive priority is shorter delivery lead-time. Capacity planning, order acceptance/rejection, and attaining high due date adherence are the main operations issues. The MTS systems offer a low variety of producer-specified and typically, less expensive products. The focus is on anticipating the demand (forecasting), and planning to meet the demand. The competitive priority is higher fill rate. The main operations issues are inventory planning,

\(^{1}\text{This chapter has been published as: Soman, C. A., Van Donk, D. P. and Gaalman, G. (2004a), Combined make-to-order and make-to-stock in a food production system, International Journal of Production Economics, 90(2), 223–235.}\)
lot size determination and demand forecasting. The performance measures are product focused, e.g. line item fill rate, average inventory levels. The available literature (e.g. Kingsman et al. 1996, Silver et al. 1998, Vollman et al. 1997) has widely addressed these issues in pure MTO and pure MTS production.

While there is a large body of literature on MTO and MTS production control, lesser and lesser production systems are either fully MTS or MTO in practice (see Williams 1984, Adan and Van der Wal 1998). The combined MTO-MTS problem has been relatively neglected in literature and to the best of our knowledge only a handful of papers has been explicitly dealing with this combined problem. Further, these papers have been rather limited in exploring all issues relevant for combined MTO-MTS situations and little has been done in positioning the different contributions.

It is important to recognize that very different managerial actions than those required in pure MTO and pure MTS strategy are necessary in a combined MTO-MTS production situation because of the different strategy contexts in which the products are produced. We postulate that a mix of MTO and MTS products and their interaction with the limited shared capacity opens interesting possibilities as well as problems for production planning. For example, on the one hand, MTS products might be manufactured to fill capacity in periods of low demand for MTO items but on the other hand, we do not yet fully understand these interactions to answer the questions such as how much inventory should be kept or how due dates should be set in the combined MTO-MTS production situation.

In our discussion, we mainly focus on the food processing industries, where combined MTO-MTS production is quite common. Food processing industries are part of very competitive supply chains and have to cater to an increasing number of products and stock keeping units (SKUs) of varying logistical demands like specific features, special packaging, short due dates. In addition, they differ from the discrete parts industry not only on the basis of kind of products, but also on market characteristics, the production process, and the production control. For example, limited shelf life of products and presence of sequence dependent setups add another dimension to the combined MTO-MTS problem. Hence, combined MTO-MTS production in food processing industries is an interesting and relevant research subject.

The organization of the chapter is as follows. In the next section we review the state-of-the-art in the area of combined MTO-MTS production research and
bring out the variety of production planning decisions arising in such situations. In section 2.3, we look at the food processing characteristics and assess the existing MTO-MTS literature in the context of its applicability to the food processing industries in section 2.4. In section 2.5, we present a comprehensive hierarchical planning framework covering the important decisions in the combined MTO-MTS situation. Conclusions and suggestions for future research are provided in section 2.6.

2.2 Literature review

There are only a handful of research papers that explicitly talk about the combined MTO-MTS situation. In this section, we review the work of Williams (1984), Bemelmans (1986), Li (1992), Carr et al. (1993), Federgruen and Katalan (1994, 1999), Adan and Van der Wal (1998), Arreola-Risa and DeCroix (1998), Nguyen (1998), Carr and Duenyas (2000) and Rajagopalan (2002), which yield important insights for the combined MTO-MTS situation. Table 2.1 provides an overview of the literature in terms of subjects addressed; demand, production and process structure considered; performance criteria used; and the solution approaches.

One of the first studies on combined MTO-MTS production system is credited to Williams (1984). This research deals with many questions raised by MTO products– which products should be stocked? What special business (MTO) should be accepted? How should one choose the batch sizes for MTS? The waiting time for the availability of the capacity for the individual products is estimated using an approximation to a M/G/m queue. Bemelmans (1986) considers fast-moving and slow-moving products (with batch-size equal to one) and presents the situation as a capacitated, single-machine, multi-product planning problem. He describes a concept of capacity oriented inventory– uncertainty in the demand of a certain product can be covered by the inventory of another product, whose demand is larger or less uncertain. This idea might be further extended to having (extra) inventory for MTS to have more capacity available for MTO.

To have an exact and tractable analysis, Carr et al. (1993) assume that no setup times and costs are incurred. The MTO/MTS decision is based on the ABC classification. A production strategy labelled as “No B/C policy”, wherein the B and C category items are produced on order and A category items are MTS, is followed. They model the system as M/D/1 queue and provide the estimates of
Table 2.1: Overview of literature on combined MTO/MTS production situation

<table>
<thead>
<tr>
<th>Paper</th>
<th>Subjects addressed</th>
<th>Demand-Product-Process structure</th>
<th>Performance criteria</th>
<th>Solution approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Williams (1984)</td>
<td>MTO/MTS partitioning Lot sizes for MTS product</td>
<td>Stochastic demand, Multi product, multi (identical) machines Non-preemptive priority for MTO items over MTS items</td>
<td>Minimizing sum of inventory holding costs, stock out costs and setup costs</td>
<td>Approximations of M/G/m queues</td>
</tr>
<tr>
<td>Bemelmans (1986)</td>
<td>Decomposition of items into slow and fast movers Conditions for product and capacity oriented approaches</td>
<td>Stochastic demand Single-machine, multi-product, multi-period capacitated problem Batch sizes equal to 1</td>
<td>Minimizing sum of inventory holding costs, stock out costs</td>
<td>Queuing theory and Math Programming</td>
</tr>
<tr>
<td>Li (1992)</td>
<td>Impact of customer behaviour and market on MTO/MTS partitioning</td>
<td>Stochastic demand, Single product Price, quality, delivery lead-time variations The firm may not get all the orders</td>
<td>Profit maximization</td>
<td>Stochastic optimization with infinite time horizon</td>
</tr>
<tr>
<td>Carr et al. (1993)</td>
<td>Exact expressions for cost of a strategy for an example of MTO/MTS situation</td>
<td>Unit demand with stochastic arrival time ABC like classification for MTO/MTS decision (No B/C strategy), No setups</td>
<td>Minimizing sum of inventory holding costs, stock out costs</td>
<td>M/D/1 queue with two priority class, Pre-emptive resume between priority class and FCFS within a class</td>
</tr>
<tr>
<td>Federgruen and Katalan (1994, 1999)</td>
<td>Production sequencing &amp; base stock levels Comparison of priority rules</td>
<td>Stochastic demand Cyclic schedule and base-stock policy</td>
<td>Minimizing sum of inventory holding, stock out &amp; setup costs</td>
<td>Results of M/G/1 queues with vacations used</td>
</tr>
<tr>
<td>Adan and Van der Wal (1998)</td>
<td>Effect of combining MTO &amp; MTS on the production lead time in single &amp; two-stage production</td>
<td>Stochastic demand, two types of product No backordering for MTS product No setup times</td>
<td>Mean no. of orders in the queue and mean production lead-time</td>
<td>Markov process with states defined by number of MTO orders in the queue and MTS inventory on hand</td>
</tr>
<tr>
<td>Paper</td>
<td>Subjects addressed</td>
<td>Demand-Product-Process structure</td>
<td>Performance criteria</td>
<td>Solution approach</td>
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<td>------------------------------</td>
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<td>---------------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Arreola-Risa and DeCroix (1998)</td>
<td>MTO/MTS partitioning</td>
<td>Stochastic demand and manufacturing times, Single stage multi product system</td>
<td>Minimizing sum of inventory holding costs, stock out costs</td>
<td>M/G/1 queue results</td>
</tr>
<tr>
<td>Nguyen (1998)</td>
<td>Estimation of fill rate &amp; average inventory level</td>
<td>Unit demands with stochastic arrivals, Lost sales case, No setup time</td>
<td>Line item fill rate and average inventory levels for MTS items</td>
<td>Mixed queuing network, Use of the heavy traffic limit theorem</td>
</tr>
<tr>
<td>Carr and Duenyas (2000)</td>
<td>Joint admission control and sequencing problem</td>
<td>Single machine and two types of product, No backordering, No setup times, Preemption allowed, MTO orders can be rejected</td>
<td>Profit maximization</td>
<td>Markov decision process for 2-class M/M/1 queue</td>
</tr>
<tr>
<td>Van Donk (2001)</td>
<td>Locating customer order decoupling point (CODP)</td>
<td>Limited intermediate storage between two stages of food production system</td>
<td>Service levels and cost trade-off</td>
<td>Case study Application of CODP concept</td>
</tr>
<tr>
<td>Rajagopalan (2002)</td>
<td>MTO/MTS partitioning Deciding Reorder point and replenishment quantity</td>
<td>(Q,r) inventory policy for MTS products, No sequence dependent setups, Minimum service level constraints for products</td>
<td>Minimizing sum of inventory holding costs, stock out costs and setup costs</td>
<td>Non-linear integer program with service level constraints, Heuristic procedures</td>
</tr>
</tbody>
</table>

Table 2.1: Overview of literature. continued.
the number of orders in the queue, average-waiting times in the system. They show that the “No B/C policy” incurs less cost than pure MTS strategy, especially under high traffic intensity. Adan and Van der Wal (1998) also present a similar model with an extension to two-stage production. They consider the production system as Markov process with states defined by the number of MTO orders in queue and MTS inventory on hand and derive expressions for mean number of orders in the queue and mean production lead-time.

The question whether a particular product will follow a MTO or MTS strategy is the discussion focus in Li (1992), Arreola-Risa and DeCroix (1998), and Van Donk (2001). Li (1992) studies the impact of market competition and customer behaviour based on price, quality, and expected delivery lead-time on the MTO/MTS production decision in a single product case. Arreola-Risa and DeCroix (1998) provide optimality conditions for the MTO/MTS partitioning in a multiproduct, single machine case with FCFS scheduling rule. They study the effect of manufacturing time diversity on MTO/MTS decision for backorder-cost cases of dollar per unit and dollar per unit per time. Their result shows the extent to which reducing manufacturing-time randomness leads to MTO production. Van Donk (2001) describes the application of ‘customer order decoupling point’ (CODP) concept in a case of food processing company.

Federgruen and Katalan (1994, 1999) address a variety of strategic questions—the number and types of products that should be manufactured to stock or to order, the effects of adding low volume specialized items to a given product line on the stock system. They present a class of cyclic base stock policies for which a variety of cost and performance measures can be evaluated by the suggested analytical methods for the polling model. They develop cost curves for different priority rules under different circumstances, which can be used to calculate a marginal break-even price at each of additional utilisation due to addition of MTO items.

Nguyen (1998) models the combined MTO-MTS situation as a mixed queuing network. She uses the heavy traffic limit theorem in developing the procedure for finding estimates of fill rates and average inventory levels. Unlike Williams (1984), Rajagopalan (2002) allows low demand items to follow the MTS strategy. He provides a heuristic procedure to solve a non-linear, integer programming formulation of the problem that determines the MTO/MTS partition and the batch sizes for the MTS items.
Joint order acceptance/rejection and sequencing problem is discussed in Carr and Duenyas (2000). They consider a 2-class (MTO and MTS) M/M/1 queue with no backordering for MTS product and provide a structure of optimal admission control and sequencing policies in terms of production threshold curve and acceptance threshold curves that are functions of MTS inventory level and MTO queue size.

2.2.1 MTO-MTS issues in the literature

It is clear from the literature that there are diverse issues that need to be addressed in the combined MTO-MTS production. The question whether a particular product will be made to stock or made to order is the principal issue in designing and managing the production planning and control function. This MTO versus MTS decision is more strategically oriented and is complicated due to various factors involved. The solution needs to consider the trade-offs between product-process characteristics and the demands from the market. Another main decision is to find a suitable production and inventory policy. The main issue here is finding a balance between the possibilities of buffering (in time and quantity) the uncertainty of orders by deciding suitable due dates and/or by finding suitable levels of stocks of MTS product. Thus, these are the decisions regarding capacity allocation, order acceptance, lot sizes and inventory policy. Then there are operational scheduling and control decisions, which deal with issues like production sequencing.

In the next sections, we understand the food processing industry characteristics and assess the above literature in the context of it.

2.3 Food production system characteristics

Some recent empirical studies (see Van Dam 1995, Van Donk 2001) show that the combination of MTO and MTS is quite common in food processing industries. Several reasons exist why the combined MTO-MTS grows in significance in food processing industry. Van Donk (2001) mentions that food processing companies have to deal with an increase in logistical demands from their customers. Firstly, being part of very competitive supply chains, food processing companies cater to an increasing number of products and SKUs with client specific features, special packaging etc. to increase or maintain the market share. Secondly, retailers and wholesalers expect small deliveries within short and dependable time window. At the same time, they do not accept two subsequent deliveries with the same ‘best before’ date, even if they will sell the product well.
before that date. This means that customers prefer a MTO policy with short response time. Thirdly, consumer behaviour is more erratic (see Meulenberg and Viaene 1998). This requires logistic and production systems to respond quickly to changing customer behaviour. As a consequence of this product/SKU proliferation and shorter production cycles, manufacturers are forced to shift a part of their production system from MTS to MTO and are operating under a hybrid MTO-MTS strategy. Producing a very large number of products on pure MTO basis is not viable because of large number of setups that are required and pure MTS is also ruled out because of unpredictable demand and the perishable nature of the products.

As a first step in developing a production planning and control framework for combined MTO-MTS production food processing industry, we investigate the production characteristics and a variety of issues that need to be addressed by the management. These are in addition to increased logistical demands of the market as described in the previous paragraph. The discussion is largely motivated by the food processing industry case studies conducted by the researchers at the University of Groningen (see Ten Kate 1994, Van Dam 1995, Van Donk and Van Dam 1996, Van Wezel and Van Donk 1996, Van Dam et al. 1998, Van Donk 2001, Van Wezel 2001).

A typical food processing process is illustrated in Figure 2.1. Two stages can be distinguished: a processing stage during which the products are manufactured, and the packaging stage in which they are packaged.

The following characteristics, compiled from the above mentioned literature, are found in case of food processing industries:

1. Plant characteristics

   (a) Expensive capacity with flow shop oriented design because of conventional small product variety and high volumes.
2.4 MTO-MTS in food processing industry

(b) Extensive sequence dependent setup and cleaning times between different product types.
(c) Limited storage space.

2. Product characteristics
(a) Variation in supply and quality of raw material.
(b) Limited shelf life for raw materials, semi-finished and finished products.
(c) Volume or weight as the unit of measure unlike the discrete manufacturing.
(d) Special storage requirements (e.g. cold storage).

3. Production process characteristics
(a) Processes having variable yield and processing time.
(b) A divergent flow structure— a product can be packaged into many SKU sizes.
(c) Multiple recipes for a product.
(d) Packaging stage is labour intensive whereas the processing stage is not.
(e) Production rate mainly determined by the capacity.

In most of the cases, a subset of these characteristics is present. Each of these factors has to be taken into account for developing a production planning and control framework. For example, high setups and an orientation to use capacity as much as possible, leads to longer production runs and finished good inventory. In many cases, the intermediate stock point as depicted can only store temporarily, due to the instability and perishability of the products or because of limited capacity and hence, the ‘postponement strategies’ suggested by the latest literature (see Van Hoek 2001) are not fully applicable in many food processing industries. Also, unlike discrete industries, capital and capacity intensity of the equipment makes use of dedicated lines for some products and hence, the simplified planning rather unlikely.

2.4 MTO-MTS in food processing industry

Having understood the food processing industry characteristics, we now turn to the various planning decisions involved in a combined MTO-MTS production
situation. For the discussion that follows, we assume that no intermediate storage is possible and consider a combined MTO-MTS food production system as single equipment. This equipment can be considered as the bottleneck facility out of the processing and packaging stages. The demand is uncertain. For MTO items, no finished goods inventory is maintained. Each order for a MTO product has an agreed upon due date linked to it. The firm aims to deliver the product by this date. The MTS orders are fulfilled from the stock. All products have limited shelf life. A sequence dependent setup time is incurred, when there is changeover from production of one product to another. The presence of the sequence dependent setup times makes formation of product families attractive. The changeover times between products of the same family are relatively less and hence can provide some extra processing time, especially useful in the high utilisation situation under which we are operating. We are interested in deciding the production inventory strategies in such situations. The performance of the manufacturing system will be judged by the capacity utilisation, order focused measures for the MTO product and product-focused measures for the MTS items.

While the production structure as presented above seems relatively simple, the complexity of the production planning decisions that have to be taken for the combined MTO-MTS system is large. In the following sub-sections, we discuss the main decisions under three categories as identified in section 2.2.

### 2.4.1 MTO versus MTS decision

Many papers (Williams 1984, Carr et al. 1993) suggest the use of simplistic rules, e.g. ABC classification or its variants, to tackle the important issue of MTO/MTS. The high volume items are produced to stock and low volume items are produced to order. However these approaches only consider demand characteristics and totally ignore the production and market characteristics, like manufacturing time, response time etc. and food processing characteristics like setup times and perishability.

The ‘customer order decoupling point’ (CODP) concept, put forth by Hoekstra and Romme (1992), suggests a qualitative way to solve this MTO/MTS question. The customer order decoupling point separates the order-driven activities from the forecast driven activities and is the main stocking point from which deliveries to customers are made (for elaboration and application of CODP concept in food industry see Van Donk 2001). Using the product-market and process characteristics, and considering the desired service level and associated inven-
tory costs, this concept helps in locating the decoupling point and thus, the MTO/MTS decision. The CODP concept suggests that the typical MTO candidates are– (a) Products contributing little or irregular workload to the manufacturing system, e.g. export orders and tenders, (b) Items with short setup times, (c) Items with high holding cost, (d) Customized products, (e) Highly perishable products. Though this seems logical, it is felt that this is based on only single product-by-product analysis and may not hold true when a group of products and their interactions with capacity are considered. We conjecture that these interaction effects between MTO and MTS are the most intriguing, but least researched and understood issues within this field.

2.4.2 Production and inventory policy decisions

Here, we are interested in the various issues revolving around the capacity coordination, given the firm MTO orders and anticipated demand for the MTS items. The aim is to allocate the capacity among different products for maximizing the expected profit while attaining the desired minimum service levels in terms of due date performance for MTO product and line item fill rate for MTS items. This calls for adopting suitable and tailored production and inventory strategies.

The important questions are– How to do capacity allocation among MTO and MTS product? Should we adopt a fixed cyclic sequencing strategy or a dynamic sequencing? As mentioned earlier, the control of setup times is a major concern in the food processing industry and hence products are grouped in families and a cyclic production policy is generally followed. What should be the length of the production cycle? What should be number of runs per family per production cycle? What should be the run length for each family? What should be the run length for MTS items within a family run? What are the acceptance/ rejection criteria for MTO orders? How to set due dates for the MTO orders? How much safety stock and cycle stock should be maintained for MTS items?

Here, it is also required to have an understanding of the effect of adding MTO items or moving MTS items to MTO in the product portfolio. MTO production of some of the items means reduction in the inventory of these items but there may be an increase in the inventory of the MTS items to achieve the equivalent service levels. This can be explained with the help of results from Karmarkar et al. (1985) and Bemelmans (1986). No inventory for MTO items means an increase in the number of setups and hence the machine utilisation. This finally increases the production lead-time. This can only be reduced by increasing the
cycle stock and safety stock of the MTS items. Thus there is a complex trade-off between decreasing inventory of some items and increasing the cycle and safety stock of other items.

The limited shelf life of the food products is also an important consideration. It can pose limits on the safety stock levels and cycle length for the products.

2.4.3 Operational decisions

There are certain operational issues that firms need to answer on a regular basis. The first question is at the interface of the sales and production functions. The order acceptance/rejection decision has to be based on the characteristics of the already accepted orders and possibility of generating feasible schedule, which includes the new order. The second question is related to the operational scheduling and sequencing. The firms need to define the scheduling rules for variety of situations that may arise answering the question– which product to produce next?

2.4.4 Applicability of MTO-MTS literature in food processing industry

It is felt that the field of MTO-MTS research is still in its infant stages. Though the literature dealing with the combined MTO-MTS situation, as discussed in the section 2.2, helps in better understanding of different issues involved, they do have limited applicability in the food processing industry.

The MTO-MTS literature is mainly characterised by queuing theory applications with strict limitations and pre-requisites. The assumption of equal cost structure for all products is unlikely to hold given the large number of SKUs to be produced. The assumptions of batch sizes of one, no setups, and a pre-emptive resume production policy are also unrealistic owing to the fact that there are large and sequence dependent setups present in the food processing industry. Moreover, the stress on costs as the only performance measure is also not conforming to the way the decisions are taken in practice. Due-date performance might be more important, especially in the short term.

The very important decision of partitioning products in either MTO or MTS is in most of the literature taken on the basis of volume only and it is assumed that the MTO-products do have a low volume. In food processing this is not always the case. Due to tenders, export orders and promotional activities (special
2.5. Hierarchical planning framework

We argue that the available literature is limited not only in its applicability for real-life situations but also in explaining the fundamental interactions between two types of orders competing for a shared capacity and the use of time (due dates) and quantity buffers (inventory).

2.5 Hierarchical planning framework

It is obvious that all the issues raised in the previous section cannot be handled simultaneously. The whole problem is very complex and analytically intractable because of presence of sequence dependent setup and the congestion effects. A hierarchical decision-making is a reasonable approach to solve the issues involved. In this section, we present a generalised hierarchical planning framework that extends the underlying principles discussed in the well-known hierarchical production planning literature from MIT (viz. Hax and Meal 1975, Bitran and Hax 1977). The essential idea of having such a hierarchical approach is the partition of global problem into smaller manageable component sub-problems. These sub-problems are either to be solved sequentially, such that, the solution of a sub-problem poses constraints on the subsequent sub-problem (each level solves its own problem and performance feedback is given to the higher level) or solved simultaneously in a coordinated way.

The above mentioned literature on hierarchical production planning (and other as reviewed by McKay et al. (1995)) attempts to solve a "static" problem without discussing the dynamic events happening in the manufacturing system. Also, it does not answer some of the key questions like– How many levels are appropriate? Which decisions to take at which level of the hierarchy? Although the answers to these will depend on the organization or the case being studied, no attempts have been made to tackle these important questions. Only general guidelines are provided– Which decision to take at which level is dependent on the time horizon for the decision and level of aggregation. Higher levels are concerned about product groups and larger time horizon while lower levels deal with individual orders/product and shorter time horizon.
An alternative stream of hierarchical planning literature (see Schneeweiss 1995), addresses the dynamic nature of decision making in some way but the two key questions about the number of decision levels and which decisions are to be taken at which level, remain unanswered.

We follow Gershwin’s (1989) concept of ‘frequency separation’ in coming up with the hierarchy and answering the two questions above. Gershwin considers scheduling problems in the dynamic manufacturing system with machine failures, repairs, setups, demand changes, etc., and he proposes a hierarchical structure based on the frequency of occurrences of different types of events. This framework is based on the assumption that events tend to occur in a discrete spectrum, which defines the hierarchical levels. The levels of the hierarchy correspond to classes of events that have distinct frequencies of occurrence. The more frequent activities are the lower level activities and the less frequent ones are at the higher level. Table 2.2 shows typical dynamic events/activities and their frequency of occurrence.

<table>
<thead>
<tr>
<th>Operation (production)</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order arrival</td>
<td>High</td>
</tr>
<tr>
<td>Equipment setup</td>
<td>High</td>
</tr>
<tr>
<td>Equipment cleanup</td>
<td>High</td>
</tr>
<tr>
<td>Product transport / storage</td>
<td>High</td>
</tr>
<tr>
<td>Production sequencing</td>
<td>High</td>
</tr>
<tr>
<td>Machine breakdown / maintenance</td>
<td>High, medium</td>
</tr>
<tr>
<td>Order acceptance and due date determination</td>
<td>High, medium</td>
</tr>
<tr>
<td>Manpower allocation</td>
<td>High, medium, low</td>
</tr>
<tr>
<td>Due date changes</td>
<td>Medium</td>
</tr>
<tr>
<td>Lot size determination</td>
<td>Medium</td>
</tr>
<tr>
<td>Rush order arrival</td>
<td>Medium, low</td>
</tr>
<tr>
<td>Production cycle determination</td>
<td>Medium, low</td>
</tr>
<tr>
<td>Forecast changes</td>
<td>Low</td>
</tr>
<tr>
<td>Market changes</td>
<td>Low</td>
</tr>
<tr>
<td>Capacity addition / depletion</td>
<td>Very low</td>
</tr>
<tr>
<td>MTO-MTS determination</td>
<td>Very low</td>
</tr>
<tr>
<td>Grouping of items into families</td>
<td>Very low</td>
</tr>
</tbody>
</table>

Figure 2.2 provides an overview of the generalised hierarchy of decisions involved in the dynamic, combined MTO-MTS production situations. There are three levels of decisions in the hierarchy. The decisions related to high frequency
events from the table 2.2 are at the lowest level, the medium frequency decisions relate to the second level of hierarchy whereas the decisions related to less frequent events reside at the top level of the hierarchy. In the following paragraphs, we describe these decision levels in more detail.

At the first level, there are decisions that relate to determining which products to manufacture to order and which products to manufacture to stock. The determination of product families and setting the target service levels for these families is also done at this level. This MTO/MTS decision level uses the similarities in product, process and market characteristics of the product to form product families. The information needed for locating the decoupling point (see Van Donk 2001) will be used to decide on MTO/MTS partitioning. Based on the expected sales volume and revenues for these products, the target service levels are set in terms of line item fill rate for MTS products and response time for MTO products. Feedback on realized line item fill rate and response time in previous periods is also used as an important input. The planning horizon is a few months up to a year and this decision is taken periodically without too much operational details.
We call the second level as capacity coordination. At this level the demand and capacity is balanced. On the basis of orders on-hand and the forecast for customer orders, the available capacities and stocks, realized efficiency in previous periods, and the feedback regarding the realization of plans, the decisions are made at this level concerning the allocation of production orders for both MTO and MTS product to planning periods. This level specifies the target inventory levels for MTS product in each planning period and sets policies for order acceptance and due dates setting for the MTO orders. Production run length and production cycle length for each family and/or product is also specified. Another decision at this level is purchasing special packing materials with long lead-times. The time horizon is typically a few weeks to a month.

At the third level, there are scheduling and control decisions. The production orders are sequenced and scheduled. The sequence should be so as to meet the inventory and due date targets set at the upper levels while minimizing the total setup and cleaning time. The exact starting and ending time of a production order is determined. The rescheduling because of unforeseen reasons is also done at this level. The time horizon for this level is typically from a day to a week and is worked out with as much detail as is needed. A regular feedback on due date performance and line item fill rate is given to the top levels.

2.5.1 Comments

It may be noted that duration of activities also needs to be considered while deciding the hierarchy. For example, in food process industry the setup and cleaning times are quite high. Although setups are frequent and must, their impact has to be considered at the capacity coordination level as well. Also, the rush orders from the strategic customers though less frequent, may still have to be handled at the lower levels of hierarchy.

The conceptual framework suggested in this section is a first attempt to structure the production planning decisions in a combined MTO-MTS production situation. Though it is just another way of looking at the decision-making and a generic but not an in-depth prescription for structuring the specific levels for all the MTO-MTS situations, it can be used as a starting point for designing or redesigning the planning and scheduling hierarchy structure for a particular situation. However, several other important points need to be addressed on a case-by-case basis: when is decision level activated, when the decisions are deferred in view of the dynamic events in Table 2.2.
2.6 Conclusions and future research

This chapter investigated a number of issues with respect to the combined MTO-MTS situation in food processing industries. While a number of papers are present with respect to combined MTO-MTS production, the specific food processing industries have hardly been dealt with in literature. We argued that this is certainly needed. From our description of food processing industries a number of specific characteristics can be derived that are of special relevance for this combined situation: high capacity utilisation, sequence dependent setups and limited shelf live. We reviewed the literature on MTO-MTS and concluded that some useful ideas are present. However, the majority of contributions do not address those specific characteristics of food processing. Moreover, most contributions are highly mathematically oriented and have some rather restricted assumptions.

This chapter introduces a general framework to decide on the main problems in managing a combined MTO-MTS system in food processing. The framework combines a three level decision model with contributions from MTO-MTS literature. We conclude that the framework is a valuable contribution to both the description of the MTO-MTS production situation and possibly to the managerial decision-making in organisations.

It is felt that further research should be directed but need not be restricted to the following areas. Firstly, further refinement of the hierarchical framework is needed. Each of the levels in the hierarchy contains a specific decision for combined MTO-MTS situation. Quantitative decision aids are to be developed in the context of the hierarchy. It is clear from the discussion in this chapter that the interaction effects between MTO-MTS orders and shared capacity are captivating, but yet not understood well. The presence of setups, and due dates for MTO products make queuing models less tractable analytically. Simulation studies might be helpful to study the MTO/MTS decision and the interactions between the products and the capacity under varying demand patterns, setup times and processing times. Secondly, in food processing industry stability and maintainability of the production cycle are the main performance measures rather than cost measures at the scheduling and control level. How to achieve stable schedules in dynamic, combined MTO/MTS is an open question. Finally, we think that the scientific community could benefit from more empirical studies. It would be interesting to know how planners deal with the combined MTO-MTS situations in practice and compare with the hierarchical framework suggested in this chapter. An investigation of the demand-product-process characteristics
that led to particular choices made for the decision structures in practice is also appealing.
Chapter 3

A decision aid for make-to-order and make-to-stock classification

Managers in food processing industries find it difficult to decide which products to make to order and which products to stock. This has been a concern for academic researchers as well. A discussion of the existing approaches is presented and is followed by a description of an MS Access/Excel based tool that is an aid for managers in taking such decisions. The tool is easy to use and maintain but still gives managers a front-end that consolidates various theoretical concepts like ABC analysis, order penetration point, and customer order decoupling point.

3.1 Introduction

Most of the textbooks on production management, e.g. Vollman et al. (1997), classify and define the production strategies as make-to-order, make-to-stock, and assemble-to-order. They relate these approaches to choosing a master production scheduling (MPS) approach. This is done using the basic unit of control to be used in MPS. A make-to-order approach to MPS is typically used when the product is manufactured to individual customer order, i.e. a basic MPS unit is a customer order. In make-to-stock, the MPS is based on end items, and these end products are produced to meet forecast demand. The customer orders are filled directly from the stock. In assemble-to-order (ATO), the MPS is based on some group of end items and product options. In these discussions, however, it is assumed that the strategy that a particular product should follow has been decided and is given. In this chapter, we address how to make this strategic
decision.

At the outset, readers should note that our definition of MTO is simple—there is no inventory held in stock for MTO recipes. We look at a specific class of MTO recipes: the customer-specific, tailor-made, one-off recipes (products) are obviously MTO but there are certain recipes that could be produced either to stock or to order. Such recipes are considered for the MTO versus MTS categorisation decision in this chapter. Assemble-to-order is, however, kept out of discussion since in many food processing industries intermediate storage possibilities are limited or do not exist at all.

Traditionally, food and process industries have been associated with commodity products and flow-oriented processes (p.7-8, Vollman et al. 1997) and hence MTS is the most likely policy. However, as suggested in chapter 2, with increased competition, shorter product life cycles, and growth in number of SKUs, the choice of MTO or MTS is increasingly becoming an important topic for these industries as well. This MTO versus MTS decision is more strategically oriented, as it has a direct impact on the customer lead-time that can be offered, and is complicated due to various factors involved. The solution needs to consider the trade-offs between costs, product-process characteristics, and the demands from the market along with the plant capacity. A lot of concepts have been proposed previously to make this decision viz. ABC analysis, ‘customer order decoupling point’ (Hoekstra and Romme 1992), ‘order penetration point’ (Olhager 2003), ‘lead-time gap’ (Christopher 1998). While these concepts make valuable contributions, their application in practice is rather difficult. The application is further worsened by the use of various terminologies floating around. The aim of this chapter is twofold—(i) to integrate various existing theoretical approaches that could be used for MTO versus MTS decision, and (ii) to translate them into a practical instrument.

The chapter is organised as follows—First, the literature that helps us take MTO or MTS decision is reviewed in the next section. The key factors affecting the MTO/MTS decision are identified and are used to develop a practical decision aid to solve the problem. A decision aid which allows manufacturers to partition the products into MTO and MTS categories while respecting the delivery service requirements and the constraints posed by products, processes, and market is described in section 3.3. This tool can be used on any computer running Microsoft Access/Excel with no extra investment. Conclusions and further comments are provided in section 3.4.
3.2 Literature review

A few useful concepts and models are available in the literature. *ABC* analysis (sans product value) has been widely used with high volume *A* class items produced to stock while low volume *B* and *C* class items considered as MTO. Many papers (Williams 1984, Carr et al. 1993) suggest the use of such simplistic rules. This way of classification, however, considers only the demand factor.

Li (1992) takes a marketing perspective. He studies the impact of market competition and customer behaviour based on price, quality, and expected delivery lead-time on the MTO/MTS production decision in a single product case. Here, the discussion is on ‘what happens when’ one of the factors changes. He concludes that competition can breed a demand for make-to-stock, just as other economic phenomenon such as economies of scale, uncertainty or seasonality, and that delivery-time competition decreases producer’s welfare. Arreola-Risa and DeCroix (1998) provide optimality conditions for the MTO/MTS partitioning in a multiproduct, single machine case with the first-come-first-served scheduling rule. They study the effect of manufacturing (processing) time diversity on the MTO/MTS decision for backorder-cost cases of dollar per unit and dollar per unit per time. Their result, using *M/G/1* queuing analysis, shows that holding cost rate, backordering cost rate, and distributions of manufacturing times play an important role in MTO versus MTS decision. They conclude that reducing manufacturing time randomness leads to more MTO production.

Sox et al. (1997) focus on total quantity of inventory and on-time delivery, rather than costs. The goal is to fulfill orders within a certain service time window of *T* periods. The primary stock control parameter is the total base stock. They provide expressions for fill rate using *M/M/1* queue with multiple products, base stock inventory policy, one-for-one inventory replenishment, and first-in-first-out order scheduling with service within *T* periods. These results are used to allocate the aggregate inventory to the items. The high demand items get stocks assigned to them while low demand items do not. The service of these low demand items is maintained by giving them higher production priority when a demand occurs. Though the authors do not explicitly talk about the MTO/MTS decision, it is clear that their model can be used for that decision. It is felt that despite some restrictive assumptions, like no setup or changeover time, the model can be extended for certain food (process) industries. A lot of food industries have special storage requirements, e.g. cold storage, and a limited storage capacity. This may allow only a few products to be stored. This model can be used to decide which products get base stock assigned to them, i.e. which products
to store.

The ‘customer order decoupling point’ (CODP) concept, developed by Hoekstra and Romme (1992), is more comprehensive and looks at market, product, and production related factors to arrive at the MTO/MTS decision. The customer order decoupling point separates the order-driven activities from the forecast-driven activities and is the main stocking point from which deliveries to customers are made. Using the product-market and process characteristics, and considering the desired service level and associated inventory costs, this concept helps in locating the decoupling point and thus, the MTO/MTS decision. This concept has been used in a number of case studies across various manufacturing sectors including food processing e.g. Van Donk (2001). This concept is also known as ‘order penetration point’ (OPP) and has been discussed in Olhager (2003) and the references therein. Olhager (2003) further presents a conceptual impact model for the factors affecting the positioning of the order penetration point. Most of these papers on CODP and OPP discuss ‘what happens when’ a certain factor forces the CODP to shift forward and backward. These papers recognise that the decoupling point choice involves a trade-off between delivery time and inventory costs. This trade-off can viewed as a problem of minimising the costs while meeting market requirements and satisfying process constraints. Regarding delivery time, the major factor is the production to delivery lead time ratio ($P/D$) ratio (Christopher (1998) uses the term lead-time gap for relation between production and delivery lead times) while the costs are mainly affected by relative demand volatility (RDV). The RDV is defined as the coefficient of variation, i.e. the ratio of standard deviation of demand and the average demand.

We now take a closer look at $P/D$ ratio and RDV since we will be making use of these factors in section 3.3.

If $P/D$ is greater than one, MTO strategy is not possible and MTS is the only choice. If the ratio is less than one, MTO is possible but it may also be possible to produce to stock to gain economies of scale. This is expressed through the RDV, such that a low RDV indicated that some recipes can be produced to stock. If the RDV is high it is not reasonable to use MTS policies since this would mean carrying excessive safety stock inventory. RDV has also been prescribed by D’Alessandro and Baveja (2000) for MTO-MTS classification. They use RDV and average demand volume to categorise products into MTO and MTS. The products with high volume, low variability are MTS products; while products
with low volume and high variability are MTO products.

While the concepts discussed in this section help us understand the complex trade-offs involved in MTO or MTS decision and provide guidelines for it, there is no easily available, ready-made instrument that will achieve the same in practice. Moreover, the capacity considerations are ignored in these concepts since each product is considered in isolation during the decision process. It is felt that there is a lack of an instrument that considers product, market, process characteristics and also takes into account capacity constraints. The next section fills this void. An attempt has been made to develop a decision aid for MTO or MTS decision that takes into account the key factors stressed in the above literature viz. service delivery requirement, demand variability, cost considerations etc., and process constraints, mainly in the form of limited available capacity.

### 3.3 Decision aid

All manufacturers want to meet the service requirements at minimum cost. Therefore, in deciding MTO or MTS partition, we concentrate on two important aspects: (i) inventories are held to attend delivery service requirements, or (ii) to provide cost savings. In order to do this, we start analysing, first, if service considerations force us to keep the item in stock, regardless of the cost considerations, and if this is not the case we do cost calculations to arrive at the decision. The procedure followed is thus sequential. We start with the delivery service requirement analysis, followed by the demand and cost analysis, finally capacity requirement analysis is done to check and achieve the feasibility of the MTO-MTS classification. Figure 3.1 shows the architecture of this procedural tool. Recipe (product) master and the order book are the main input for the system. Figure 3.2 shows a screenshot of a recipe master input while figure 3.3 shows the structure of the order book. One can safely assume that the exercise of getting this data for any company is easy and rather trivial. Since recipe data is the core of food industries and all the orders are recorded, these should always exist in MRP/ERP systems. We now explain the each step in the sequential procedure.

#### 3.3.1 Service considerations

For each recipe one can associate a desired maximum customer delivery lead time that is acceptable to the customer. This delivery lead time can be determined by taking into account the delivery history of the product (available from the order book) and the market benchmarks. Similarly, manufacturing lead time
Chapter 3. A decision aid for make-to-order and make-to-stock classification

Data Input
Recipe master
Order book
Production book
Process constraints
Service requirements

Output reports
MTO-MTS partition
Demand analysis
Cost report

1. Service considerations
P/D ratio

2. Demand analysis
Volume, variability etc.

3. Cost analysis
Inventory, setup, and safety stock costs

4. Capacity considerations
Rough-cut capacity planning, Feasibility

Figure 3.1: Architecture of MTO-MTS decision aid

Figure 3.2: Input screen: Recipe Master
3.3 Decision aid

3.3.1 Decision aid

Figure 3.3: Order book

can be computed for each recipe from previous production order book history or by estimates provided by shop supervisors. This can also be computed using the discussion and procedures provided later in chapter 4.

The decision rule is straightforward— if the manufacturing lead time is larger than the desired maximum customer delivery lead time, i.e. if the $P/D$ ratio is greater than one, the recipe is classified as MTS otherwise there is no need to stock it based on service requirements. The demand and cost analysis has to be taken up in that case.

3.3.2 Demand analysis

In this section, we describe the demand analysis that forms the core of the model. The classical $ABC$ analysis can be easily carried out from the input. However, it is felt that this categorization is too simplistic and does not account for differences in uncertainty that exists in the demand among various products. Instead, a demand variability analysis, in the form of RDV, as suggested in D’Alessandro and Baveja (2000) is followed. Figure 3.4, shows a plot of average weekly demand on the x-axis and demand variability (coefficient of variance) on the y-axis. It is possible to categorise products into 4 groups— (a) High volume, low variability, (b) High volume, high variability, (c) Low volume, low variability, and (d) Low volume, high variability. The products in the high-volume,
low variability are candidates for MTS production. Most of the product recipes belonging to the low volume, high variability category should be produced on MTO basis. Many recipes belong to the high volume, high variability category and may be produced on MTS basis. However, more safety stock levels would be required for such recipes and economic considerations discussed in section 3.3.3 come into the picture. It is also recommended that closer ties should be sought with the customers in order to reduce their variability.

While doing this analysis, some difficulty arises because of the subjectivity involved in drawing up the lines that partition high demand items from the low demand items and high demand variability and low demand variability. These are the likely areas of conflicts as well as newer opportunities for sales and production departments. For example, classifying a particular product as MTO rather than MTS can have serious implication in terms of longer lead-times for customers, less inventory, more setup time but this also allows differentiated service for different customer classes. Sales and production departments should jointly decide on ‘what is high demand’ and ‘what is high variability’. Some simple rules can be defined, e.g. a vertical partition to take place at a certain percentage of total demand.
3.3.3 Economic considerations

In this section, the cost of producing a recipe to stock and to order are compared. This model is adapted from chapter 4 of Magee and Boodman (1967). The assumptions and the data of the problem are as follows:

- The annual expected demand for the recipe is $D$ units/year, a number of $N$ orders are received annually from the customer.
- There is a fixed charge of $A$ euros/order for the manufacturing setup.
- It costs $PC$ euros/time unit of machine usage (production and setup time)
- The production rate is $P$ units per time unit and the average setup time for the item is $S$ time units.
- If the recipe is stocked, it is ordered in economic order quantities $Q$; also, to protect against uncertainty a safety stock ($SS$) is held. In some cases it may be necessary to change these using order quantity modifiers on account of technological constraints like shelf life, minimum batch size etc. These can be easily brought in but are ignored in this chapter.
- It costs $C_{MTS}$ euros/unit to produce the recipe for stock; it costs $C_{MTO}$ when it is on order; the two costs are established by assuming that in MTO case the expected order size is $D/N$ units, and in the MTS case it is $Q$ units. In some cases, it may be possible to combine MTO orders into one production order but here we will assume that it is not done because of the large product variety and shorter lead time requirements. The combining of orders may lead to long and varying lead times.
- Stock is carried at a charge of $r$ euros per unit per year.
- Service level is high enough so as to make the backorder cost negligible.

If we produce the recipe on the MTO basis, the average total processing time, $TPT_{MTO}$, for each order is:

$$ TPT_{MTO} = S + \frac{D}{N \times P} \quad (3.1) $$

$C_{MTO}$, the cost per unit is then given by:

$$ C_{MTO} = \frac{TPT_{MTO}}{D/N} PC \quad (3.2) $$

The total cost is the sum of ordering cost and the cost of the recipe itself. It can be given by:

$$ TC_{MTO} = N \times A + D \times C_{MTO} \quad (3.3) $$
When the product is stocked, the average total processing time, $TPT_{MTS}$, for each batch is:

$$TPT_{MTS} = S + \frac{Q}{P}$$  

(3.4)

$C_{MTS}$, the cost per unit is then given by:

$$C_{MTS} = \frac{TPT_{MTS}}{Q} PC$$  

(3.5)

The expected annual cost $TC_{MTS}$ is:

$$TC_{MTS} = \frac{D}{Q} QA + \left[ \frac{Q}{2} + (SS) \right] r + D \times C_{MTS} + C_{syst}$$  

(3.6)

where $C_{syst}$, euros/year, is the system cost (the recipe’s share) of having the item stocked. It is also possible to exclude this, since it can be incorporated in the inventory holding cost rate $r$.

The decision rule be applied is: if $TC_{MTO} < TC_{MTS}$ the recipe is classified as make-to-order; otherwise it is a MTS recipe.

Note that in order to compute the total cost we need the estimates of all the parameters involved. Most of them are already available in the recipe master and the order book. The required safety stock can also be taken from historical records, if the recipe was previously stocked; if not, an approximation can be used in the following form:

$$(SS) = k \sqrt{\frac{D}{12}}$$  

(3.7)

where $k$ is the safety factor, and $l$ is the lead time, in months. This approximation is used for high variability recipes in RDV analysis, and assumes that demand during the lead time $l$ follows Poisson distribution; after all, this assumption is not that bad when we recall that these are the slow-moving items. For fast moving items i.e. low variability recipes, normally distributed demand approximation is used.

Figure 3.5 shows a screenshot of the output of the economic considerations.

### 3.3.4 Capacity constraints

Once we follow the sequential procedure described above—service considerations, demand analysis, cost considerations—we get an initial solution to the MTO/MTS partition. However, so far we have considered the recipes one by
one and have neglected their interactions with the capacity. We are not yet sure whether we have sufficient capacity to follow the MTO/MTS partition obtained so far. To do this, a rough-cut capacity check (i.e. ignoring congestion effects like machine interference) is performed. It is checked whether we have sufficient capacity to produce the initial MTO/MTS partition solution. This can be accomplished using the following expressions.

The annual capacity, $X_{MTS}$, required by the recipe if it is produced to stock is simply the average total processing time of the batch multiplied by the number of batches per year. It is given by:

$$X_{MTS} = TPT_{MTS} \times \frac{D}{Q}$$  \hspace{1cm} (3.8)

The annual capacity, $X_{MTO}$, required by the recipe if it is produced on order is simply the average total processing time of orders multiplied by the number of orders. It is given by:

$$X_{MTO} = TPT_{MTO} \times N$$ \hspace{1cm} (3.9)

The total capacity needed for the given MTO-MTS partition is then given by the expression:

$$\sum X_{MTO} \times y + X_{MTS} \times z \quad \text{where } y, z = 0 \text{ or } 1$$  \hspace{1cm} (3.10)
where,
\[ y = 1 \text{ if a product is produced on MTO basis; 0 otherwise; } \]
\[ z = 1 \text{ if a product is produced on MTS basis; 0 otherwise; } \]
\[ y + z = 1 \text{ if the product is offered; 0 otherwise.} \]

In case it is observed that there is a shortage of capacity, i.e. the capacity obtained using the expression (3.10) is less than the available capacity, an iterative procedure is followed to modify the existing MTO/MTS partition. The procedure starts by changing the category of that recipe where increase in total costs (by moving it from MTO to MTS category or vice versa) is minimal. After each iteration a capacity check is done again for checking the feasibility of the partition. The procedure terminates when a feasible partition is found or when all items have been checked. In the later case, it is clear that the company has capacity shortage. Then, the company may choose not to offer some recipes with low volume, low variability. Low volume, high variability recipes can be offered on MTO basis, if they have high contribution margins.

Alternatively, it is also possible to use the following formulation for the rough-cut capacity planning instead of the iterative procedure (with feasibility checks) described above.

\[
\min \sum (TC_{MTO_i} \times y_i + TC_{MTS_i} \times z_i) \quad : \text{Total cost}
\]
\[
\sum (X_{MTO_i} \times y_i + X_{MTS_i} \times z_i) \leq X \quad : \text{Capacity constraint}
\]
\[
y_i + z_i = 1 \quad : \text{Product is offered}
\]
\[
y_i, z_i = 0 \text{ or } 1 \quad : \text{MTO or MTS}
\]

This integer(binary) linear programming model chooses \( y_i \) and \( z_i \) (decision variables) in such a way that the total cost is minimised while the capacity constraint is satisfied. The model is solved using the SOLVER available in Microsoft Excel. Few \( y_i \) and \( z_i \) values will have to be preset using the outcome of the earlier steps, e.g. for a certain recipe, the service requirements may force \( z_i = 1 \), i.e. product has to be produced on MTS basis irrespective of the cost.

There are various output reports available from the decision aid. The most important report suggests the MTO/MTS partition for each recipe along with the justification of the decision. The justification comes from service level requirements, demand analysis, and cost considerations discussed in this section.
3.4 Conclusion

In this chapter, a simple and easy to understand tool for the MTO or MTS decision is presented. This decision, though strategically oriented and complex, influences the production planning and control function of any company. Such decisions are generally taken once every 6 months or a year. The tool presented gives a unified treatment of various trade-offs and considerations that go into taking the decision. There are no data or investment requirements on the part of the company to make use of this tool. The familiar interface of Microsoft Access/Excel makes the use of the tool even more attractive. Here, we must state that this tool has not been fully implemented in a real-life setting but the initial feedback is satisfactory.

It is felt that the decision aid presented in this chapter is the first ever attempt at developing a ready-made tool for MTO/MTS decision in food processing industries. There are obviously certain limitations with the presented approach. The tool considers only service delivery time requirements, demand variability, and cost considerations. The tool looks at only the two extremes MTO and MTS. It ignores ATO. However, ATO situations are very rare in food processing industry given the fact that the intermediate products are mostly volatile. The logical extension of the aid presented in this chapter should include other factors that impact the MTO-MTS decision. Shelf life, for example, can be easily brought in cost considerations. The cost model used in this paper while useful has certain drawbacks: we used deterministic approach with constant demand, and infinite capacity assumptions as in classical independent lot size formula (although the capacity constraints were brought in later). Future models should aim at considering multiple products for determining lot sizes and MTO versus MTS option simultaneously. Another unanswered question is about selection of basic unit (recipe or SKU) for doing the analysis similar to one presented in this chapter. In-depth demand analysis; and commonality indices for SKUs and recipes should help in this regard.
Chapter 4

Medium term capacity coordination

This chapter discusses the capacity coordination in the medium term. Lot sizing is at the heart of this. The Economic Lot Scheduling Problem (ELSP)—the problem of scheduling several products on a single facility—provides the bulk of the background knowledge. After a brief overview of the published ELSP approaches, we discuss the possible modifications and extensions to them that need to be adapted for application in food processing industry. Special attention has been given to specific characteristics of limited shelf life and a combination of MTO and MTS.

4.1 Introduction

Given the partitioning of the product range into MTO and MTS categories, the production and inventory (order acceptance rule, restocking and inventory control rules, etc.) policy needs to be determined. As discussed in chapter 2, the literature on the combined MTO-MTS has addressed these issues in a limited way. In some papers, in order to make solutions analytically tractable it is assumed that setups do not exist (e.g. Carr et al. 1993, Carr and Duenyas 2000). Some others advocate (cyclic) base-stock policies for the MTS items (e.g. Federgruen and Katalan 1994, 1999).

The literature does not pay any attention to two important food processing characteristics: limited shelf lives and sequence dependent setups. The perishable nature of products limits the possibilities for stocking. Sequence dependent setups (especially as there are families of related products) may make it relatively easier and economical to produce MTO items if a combination with MTS items
from the same family can be made. Due to relatively large and sequence dependent setups, there is a tendency to produce in a recurring, cyclic pattern. Such cyclic patterns, although quite common in food processing companies, have been addressed by only Federgruen and Katalan (1994, 1999) in the MTO-MTS literature. Establishing such patterns has been the object of study of the literature on ELSP– Economic Lot Scheduling Problem (e.g. Elmaghraby 1978). In this text, we chose to adapt ELSP based approaches. The main reason is that the food processing industries are traditionally MTS companies and are in transition toward more MTO. The presence of regular demand products, high setup time makes cyclic schedules like those generated by ELSP more attractive than acyclic schedule approaches that might come from pure MTO based approaches.

The aim of this chapter is to develop an approach for finding a production cycle for the combined MTO-MTS situation in food processing industries. The objective is to make adaptations to ELSP approaches to be able to incorporate various food processing industry characteristics in the development of a production cycle. First, a brief description of ELSP is presented in section 4.2. Then, some extensions needed for food industries are discussed in section 4.3. Sections 4.4 and 4.5 address two of these extensions in more details– limited shelf life issues and the incorporation of MTO in ELSP respectively. Concluding remarks are provided in section 4.6.

4.2 Economic Lot Scheduling Problem

Chapter 2 described the main types of decisions in combined MTO-MTS situations. One of the decision areas is the determination of the production and inventory policy. In the context of make-to-stock only, a large number of publications deals the problem of producing a number of different products to stock on the same facility. We address the basic results from this research area (usually labelled as the Economic Lot Scheduling Problem (ELSP)) in order to use and adapt these for the combined MTO-MTS. The ELSP problem deals with scheduling the production of several products on a single facility. The objective is to minimise the sum of holding cost and setup cost in the long run, under the restriction that all demand is satisfied. This problem has been studied in the literature for around 45 years (see e.g. Rogers 1958). The basic assumptions of the problem are that demand is constant and continuous for each product; all the demand should be fulfilled immediately i.e. no backordering; production rate is constant and only one product can be produced at a time; usually a setup (sequence independent) is required for producing a product, incurring a setup
cost; constant holding cost rate for carrying inventory of each product. Most methods are essentially built on the classical EOQ with the adaptation for the multi-product case. In principal, the decisions are made at an intermediate level between strategic and operational, comparable with the level—capacity coordination in medium term—of the hierarchy in section 2.5.

The ELSP problem is known to be NP-hard (Hsu 1983) and most solution approaches are heuristic algorithms (e.g. Elmaghraby 1978, Lopez and Kingsman 1991). Two approaches are widely used in the literature: the basic period approach (introduced by Bomberger 1966) and the common cycle approach. The basic period approach tries to find a fixed, relatively short period of time: the basic period. For each product a factor is determined that indicates whether it will be produced each period, every second, third or fourth, etc. period. Thus, the individual items have different cycle times, which are integer multiples of basic period. The aim is to find the optimal basic period and these factors for each product, while a feasible schedule is still possible. A feasible schedule means that the total time for production and setups does not exceed available capacity. Doll and Whybark (1973) and Haessler (1979) provide well-known heuristics in the basic period approach. The common cycle approach tries to find a cycle which accommodates production of every product exactly once during each cycle and is a special case of the basic Period approach. This common cycle should be long enough to produce every product. Dobson (1987) introduced a third approach called ‘time varying lot size approach’. In this variant of a cyclic schedule, items are allowed to be produced more than once in a cycle like in the basic period approach. In addition, different lot sizes are allowed for any given item during a cyclic schedule.

In the next section, the applicability of ELSP approaches is discussed and extensions for the food processing industries are provided.

4.3 ELSP in food processing industries

As discussed in the previous section the emphasis in ELSP approaches has been on finding cost effective cyclic schedules. In a cyclic schedule the facility is setup for products in a sequence that repeats forever. The inventory positions repeat after each cycle. Key to this repeating property is the assumption of deterministic demand. In practice, however, demands are random. Further, assumption of no stockouts is too strict in the presence of randomness.
If we look at the food processing industries, cyclic schedules are common. Sequence dependent setup times are incurred before the production starts. The products do have limited shelf life also, which limits the amount of inventory that can be carried without spoilage. In a number of food processing companies, there are many product families as well. The setup structure is family setup. A major setup is incurred when product family changes and a minor setup within products of the same family. As discussed earlier in chapter 2, the companies are also moving from a pure make-to-stock (MTS) strategy and are producing more and more products to make-to-order (MTO). How to take care of MTO products within the cyclic schedules? In the following paragraphs, we review and discuss ELSP literature that can be adapted for various food industry characteristics mentioned above.

1. Case of random demand: Stochastic ELSP (SELSP)

SELSP methods that are found in the literature have employed variable lots, idle times and safety stocks to take care of the random demands. Leachman and Gascon (1988) developed a heuristic procedure based on ELSP using target cycles combined with a continuous adjustment of production cycles. Their goal was to adequately space inventory runout times in order to balance the effect of random demand changes. Gallego (1990) uses optimal control theory to find an optimal target cyclic schedule and a linear recovery policy for the case of disruption to the cyclic schedule. Bourland and Yano (1994) examine the use of capacity slack and safety stock in SELSP. They use a static continuous review control policy and present a mathematical program that determines the cycle length, the allocation of idle times among the items, and the cycle safety stocks. Kelle et al. (1994) provide a model to determine target schedule and required safety stocks so as to minimise the sum of setup and holding cost subject to a service level constraint. They use a procedure similar to Doll and Whybark (1973) but also include safety stocks that, in turn, depend on cycle length. Sox et al. (1999) provide a detailed overview of SELSP literature.

2. Sequence dependent setup time

The common cycle method results in a solution where the cycle times for each product are the same and each product is produced exactly once during the cycle. No constraint on the order in which products are produced is imposed. We can thus first attempt to produce a sequence of products that minimises the total setup time required in the cycle. These values can then be used in the calculation of the optimal cycle time. To put it simply, we use a fixed sequence strategy. This product sequencing is essentially a variant of the well-known travelling salesman problem (TSP) and
is known to be NP-hard. In basic period ELSP approaches, the only possible option to incorporate sequence dependent setups is to use an average value for each product in the beginning to decide on the production frequencies. These production frequencies are then used to create an initial production schedule which is then modified using the sequence dependent setup time data. This problem is a Travelling Salesman Problem with sub-tours. Dobson (1992), Lopez and Kingsman (1991) use this approach.

3. Family structure setup

Inman and Jones (1993), McGee and Pyke (1996) provide methods for disaggregation of family schedules in part schedules. McGee and Pyke first, use an iterative goal seeking program (in Microsoft Excel) for allocating the major setup cost and setup time to the products in the family. Then they use a procedure similar to that of Doll and Whybark (1973). Ham et al. (1985) provide a common cycle approach that considers a family structure setup.

4. Shelf life

The additional constraints are to be added to ELSP problem to take care of limited shelf life for products. These constraints require that cycle time for a product should be less than its shelf life to avoid any spoilage. The existing literature that considers ELSP and shelf life for products, e.g. Silver (1995), Viswanathan and Goyal (1997), has assumed a common cycle approach and an unrealistic assumption of possibility of deliberately reducing the production rate. In many food processing industries, where limited shelf life for products is common, changing the production rates is not allowed at all because it may result in products with poor quality.

5. MTO-MTS

No research has been done so far on the determination of production cycle and lot-sizes under combined MTO-MTS using ELSP approach with the notable exception of Federgruen and Katalan (1994, 1999). They use a cyclic base stock policy to address lot sizing in combined MTO-MTS production situation. Their method is essentially a variant of common cycle policy i.e. every product is produced exactly once in a cycle. It has been widely acknowledged that the performance of such a policy deteriorates as the product variety increases. We provide other possibilities of incorporating MTO in ELSP in section 4.5.

While all the characteristics discussed above are relevant and important, we look at only the last two extensions in more details in section 4.4 and 4.5 respectively.
tively. The other characteristics are open for further research.

In the next section, we allow products to be produced more than once in a cycle and do not allow reducing production rates. A comparative review of various ELSP approaches, Lopez and Kingsman (1991), report that Haessler’s algorithm (1979) is superior in performance, in terms of ‘achieving economical and realistic schedules’, to all other basic period approaches because of its convenient blend of analytical calculation, and limited enumeration. It may also be noted that this algorithm has an explicit built-in procedure for feasible schedule generation. A modification to Haessler’s basic period procedure to account for the shelf life is presented. The proposed ‘branch-and-bound like’ procedure exploits the extra shelf life constraints to efficiently achieve a feasible solution. Numerical examples are presented to show that our approach outperforms the common cycle approach with shelf life considerations.

### 4.4 ELSP with shelf life considerations

In food processing industries, products do have limited shelf life that restricts the amount of inventory that can be carried without spoilage. This adds another dimension to ELSP. There are a limited number of ELSP research papers that deal with shelf life considerations. We now briefly review these.

#### 4.4.1 Literature overview

Silver (1989) studies an instance of the ELSP problem with shelf life considerations where an unconstrained common cycle solution violates the shelf life constraint of exactly one item. He considers options of either (a) deliberately slowing down the production rate for that item, or (b) reducing the common cycle time. He proves that it is effective to reduce the production rate. Sarker and Babu (1993) consider the same model as Silver while incorporating the production time costs. Their computational results indicate that the choice between ‘reducing production rate’ and ‘reducing the production cycle time’ is not as straightforward as Silver has suggested. It depends on the problem parameters such as shelf life, machine setup times (and costs), the production times and unit inventory costs. Goyal (1994) and Viswanathan (1995) postulate that it may be economical to produce some of the items more than once in a cycle but raise concerns about obtaining feasible schedules in such cases. Silver (1995)

---

and Viswanathan and Goyal (1997) provide heuristics for simultaneous optimization of cycle times and production rates in the cases where exactly one, and more than one item has binding shelf life constraint respectively. Viswanathan and Goyal (2000) show that allowing backordering can reduce the costs substantially while respecting the shelf life constraint. Chowdhury and Sarker (2001) and Goyal and Viswanathan (2002) discuss the problem of determining the optimum production schedules and raw material ordering policy under three options – adjusted production rate, adjusted cycle time, simultaneous adjustment of production rate and cycle time.

Most of these papers assume that reduction of a production rate does not incur additional costs. Also, in all papers, it is assumed that idle capacity cannot be used for other (more profitable) purposes. We think that these are not realistic assumptions in many situations. In the cases of high system utilisation, there are obviously limits on reducing the production rates. Also in many cases, like in food processing industry where limited shelf life for products is common, changing the production rates is not allowed at all because it may result in products with poor quality. We will, hence, stick to fixed production rates in the discussion. All the papers discussed above use the common cycle policy. This has some practical implications. Consider an example using the common cycle approach– if the shelf life of some product is very small, it will significantly reduce the cycle length for other products as well, which may have higher ‘natural’ cycle lengths and hence will lead to a solution with higher costs (‘Natural’ cycle lengths are the single product cycle lengths, as if they are produced independently). A motivation for allowing multiple production runs for some products stems from this. In other words, the products differ from each other in terms of production rates, demand rates, inventory costs, setup time and costs etc. and hence do have different natural cycle lengths. If the diversity in these natural cycle lengths is large, the common cycle policy may not be the most economical option. Hence, we will allow products to be produced more than once in a cycle.

The main contribution of this section is the development of a basic period solution procedure for the ELSP problem with shelf life considerations. In contrast to the previous work, it does not allow reducing production rate and does not restrict the solution to a common cycle solution. The heuristic presented here builds on Haessler’s procedure (1979) for ‘solving ELSP and feasible schedule generation’.
The organization of the section is as follows. Section 4.4.2 presents the problem formulation. The heuristic for finding a solution to the ELSP problem with shelf life is described in section 4.4.3. Section 4.4.4 presents computational results. A numerical example illustrates the heuristic procedure. Then the comparison of the suggested procedure and common cycle solution using the well-known problem data set is presented. The conclusions and future research directions are outlined in section 4.4.5.

4.4.2 Problem Formulation

The basic assumptions of the ELSP problem with shelf life considerations are –

- There is a constant, continuous demand rate for each product. All the demand should be fulfilled immediately i.e. no backordering is allowed.
- The production rate for each product is constant. The facility can produce only one product at a time.
- A sequence independent setup time (and cost) may be incurred before the start of the production of a product.
- There is a constant holding cost rate for each product for carrying inventory.
- The products have limited shelf life and no spoilage is allowed.
- Stock is used on a first-in-first-out basis.

The following notation is used in this section. For each item \(i = 1, \ldots, N\); the following parameters are assumed to be given:

\[
\begin{align*}
    d_i & : \text{constant demand rate (units per unit time)} \\
    p_i & : \text{constant production rate (units per unit time)} \\
    c_i & : \text{setup cost per production lot of product } i \text{ ($)} \\
    u_i & : \text{setup time per production lot of product } i \text{ (unit time)} \\
    h_i & : \text{inventory holding cost ( $ per unit per unit time)} \\
    s_i & : \text{shelf life (unit time)}
\end{align*}
\]

We define \(T_i\) as the cycle time for product \(i\), i.e. the time that elapses between the commencement of two successive production runs of product \(i\). The ELSP problem with shelf life constraints is to find feasible cycle times \(T_1, \ldots, T_N\) for which, the average cost per unit time (setup costs plus inventory costs), \(V\), of
producing all \( N \) products is minimized.

The total cost \( V \) is equal to \( \sum V_i \) where \( V_i \) is the cost per unit for producing product \( i \) and is given by

\[
V_i = \frac{c_i}{T_i} + h_i T_i d_i (1 - \frac{d_i}{p_i}) / 2
\]  

(4.1)

We will use the basic period approach where each \( T_i \) is an integer multiple \( k_i \) of a time interval \( T_{BP} \) that we refer to as a basic period. Thus for each product:

\[
T_i = k_i T_{BP} : \text{the cycle time for product } i
\]

\[
PT_i = T_i d_i / p_i : \text{the processing time per lot for product } i
\]

\[
TPT_i = u_i + T_i d_i / p_i : \text{the total production time per lot for product } i
\]

Using above definitions and (4.1), the total cost \( V \) can now be written as:

\[
V = \sum V_i = \sum \frac{c_i}{k_i T_{BP}} + h_i k_i T_{BP} d_i (1 - \frac{d_i}{p_i}) / 2
\]  

(4.2)

Each item has a shelf life of \( s_i \) time units. A too large value of cycle time \( T_i \) could lead to spoilage of some units of item \( i \), which would violate our assumption. Given the assumption that stock is used on first-in-first-out basis, and production and demand rate of products are constant, the maximum duration an item is held in stock is \( T_i (1 - \frac{d_i}{p_i}) \). Thus, to avoid spoilage of any item we have the condition [as in Silver 1989]

\[
T_i (1 - \frac{d_i}{p_i}) \leq s_i
\]

Since we are using the basic period approach where \( T_i = k_i T_{BP} \), the above shelf life constraint can be rewritten as

\[
T_{BP} \leq \min_i \left\{ \frac{s_i}{k_i (1 - \frac{d_i}{p_i})} \right\}
\]  

(4.3)

It is clear from (4.3) that for a given set \( K \), which consists of \( k_i \) values for each product, \( T_{BP} \) has an upper bound and is given by

\[
T_{BP} \leq \min_i \left\{ \frac{s_i}{k_i (1 - \frac{d_i}{p_i})} \right\}
\]  

(4.4)

Keeping in mind that there must be sufficient time to handle the average number of setups required for all products, a lower bound for \( T_{BP} \) can be specified as

\[
T_{BP} \geq \frac{\sum u_i / k_i}{(1 - \sum d_i / p_i)}
\]  

(4.5)
Here, it may be noted that this is a necessary condition but is alone not sufficient to ensure a feasible schedule generation. Given that total time required on the facility for a production of item $i$ is $TPT_i$, and production runs of product $i$ must begin at $k_i T_{BP}$ time units apart, a feasible schedule is the schedule of length that is equal to the least common multiple (LCM) of $k_i$ values times $T_{BP}$ and which does not have interference between the times that each product has to occupy on the facility.

To get a more clear idea of what a ‘feasible schedule’ is, an illustration is given in figure 4.1. It shows a production schedule that satisfies the problem described in previous paragraphs. The manufacturer produces items 1,2,3,4 with basic period of $T_{BP}$ and $k_i$ values of 1,2,2,4 respectively. Item 1 is produced in every basic period while items 2 and 3 are both produced in the first and third basic periods. Item 4 is produced in the second basic period only. The total cycle length is of $LCM(k_i) * T_{BP}$ time units. The inventory versus time profiles for only items 1 and 3 are drawn. The cycle time and the maximum duration for which a unit of product 3 can be held in the stock are also shown. This maximum duration should be less than $s_i$, the shelf life, in order to avoid spoilage.

Obtaining the solution $(T_{BP}, K)$, which comprises of the basic period length $T_{BP}$, the vector $K$ of item multiplier values $k_i$, that minimizes (4.2) while satisfying (4.3) and (4.5) and is capable of generating a feasible schedule is the focus of this section.

### 4.4.3 The basic period approach solution

In this section, we present a modification of Haessler’s procedure (1979) to find out the basic period length and production frequencies that minimize total setup and inventory costs while satisfying shelf life constraints. Before presenting the solution approach, we would like to state some preliminary remarks that will help us in achieving feasible and better cost solutions.

#### Preliminary remarks

The method described in the section is essentially a search procedure within a solution space $(T_{BP}, K)$, where $K$ is a vector of integer multiples $k_i$. The method iteratively reduces the search space and then performs a quite exhaustive search to get improvement in the solution. It may be noted that the solution space $(T_{BP}, K)$ is bounded because of the following reasons—
4.4. ELSP with shelf life considerations

Figure 4.1: Example of a feasible solution for ELSP with shelf life considerations
1. Because of the shelf life constraints, for a given set $K$, $T_{BP}$ has an upper bound given by (4.4). There is also an overall upper bound on $T_{BP}$ irrespective of $K$ and is given by $\min \{s_i/(1-d_i/p_i)\}$.

2. $T_{BP}$ has a lower bound greater than zero, given by (4.5).

3. Since $k_i$ can take only positive integer values, it has a lower bound of 1.

4. From (4.5), it is clear that if the denominator is greater than zero (i.e. utilisation level less than 100%), the $T_{BP}$ has a lower bound greater than zero in order to get a feasible solution. This prevents each $k_i$ from getting infinitely large since $T_i = k_iT_{BP}$ and can take only finite values. Thus, there are bounds on $k_i$ as well.

It is obvious that, the number of values that $k_i$ can take within these bounds may still be very large. We will, however, restrict these values to power-of-two i.e. $\{1, 2, 4, 8, 16, \ldots\}$. This will reduce the search space drastically without too much sacrifice of optimality. Maxwell and Singh (1983) provide an economic rationale and justification of such power-of-two restriction that is widely used in ELSP literature. They prove that using such policy results in a 6% costlier solution in the worst case. The construction of repetitive feasible schedule also becomes easier in case of power-of-two, since $LCM(k_i)$ takes the value of $\max(k_i)$.

In the basic period ELSP approaches without shelf life (e.g., Haessler, 1979), for a fixed $K$, if a feasible schedule can be generated for a certain basic period length of $T_{BP}'$ then a feasible schedule can be generated for all basic period lengths which are greater than $T_{BP}'$. The converse is also true – if a feasible schedule cannot be generated for a basic period length of $T_{BP}'$ then a feasible schedule cannot be generated for the basic period lengths smaller than $T_{BP}'$. During our search procedure, we will make use of this property effectively after ensuring that the shelf life constraints are not violated.

Since shelf life constraints put an upper bound on $T_{BP}$ values for a fix set $K$, we will check if a feasible schedule can be generated for $T_{BP}$ equal to this upper bound, which is given by (4.4). If a feasible schedule exists, then only it makes sense to search for $T_{BP}$ value less than this upper bound in order to get a feasible and least cost solution for the current values of $k_i$.

If a feasible schedule cannot be generated using the $T_{BP}$ upper bound, then the only way of achieving feasibility is to increase the production frequencies (i.e. reducing $k_i$) of some item(s). This will allow $T_{BP}$ to take higher values than
before since new \( k_i \) values will be providing higher upper bound. This in turn may yield a feasible schedule. Once the feasibility is achieved, an analysis of sensitivity of \( k_i \) with respect to current \( T_{BP} \) value is done in pursuit of a lower cost solution.

In some cases, it may happen that the successive iterations do not yield any feasible solution and thus all \( k_i \) values will be reduced to 1. In such cases, we get the common cycle solution, which is the same as the option of reducing the common cycle time so as to meet shelf life constraint (as in Silver 1989, and Sarker and Babu 1993).

**The basic period approach for ELSP with shelf life**

Now we present a modified basic period algorithm for ELSP with shelf life considerations. The solution procedure has the following main steps – 1) Finding production frequencies for each product, 2) Checking for shelf life constraint violation, 3) Forming a production schedule 4) Achieving feasibility and lower cost solutions by increasing \( T_{BP} \) or reducing \( k_i \) through sensitivity analysis.

**Step 1:** Use Doll and Whybark (1973) procedure with the power-of-two policy to get good starting values of \( k_i \) and \( T_{BP} \). This procedure is described in appendix A.1 at the end of this chapter.

**Step 2:** Ensure that \( T_{BP} \) satisfies the constraint given by (4.5).

\[
T_{BP} = \max \left\{ T_{BP}, \frac{\sum u_i/k_i}{(1-\sum d_i/p_i)} \right\}
\]

**Step 3:** Ensure that \( T_{BP} \) satisfies the shelf life constraint given by (4.4).

\[
T_{BP} = \min \left\{ T_{BP}, \min_i \left[ \frac{s_i}{k_i(1-d_i/p_i)} \right] \right\}
\]

A check is done if a feasible schedule can be generated for the basic period length of \( T_{BP} = \min \{s_i/k_i(1-d_i/p_i)\} \). If yes go to step 4, otherwise go to step 5. The feasibility check is done using the procedure described in appendix A.2 at the end of this chapter.

**Step 4:** The basic period \( T_{BP} \) as obtained in step 2 is systematically increased till feasibility is achieved or till it reaches \( \min_i \{s_i/k_i(1-d_i/p_i)\} \). If this feasible solution is the lowest cost feasible solution so far, save it as the ‘current best solution’ and continue to step 5.
Step 5: This step involves following substeps

(a) If $\max(k_i) = 1$, go to step 7.

(b) For each product with $k_i > 1$, halve the value of $k_i$ and calculate the lower bound of the cost per unit time, $V_i$, using (4.2), where $T_{BP} = \left\{ 2\left[ \sum c_i/k_i \right] / \left[ \sum h_i d_i k_i (1 - d_i/p_i) \right] \right\}^{1/2}$.

(c) Sort the products in ascending order of their cost $V$ and store in a list.

(d) If there is any ‘current best solution’ stored (in step 4), ignore those products which give higher minimum costs than the ‘current best solution’ and update the list. If the list is empty the procedure terminates and the ‘current best solution’ is the final solution.

(e) Choose the first product in the list.

(f) Using equation (4.4), calculate upper bound with new $k_i$ values. i.e. $k_i$ value for this product is halved while others retain their $k_i$ values from step 2.

(g) Check if it is possible to generate a feasible schedule for new $K$ vector and with $T_{BP}$ equal to new upper bound as in (f). If a feasible schedule can be generated, go to step 6.

(h) Choose the next product in the list and go to (f). If end of the list is reached, choose the first product in the list and go to step 6.

Step 6: Halve the $k_i$ value of the product obtained in step 5. If $\max(k_i) > 1$ go to step 2, otherwise go to step 7.

Step 7: Stop the procedure. If there is a ‘current best solution’, it is the final solution otherwise use the common cycle approach (the option of reducing the production cycle time as in Silver 1989).

The method differs from Haessler’s procedure mainly in steps 3–6. In Haessler’s procedure $T_{BP}$ can be increased till a feasible schedule is achieved for a fixed values of $k_i$ whereas we can’t do it always because of the upper bound on $T_{BP}$ imposed by shelf life constraints. We, thus, have to resort to reducing $k_i$ values instead. We perform sensitivity analysis on $k_i$ values not only for searching better cost solutions but also to achieve feasibility.

The method presented above has concepts similar to those in branch & bound methods. In step 3 and/or 4, we start with the root node. Steps 5(b), 5(c) provide a list of next nodes to be examined, while step 5(d) helps us in reducing search space by discarding non-promising nodes. Steps 5(e), 5(f), 5(g) and 6...
deploy depth-first-search technique on remaining nodes to arrive at feasible and better cost solution.

We would also like to point out that there is no feasible solution for even the common cycle approach if the shelf life of some product is too short to accommodate the setups for different products. i.e.

\[
\text{If } \min_i \left\{ \frac{s_i}{(1-d_i/p_i)} \right\} \leq \frac{\sum u_i}{(1-\sum d_i/p_i)}, \text{ then there is no feasible ‘common cycle solution’}. 
\]

The details of Doll and Whybark (1973) procedure with the power-of-two policy used in step 1 and the procedure for generating production schedule used in Steps 3–5 are given in the appendix at the end of this chapter.

### 4.4.4 Computational results

In this section, we report our computational results using the proposed procedure. First, a numerical example illustrating the procedure is presented. Later, results from different experiments are also presented.

We will use the well-known Bomberger problem data with additional shelf life factor for each product (see table 4.1). The step by step illustration of the procedure is provided in table 4.2.

The feasible schedule (in terms of allocation of products to basic periods) for the saved best-cost solution is given in table 4.3. The total of setup and inventory costs for this schedule is $31,951 per day.

#### Table 4.1: Bomberger problem with shelf life of products – 88% utilisation

<table>
<thead>
<tr>
<th>Product</th>
<th>Cost per item*</th>
<th>Setup cost</th>
<th>Production rate</th>
<th>Demand rate</th>
<th>Setup time</th>
<th>Shelf life</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Items/day</td>
<td>Items/Day</td>
<td>Items/day</td>
<td>Items/Day/</td>
<td>Hours</td>
<td>Days</td>
</tr>
<tr>
<td>1</td>
<td>0.0065</td>
<td>15</td>
<td>30000</td>
<td>400</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>0.1775</td>
<td>20</td>
<td>8000</td>
<td>400</td>
<td>1</td>
<td>150</td>
</tr>
<tr>
<td>3</td>
<td>0.1275</td>
<td>30</td>
<td>9500</td>
<td>800</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>0.1000</td>
<td>10</td>
<td>7500</td>
<td>1600</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>2.7850</td>
<td>110</td>
<td>2000</td>
<td>80</td>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>0.2675</td>
<td>50</td>
<td>6000</td>
<td>80</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>1.5000</td>
<td>310</td>
<td>2400</td>
<td>24</td>
<td>8</td>
<td>200</td>
</tr>
<tr>
<td>8</td>
<td>5.9000</td>
<td>130</td>
<td>1300</td>
<td>340</td>
<td>4</td>
<td>150</td>
</tr>
<tr>
<td>9</td>
<td>0.9000</td>
<td>200</td>
<td>2000</td>
<td>340</td>
<td>6</td>
<td>150</td>
</tr>
<tr>
<td>10</td>
<td>0.4000</td>
<td>5</td>
<td>15000</td>
<td>400</td>
<td>1</td>
<td>150</td>
</tr>
</tbody>
</table>

#### Table 4.2: Suggested procedure

<table>
<thead>
<tr>
<th>Common cycle solution</th>
<th>Suggested procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common cycle length (days)</td>
<td>38.136</td>
</tr>
<tr>
<td>Daily Cost ($)</td>
<td>41.374</td>
</tr>
</tbody>
</table>

| Basic period length (days) | 23.630 |
| Daily cost ($) | 31.951 |

* Annual inventory cost = 10% of item cost and one year = 240-8 hour days
Table 4.2: Illustration of solution procedure

<table>
<thead>
<tr>
<th>Step</th>
<th>Iteration 1</th>
<th>Iteration 2</th>
<th>Iteration 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 1</td>
<td>$K = {8, 2, 2, 1, 2, 4, 8, 1, 4, 2}$</td>
<td>$K = {8, 2, 2, 1, 2, 4, 8, 1, 2, 2}$</td>
<td>$K = {4, 2, 2, 1, 2, 4, 8, 1, 2, 2}$</td>
</tr>
<tr>
<td></td>
<td>$T_{BP} = 20.379$, Cost = 31.956</td>
<td>$T_{BP} = 23.534$, Cost = 31.922</td>
<td>$T_{BP} = 23.630$, Cost = 31.951</td>
</tr>
<tr>
<td>Step 2</td>
<td>$T_{UB}^{BP} = 12.889$</td>
<td>$K = {8, 2, 2, 1, 2, 4, 8, 1, 2, 2}$</td>
<td>$T_{BP} = 23.630$, Cost = 31.951</td>
</tr>
<tr>
<td></td>
<td>$T_{BP} = 20.379$</td>
<td>$T_{BP} = 14.484$, $T_{BP} = 23.534$</td>
<td>$T_{BP} = 23.689$, $T_{BP} = 23.630$</td>
</tr>
<tr>
<td>Step 3</td>
<td>$T_{UB}^{BP} = 12.669$, No feasibility</td>
<td>$T_{UB}^{BP} = 12.669$, No feasibility.</td>
<td>$T_{UB}^{BP} = 25.253$, Feasible Solution.</td>
</tr>
<tr>
<td></td>
<td>Go to Step 5</td>
<td>Go to Step 5</td>
<td>Go to Step 4</td>
</tr>
<tr>
<td>Step 4</td>
<td></td>
<td></td>
<td>Solution Saved. $T_{BP} = 23.630$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>‘Current best solution’ = 31.951</td>
</tr>
<tr>
<td>Step 5</td>
<td>Product $T_{UB}^{BP}$ $V$</td>
<td>Product $T_{UB}^{BP}$ $V$</td>
<td>Product $T_{UB}^{BP}$ $V$</td>
</tr>
<tr>
<td></td>
<td>1 25.253 32.005</td>
<td>10 12.669 31.951</td>
<td>9 25.253 31.951</td>
</tr>
<tr>
<td></td>
<td>10 12.669 32.128</td>
<td>2 12.669 32.182</td>
<td>1 25.253 32.107</td>
</tr>
<tr>
<td></td>
<td>2 12.669 32.250</td>
<td>2 12.669 32.122</td>
<td>3 25.253 32.148</td>
</tr>
<tr>
<td></td>
<td>3 12.669 32.276</td>
<td>6 12.669 32.238</td>
<td>6 25.253 32.246</td>
</tr>
<tr>
<td></td>
<td>6 12.669 32.381</td>
<td>7 12.669 32.786</td>
<td>7 25.338 32.806</td>
</tr>
<tr>
<td></td>
<td>7 12.669 33.158</td>
<td>7 12.669 33.037</td>
<td>5 25.253 33.053</td>
</tr>
<tr>
<td></td>
<td>5 12.669 33.554</td>
<td>9 12.669 34.491</td>
<td>9 25.253 34.500</td>
</tr>
<tr>
<td></td>
<td>No feasible Solution using new $k_i$ values and $T_{UB}^{BP}$. First product, product 9 is selected</td>
<td>Feasible Solution using $k_1 = 4$ and new $T_{UB}^{BP}$ Product 1 is selected</td>
<td>Step 5 (d) Gives empty list.</td>
</tr>
<tr>
<td>Step 6</td>
<td>$k_9 = 2$, Go to Step 2</td>
<td>$k_1 = 4$, Go to Step 2</td>
<td>Procedure Terminates</td>
</tr>
<tr>
<td>Step 7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 4.3: Allocation of products to basic periods – 88% utilisation case

<table>
<thead>
<tr>
<th>Product</th>
<th>$k_i$</th>
<th>$TPT_i$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1</td>
<td>5.166</td>
<td>5.166</td>
<td>5.166</td>
<td>5.166</td>
<td>5.166</td>
<td>5.166</td>
<td>5.166</td>
<td>5.166</td>
<td>5.166</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>8.784</td>
<td>8.784</td>
<td>8.784</td>
<td>8.784</td>
<td>8.784</td>
<td>8.784</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2.488</td>
<td>2.488</td>
<td>2.488</td>
<td>2.488</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>2.390</td>
<td>2.390</td>
<td>2.390</td>
<td>2.390</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>1.385</td>
<td>1.385</td>
<td>1.385</td>
<td>1.385</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>1.510</td>
<td>1.510</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>1.385</td>
<td>1.385</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>2.890</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Total time used**: 23.118 22.747 23.118 22.742 23.118 22.747 23.118 19.852
It can be seen that the procedure results in lower costs than the common cycle solution approach (Option of reducing cycle times as in Silver 1989, Sarker and Babu 1993) which gives a solution with common cycle of 38.136 days and cost of $41.374 per day.

We also conducted different experiments to compare the suggested procedure to the common cycle procedure with shelf life considerations (see table 4.4). They provide an evaluation of two factors—utilisation and product diversity. High levels of utilisation make it more difficult to develop feasible schedules where multiple runs are evenly spread over time. The product diversity factor determines the range of values for production rate $p_i$ and demand rate $d_i$. It is well known from ELSP literature that high product diversity leads to some products being produced more frequently than others. We use the Bomberger data set for different utilisation levels with addition of shelf life for each product. The impact of shelf life can be easily seen through the changes in production frequencies of the products. The products are required to be produced more often to avoid spoilage. The comparison with common cycle solution is also presented in table 4.4. It is evident that the suggested procedure results in lower cost than the common cycle solution approach at all utilisation levels. The cost savings are up to 40% in case of low utilisation.

In the data set of Table 4.1, the highest demand item (product 4) has the lower shelf life. More frequent production of this product ($k_i = 1$) could take care of the situation. We conducted another set of experiments with a low demand item (product 7) having a low shelf life. It is interesting to note that in the case of a shelf life of 30 days for product 7 (all other parameters being same as in Table 4.1), there is no feasible solution. This shelf life for product 7 is too short even to accommodate the setups for different products. If the shelf life of this product is 40 days, we get a common cycle solution (which of course is quite costlier as compared to the situation if shelf life for this item was relatively higher). This example definitely provides a motivation for designing products with higher shelf life in order to get lower cost production schedules. These experiments also support a generally accepted fact that the low demand items with low shelf lives are candidates for make-to-order (see Soman et al. 2004a). Allowing backordering for such items as in Viswanathan and Goyal (2000) is another possibility.

4.4.5 Concluding remarks

The researchers working on ELSP with shelf life considerations have focussed too much on the option of deliberately reducing production rates. In many in-
Table 4.4: Experiments at various utilisation levels

<table>
<thead>
<tr>
<th>Product</th>
<th>22%</th>
<th>44%</th>
<th>66%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Step1 $k_i$</td>
<td>Final $k_i$</td>
<td>Production Periods</td>
</tr>
<tr>
<td></td>
<td>values</td>
<td>values</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>4</td>
<td>1,5</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>2</td>
<td>1,3,5,7</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1,3,5,7</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>ALL</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>2</td>
<td>1,3,5,7</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td>4</td>
<td>1,5</td>
</tr>
<tr>
<td>7</td>
<td>16</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>1</td>
<td>ALL</td>
</tr>
<tr>
<td>9</td>
<td>4</td>
<td>4</td>
<td>1,5</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>2</td>
<td>1,3,5,7</td>
</tr>
</tbody>
</table>

CC solution (days) | 31.690 | 33.582 | 35.714 |
Cost per day ($)    | 32.357 | 35.373 | 38.379 |
Basic period solution (days) | 25.063 | 25.126 | 25.189 |
Cost per day ($)    | 18.765 | 24.449 | 28.459 |
dustries and especially, in food processing industry this option is not at all applicable since it will result in products with quality and yield that is different than expected. Also, the previous research has considered only the common cycle approach. This is in spite of the fact that a large body of ELSP literature has shown that the basic period approach outperforms the common cycle approach.

Haessler’s procedure has been adapted for determining the cycle times for the lot-scheduling problem to account for constraints imposed by shelf life of products. Unlike other ELSP literature with shelf life considerations, the proposed algorithm allows products to be produced more than once in a cycle. The procedure presented here can never result in higher cost solutions than the common cycle approach. In the worst case, the procedure yields the common cycle solution. If the shelf life of some product is quite different than others, then the cost benefits that are achieved through the use of our procedure are quite significant (up to 40% lower costs in the experiments carried out).

The products having limited shelf life are very common in food processing industries. However, these industries are also characterized by sequence dependent setups times (and costs). The procedure presented in this section cannot be directly used in such situation. The economic lot scheduling problem that considers both shelf life constraints and sequence dependent setups is a challenging problem for future research. In this section, for each item the production lots are of equal size and are equally spaced and the solution procedure can leave idle times in the schedule. In view of this, it may be a logical extension to modify other ELSP approaches like time-varying lot sizes (Dobson 1987) to take care of shelf life constraints. As pointed out in chapter 2 and Soman et al. (2004a), combined make-to-stock and make-to-order food production system are becoming more common. In this context, it will be interesting to study the ELSP procedures so as to incorporate make-to-order and is explored in section 4.5. Our numerical results with low-demand, short shelf life products show that further research on this is needed. We would also like to mention, as pointed out by Van Donk (2001), that in practice many products have a reasonably long technical shelf life but retailers do not accept successive deliveries with identical ‘best-before-dates’. The result is that from a technical point of view products are fresh but are commercially obsolete. Thus, schedulers at food manufacturers may not only want to reduce storage time of products in their warehouses and provide longer storage possibilities for retailers but also need to ensure that successive deliveries do not have identical best-before-dates. This, however, may lead to more frequent production. The existing literature on lot scheduling problem
4.5 Incorporating MTO in ELSP

The logic of ELSP approaches is that a product is manufactured during a cycle and that inventory will be sufficient to cover demand until the next lot will be produced. As discussed in section 4.3, the normal ELSP (as some other EOQ-based policies) is not directly applicable for real-life situations. But within the ELSP approach hardly any attempts have been made to incorporate make-to-order production, so far. The objective of this section is to explore how we can adapt ELSP procedures for the combined MTO-MTS in an abstract sense. The second objective is to provide some directions for determining a production cycle in real-life situations.

The main problem in incorporating MTO items is that demand is not known in quantity and/or timing. This complicates the standard ELSP but the combination of MTO and MTS offers (as suggested by Bemelmans 1986) the possibility to buffer part of this uncertainty with additional stock of MTS. Some further complications arise because food processing industries usually have family setup structures that favour production in a (family-)cycle (Van Donk 2001). A cycle usually ends with a major cleaning of the equipment. In order to structure the discussion we distinguish some different situations with respect to demand and the nature of setups. In the normal ELSP approaches demand is supposed to be deterministic, so we start with situations that only in a limited way deviate from that basic situation. Next, in case of MTO items uncertainty with respect to demand can be uncertainty in quantity (and capacity needed) or in the specification of the product (but with a stable capacity requirement). Next to exploring the influence of demand of MTO, we investigate the setup structure by assuming a family structure.

4.5.1 Stable MTO demand, no family structure

Suppose the aggregate demand for MTO items is deterministically known and constant over time, but demand for each single MTO item is not known. A practical example might be that the colour or type of packaging is specified just

\[\text{with shelf life considerations has not dealt with the effects of such commercial compulsions on the food manufacturers. We think that developing models for reducing storage life is an interesting area for further research.}\]

\[\text{Earlier version of this section has appeared in Van Donk, D. P., Soman, C. A. and Gaalman, G. (2003), ELSP with combined make-to-order and make-to-stock: Practical challenges in food processing industry, 1st joint POMS-EUROMA International Conference, Como Lake, Italy, vol. II, pp. 769–778.}\]
before production. Now, we can treat all MTO items together as an additional product with known demand. Under these assumptions, the normal ELSP procedures can be followed to determine the production cycle, the amounts to be produced, based on the minimisation of costs. In fact, we treat the MTO items here as MTS items that have no stock. Depending on the parameters, an amount of capacity is reserved for the MTO items. This is illustrated in figure 4.2. The capacity planned for MTO can be used to produce the MTO items that are actually ordered during each cycle. If the due date of MTO items is known, the length of it can be used as an additional constraint in determining the cycle length. The due date can be used for the determination of a ‘natural’ cycle length for the MTO, as starting values in procedures like Doll and Whybark (1973). Due dates for MTO can also be determined as a result of making a feasible schedule. Then, a trade-off exists between the length of the due date (longer due dates can be associated with higher costs) and the setup costs. In general, the length of the cycle determines the maximum due date for MTO. From a more practical point of view, it is interesting to note that order acceptance and due date determination are quite simple. Given the cycle time, due dates are fixed and all MTO orders can be accepted and delivered.

4.5.2 Unstable MTO demand, no family structure

Here we assume that the aggregate demand needed for MTO is not deterministic and has a large variance over time. If demand is low compared to capacity, it is easy to reserve enough capacity to cope with even the largest variations in demand of MTO items. If capacity is more restricted, finding a cycle is not that easy. Making a reservation (e.g. based on the expected value) for the MTO items is rather risky, as either demand for MTO will be much higher or much lower. However, on average capacity for MTO will be needed and used. In order to cope with the variance in demand of MTO, two possibilities exist. Varying the due date of MTO: which is basically a buffer in time, or buffering uncertainty of MTO with an (additional) inventory of a MTS item (following the idea of Bemelmans 1986). The safety stock of the MTS is consumed less if demand for MTO is

![Figure 4.2: Capacity reservation for MTO products](image-url)

Items A, B, C are MTS while D denotes the MTO items
low and is consumed more if demand for MTO is high. It is interesting to note that we even need safety stock in case demand of MTS is totally deterministic and randomness only in MTO items. The cycle length can be determined in the same way as in the previous case, based on the average demand for MTS items. The remaining problem is to determine safety stock levels for the MTS item. This strategy needs a clear operational control in order to maintain the level of stock and accept MTO orders. It is very important to keep the cycle length constant: then the availability of production capacity is guaranteed. From a practical point of view, clear operational control will be needed and occasionally orders need to be refused due to lack of capacity or when safety stocks are too low to deliver MTS items.

### 4.5.3 Family structure setup

Here we assume that the products have sequence dependent setups and more specifically some kind of family structure: with large setups for a family and smaller setups for the family members. It is worth noticing, that in contrast to normal ELSP, setup control grows in importance. In general, a family consists of both MTO and MTS items and given the large family setup it is preferred to produce all products of a family after a family setup to minimise family setups. Given the family structure, again the two above situations (stable or unstable demand for MTO) can be assumed. Figure 4.3 illustrates one such situation. There are three product families each having a few products. Product 1 in family A carries extra inventory to account for unstable MTO demand.

If we assume that MTO items are fairly stable in demand on a family level, we might use the approach of Atkins and Iyogun (1988) that is based on deterministic demand. This method determines the frequency for each family first (based on the family setup and aggregate family demand) and then the production frequency for each item within a family, based on the allocation of the major family setup to the items. One major problem with two applications (McGee and Pyke 1996, Strijbosch et al. 2002) is, however, that 20-30% idle time (including maintenance and breakdowns) is allowed, while in food processing capacity utilisation is high. Note that the stable demand, no family structure situation discussed above now holds for each family.

If it is assumed that the variance in demand of MTO items is large, more problems arise. Now we might estimate total capacity needed for all MTO items during a cycle: assuming that the individual variance of MTO items is absorbed in the aggregate forecast. The reserved capacity is (as part of the execution of
production control) allocated to different families on the basis of actual orders for MTO items. An alternative is to estimate the demand on a family level in which case the second situation of above (unstable MTO demand, no family structure) holds. However, if variability in MTO demand differs across families or if it is assumed that some families contain only MTO or MTS items, it can be rather difficult to find a buffer in time or buffer in stock of a MTS item. In all cases, one has to decide how uncertainty in MTO can be buffered by MTS items and which items from what family are the best candidates for carrying buffer inventory. Under tight capacity utilisation keeping the run length of families constant as well as the cycle time for individual items might be problematic. All in all, production control: both in planning MTO, controlling capacity, checking inventory levels and determining due dates will need a lot of attention.

The practical implications for management are the same as in the two situation described. The determination of the whole cycle will be rather complex in this case.

4.5.4 High variance in MTS and family structure

If we assume that MTS items show a rather large variance in demand, the possibilities to buffer MTO will be more difficult. Now, an alternative for the normal ELSP-like approaches can be derived from the ‘can-order’ policies, also described as \((s, c, S)\) policy. Here \(s\) is the reorder point, \(c\) is the can-order point and \(S\) is the order-up-to level. This policy is used to initiate production for a prod-
uct that has reached its reorder point and to produce other items from the same family that have reached their can-order level (see Silver et al. 1998, Federgruen et al. 1984). This approach can be adapted for the combined MTO-MTS case.

We determine a family sequence, based on aggregate demand for a family. During a family run both MTO and MTS (that are on or below their reorder point) must be produced, supplemented with can-orders to fill family capacity. (Silver et al. 1998) suggest that optimising can-order policies (without MTO) is complicated and inferior to the method of Atkins and Iyogun (1988). However, as far as we know it is not tested explicitly for the combined MTO-MTS case. We think that this approach could be well implemented if the aggregate demand on a family level is rather stable. Silver et al. (1998) remark that this approach is well suited for situations where savings in setups are important as in the food processing industry. If the MTO orders are large compared to MTS, then the start of a family might be induced by the arrival of a MTO item order that is supplemented with MTS. However, a fixed cycle is then abandoned.

From a managerial point of view, it can be noted that this type of control needs a clear order acceptance policy and a good collaboration between scheduling and order acceptance.

### 4.5.5 High utilisation and controlling setups

The last situation we explore is the case of high capacity utilisation as is often found in food processing and other process industries. Now the main aim is to control the time for setups and/or the amount of setups. This approach is more top-down, starting with limiting the time for setups for a year and then determining the available setups for a month or week. A possible solution method is to allocate setup time to families based on the demanded amounts. Another approach is to add restrictions to the previously mentioned methods. Limiting the number of setups for a time period can also pose natural constraints on the number of MTO orders that can be accepted during that period. In any case the amount of production capacity or time available for manufacturing is fixed in advance. We think that further elaboration of the different options into more concrete decision tools is needed. We assume that some of the approaches are less usable if the percentage of MTO items is large, because buffering possibilities with MTS items is then limited. Next, actually determining the sizes of buffers is not directly straightforward. Introducing another food processing characteristic such as limited shelf life will give additional problems as discussed in the previous section.
4.6 Conclusion and discussion

This chapter investigated the capacity coordination in the medium term. The main problem that has to be addressed at this level is the allocation of capacity to different products and product families. ELSP literature has been widely used for these purposes in the case of pure MTS situations. This chapter builds on basic period ELSP approaches and provides solutions to problems arising from certain food processing characteristics. Shelf life constraints have been included in a formulation and a heuristic is presented which will never perform worse than the existing common cycle approaches. Incorporating MTO in ELSP has been addressed for the first time in the research literature. We specially looked at various demand patterns, presence of family structure setup. Several ideas and managerial insights are provided on various production situations. Although the discussion is conceptual in nature, it can be used to translate the ideas into analytical models. However, we do not do that so far.

In this chapter, we relied heavily on ELSP procedures developed for pure MTS situations. This seems logical given the fact that the food processing industries are traditionally make-to-stock companies and are only now producing a small proportion of their production on make-to-order basis. However, with the product portfolios of the companies expanding rapidly, the proportion of MTO products is bound to increase. In such cases, the ELSP approaches minimising the sum of inventory and setup costs may not be helpful as the inventory costs will be less relevant. The cyclic policies will, however, still be attractive given the environment consisting of product families and high setup time. The determination of cycle times (for families) is then essentially a trade-off between required customer order lead time and the setup times. Examples of such production planning and control rules based on cyclic production and pure make-to-order environment are suggested by Bertrand et al. (1990) in chapter 9, and Dellaert (1989). The control of cycle time, so as to avoid extra setups and ensure productive capacity, at the operational level can generally be achieved in two ways: (1) The standard customer order lead time for a product should be at least equal to the cycle time of its product family. This will ensure that each product will have at least one production opportunity during its lead time. (2) Order acceptance function—while accepting an order the workload level (already planned plus workload from the new order using the standard customer lead time) is checked against the productive capacity available. In case a capacity problem occurs, then either the order is rejected or the other possibilities are to be considered. These possibilities include a use of parallel equipment (if available), negotiable due-date and price.
Appendix

For the sake of completeness, we have chosen to spell out in details two important steps in the basic period procedure suggested in section 4.4.3. These are namely the Doll and Whybark (1973) procedure for finding the starting solution (step 1) and the procedure for generating schedules (used in steps 3–5).

A.1 Doll and Whybark procedure with the power-of-two policy

This is an iterative procedure to simultaneously determine product multipliers $k_i$ and the basic period $T_{BP}$.

**Step a**  Determine $T_i$ independently for each product

$$T_i = (2c_i/[h_id_i(1 - d_i/p_i)])^{1/2}$$

**Step b**  Select the smallest $T_i$ as the initial estimate of the basic period $T_{BP}$.

$$T_{BP} = \min(T_i)$$

**Step c**  Determine the integer multiple $k_i^-$ and $k_i^+$ for each product defined by

$$k_i^- \leq T_i/T_{BP} \leq k_i^+$$

Where $k_i^- = \{1, 2, 4, 8, 16, \ldots \}$ the next lowest power-of-two integer multiple, and $k_i^+ = \{1, 2, 4, 8, 16, \ldots \}$ the next higher power-of-two integer multiple.

**Step d**  The $k_i$ value is set to either $k_i^-$ or $k_i^+$, the one incurring less costs using equation (4.1).

**Step e**  Recompute the basic period time $T_{BP}$ using the new estimates of $k_i$.

$$T_{BP} = \{2[\sum c_i/k_i]/[\sum h_i d_i k_i (1 - d_i/p_i)]\}^{1/2}$$

**Step f**  Return to step c to determine new $k_i^-$ and $k_i^+$, using $T_{BP}$ from step e. The procedure terminates when consecutive iterations produce identical values of $k_i$ at step d.

This method gives $T_{BP}$, $k_i$ and hence the production times $TPT_i$ can be calculated.
A.2 Creating a Production schedule

1. The complete rotation cycle is of length \( T = \max(k_i)T_{BP} \) and has \( \max(k_i) \) slots each having \( T_{BP} \) units of time available.

2. Sort the item in ascending order of their \( k_i \). Products with the same \( k_i \) are sorted in descending order of total production times \( TPT_i \).

3. Assign the item at the top of the list to the basic period slot that has sufficient time available for its production, and in a similar fashion to subsequent slots with intervening gaps of \( k_i - 1 \) slots. Until \( \max(k_i)/K_i \) assignments for that item have been made. If such assignments are not possible, a feasible schedule cannot be generated and the procedure stops.

4. Update time available in each slot and delete the item from the list. If the list is non-empty return to step 3 above; otherwise a feasible schedule has been generated and the procedure stops.
In this chapter\(^1\) the previously under-researched problem of scheduling a single stage, capacititated, hybrid make-to-order (MTO) and make-to-stock (MTS) production system with stochastic demand is examined. In the pure MTS situation, cyclical production planning and Economic Lot Scheduling Problem (ELSP) procedures are widely used. For the hybrid MTO/MTS production situation, however, no mature theory exists. We build on the ELSP literature and make some modifications to incorporate MTO products. At the tactical level, target cycles (kept long enough to trade-off changeover and inventory costs) are calculated while at the operational level, the general idea is to try and follow these target cycles, and make adjustments to them in order to a) avoid stock-outs for MTS products and, b) have short lead-time for MTO products while keeping the overall costs as low as possible. Through an extensive simulation study, we evaluate various run-out time scheduling and sequencing heuristics and provide a more complete understanding and managerial insights in the case of hybrid MTO/MTS environment with stochastic demand. It is clear that the methods that perform well for pure MTS situations do not necessarily perform well for hybrid MTO/MTS situation.

\(^1\)This chapter has been accepted for publication: Soman, C. A., Van Donk, D. P. and Gaalman, G. (2004d), Comparison of dynamic scheduling policies for hybrid make-to-order and make-to-stock production systems with stochastic demand, *International Journal of Production Economics*, Article in press. The footnotes and appendix have been added later to have an improved clarity.
5.1 Introduction

The problem of scheduling the production of several products with stochastic demand on a single facility with the objective of reducing the sum of holding costs and setup costs in the long run has been studied in the literature under the name of SELSP—Stochastic Economic Lot Scheduling Problem. The solution to this problem is known to be quite difficult. It is well known that even in the absence of stochastic demand and setup costs this problem is NP hard (Hsu 1983). This is the reason for the use of heuristic procedures. Recently, some research papers are published on SELSP. Sox et al. (1999) present a detailed review of the SELSP approaches.

In many industries, especially in the food processing industries, the product variety is very large and contains a mix of make-to-order (MTO) and make-to-stock (MTS) products (see Soman et al. 2004a). This adds another dimension to SELSP because the production planning focus for the MTO products is different than the one for the MTS products. For MTS products anticipating the demand (forecasting), planning to meet the demand, and achieving high fill rates takes the center stage whereas for MTO products it is the order execution. The performance measures are also order focussed, e.g. average lead-time and average order lateness/tardiness and the competitive priority is shorter delivery lead-time. Although such a MTO-MTS combination with stochastic demand is very common in practice, limited research has been done and reported so far.

One of the first studies on combined MTO-MTS production system is credited to Williams (1984). He provides the way of estimating the waiting time for the availability of the capacity for the individual products using approximation to M/G/m queue, which aids in choosing the batch sizes for MTS and to determine the probability with which the orders for MTO products satisfy the quoted lead-time. Rajagopalan (2002) addresses a similar problem. He provides a heuristic procedure to solve a non-linear, integer programming formulation of the problem that determines the MTO/MTS partition and the batch sizes for the MTS items. He, unlike Williams (1984), allows low demand items to follow the MTS strategy.

Federgruen and Katalan (1994, 1999) address a variety of strategic questions—the number and types of products that should be manufactured to stock or to order, the effects of adding low volume specialized items to a given product line on the stock system. They present a class of cyclic base stock policies for which a variety of cost and performance measures can be evaluated by the analytical
methods suggested for the polling model. They develop cost curves for different priority rules under different circumstances, which can be used to calculate a marginal break-even price at additional utilization due to addition of MTO items.

Williams makes the assumption that lower demand items are MTO and higher demand items are MTS. The primary focus of Rajagopalan is to choose the MTO or MTS strategy for each of the items whereas Federgruen & Katalan focus on choosing the proper “ interruption” discipline within the cyclic pattern. For an elaborate literature review of combined MTO-MTS situations, see chapter 2 or Soman et al. (2004a). The above mentioned papers provide us with insights on deciding the batch sizes for MTS items but there are certain operational issues that firms need to answer on a regular basis. The firms need to define the scheduling and sequencing rules for a variety of situations that may arise in answering the basic questions– which product to produce next, when to produce, and how much to produce?

In this chapter, we address these operational issues in MTO/MTS production situations in order to fill the gap that exists in the literature. We examine the problem of scheduling and sequencing in hybrid MTO/MTS food processing environment and report on the development of a production and inventory control policy. The main question is whether the proven dynamic scheduling methods for pure MTS situation are also suitable for the combined MTO/MTS situation? Since MTO products do not have any finished goods inventory (by definition), we explore a simple policy of giving priority to them when their demand occurs to achieve a good lead-time performance. Simulation analysis is employed to test this idea and its impact on regular MTS production and the choice of the heuristic under different environmental conditions. A production system is considered as single equipment, which is characterized by limited capacity, and stochastic stationary demand.

We build on the ELSP literature and the various dynamic sequencing methods for the pure MTS situation. The ELSP solution procedures of Doll and Whybark (1973) and Haessler (1979) are used to set target cycle and target lot sizes whereas at the operational level the dynamic sequencing methods viz. Economic Manufacturing Quantity (EMQ), Fransoo (1993), Vergin and Lee (1978), and Gascon (Leachman and Gascon 1988) vary both the production sequence and lot sizes to accommodate the demand variation. Gascon et al. (1994) compare these methods (elaborated in section 5.3) for a particular production data set under
different demand environments and report that Vergin and Lee, and Gascon heuristics perform better in all the situations they test. Soman et al. (2004c) compare these heuristics again for a variety of problem data sets. In addition to the conventional cost based performance measure they also include line item fill rate, cycle time stability, inventory levels, number of setups incurred, to gain more insight into the working of these methods. The effect of inventory costs, setup costs, utilization is analyzed through a simulation study. They conclude that the cost based performance measures are deceptive. Based on operational performance criteria, they provide managerial insights and guidelines on which method to use and when. In this chapter, we move further and investigate the working of these methods in the presence of both MTS and MTO products.

The organization of the chapter is as follows. In the next section, we state a general model and the assumptions of the hybrid MTO/MTS production scheduling problem in a food production system. Section 5.3, presents various scheduling approaches, which can be used in hybrid MTO/MTS production situations. Sections 5.4 and 5.5 present a simulation study and its results to compare various approaches to the lot-scheduling problem in the context of hybrid MTO/MTS production under different utilization levels. Finally, conclusions and suggestions for future research are provided in section 5.6.

5.2 Problem description

We consider a problem of scheduling a single facility with limited capacity and with multiple MTO and MTS products, each with random demand. The objective is to a) avoid stock-outs for MTS products and, b) have short lead-time for MTO products while keeping the overall costs as low as possible. We make the following assumptions in this chapter–

- Production rate for item $i$ is deterministic and constant and is given by $p_i$
- Only one product can be produced at a time
- Production setup times $c_i$ and setup costs $U_i$ are independent of the production sequence
- Inventory carrying costs are proportional to the inventory levels
- MTS demand, when out of stock, is lost and the lost sales costs are proportional to the number of units lost and cost per unit item
- Product demands are stochastic (with normal distribution), but stationary (mean $d_i$)
• Total amount of demand for MTO items is stationary over a period of time but individual MTO demands (normal distribution) and timings (negative exponential interarrival) are not known

• MTO orders have priority over MTS production

• Preemption is not allowed

• Production capacity is sufficient to meet the demands

We define MTO products simply as the products for which no inventory is held in the stocks. The typical examples are products with highly irregular demand, client-specific products, tendered products, trial products, or products with very short shelf life.

5.3 Scheduling rules for the combined MTO-MTS production situation

Run-out methods of scheduling and sequencing are widely used in industry as they are easy to understand and implement. In this section, we present a brief summary of various run-out based scheduling rules that will be compared through the simulation model. At the production decision moment, the run-out time, \( RO_i \), for each item is calculated. \( RO_i \) is the time for which current inventory levels, \( I_i \), will last and is given as\(^2\)–

\[
RO_i = \frac{I_i}{d_i}
\]

The items are re-indexed such that \( RO_1 < RO_2 < RO_3 < \ldots \). The first product is then chosen as the product to be produced next. In the case of MTO products \( RO_i \) takes the value of the due date, \( DD_i \), of products minus the time at the decision moment.

We would like to stress the fact that the cycle times for products, \( T^*_i \), in EMQ are based on EOQ calculations whereas in other heuristics, they are derived from the basic period approach of Doll and Whybark (1973) and Haessler (1979)\(^3\). Thus, we follow a two step approach— at the tactical level, we calculate a target cycle and target batch sizes for the products and at the operational level we use

\(^2\)A better estimate of run-out time, \( RO_i = (I_i - s_i)/d_i - c_i \), where \( s_i \) is the safety stock (defined later) can also be used instead.

\(^3\)For the EMQ method, \( T^* = (2U_i/[h_i d_i (1 - d_i/p_i)])^{1/2} \). For the other methods, \( T^*_i = k_i T^* \), where \( T^* \) is the basic period calculated using the procedures described in the appendix to section 4.4.
the various methods, described in this section, to sequence and schedule them.

In the implementation of all the methods that are described below, we also included a minimum run length constraint to prevent cycle lengths from becoming too short. This constraint acts as a production quantity modifier i.e. the production quantities will be raised if the production run lengths are too small.

### 5.3.1 EMQ

This rule is fundamentally a multi-item \((s, S)\) policy. It is based on the cycles of independent manufacturing quantities calculated using the EOQ formula. The reorder of an item takes precedence over completion of the replenishment of another item i.e. the production of the current item continues until inventory of that product builds to \(S\) or the inventory of some other product falls below its safety stock level \(s\). The production quantity for the product selected for production can, thus, be given as–

\[
\text{production_qty} = \min \left\{ s_1 + T_1^* d_1 \left( \frac{1}{p_1} - 1 \right) - I_1, \left( \frac{I_2 - s_2 - c_2 d_2}{d_2} - c_1 \right) p_1 \right\}
\]

The first term in the above expression is simply the difference between the \(S\) value of item 1 and its current inventory level \(I_1\). The second term consists of the production rate of item 1, \(p_1\), multiplied by the time available for item 1 till inventory of item 2, \(I_2\), drops to \(s_2\). The correction for the incurred setup time is also applied.

### 5.3.2 Vergin and Lee

The Vergin and Lee (1978) method refines the approach of Magee and Boodman (1967), which suggests that it is more economical to set a total inventory sufficient to provide for cyclic fluctuation in total demand for all products than to monitor the actual production operation to keep the inventory balanced among several products. They derive a ratio, \(a_i\), for each product based on the target run length of each product compared with other products. Vergin and Lee use these ratios to monitor cycling of products. Production of an item continues till i) inventory of some product runs out, or ii) inventory of product \(i\) builds up to proportion \(a_i\) of the total inventory on hand. At this point production is shifted to the product with zero inventory or the one with the lowest \(RO_i\) or \(DD_i\) (in case of MTO products). The ratio \(a_i\) for each product is the ratio of maximum inventory of item \(i\) and the average total inventory in the system (i.e. all products).
It is given by the following expression—

\[ a_i = \frac{(1 - d_i/p_i)k_id_i}{1/2 \sum_i (1 - d_i/p_i)k_id_i} \]

It may be noted that the above expression is slightly different than the one in Vergin and Lee (1978). Their expression assumes a common cycle (i.e. each product is produced only once in the cycle) whereas we use the basic period approach i.e. allow products to be produced more than once in the cycle. The factor \( k_i \) indicates that product \( i \) is produced once in every \( k \) basic periods.

Since this method can lead to more production than required to meet the demand Vergin and Lee advocate the prevention of excess production. This means establishing a maximum inventory level for each product. During the product build up, when inventory reaches this level production shifts to another item. We chose to use \( S_i \), like in the EMQ rule, as this level. Thus, the production quantity of a selected product is—

\[
\text{production_qty} = \min \left\{ S_i - I_i, \left( \frac{I_2 - s_2 - c_2d_2}{d_2} - c_1 \right) p_1, a_1 \sum_i I_i - I_1 \right\}
\]

5.3.3 Fransoo

Fransoo (1993) suggests a simple policy aimed at achieving stable cycle times. The idea is to stick to target cycle times as much as possible. Unlike the previous two methods, the production quantity of the product chosen for the production is not affected by the event of some other product running out. In high utilization case, this may save the number of setups and hence the productive capacity but at the same time some orders may be lost. Based on the run-out times, a product \( i \) with \( \min(RO_i, DD_i) \) is indexed as 1 and is selected for the production and the production quantity is given as—

\[
\text{production_qty} = s_1 + d_1T_1^* - I_1
\]

5.3.4 Dynamic cycle length heuristic

This heuristic (Leachman and Gascon 1988), termed as Gascon throughout the chapter, integrates the feedback control based on the monitoring of inventory levels with the maintenance of economic production cycles. The policy is applied time period by time period to make decisions concerning which items to produce in what quantities during the next time period. These quantities reflect production cycles revised each time period in response to differences between
projected and actual inventory levels and in response to changes in demand rates. The method employs the concept of positive and negative slack- if it is estimated that there will be enough time to replenish each item after that item’s inventory falls to its reorder point and before the next item’s inventory falls to its reorder point, then there is a positive slack. In contrast, if there is insufficient time to replenish one item before another item runs out of stock, then there is a negative slack between those items.

In case of the negative total slack, the cycle lengths of all items are proportionately reduced from the target lengths just enough to eliminate negative total slack. Such adjustments restore the balance in the production system. The heuristic involves arranging the products based on the run-out lengths, $RO_i$, and the following steps–

1. Calculate $TS_j$, the total slack available for the replenishment of item $j$, $j = 2, 3, \ldots, n$. It is obtained by subtracting the setup and production times of items to be produced before the item $j$ from its runout time, $RO_j$. Mathematically it can expressed as–

$$TS_j = RO_j - \sum_{i=1}^{j-1} c_i - T^* \sum_{i=1}^{j-1} \frac{k_i d_i}{p_i}, \quad j = 2, 3, \ldots, n$$

2. If for some $j$ the slack is negative, then the target cycles $T_i = k_i T^*$ cannot be maintained. To resolve the infeasibility, the fundamental cycle time $T^*$ is reduced to a value $T$ such that $TS_j \geq 0, j = 2, 3, \ldots, n$. This revised fundamental cycle time, $T$, is called the operational cycle time and is calculated using the following formula–

$$T = \left\{ \min T^*, \min_{j=2,\ldots,n} \frac{RO_j - \sum_{i=1}^{j-1} c_i}{\sum_{i=1}^{j-1} \frac{k_i d_i}{p_i}} \right\}$$

3. Take a downperiod, if the total slack $TS_j > 1$. Otherwise, produce item 1, in the quantity $s_1 + d_1 T k_1 - I_1$

Here, we would like to mention that our implementation of the Gascon method does not include the availability of a forecast over a planning horizon. Hence the average demand is used for calculation of cycle times. This is a one-time calculation as against cycle time calculation at every decision moment in Gascon’s original method. The current implementation can, thus, result only in lowering of cycle times (than target cycle times obtained through Haessler/Doll-Whybark procedures) when a stock out situation is foreseen. In the case of high utilization,
this will result in a high number of setups, through which productive capacity is lost and also resulting in lost sales. However, with this implementation, we use the same demand information for all methods, making it a fair comparison.

5.4 Simulation model

A simulation model is developed (using Simple++) to evaluate the performance of a hybrid MTO/MTS food processing system under different scheduling heuristics. The model has two main modules– an order generator module that generates the orders based on the demand distribution, and a shop floor control module that contains the shop configuration under investigation and the various scheduling rules to operate the shop. There are various data sub-modules to measure the performance of the shop. For MTS products, we are interested in line average fill rate and average inventory levels. For MTO products, we are interested in average flow times i.e. achievable due dates. We also gather the cycle times for the MTS products and analyze the cycle time stability. Cost measures– inventory costs, setup costs, lost sales cost– are also in place. Each of these modules is developed with a lot of flexibility and can be customized to mimic real life situations to the greatest extent possible.

5.4.1 Model dynamics

The “target cycle” times are pre-calculated either using a) EMQ, or b) Doll and Whybark and Haessler procedure. Safety stock $s$ and order up-to levels $S$ for MTS products are pre-calculated based on the mean and standard deviation of the demand during replenishment lead time and desired service level. These target cycle times, safety stocks, and order up-to levels are used as inputs at the operational decision level.

The timing sequence in the simulation model is as follows–

1. At the beginning of the period, the demand for each item is generated. The MTS demand is fulfilled from the stock. The inventory balance is updated. If demand cannot be met, it is lost. The MTO orders are due immediately and join the production order pool.

2. At the end of each production run, the run-out times are calculated for all the products and the one with the smallest run-out time is selected for the next production run.

\[\text{These calculations are provided in the Appendix B.1 of this chapter.}\]
Table 5.1: Bomberger problem with MTO products (88% MTS utilisation)

<table>
<thead>
<tr>
<th>Product</th>
<th>Cost per item*</th>
<th>Setup cost</th>
<th>Production rate</th>
<th>Demand rate**</th>
<th>Setup time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Items/day</td>
<td>Items/Day</td>
<td>Items/day</td>
<td>Items/Day</td>
<td>Hours</td>
</tr>
<tr>
<td>1</td>
<td>0.0065</td>
<td>15</td>
<td>30000</td>
<td>400</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.1775</td>
<td>20</td>
<td>8000</td>
<td>400</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>0.1275</td>
<td>30</td>
<td>9500</td>
<td>800</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>0.1000</td>
<td>10</td>
<td>7500</td>
<td>1600</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>2.7850</td>
<td>110</td>
<td>2000</td>
<td>80</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>0.2675</td>
<td>50</td>
<td>6000</td>
<td>80</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>1.5000</td>
<td>310</td>
<td>2400</td>
<td>24</td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>5.9000</td>
<td>130</td>
<td>1300</td>
<td>340</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>0.9000</td>
<td>200</td>
<td>2000</td>
<td>340</td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>0.4000</td>
<td>5</td>
<td>15000</td>
<td>400</td>
<td>1</td>
</tr>
</tbody>
</table>

* Annual inventory cost = 10% of item cost and one year = 240-8 hour days
** Normal distribution, Coefficient of variance- 0, 0.1, 0.3
Lost sales cost = 10% of item cost
MTO demand Negative exponential interarrival mean 21 days
Mean order demand 280 units/day, Normal distribution CoV 0.3
Setup cost 300, Setup time 4 hrs
Processing rate 4000 units/day, Orders due immediately

3. The production start times and the production quantities are calculated based on the scheduling heuristic rule chosen.

For each scheduling heuristic, a simulation run lasts for 3000 periods initially (when performance measures are re-initialized) and for another 3000 periods. At the end of this, simulation statistics are gathered and reset. There are 5 simulation runs by using five common random number seeds. At the end of the simulation, there is a summarization of the output of the simulation experiments.

5.4.2 Experimental factors, levels

To evaluate and compare the scheduling rules, discussed in the earlier section, we use the Bomberger dataset, which is most commonly used in ELSP literature (e.g., Haessler 1979), as shown in table 5.1. The demand rate shown in this table is for the case where utilisation is 88% (excluding setup time and MTO production, is at almost full capacity including these factors). The demand rates for other utilisation cases are obtained by proportionately changing those shown here. For example, at 44% utilisation the demand rates for all the products will be half of the demand rates shown in the table 5.1.

We conducted a simulation study at 5 different utilization levels (22, 44, 66, 77, and 88%) and by changing various parameters such as demand coefficient of variance (0, 0.1, 0.3) over a period (a day), carrying costs, setup costs, lost sales

5 Such common random number technique is used to reduce the variance among experiments. The same warming up period, the same run length and the same number of runs are used in all experiments to enable the use of there common random numbers. For an elaboration of this technique see Law and Kelton (1991).
costs, MTO-MTS mix, demand pattern amongst products (pareto shape). In the remaining of this chapter we will, however, stick to the discussion related to impact of MTO addition and hence won’t present the impact of costs and product mix as it can be assumed to be given for a specific case. It is well known that even for the specific case, lost sales costs are probably the most difficult to determine (Silver et al. 1998, pg. 241-243). We still decided to include the lost sales cost as it gives an indication of service levels for fulfilled demand. We chose a modest value of 10% of item cost.

5.5 Simulation results and analysis

Figure 5.1, shows the cost performance of the different scheduling methods at different utilization levels. Vergin and Lee method clearly outperforms other methods in both pure MTS and combined MTO/MTS situation. The sum of setup, inventory and lost sales costs over the simulated period in the case of Vergin and Lee method is much less than in the case of the other three methods. EMQ and Fransoo methods have a similar cost performance. In the high utilization case, the performance of Gascon method deteriorates drastically.

There are three curves in each of these figures. The difference in “Pure MTS” and “Combined MTO/MTS” curves in each of the figures 5.1(a–d) represents the extra cost incurred because of the addition of the MTO products. We have also included a cost curve for combined MTO/MTS situation with setup costs for MTO products excluded. This curve tells us if there is any change in the cost incurring from MTS products. It is clear that at lower utilization level, there is not much impact of addition of MTO products on MTS costs but at 88% utilization, there is a significant increase in the costs. The widening differences in the curves at higher utilization indicate the need to exercise caution while accepting the, seemingly lucrative, special MTO orders.

Figure 5.2, shows the average MTO flow time for the different scheduling methods at different utilization levels. MTO flow time is the difference between the order arrival and the order completion time. In other words, it is the time spent by MTO orders in the system. The MTO flow times achieved in the experiments increase, in general, with utilization level for all the methods. For Vergin and Lee method, it increases quite rapidly as compared to other methods. It is interesting to note the lower flow times for Gascon method at 88% utilization. This is discussed later in this section.

6The cost buildup is shown in Appendix B.2 of this chapter.
Figure 5.1: Impact of MTO addition
5.5. Simulation results and analysis

Figure 5.2: MTO flow time

The curves in figures 5.1 and 5.2 can be used as an input to the sales department in order acceptance, due date quotation and price negotiations.

Figure 5.3, shows the line item fill rates (LIFR) for MTS items of the different scheduling methods at different utilization levels. All the methods achieve more than 93% fill rate. EMQ and Fransoo methods perform better in both pure MTS and combined MTO/MTS situations. The performance deteriorated for all the methods at higher utilization levels.

The observations from figures 5.1–5.3 and from the experiments with 0.1 and 0.3 demand coefficient of variance are similar and hence the later are not shown in the form of plots.

While figures 5.1–5.3 provide us the overall performance of the methods, tables 5.2–5.5, help us in detailed understanding of the methods. These tables show the data for 88% utilization case. Table 5.2, shows the average inventory that was held in the stock during the simulated period. Vergin and Lee method carries more inventory for each of the products while Gascon has the least. This is also related to the number of production runs and hence the number of setups done.
This is shown in table 5.3. The expected number of setups based on the Haessler (1979) procedure is also shown for the comparison. It is interesting to note that Vergin and Lee method has least number of setups while Gascon method has more setups in general. In case of products 4,8, and 9 the difference in number of setups is very high. It is intriguing to know that these are the products with high machine usage \((d_i/p_i)\).

Table 5.4 shows, for each of the methods, the percentage of lost sales for each product. Gascon method has more lost sales than other methods and the differences are wider for products 4,8 and 9 which have high \((d_i/p_i)\) ratio i.e. machine usage. Table 5.5 shows the performance of each method in terms of cycle time stability. The target cycle times from EMQ and Haessler (1979) procedure are also shown. The cycle time stability is represented by coefficient of variance (CoV) of cycle times achieved. Again, products 4,8 and 9, the products with high \((d_i/p_i)\) ratio, are problematic. They have a high coefficient of variance for cycle times. Fransoo method, which claims to lead to better cycle time stability does not seem to do so for all products.

As seen from tables 5.3 and 5.5, it is clear that the products 4,8, and 9 i.e. the
5.5. Simulation results and analysis

Table 5.2: Average inventory levels for products

<table>
<thead>
<tr>
<th>Product</th>
<th>EMQ</th>
<th>V &amp; L</th>
<th>Fransoo</th>
<th>Gascon</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32933</td>
<td>35479</td>
<td>29794</td>
<td>29555</td>
</tr>
<tr>
<td>2</td>
<td>9443</td>
<td>17859</td>
<td>10160</td>
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</tr>
<tr>
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<td>15402</td>
<td>35803</td>
<td>18579</td>
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</tr>
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<td>16095</td>
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Table 5.3: Number of setups for products

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<th>Product</th>
<th>EMQ Expected</th>
<th>EMQ Actual</th>
<th>V &amp; L Expected</th>
<th>V &amp; L Actual</th>
<th>Fransoo Expected</th>
<th>Fransoo Actual</th>
<th>Gascon Expected</th>
<th>Gascon Actual</th>
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<td>81</td>
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<td>36</td>
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<td>40</td>
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<td></td>
</tr>
</tbody>
</table>

Table 5.4: Percentage of lost sales for products (x100)

<table>
<thead>
<tr>
<th>Product</th>
<th>EMQ</th>
<th>V &amp; L</th>
<th>Fransoo</th>
<th>Gascon</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.01</td>
<td>0.01</td>
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<td>0.01</td>
<td>0.03</td>
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</table>
Table 5.5: Cycle time stability for products

<table>
<thead>
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<th>Product</th>
<th>EMQ</th>
<th>V &amp; L</th>
<th>Fransoo</th>
<th>Gascon</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>Target cycle</td>
<td>Actual cycle time</td>
<td>CoV*</td>
<td>Target cycle</td>
</tr>
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<td>1</td>
<td>167.53</td>
<td>156.44</td>
<td>0.06</td>
<td>94.52</td>
</tr>
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<td>46.37</td>
<td>40.97</td>
<td>0.10</td>
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<td>0.11</td>
<td>47.26</td>
</tr>
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<td>72.13</td>
<td>0.09</td>
<td>47.26</td>
</tr>
</tbody>
</table>

* Coefficient of variance of cycle times achieved
products with high $d_i/p_i$ ratio behave specially. All the scheduling methods seem to be biased toward these products. These products are pulling their production runs forward at the expense of products with low $d_i/p_i$. This results in more setups and shorter cycle times. For Vergin and Lee method, which incurs lesser number of setups than expected in contrast to other methods, if we look at the cycle times achieved for each product then we can see that the number of setups for products 4, 8 and 9 are relatively higher and the cycle times are relatively shorter. These products are produced more frequently and hence have relatively lesser inventory holdings. Since the runout time, defined as $I_i/d_i$, is used in all the methods as the priority rule it looks natural that these products with less $I_i$ and high $d_i$ are picked frequently for the production. It is beyond the scope of this text to investigate in detail why this phenomenon occurs. Now, we discuss the working of each method.

5.5.1 EMQ and Fransoo methods

One interesting observation is that although EMQ method and Fransoo method are not identical, the results were often very close. One possible reason for this is the fact that although the cycle times are calculated independently for each product, the multi-item $(s, S)$ policy take into account the capacity considerations by checking running out of other products.

These methods perform reasonably well both in pure MTS and combined MTO-MTS situation. Since these methods do not respond to every fluctuation in very short term, they achieve better cycle time stability. Line item fill rates are also very high. It seems that ‘Law of averages’ works here—demand is low in some period and is high in some period. It is surprising that the performance of these methods in terms of line item fill rate degrades only slightly (plots not shown) when demand variance is increased. The higher safety stocks are able to handle this.

It was expected that the EMQ procedure would result in higher costs\(^7\), since it does not take into account feasible schedule generation but it has resulted in cost effective solutions. There are at least two reasons that can be attributed to

\(^7\)The similar performance of EMQ and Fransoo method is intriguing. This seems rather counter intuitive as it suggests that it does not make sense to use ELSP, but rather just use independent lot sizes. Is this a reason why EMQ methods and not ELSP methods are used in practice? A deeper look into these methods reveals that these are not too different from each other. In the EMQ method, the capacity constraints are ignored initially but are brought in later: the production quantity of the product to be produced next is modified because of some other product running out. In Fransoo method, the capacity constraints are partly taken into account via the use of ELSP method in the first step itself.
this. The production runs are longer and hence number of setups required is less. Also, the EMQ method has higher safety stocks.

### 5.5.2 Vergin and Lee method

This method performs extremely well in terms of costs for both Pure MTS and combined MTO/MTS situation. Addition of MTO products lowers the performance of the method drastically. MTO flow time performance is, however, the worst for this method. The method is very good at avoiding small production runs and thus can be very useful in situation where setup times are significantly high. The good feature is that it looks at inventory levels of all products. But as we have found from the set of experiments conducted, the better performance is achieved through high inventory levels. The method relies on building up the stockpiles to achieve high line item fill rate. The situations where inventory costs are higher as compared to setup costs, this method may prove costly. In the presence of MTO products, the performance deteriorates since the MTO products have to wait too long for their production turn because of long production runs of MTS products.

In food processing industries, one may think that this method will perform better since it avoids costly and time consuming setups but if there are products with short shelf life, the method may lead to product obsolescence (Soman et al. 2004b). Special cold storage requirements for products can also put a limit on holding the inventories.

### 5.5.3 The Gascon method

Gascon method tries to avoid stock-outs at any cost (as the problem is tackled as a stock-out avoidance problem), without due considerations to setup time and cost. This leads to higher costs and also lost sales in high utilization case since there is loss of productive capacity in the form of frequent setups. The method is too dynamic and brings nervousness to the system. It results in too small cycles, which may not be desirable economically. Though the method performs poorly in terms of costs, it is performing well in terms of MTO flow time because of smaller MTS production runs.

### 5.6 Conclusions and future research

The hybrid MTO/MTS production situation while very common in practice is addressed scarcely in the literature. The void is even more when it comes to the
operational scheduling in such situations. In this chapter we try to fill this gap. We use four different, proven run-out time based dynamic scheduling methods from the pure MTS literature in the case of combined MTO/MTS situation. We compare their performance by several criteria to check if they are also suitable for hybrid production mode.

When it comes to the choice of a suitable scheduling method, the simulation study presented in this chapter remains inconclusive in some respects. It is clear that the methods that perform well for pure MTS situations do not necessarily perform well for hybrid MTO/MTS situation. However, none of the scheduling methods, over a long simulated period, exhibited a clear dominance over other methods in terms of all performance measures. This in itself is a significant result. It suggests that the choice of scheduling rules to control a hybrid MTO/MTS production system, such as the ones described in this study, should not be restricted to a tool that will ensure optimal cost performance for the system. Other performance measures, and considerations such as simplicity in the applicability of the rule may well prove to be a dominant factor in deciding scheduling rules. For example, in the simulation study presented in this chapter EMQ and Fransoo methods which are simpler and unsophisticated as compared to Vergin and Lee and Gascon methods perform reasonably good for all performance measures.

It is also clear from the study that, irrespective of the method used, the companies should be very careful in accepting special business in the form of MTO products in the cases of high system utilization. In such cases (near 100% utilization), it may be wiser to phase out some MTS products in order to include special business opportunities from special orders/ MTO products, which typically have more contribution margin.

It was also observed that the products with high machine usage i.e. high $d_i/p_i$ ratio are special in the sense that all the methods seem to be biased for these products and react too quickly in selecting them and hence have a high number of setups and also poor cycle time stability which is not desired by manufacturers. Further investigation is required on why these products are behaving in a special way?

We do not suggest that the methods compared here are the best that one can come up with and implement. These can be improved upon, for example by having the possibility of backordering in the Gascon method– When run-out
times are low i.e. working inventories are low, the scheduler may wish to avoid short production runs and may want to incur backorder penalties so as to increase the length of production runs and reduce setup costs per unit of time. The extended Gascon method will result in better performance measures since the scheduling heuristic will give consideration to the backorder/setup cost relationships as well. It will also have nice features of Gascon’s original method—accommodating seasonal demand changes through the use of tactical planning level. In short, Gascon method has disadvantages in terms of cycle time stability because of overreaction and hence the extended version should have the idea of not reacting short-sightedly.

It also seems unrealistic that production decision is taken only at the end of a production run of some product or at the start of the day (as done in this chapter). This decision is also only for the next product to produce. This is definitely not going to help the raw material procurement department. The methods discussed are too dynamic and are not easily implementable. Use of a review period method looks more practical. Increased safety stocks because of use of review period, could also be a choice to avoid the stock-outs.

In this chapter, we did not include the MTO demand information in terms of additional capacity requirements while deriving the target cycle for the production. When MTO demand proportions are higher, than those considered in this chapter, it may be wise to either explicitly reserve the capacity for them or to include idle time in MTS schedules or MTS products might be manufactured to fill capacity in periods of low demand for MTO items in order to have stored capacity in the form of inventories. Van Donk et al. (2003) suggest some conceptual ways of how to incorporate MTO in ELSP. Those could be build upon to develop implementable heuristics. Although the fixed sequence strategy provides low opportunities to react to short term demand, it is appealing for situations with sequence dependent setup times (and costs) and also for two-stage (or multistage) system, where dynamic sequencing can cause unforeseen problems in the raw material (or packaging) material procurement. Comparison with Federgruen and Katalan’s (1999) cyclic base stock policy (polling model) would also be an interesting topic for the further development in the area of hybrid MTO/MTS production.
Appendix B.1: Safety stock calculation

If product $i$ is scheduled to be produced every $T^*_i$ time units, the production time is $T^*_i d_i / p_i$. The remainder of the cycle, $T^*_i - T^*_i d_i / p_i$, until the product $i$ is produced again, is used by the other products. Thus, safety stock must cover the demand uncertainties during the protection interval:

$$L_i = T^*_i (1 - d_i / p_i)$$

For stationary demand, safety stock is defined to be the expected inventory level at the time of beginning of the next production cycle. We deploy, the most commonly followed approach of providing a required service level, $\alpha_i$, is through the use of safety stock, $s_i$, given by:

$$s_i(L_i) = f_i \sigma_i(L_i),$$

where $\sigma_i(L_i)$ is the standard deviation of the demand during the protection time $L_i$. The safety factor $f_i$ which is based on the service level $\alpha_i$ can be specified by using the normal distribution (see pg. 266-267, 724-734 of Silver et al. 1998). The service factor is denoted as $k$ therein. We use $f_i = 1.65$ corresponding to the service level of 95%.

The standard deviation of demand during the protection time $L_i$ can be approximated well by:

$$\sigma_i(L_i) = \tilde{\sigma}_i L_i^c$$

where $\tilde{\sigma}_i$ is the standard deviation of one-period ahead demand forecast and $c$ is a constant that must be estimated empirically (see pg. 114-116 Silver et al. 1998). Values for $c$ generally ranging from 0 to 1. We use a value of 0.5 in this study.

Once the safety stock is calculated, the order up-to levels $S_i$ are calculated as follows:

$$S_i = s_i + T^*_i d_i (1 - d_i / p_i)$$
## Appendix B.2: Total cost buildup

The following table shows the cost elements used to build up figure 5.1.

### Inventory cost

<table>
<thead>
<tr>
<th>Utilization</th>
<th>Pure MTS</th>
<th>Combined MTO + MTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EMQ V &amp; L Fransoo Gascon</td>
<td>EMQ V &amp; L Fransoo Gascon</td>
</tr>
<tr>
<td>22</td>
<td>359.88   645.97 345.22 150.28</td>
<td>358.22 658.60 343.32 153.31</td>
</tr>
<tr>
<td>44</td>
<td>604.10   1021.12 650.60 320.93</td>
<td>596.44 1001.01 648.80 314.64</td>
</tr>
<tr>
<td>66</td>
<td>794.55   1045.14 896.31 474.11</td>
<td>783.03 974.38 842.22 488.66</td>
</tr>
<tr>
<td>77</td>
<td>791.48   1225.26 899.77 564.50</td>
<td>770.72 1322.22 822.02 554.74</td>
</tr>
<tr>
<td>88</td>
<td>902.64   1362.76 995.20 737.06</td>
<td>894.47 912.26 794.92 736.98</td>
</tr>
</tbody>
</table>

### Setup cost

<table>
<thead>
<tr>
<th>Utilization</th>
<th>Pure MTS</th>
<th>Combined MTO + MTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EMQ V &amp; L Fransoo Gascon</td>
<td>EMQ V &amp; L Fransoo Gascon</td>
</tr>
<tr>
<td>22</td>
<td>68070    12085 65555 24495</td>
<td>68070 12085 65445 24235</td>
</tr>
<tr>
<td>44</td>
<td>75460    21425 83380 37470</td>
<td>75320 20895 83440 37450</td>
</tr>
<tr>
<td>66</td>
<td>78670    31215 88195 55575</td>
<td>78710 33460 87535 58970</td>
</tr>
<tr>
<td>77</td>
<td>87430    20295 98795 88100</td>
<td>84710 21615 93155 92320</td>
</tr>
<tr>
<td>88</td>
<td>94280    26200 105265 159465</td>
<td>87270 33085 72205 140050</td>
</tr>
</tbody>
</table>

### Lost sales cost

<table>
<thead>
<tr>
<th>Utilization</th>
<th>Pure MTS</th>
<th>Combined MTO + MTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EMQ V &amp; L Fransoo Gascon</td>
<td>EMQ V &amp; L Fransoo Gascon</td>
</tr>
<tr>
<td>22</td>
<td>0.00     0.00 0.00 33178.35</td>
<td>0.00 0.00 0.00 37745.19</td>
</tr>
<tr>
<td>44</td>
<td>0.00     0.00 0.00 57681.28</td>
<td>0.00 45.90 0.00 57144.33</td>
</tr>
<tr>
<td>66</td>
<td>0.00     2797.59 0.00 39868.93</td>
<td>0.00 4700.85 0.00 55495.87</td>
</tr>
<tr>
<td>77</td>
<td>0.00     9575.82 0.00 38946.56</td>
<td>3340.25 20785.03 2190.13 48494.46</td>
</tr>
<tr>
<td>88</td>
<td>0.00     33707.54 0.00 78760.18</td>
<td>47101.88 57438.03 63157.38 155038.48</td>
</tr>
</tbody>
</table>
Chapter 6

Illustrative case study

This chapter\(^1\) illustrates the conceptual production planning and inventory control framework for combined make-to-order/make-to-stock situations developed in chapter 2. The framework is applied in the case of a firm that produces 230 products on a single line with limited capacity. Areas of improvements in the framework have been identified and possible analytical decision aids are suggested. In particular, short term batch scheduling problem requires more attention and a heuristic to solve that problem is provided.

6.1 Introduction

In this chapter we deal with the implementation of a production planning and scheduling framework for a medium-sized multi-product food processing company in the Netherlands. Before outlining the details of the generic problem and the solution approach it is appropriate to give a brief description of the plant under consideration. Throughout the discussion, we avoid excessive details of the case to keep it illustrative so that a lot of companies can associate themselves with the situation in this study.

The company produces 230 different products, which differ in recipe (40 types), granule (30 sizes) and packaging. The production process has three steps: processing, granulating and packaging (see figure 6.1). The processing stage consists of several steps: mixing of raw materials according to recipe and a number

\(^1\)The content of this chapter are from: Soman, C. A., Van Donk, D. P. and Gaalman, G. (2004e), Capacitated planning and scheduling in combined make-to-order and make-to-stock food industry: An illustrative case study, 13th International symposium on inventories, Budapest, Hungary, August 2004, Under review.
of subsequent processing steps that are executed without interruption or intermediate storage. Then the semi-manufactured product may be stored in one of the 11 silos or can be granulated, directly. Next, the product is separated into several fractions that are made of the same recipe but differ in the size of the granule. In the last step the product is put into bags of different sizes with (sometimes) a client-specific text on it. Now, the finished product can either be delivered to the customer or can be stored. The material flow is divergent—there are 40 types of recipes, 110 semi-finished products after the granulation stage, and 230 stock keeping units (SKUs) after the packaging stage.

Figure 6.1: The production process at the food processing company

For many years it was a common policy for the company to produce in large batches to keep production costs low and limit the number of setups. This seemed to be a good policy. The last decade showed a number of changes, gradually growing in significance. Firstly, consumers’ wishes seem to be changing in an ever-growing rate, causing an increase in packaging sizes, the number of products, as well as in the number of new products introduced. Secondly, many retail players in the food supply chain are restructuring their supply chain both in a physical and information flow sense. The aims are reduction in inventories, faster replenishment and shortening of cycle times. The result for the case company is that logistical performance needs to be improved: faster, reliable, and more dependable. In the similar companies, there are examples of reductions in lead-time from 120 hours in the past to 48 hours now and still further reductions are to be expected. Thirdly, the above-mentioned changes have to be realized in a market characterized by low margins in retailing, and mergers and acquisitions in retail chains. Both lead to a downward pressure on prices paid to producers.

As a consequence of the huge increase in product variety and shorter lead-time requirements of the customers, the company is forced to shift a part of its production system from make-to-stock (MTS) to make-to-order (MTO) and has to operate under a hybrid MTO-MTS strategy. For this typical food-processing
firm with limited capacity, producing a very large number of products on pure MTS basis is not viable because of unpredictable demand and the perishable nature of the products. Also, pure MTO is ruled out because of the large number of relatively long, costly setups that are required. On the one hand there is a need to be flexible and react to customer demand, and on the other hand there is a wish to restrict setups and produce economically using stable, repetitive cycles. In the production inventory research related to food processing industries (e.g. Claassen and Van Beek 1993, Randhawa et al. 1994, Tadei et al. 1995), combined MTO-MTS production situations have been ignored with the notable exception of Soman et al. (2004a). They discuss various MTO-MTS issues that companies need to address viz. MTO or MTO decision, finding suitable production inventory policy, operations scheduling, etc. All these issues have to be tackled in the presence of specific characteristics of the plant e.g. limited shelf life of products, sequence dependent setup times when shifting from one recipe to the other (these recipes have different colours), very short customer lead-times. Obviously all these issues cannot be resolved simultaneously. They provide a decision hierarchy based on the state-of-the-art literature study but it remained to be seen whether this framework could be applied in a real life setting.

The framework from chapter 2 looks tailor-made for the case company because of the similar environmental setting. The aim of this chapter is to implement this particular production planning and scheduling framework for the combined MTO-MTS production situation in food processing industries and test its applicability. Moreover, we identify the areas of improvements and suggest analytical decision aids. In particular, we provide a heuristic for a short-term batch scheduling problem that, in our view, demands more attention. Although the push for development of such an heuristic comes from a particular case, the approach is more generic in nature.

The chapter is organised as follows. In section 6.2, we describe the current planning and scheduling method at the case company and the associated problems. In section 6.3, we apply the hierarchical planning model as discussed in chapter 2, Soman et al. (2004a) in the case of the plant under consideration. Section 6.4 outlines a heuristic algorithm for the short-term MTO-MTS batch-scheduling problem. Conclusions and suggestions for future research are provided in section 6.5.
6.2 Current planning and scheduling practice

The case study was carried out for a period of 6 months in which the researchers regularly visited the company. Data collection was by interviewing the people, studying documents and analyzing numerical data. We do have access to the order book and production book for last couple of years. One of the authors has long-term contact with the firm and a number of Master’s thesis projects have been carried out previously. Both the length of the study period and the use of different methods, interviews with different persons from various departments and the combination of qualitative and quantitative data, as suggested by McCulcheon and Meredith (1993), improves our data validation and the reliability of the findings. Based on our understanding, we now describe the current scheduling practices at the firm and identify the problems associated with it.

The production planning in the company consists of a two-stage hierarchy—medium term planning and detailed scheduling. Medium term planning is mostly carried out by the enterprise resource planning (ERP) software. Though the company uses this mainly for non-manufacturing functions (e.g. accounting, purchasing etc.), it is also deployed for generating purchase orders for raw materials and production orders for semi-finished or end products. These MRP runs are executed weekly. The detailed scheduling level transforms the weekly production orders into production schedule comprising of: the sequence of production orders, and the run-length and the starting time for each production order. The detailed scheduling activities in the plans are performed manually.

As mentioned above, the detailed scheduling method is aimed at answering what, how much, and when to produce. Everyday, the planner and scheduler receive a list of orders from the sales department. This list consists of known (accepted) orders which have due dates attached to them. Based on the inventory levels on hand, it is determined if these customer orders can be shipped from finished goods inventory or from the intermediate silos or need to be produced completely. Now the planner knows what to produce. Next question is how much to produce. Here, an estimate is first made about the time before the next production starts (cycle time) for the same recipe. This estimate is based on the demand pattern realised during the last four weeks and planner’s experience. The production quantity is then determined by adding the known demand during the cycle time and demand forecast during the cycle. There are various production quantity modifiers because of technological constraints, which are mostly in the form of minimum and maximum batch sizes, and yield losses etc. Applying these modifiers gives the production order quantities. When to
Figure 6.2: Planned production schedule
produce is answered next. The orders are scheduled backwards from their due dates. It can be placed in the sequence in such a way that it fits in the preferred colour sequence which minimises the total setup time.

The current detailed planning and scheduling procedure is manual. Although some rules of thumb have been developed over the years, it is effectively a trial-and-error method with lot of daily adjustments. Figure 6.2 shows a typical production schedule generated during the period of week 5 to week 13 in 2004 for the processing stage. The numbers in the boxes represent recipe number and the length of the box shows the length of the planned production runs.

One can observe a few problems with the current scheduling procedure-

1. Though the company works 6-days-a-week, invariably there is production scheduled on almost all the Sundays.

2. The schedules do not show any regular pattern, which may be desirable for raw material and manpower planning. The cycle times for recipes vary a lot from one cycle to another. The cycle time calculation is too crude.

3. Although production orders belonging to the same colour are reasonably clubbed together, there seems to be no preferred fixed production sequence between colours.

4. Schedules often fail to realise weekly production targets, and frequent rescheduling takes place.

5. Inventory levels tend to grow.

6. MTO-MTS segregation is not very clear.

### 6.3 Application of MTO-MTS hierarchical planning

It is clear from the discussion in the previous section that the production planning and scheduling procedures in the company can be considerably improved if some formalised approach is followed. The approach that we follow is the conceptual hierarchical production planning framework for MTO-MTS production situations as discussed in chapter 2, Soman et al. (2004a). It is reproduced in figure 6.3. The MTO/MTS segregation is determined first. Then, a capacity coordination plan, which provides lot sizes and safety stocks for MTS products, is determined. Finally, detailed scheduling decisions are worked out. We are particularly interested in testing the applicability of the framework and the development of analytical/quantitative decision aids in the context of the hierarchy.
We want to know if some important decisions are missing from the conceptual hierarchy. These decisions then can be brought in to refine the hierarchy.

![Diagram](image)

**Figure 6.3: Hierarchical approach to MTO-MTS problem**

### 6.3.1 MTO/MTS

The hierarchy advocates the use of the customer order decoupling point (CODP) concept as a qualitative way to make the MTO/MTS decision. The CODP separates the order-driven activities from the forecast driven activities and is the main stocking point from which deliveries to customers are made. The concept uses product-market and product-process characteristics and considering the desired service level and associated inventory costs helps in locating the decoupling point and thus, the MTO/MTS decision. The elaboration and application of the CODP concept in the food company in the case is reported in Van Donk (2001).

The demand analysis forms the main activity in order to segregate MTO and MTS products. The classical pareto analysis is the starting point. Many companies, categorise the items into either A, B, or C categories. Category A items are MTS items while items belonging to B and C category are MTO items (e.g.
Williams 1984). We think that this categorisation is too simplistic and does not account for differences in uncertainty that exists in the demand among various products. For some products, demand is uncertain but predictable and for others demand is not predictable. Examples of such observed demands for some recipes are given in figure 6.4. It is obvious that one should not treat these recipes in the same way.

![Figure 6.4: Example of observed demand for some recipes](image)

We follow the RDV analysis suggested in chapter 3. Such demand variability analysis is also suggested in D’Alessandro and Baveja (2000) and followed by Huiskonen et al. (2003) to segment products into homogeneous groups. Figure 6.5 shows a plot of average weekly demand on the x-axis and demand variability on the y-axis. The products in the high-volume, low variability are candidates for MTS production. Most of the product recipes belong to low volume, high variability category and should be produced on MTO basis. Many recipes belong to high volume, high variability category and should be produced on MTS basis. However, more inventory levels would be required for such recipes. It is recommended that closer ties should be sought with the customers in order to reduce their variability.

While doing this analysis, some difficulty arises because of the subjectivity involved in drawing up the lines that partition high demand items from the low demand items and high demand variability and low demand variability. However, some simple rules can be derived. For example, in this case the typical production batch is 1700 kg, therefore the products with average weekly demand greater than 3400 kg (two batches per week) were designated as high volume. This roughly translates into minimum production run length of 2 hours. These
partitioning lines are the likely areas of conflicts as well as newer opportunities for sales and production departments. For example, classifying a particular product as MTO rather than MTS can have serious implication in terms of longer lead-times for customers, less inventory, more setup time but this also allows differentiated service for different customer classes.

The product-process analysis is also undertaken. In general, the typical MTO candidates are items with low setup times, items with high holding costs, customized products, and highly perishable products.

Moving a lot of products from MTS to MTO is likely to provide some improvements in the customer service. This is largely due to the fact that currently too many end items are stored and cause problems with inventory control and shelf lives of the products. With the suggested MTO/MTS segregation, the number of obsolete products as well as inventory costs are expected to be far less than they are now.

The MTO or MTS decision is strategically oriented and is complicated due to complex trade-offs involved between various demand and product-process characteristics. We submit that no MTO/MTS partition can be claimed as an optimal
one. As a starting point for the implementation, joint meetings of sales and pro-
duction people should be arranged to show the result of detailed analysis\(^2\) and
discuss the implications of various scenarios. In spite of this, in principle, one
has to and one can decide upon a certain MTO/MTS segregation. We now turn
our attention to the medium term capacity planning level.

### 6.3.2 Medium term capacity-planning

The aim of this planning level is to balance the demand and the capacity. On the
basis of orders on-hand and the forecast of customer orders, and the available
capacities and stocks the decisions are made concerning the allocation of pro-
duction orders to planning periods. This level specifies the target inventory lev-
els for MTS product in each planning period. The target production run length
and production cycle length for each family and/or product has to be specified.

Due to presence of relatively large and sequence dependent setups, the option
of creating a recurring, cyclic production seems attractive. Establishing such
patterns has been a subject of study of the vast literature on the Economic Lot
Scheduling Problem— ELSP (see Silver et al. 1998 and the reference therein).
However, within this literature the focus is on make-to-stock items and the aim
is to minimise the total amount of inventory and setups costs. Incorporating
make-to-order items has not yet been studied in that part of the literature. The
literature on combined MTO-MTS does not address this problem of determining
the production cycle as well. Specifically, common characteristics in food pro-
cessing as sequence-dependent setups or limited shelf lives are not addressed.

The main problem in incorporating MTO items is the unpredictive nature of de-
mand in terms of quantity and/or timing. We consider various alternatives to
make adaptations to ELSP approaches to be able to incorporate make-to-order
and make-to-stock items in a production cycle (see Van Donk et al. 2003 for a
more elaborate discussion). These options are to— (a) treat MTO-items as if be-
longing to a separate product family, (b) produce additional stock in MTS-items,
(c) reserve capacity for MTO in each cycle, or (d) use the idle time in the pure
MTS situation.

In our case, the number of MTO recipes and actual MTO orders is quite high.
Though the demand for each and every individual MTO item is not known, the
aggregate demand for MTO items is constant across time periods (weekly buck-
ets). This allows us to use the standard ELSP procedures with the additional

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\(^2\)Such analysis can be done by the decision aid developed in chapter 3.
constraint on the capacity. We reserve certain capacity for MTO in each cycle and then allocate remaining capacity among the MTS products in such a way that the sum of inventory and setup costs is minimised. The capacity planned (reserved) for MTO can be used to produce the MTO items that are actually ordered during each cycle.

The ELSP solution provides us the frequency of production and target cycle lengths for the MTS products. The safety stock levels are then determined by deploying the standard textbook method (Silver et al. 1998) that uses the demand variance and the desired service levels.

### 6.3.3 Scheduling

At this level, there are scheduling and control decisions. The production orders are to be sequenced and scheduled. The sequence should be so as to meet the inventory targets set at the capacity coordination levels while minimising the total setup and cleaning times. The problem we are dealing with here is essentially a short-term batch-scheduling problem (e.g. Méndez and Cerdá 2002). The presence of MTO products alongside MTS products and their interaction with the limited shared capacity opens interesting possibilities as well as problems for production scheduling. For example, on the one hand, MTS products might be manufactured to fill capacity in periods of low demand for MTO items but on the other hand, we do not yet fully understand these interactions. The production planning framework does not provide any specific way of tackling this. This is a major area where some analytical aids are needed most. This need is also apparent from our discussion of current scheduling practices in section 6.2. We provide a heuristic to solve this problem in the next section.

### 6.4 Short-term batch scheduling problem

Based on our analysis of the case, we state the following assumptions and the requirements—

- The processing stage is the bottleneck
- There is sufficient silo space
- Granulating and packaging facilities have enough capacity
- The production run for any order should never be less than the specified minimum run time
• Changeover times are sequence dependent (family setup structure)
• A specified time period is one-week long
• MTO orders have to be shipped before certain due dates
• MTS (replenishment) orders are to be completed before the end of the planning period

At the beginning of every week, it is aimed to determine a production schedule comprising of:
• The set of production orders to be accomplished at the processing stage
• The sequence of production orders
• The run-length and the starting time for each production order
so as to minimize the overall make-span while strictly meeting the specified due dates for MTO orders.

We now provide a step-by-step approach to solve the MTO-MTS batch-scheduling problem. The outline of the scheduling procedure is shown in figure 6.6.

**Step 1. Generate the candidate list for production orders**
To determine which products to produce, a list of candidate production orders is created at the beginning of the week. The list includes all the MTO orders that are due in the forthcoming week (and all unfinished and over-due orders from the previous weeks) and all the MTS products that are likely to runout in the coming week. The runout time is defined as the number of days the current inventory is likely to last based on the expected usage rate.

The product list is sorted on the due-date (runout time) in ascending order. The runout time is also calculated for products that are not likely to runout in the coming week. These are waitlisted candidates and will be included in the production schedule only if there is some idle capacity left. In short, we have created a list of ‘must-order’ products and ‘can-order’ products.

**Step 2. Generate the preferred production sequence**
The ‘must-order’ products are grouped based on their colour, i.e. family type. The families are lined up one-after-another in such a way that the setup time is minimized. This is a travelling salesman problem but it is of manageable size in the context of the case discussed. The colour sequence is typically from a
Data: MTS run-out data, MTO orders and their due dates, processing times, setup matrix

Generate a list of candidate products

Generate preferred production sequence

Decide production quantities and generate schedule

MTO due dates met?

MTS orders completed before run-out time?

Capacity constraint satisfied?

Maintain the schedule generated

Solution acceptable?

Any idle time in schedule?

Insert capacity filler in the idle time

Remove infeasibility by changing the production sequence in such a way that additional setup time incurred is minimal

Remove infeasibility by evaluating the options of a) changing the production sequence, b) Changing MTS lot sizes

Remove infeasibility by changing the lot sizes of MTS items

Consider outsourcing/ overtime otherwise lost sales or delayed shipments are inevitable

Figure 6.6: Flowchart of the MTO-MTS short term batch scheduling heuristic
light shade to a darker one or vice versa. Within the family the products are sequenced based on their due date. MTO orders are given preference within the family.

**Step 3. The production quantities**

For MTO orders, the production quantities are known and cannot be changed. For MTS orders, we use an order-up-to $S$ policy. The $S$ value is determined at the capacity coordination level (section 6.3.2). The production order quantity is the difference between $S$ and on-hand inventory. The production order quantity is modified to the nearest multiple of the batch size (because of the batch production mode). There is also a restriction based on minimum run time. This acts as an order quantity modifier and avoids very short (and hence costly) production runs.

Now, we have a list of production orders, sequence of production orders, and production quantities (run-length) and thus can construct the initial production schedule. Note the completion time for each of the orders and the overall make-span.

**Step 4. Feasibility checks**

We carry out different feasibility checks on our production schedule. These are— (a) Due date compliance: It is checked whether MTO orders are completed before their due dates, (b) Stock out avoidance: Confirm that MTS orders are completed before their run-out times, (c) Capacity check: Confirm that overall make-span is less that or equal to the available weekly production hours.

If these checks are passed then the resulting schedule is feasible and optimal as well. If there is any idle capacity left in the schedule, we produce the ‘stable demand’ can-order product from the family that is produced at end of the schedule. The product will be inserted in the schedule in such a way that the feasibility is not lost. If this product has sufficient inventory to meet expected demand for the next week, then it is not produced. Instead, recipe 1, the product with highest and most regular demand in our case, is produced. This product insertion acts as a *capacity filler* and stores capacity in the form of inventory. There is no inventory obsolescence risk since these are regular demand products. This stored capacity also acts as a buffer against period of high demand.

**Step 5. Schedule improvisation (achieving feasibility)**

This is achieved by couple of ways-
a. If infeasibility is caused by due date constraint for MTO, we use the ‘pair-wise interchange’ to alter the production sequence. It is ensured that altering the production sequence results in minimal increase in the setup times.

b. If infeasibility is caused by non-conformance to MTS runout times, a couple of options are evaluated-- (i) changing the lot sizes of a certain MTS items or all MTS items, or (ii) changing the production sequence as in (a) above. The lots of stable-and-high demand MTS items can be made smaller or can be split. Alternatively, lot sizes of all the products can be reduced proportionately.

c. In the case of violation of capacity constraint, we change the lot sizes of certain MTS items or all MTS items as in (b) above.

It is possible to have human intervention while removing the infeasibilities in the schedule. The scheduler can accept the suggested schedule and make modifications to it. In the case of outright rejection of the suggested schedule, outsourcing and overtime options need to be evaluated otherwise lost sales or delayed shipments to the customers are inevitable.

6.5 Conclusions and future research

The case study presented in this chapter is quite generic in nature. A number of food processing companies face the MTO-MTS problems described in the chapter. We particularly illustrated the applicability of the hierarchical planning framework suggested in chapter 2 and Soman et al. (2004a). We observe that the framework is quite simple, generic, and yet very useful as a tool for designing or redesigning the planning and scheduling hierarchy for the combined MTO-MTS production situations. The hierarchy, however, lacks analytical decision aids. We have identified and described a few possibilities in this chapter. In particular, we provide a heuristic for the MTO-MTS short term batch scheduling problem. This heuristic can replace or can be used in tandem with the manual detailed scheduling method that is currently used in the company. Here, we must state that the ideas and solutions suggested in this chapter have not been implemented yet but are definitely under the consideration of the firm.

Further research should be directed but need not be restricted to the following areas. Firstly, a generic MTO-MTS analytical toolbox can be developed which can be used by a lot of companies that face similar problems. Secondly, it would be interesting to study the implications of the various options of incorporating
the MTO products, as suggested in section 6.3.2, in the ELSP procedures. Finally, it is possible to develop a MILP-based formulation of the MTO-MTS short term batch scheduling and the resulting solutions can be compared with those obtained by using the heuristics suggested in this chapter.

Acknowledgements

The food company is acknowledged for its willingness to provide the production and order book data. We thank P.D. and F.R. for their support and vivid discussions during and after the plant visits.
Chapter 7

Summary and discussion

Food processing industries are experiencing growing logistical demands, growing variety of products, and intense competition and as a reaction they are trying to move a part of their traditional make-to-stock (MTS) production to follow a make-to-order (MTO) strategy. This has resulted in a production situation, which is characterised by limited capacity, which is highly utilised and by a combination of make-to-order (MTO) and make-to-stock (MTS). The purpose of this thesis has been to gain insight into planning and scheduling issues in these capacitated, combined make-to-order and make-to-stock food production systems. An attempt has been made to address both the theoretical and practical aspects associated with the various subproblems involved. In section 1.2 we formulated the objectives of this research: (1) to identify the main issues that determine the nature and possibilities for controlling and planning the capacity-oriented combined MTO-MTS production in food processing industries, (2) to develop specific models for planning and scheduling in combined MTO-MTS, and (3) to use these models for improving the way planners in food processing industries do their work.

In the following sections, we take stock of the results achieved in view of these objectives.

7.1 Main issues in planning and control of MTO-MTS production

Chapter 2 addressed the objective of identifying the main issues in planning and control of combined MTO-MTS production in food processing industry. A background knowledge was gathered via a thorough literature review and some empirical evidence. The literature on MTO-MTS was evaluated vis-a-vis spe-
cific characteristics of food processing industries, e.g. presence of setup time, shelf life etc. We conclude that useful ideas are present but the majority of contributions do not address these specific characteristics of food processing. We identified the main issues and developed a generic hierarchical framework for planning and control in a combined MTO-MTS system in food processing. The framework consists of three levels associated with the three main issues identified:

- **Make-to-order versus make-to-stock decision**: The decision to produce a product to stock or on order is a strategic choice. It involves a trade-off between the product-process characteristics on one hand and the market demands on the other side.

- **Medium term capacity coordination**: The capacity allocation among MTO and MTS products, order acceptance rules, lot sizes for MTS products are to be decided at this level. The main problem here is to buffer (in time and quantity) the uncertainty of orders. This is to be done by appropriate inventory levels for the MTS products and due-dates for the MTO products.

- **Short term scheduling and sequencing**: These are the operational issues that firms need to answer on a regular basis. The firms need to define the scheduling rules for variety of situations that may arise answering the questions— which product to produce next and in how much quantity?

This conceptual framework suggested can be seen as a first attempt to structure the production planning decisions in a combined MTO-MTS production situation. It is a generic way of looking at the decision-making and is not an in-depth prescription for structuring the specific levels for all the MTO-MTS situations. Still, it can be used as a starting point for designing or redesigning the planning and scheduling hierarchy structure for a particular situation.

We conclude that the framework is a valuable contribution to both the description of the MTO-MTS production situation and possibly to the managerial decision making in organisations as illustrated in chapter 6. Moreover, this framework provides key areas for which specific planning and scheduling models in combined MTO-MTS can be developed.

### 7.2 Models for planning and scheduling in combined MTO-MTS

Chapters 3, 4, 5 relate to the second research objective of developing models needed to improve our knowledge in planning and control of combined MTO-
MTS situations. This objective has been fulfilled by exploring the hierarchical framework developed. We developed analytical tools and models to gain insights into three subproblems—MTO versus MTS, Medium term capacity coordination, Short term scheduling and sequencing—identified in the hierarchy. These tools and models are described in chapters 3, 4, and 5 respectively.

### 7.2.1 Make-to-order versus make-to-stock

Chapter 3 presented a Microsoft Access/Excel based simple but comprehensive and practical tool that aids in the MTO or MTS decision. There are some useful concepts existing in the theory viz. ABC analysis, demand variability analysis, customer order decoupling point, order penetration point. These concepts have matured greatly and are easy to understand. However, the MTO versus MTS decision using these concepts involves only item-by-item decision using item specific attributes such as demand volume, variability, manufacturing lead-time, etc. It is also felt that these concepts fail to take limited capacity into account. In light of the capacity limitation and the competition among the products for the shared capacity, the application of these concepts for the MTO-MTS categorization decision is not straightforward and is rather difficult. The model presented in this thesis takes into account the capacity constraints using a rough-cut capacity planning. This is used in conjunction with the delivery service requirements, demand profile, and cost considerations which have been identified as the most important factors in deciding MTO-MTS partition. It is argued that this is the first ever attempt to bring together and quantify the qualitative concepts in the form of a decision aid for food processing industries. Although this decision aid has not been used and implemented, so far, in a real life setting there are no reasons why it should not help practitioners.

### 7.2.2 Medium-term capacity coordination

In chapter 4 the focus was on two aspects in medium term capacity coordination: shelf life for products and incorporating MTO in the ELSP procedure. The researchers working on ELSP with shelf life considerations have a tendency to focus on the option of deliberately reducing production rates. In food processing industry this option is not at all applicable since it will result in products with quality and yield that is different than expected. Also, the previous research has considered only the common cycle approach i.e. all the products are produced exactly once in the cycle. In this thesis, these assumptions have been relaxed. We allow products to be produced more than once in a cycle by using
the basic period approach. Haessler’s procedure has been adapted for determining the cycle times for the lot-scheduling problem to account for constraints imposed by shelf life of products. The proposed algorithm can never result in higher cost solutions than the common cycle approach. In the worst case, the procedure yields the common cycle solution. If the diversity in the shelf life of products is more, then the cost benefits that are achieved through the use of our procedure are quite significant (up to 40% lower costs in the experiments carried out).

The second aspect at the medium term level discussed some possible ways of incorporating MTO in ELSP procedures. The discussion is qualitative and conceptual in nature. We specially looked at various demand patterns, presence of product families, and structure of setup in and between these product families. Some suggestions and managerial insights are provided for these situations. Moreover, the ideas presented here can be used as a starting point in translating into analytical models. In particular, it is possible to modify the existing ELSP procedures to account for the various demand and setup characteristics along with the presence of MTO items. These options, generally speaking, are to- (a) treat MTO items as if belonging to a separate product family, (b) produce additional stock in MTS items, (c) reserve capacity for MTO in each cycle, or (d) use the idle time in a pure MTS situation.

### 7.2.3 Short-term scheduling and sequencing

Chapter 5 tries to fill the void in operational scheduling literature on hybrid MTO-MTS production situations. Four different, proven run-out time based dynamic scheduling methods from the pure MTS literature are adapted and compared for their performance to check if they are also suitable for hybrid production mode. Though the study remains inconclusive in some respects, when it comes to the choice of a suitable scheduling, it is clear that the methods that perform well for pure MTS situations do not necessarily perform well for hybrid MTO/MTS situation. It is felt that the choice of scheduling rules to control a hybrid MTO/MTS production system should not be restricted to a tool that will ensure optimal cost performance for the system. Other performance measures, and considerations such as simplicity in the applicability of the rule may well prove to be a dominant factor in deciding scheduling rules. For example, in the simulation study presented EMQ and Fransoo methods which are simpler and unsophisticated as compared to Vergin and Lee and Gascon methods perform reasonably good for all performance measures. It was also clear from the study that, irrespective of the method used, the companies should be very
7.3. Illustration of planning and control models

The third research objective was addressed by means of an illustrative case study and involved the application of tools and models developed in a real life setting. This is reported in chapter 6. The case study presented in this chapter is quite generic in nature and a lot of companies can relate their situation with the one described in the chapter. In particular, the applicability of the hierarchical planning framework suggested in chapter 2 is investigated. It was observed that the framework is quite simple, generic, and yet very useful as a tool for designing the planning and scheduling hierarchy for the combined MTO-MTS production situations. A heuristic for the MTO-MTS short-term batch scheduling problem is also provided. This heuristic can replace or can be used in tandem with the manual detailed scheduling method that is currently used in the company.

7.4 Discussion (Food for thought)

In this thesis, a few models and tools for planning and control in the combined MTO-MTS food processing industries are developed. In spite of our claim that the hierarchical framework developed here is likely to be applicable in most of the MTO-MTS production situations, we acknowledge that the combined MTO-MTS research field is still an open ground, especially when it comes to the analytical models to suit the individual cases. In this section, we provide a few research guidelines. First, we revisit some of the assumptions that we have made, and later point out the important issues in combined MTO/MTS production situation that are related to this text but fall outside its scope. Here, it may be recalled that the future research possibilities in each of subproblems have been discussed in the associated chapters.

7.4.1 Assumptions revisited

In chapter 2, we listed specific characteristics of the food processing industries and commented that each of these factors has to be taken into account for developing a production planning and control framework. Although, in most of
the real life cases only a subset of these characteristics is present, it is quite clear that we, ourselves, have not considered many of those factors. We left out some of them explicitly (e.g. two or more stage production, process yield, multiple recipes for a product) to limit the size but not the scope of problem. Assumptions about other characteristics and various procedures followed in the thesis, warrant some comments. These are discussed below.

- **Strict MTO versus MTS classification:** We assumed that the products are either MTO or MTS. In practice, however, it is not uncommon to have production runs of some products on MTO basis although they have been classified as MTS. It is possible to define some policies like make-peaks-to-order (for very high customer order quantities and, of course, if customer is willing to wait) and schedule them in the periods of low demand.

- **Presence of setup time:** We mentioned the presence of sequence dependent setup time in food processing industries but instead used sequence independent setup times in some of the models. It is possible to extend the ELSP model with shelf life considerations to account for sequence dependent setup time.

- **Presence of large setup times:** The time spent on executing setup (and changeovers) in food processing industries is a major managerial issue. Some practitioners seem to reject the ELSP type of (sum of inventory and setup) cost minimisation approach. Instead, they advocate use of a setup time budget, e.g. 10% of total available time, and then try to find production cycles that meet this budgetary constraint while minimising the sum of inventory and setup cost. The ELSP literature lacks such type of approach. In our research, we account for such concerns implicitly by specifying the minimum runlength condition at the operational scheduling and sequencing level. It however, remains to be seen, if incorporating setup time budgetary constraints at the medium-term capacity coordination level are indeed better.

- **Run-out time based sequencing at the operational level:** The run-out time based scheduling methods were chosen because of their simplicity, intuitive stockout avoidance possibilities, and wider acceptance amongst the practitioners. However, it was found that these methods are too dynamic in nature and may not be suitable in the case of sequence dependent setups. Fixed sequenced policies are expected to perform better there since a preferred sequence that minimises setup time and provides extra productive capacity will be deployed. The short-term batch scheduling heuristic presented in chapter 6 is one such example.
• Due date for MTO items: The simulation study in chapter 5 assumed that the due date for MTO items is zero i.e. they are due as soon as they arrive. This was done in order to find out the lead-times that are achievable for MTO items by the use of simple policy of giving them priority during the production. Nevertheless, the discussion in section 4.5, provides some guidelines for due-date setting for MTO items.

• ELSP procedures: We used Doll and Whybark (1973) and Haessler (1979) procedure for determining the target cycles. The demand uncertainty was not included in the calculation of optimal cycle. It is possible to use the methods described in Kelle et al. (1994) and Fransoo et al. (1995). These methods include the costs of holding safety stock (to ensure a required service level) in the total cost function. The determination of cycle time is iterative since the safety stock levels depend on the cycle time itself which has to be calculated. We deployed the traditional approach: use deterministic ELSP and add safety stocks. Here, it may be again stressed that we have used not only the Doll and Whybark method but also the Haessler’s procedure, which has a built-in feasible schedule generation method. This leads to an increase in cycle time for attaining schedule feasibility and hence the less variability over the cycle time. Also, some amount of idle time is then present (to avoid interference) in some basic periods, which can also be used to address the stochastic demand. Moreover, when these methods are used in conjunction with run-out time based sequencing at the operational level, as pointed out in chapter 5, the achieved cycle times vary a lot. This means that we have uncertainty in the protection interval as well. This adds complexity to the safety stock calculations.

• Safety stock calculation: We calculated safety stock so as to achieve the required (95%) service level during the protection interval (cycle time). In this calculation, we ignored the costs associated with this stock and the lost sales (or backordering) costs. However, as seen from the results of chapter 5, these costs can be very significant even with the modest ratio of 1 between inventory cost and lost-sales cost. The safety stock calculation method which incorporates lost-sales (and/or backordering) cost is likely to improve the cost and line item fill rate performance of the system in the case of all scheduling rules.

7.4.2 Related research possibilities

In this section we dwell on the important issues in combined MTO/MTS production situation that fall outside the scope of this text.
• Order acceptance: In this text, the order acceptance, which is at the interface of sales and manufacturing functions, was not considered. Further, it was assumed that all orders are accepted. The simulation model described in chapter 5 can be deployed in order acceptance with certain adaption. It can be used to look-ahead a few periods in the future and hence predicting the order completion date and also to check its impact on existing production orders. This information can then be used for better due-date and price quotation. Development of such an order acceptance tool is an interesting research agenda.

• Costing of special products: Conventional cost accounting methods have certain drawbacks. Often, high-volume, standard products are overcosted, whereas customer specific, low volume MTO products tend to be undercosted. This is in spite of the fact that MTO products are produced in small batches and consume more resources. These special products are, however, generally speaking high contribution margin products. In a way, the MTS products tend to subsidise MTO products. Because of this, the companies run the risk of accepting increasing share of MTO products due to their apparent higher contribution margins. Orders for such MTO products are accepted without considering their impact on other regular MTS products. It is clear from the discussion in chapter 5 that such strategy can have negative influence on the performance in high utilisation cases. A special care has to be taken to accept such orders. It is hypothesised that the use of activity based costing would result in more accurate costing than the conventional costing methods.

• Product offering: The ever increasing product variety results in many low (and intermittent) demand items. The demand for these items is difficult to forecast. The production and inventory costs are also generally higher for these items than for high demand items of similar complexity. In this thesis, items for which a probability distribution for demand is not available or possible to estimate are, by definition, MTO items. A strategy of making such items on order and giving them priority during the production was followed. Another strategy, of course, is not to offer these products, i.e. to drop them altogether from the product portfolio. The food processing industries are generally reluctant to drop recipes (products) and not to add them. This is mainly due to their desire for a full product line which would enable them to become one-stop supplier. It is recommended that the companies should undertake a periodic review of their product offering in order to eliminate few products before their
financial burden is irrefutable. Such a product offering review—(a) will keep the manufacturer’s focus on main and more lucrative business, and (b) its repetitiveness is likely to refine the cost and revenue criteria of the company.

• Seasonal demand and supply: The demand was assumed stationary in this text. The models presented are based on the average demand. These models will have to be adapted for reacting to seasonality in the demand. A lot of food industries like beer, ice-cream, juice etc. face this problem. In such cases aggregate capacity requirements are seasonal and exceed the equipment capacity in certain seasons. Due to this, a build-up of the inventories before these seasons is necessary. The limited shelf life of products limit such possibility. The scheduling policies presented in this paper must be modified to be consistent with decisions made at a tactical level concerning production smoothing over the longer term. Similarly, seasonality in raw material supply can have serious implications for the planning framework.

• Parallel lines: A lot of companies offering large number of products, are traditionally using a costly, high-speed equipment for MTS products and a small, flexible equipment for low volume or special products. Increasing number of product variety and SKUs may lead companies to re-evaluate their machinery investment plans. Deciding on the number and types of equipment in order to meet the growing logistical demands is an interesting area for further study.
References


References


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Samenvatting (Summary in Dutch)

Het onderzoek dat in dit proefschrift wordt beschreven behandeld de planning en scheduling van gecombineerde make-to-order en make-to-stock productie (resp. productie op order en productie op voorraad) in de voedingsmiddelenindustrie. Ook worden beslissingsondersteunende modellen ontwikkeld voor de middellange en korte termijn.

Kenmerkend voor de voedingsmiddelenindustrie zijn één (of zeer weinig) verwerkingsstap(en) en een verpakkende stap, een divergente goederenstroom, en de beperkte houdbaarheid van producten. Deze kenmerken verschillen niet alleen van discrete industrieën, maar ook van vele procesindustrieën, zoals olieverwerkende en andere chemische industrieën. Deze kenmerken vereisen een andere benadering van de productiebeheersing.

Tijdens het laatste decennium is de voedingsmiddelenindustrie beïnvloed door de algemene industriële trend van verhoogde productverscheidenheid, kleinere ordergroottes, snellere en betrouwbaardere leverbehoeftes (d.w.z. kortere productietijd) en lagere winstmarges ten gevolge van invloedrijke klanten zoals grote detailhandelketens. In reactie hierop gaan bedrijven in deze industrie van hun traditionele make-to-stock (MTS) productie deels over naar een make-to-order (MTO) strategie. Hierdoor is er behoefte aan een systeem voor productieplanning en -beheersing dat geschikt is voor enerzijds de onzekere en groeiende logistieke eisen en anderzijds de gecombineerde MTO-MTS productie met een beperkte beschikbare capaciteit. Dit proefschrift beschrijft diverse aspecten van de genoemde situatie.

De onderzoeksdoelstellingen die in dit proefschrift aan bod komen zijn:

1. Het identificeren van de belangrijkste elementen en mogelijkheden in planning en beheersing van de capaciteitsgeoriënteerde gecombineerde MTO-MTS productie in de voedingsmiddelenindustrie.
2. Het ontwikkelen van specifieke modellen voor planning en scheduling voor de gecombineerde MTO-MTS productie in de voedingsmiddelenindustrie.

3. Het toepassen van deze modellen met als doel het verbeteren van de manier waarop planners in de voedingsmiddelenindustrie hun werk doen.

Het onderzoek is onderverdeeld in drie delen, gerelateerd aan de drie onderzoeksdoelstellingen: (1) het creëren van een raamwerk voor de productiebeheersing in gecombineerde MTO-MTS productie, (2) de ontwikkeling van analytische en simulatie modellen, en (3) de illustratie van het raamwerk voor productiebeheersing in een praktijksituatie.

Het eerste deel van de studie onderzoekt een aantal onderwerpen met betrekking tot de gecombineerde MTO-MTS situatie in de voedingsmiddelenindustrie. Een grondig literatuuroverzicht op het gebied van MTO-MTS is uitgevoerd, waaruit geconcludeerd wordt dat er een aantal bruikbare ideeën zijn, maar dat de meerderheid van de bijdragen geen rekening houdt met de specifieke kenmerken van de voedingsmiddelenindustrie. De belangrijkste beslissingsvraagstukken zijn geïdentificeerd en een generiek hiërarchisch raamwerk is ontwikkeld om de plannings- en beheersingsvraagstukken in een gecombineerd MTO-MTS systeem in de voedingsmiddelenindustrie op te lossen. Dit raamwerk bestaat uit drie niveaus:

- De keuze voor make-to-order of make-to-stock: het besluit om een product op voorraad of op order te produceren is een strategische keuze. Deze keuze is afhankelijk van een afweging tussen product- en proceskenmerken enerzijds en markteisen anderzijds.

- De capaciteitscoördinatie op middellange termijn: het gaat hier om besluiten betreffende de capaciteitstoewijzing, de orderacceptatie, de productiehoeveelheden, en het voorraadbeleid. Het kernprobleem is het bufferen (in tijd en hoeveelheid) van onzekerheid van orders door middel van een afweging tussen voorraadniveaus voor MTS producten en levertijden voor MTO producten.

- De scheduling en volgordebepaling op korte termijn: hier gaat het om operationele kwesties die bedrijven regelmatig tegenkomen. Bedrijven moeten schedulingsregels ontwikkelen voor de verscheidenheid aan situaties die zich voordoen bij het beantwoorden van de vraag: welk product wordt als eerstvolgende geproduceerd?

In het tweede deel van de studie worden analytische hulpmiddelen en modellen ontwikkeld voor elk van de niveaus in de genoemde hiërarchie, met als doel
inzicht te krijgen in de productiebeheersing van de gecombineerde MTO-MTS situatie. Deze hulpmiddelen en modellen worden hieronder kort besproken.

Wanneer het over de keuze voor *make-to-order* of *make-to-stock* gaat, m.a.w. of een product wel of niet op voorraad gelegd wordt, bestaan er een aantal bruikbare concepten in de literatuur, zoals ABC analyse, *demand-variability* analyse, het KlantenOrder-OntkoppelPunt (KOOP) en het orderpenetratiepunt. Ondanks het feit dat deze concepten al lange tijd beschikbaar zijn en makkelijk zijn te begrijpen, is hun toepassing in industriële omgevingen vaak nog niet zo makkelijk. Vooral bij beperkte capaciteit lijkt het gebruik van deze concepten problematisch. Het model dat in dit proefschrift wordt beschreven neemt deze capaciteitsbeperkingen mee door een *rough-cut capacity planning* op te stellen. Dit wordt gebruikt in samenhang met de leveringsvoorwaarden, het vraagprofiel en de kostenoverwegingen, die als de belangrijkste factoren in de keuze tussen MTO of MTS zijn geïdentificeerd. In dit verband is een eenvoudig, maar begrijpelijk en praktisch hulpmiddel ontwikkeld, dat geïmplementeerd is in Microsoft Access/Excel. Hiermee is een belangrijke aanzet gegeven om een aantal kwalitatieve concepten met betrekking tot de MTO-MTS keuze te combineren en te kwantificeren.

Bij de capaciteitsoördinatie op middellange termijn ligt de nadruk op twee aspecten: de beperkte houdbaarheid van producten en het opnemen van MTO producten in de *Economic Lot Scheduling Problem* (ELSP) procedures. Onderzoekers die aan ELSP met een beperkte houdbaarheid werken, concentreren zich vooral op de optie om de productiesnelheid te verlagen. In de voedingsmiddelenindustrie is deze optie vaak niet toepasbaar, aangezien het producten met lagere kwaliteit of opbrengst zou kunnen opleveren. Daarnaast is in bestaand onderzoek alleen de *common cycle* benadering gebruikt, d.w.z. alle producten worden precies één keer per cyclus geproduceerd. In dit proefschrift is deze veronderstelling losgelaten en kunnen producten meer dan eens per cyclus worden geproduceerd. Om dit te bereiken, is een *basic period* (basisperiode) benadering ontwikkeld voor het bepalen van de cyclustijden voor het *lot-scheduling* probleem, rekening houdende met de houdbaarheid van producten. Deze procedure zal altijd oplossingen opleveren met lagere kosten dan de *common cycle* benadering en in het slechtste geval levert de procedure de *common cycle* oplossing. Als de houdbaarheid van één van de producten veel afwijkt van die van de andere producten, dan levert de voorgestelde procedure significante kostenvoordelen op (tot 40% lagere kosten in de uitgevoerde experimenten).

Het tweede aspect op middellange termijn is de bespreking van een aantal mogelijke manieren om MTO producten in ELSP procedures op te nemen. Deze
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bespreking is kwalitatief en conceptueel van aard. Er is vooral gekeken naar verschillende vraagpatronen, de aanwezigheid van productfamilies en de aard van omsteltijden binnen en tussen deze productfamilies. Tevens worden een aantal suggesties gedaan voor het omgaan met deze situaties in de praktijk. Tenslotte worden een aantal ideeën besproken, die een startpunt kunnen vormen voor het vertalen van deze concepten in analytische modellen.

Inzichten ten aanzien van de scheduling en volgordebepaling op korte termijn zijn afwezig in de gecombineerde MTO-MTS literatuur. Een simulatiestudie is uitgevoerd om dit gat te overbruggen. Vier verschillende, bewezen dynamische scheduling methodes uit de MTS literatuur (alle gebaseerd op run-out tijd) zijn aangepast. Deze vier zijn vervolgens vergeleken met betrekking tot hun prestaties en geschiktheid voor een gecombineerde MTO-MTS productiewijze. Deze studie levert geen overtuigend bewijs welke methode de beste is. Echter, het is duidelijk dat methodes die goed presteren in zuivere MTS situaties niet noodzakelijk goed presteren in de gecombineerde MTO-MTS situatie. Hierbij valt de kanttekening te plaatsen dat de keuze voor een bepaalde schedulingmethode ook niet alleen zou moeten worden bepaald door één criterium nl. de mate waarin zo’n methode in staat is kosten te minimaliseren. Andere prestatiemaatstaven en overwegingen zoals eenvoudige toepassing van een methode, kunnen een belangrijker factor zijn in het kiezen van een schedulingregel. Op basis van de studie is het ook duidelijk dat, ongeacht de gebruikte methode, bedrijven zeer zorgvuldig zouden moeten zijn in de orderacceptatie van MTO producten in het geval van een hoge bezettingsgraad. In zulke gevallen (dichtbij een bezettingsgraad van 100%) is er een significante verhoging van de kosten van productie van de MTS producten. Hierdoor kan het ook verstandiger zijn om sommige MTS producten uit het assortiment te halen ten faveure van speciale producten (MTO), die over het algemeen meer winstgevend zijn.

Het derde deel van de studie is de toepassing van hulpmiddelen en modellen in een praktijksituatie. In het bijzonder is de toepasbaarheid van het beschreven hiërarchische planningsraamwerk geïllustreerd in de vorm van een case studie. De behandelde case studie is vrij generiek van aard en de kenmerken zullen dan ook in vele bedrijven terugkomen. Opgemerkt dient te worden dat het raamwerk eenvoudig, generiek en toch zeer nuttig is als hulpmiddel bij het ontwerpen van een planningshiërarchie voor gecombineerde MTO-MTS productiesituaties. Voor de scheduling op korte termijn is een heuristiek gepresenteerd voor het MTO-MTS lot-scheduling probleem. Deze heuristiek kan handmatige planningsmethodes, die momenteel in het bedrijf worden gebruikt, vervangen of kan samen met deze methodes worden gebruikt.