Inventory Segmentation and Production Planning for Chemical Manufacturing

by

Shardul Sharad Phadnis

M.S. Industrial & Systems Engineering
The Ohio State University, 2002

B.E. Production Engineering
University of Mumbai, 1997

Submitted to the Engineering Systems Division in Partial Fulfillment of the Requirements for the Degree of

Master of Engineering in Logistics

at the

Massachusetts Institute of Technology

June 2007

Signature of Author ....
Engineering Systems Division
May 11, 2007

Certified by ....
Stephen C. Graves
Abraham J. Siegel Professor of Management Science
Professor, Mechanical Engineering & Engineering System Division
Thesis Supervisor

Accepted by ....
Yossi Sheffi
Professor, Engineering Systems Division
Professor, Civil and Environmental Engineering Department
Director, MIT Center for Transportation and Logistics

Inventory Segmentation and Production Planning for Chemical Manufacturing

by

Shardul Phadnis

Submitted to the Engineering Systems Division
on 11 May 2007 in partial fulfillment of the
requirements for the degree of
Master of Engineering in Logistics

Abstract

Developing a cyclical schedule for producing multiple items on a single processor under stochastic demand that minimizes total setup and inventory holding costs is an important problem. This problem is faced in many continuous production environments such as chemical or petrochemical production, where the costs of switching production from one item over to another are very high. Due to high changeover costs, each item is produced in large batches and its demand is fulfilled from the finished goods inventory. Holding this inventory incurs inventory carrying costs. Therefore, good production planning policies are required to determine when and how much of each item should be produced so that the total cost of setup changeovers and holding inventory is minimized, while ensuring that sufficient inventory is available to meet customer demand which varies over time. In this thesis, I present the work done to develop production planning policies for a large chemical manufacturing company that operates in the environment described above.

The problem described above is called the Economic Lot Scheduling Problem (ELSP) and is known to be NP-hard. So, optimal solutions are hard to find and one has to rely on heuristic procedures to find good solutions. In this thesis, I first present four fundamental inventory planning models relevant to the ELSP and discuss research works that specifically address the ELSP. I then describe the characteristics of the production and the planning processes at the chemical manufacturer where this work was carried out and present a heuristic procedure to solve the ELSP. This is followed by a demonstration of how the procedure can be applied at the manufacturing company and presentation of the results of a simulation experiment conducted to test the effectiveness of the solution. Finally, I will discuss two important issues related to the implementation of the solution at the company.

Thesis Supervisor: Stephen C. Graves
Title: Abraham J. Siegel Professor of Management Science, Mechanical Engineering & Engineering System

Acknowledgements

My first and foremost thanks are due to my thesis advisor, Prof. Steve Graves. He has not only helped me understand the theory behind the subject of this thesis, but also showed me how to systematically conduct a research project. I have learned how to develop good understanding of the problem, methodically analyze the data, and then develop a practicable solution for the real world. And despite his busy schedule, he has always been available to meet with me at the earliest time and has given very thorough feedbacks on drafts of this thesis.

I am also grateful to Roger Bloemen for giving me the opportunity to conduct this research at his company. Roger is one of the very few people in industry I know who have a true appreciation for research and understand the value of treating a factory also as a laboratory to test management theories in a controlled way. Shrinivas Shastri and Amy Gilrein at this company are the ones who provided all the help to meet Roger's expectations from this work. They helped me understand the process, provided all the data I needed, made themselves available for weekly calls to answer my questions, and answered my emails expeditiously when questions surfaced between the two weekly calls. Simply put, I could not have done this work without their help.

My thanks are also due to Dr. Chris Caplice, the executive director of our program. Chris does a lot of things for the MLOG students. He makes us feel completely at home when we first arrive at MIT, gets us ready to "drink from the fire hose", sets hard deadlines to keep us on our toes, and when the darkest times of the year loom over head, offers us a round of beer at the Muddy Charles. It's hard to thank him enough for what he does for us as a group, but to me his contributions go beyond that. I was a late applicant to the MLOG program, and Chris admitted me with a fellowship and enabled me to come to MIT! And then he suggested that I work on this particular thesis and get an opportunity to work with Prof. Graves.

Another person at MIT I want to thank is the instructor of my Technical Writing class, Bill Haas. Bill's critique of my writing has helped me a lot to write a better technical document. If this thesis is easy to read, a lot of credit goes to Bill.

I have had a chance to meet some very smart people in my MLOG class, and I have made some great new friends. It would be unfair to others if I name only a few, but it would be equally unfair if I don't name any at all. So, to mention a couple of friends, I do want to thank Mike Yea (my Washington, DC pal!) for proofreading my thesis and suggesting ways to improve the document, and Bin Liu for an uncharacteristically crazy email he sent on the night I was finishing this thesis: that email and the frenzied email activity it generated was a welcome relief.

Finally and equally importantly, I want to thank my parents and my family. The qualities of diligence and optimism my parents inculcated in me have not only helped me stay sane in this fast program but also have helped me get where I am in my life today.

Working on this thesis project has been a memorable experience in more than one way, but the most valuable part for me has been the opportunity to work with Prof. Graves. Four years ago I had actually wished for a chance just to meet Prof Graves, and what I got is many orders of magnitude more than what I had dreamed of getting. Must I not thank Lady Luck for that!

Shardul Phadnis
Cambridge, MA

To my Parents

Table of Contents

List of Tables

List of Figures

Chapter 1 Introduction

This thesis is based on the work done to develop production planning policies for a chemical manufacturer of an interlayer film used in automotive windshields and architectural glass panes. The manufacturer operates a continuous-flow production line, which can produce only one product at a time, to produce variations of the interlayer film and fulfill customer demand from items held in the inventory. Changing the production line from producing one product to another incurs setup changeover costs, and storage of product incurs inventory holding costs. Thus, production of multiple items needs to be planned such that total setup and inventory holding costs are minimized. The goal of production planning is to determine quantity and sequence of production of various products, with the objective of minimizing total setup and inventory holding costs. This problem of scheduling multiple products on a single production line is known as the Economic Lot Scheduling Problem (ELSP), and has been studied for nearly fifty years (Rogers 1958). In this thesis, I present an application of the ELSP in an industrial setting. The remainder of the thesis is organized into five chapters as described below.

Chapter 2 overviews four fundamental inventory planning models: the Economic Order Quantity and the Economic Production Quantity models for deterministic demand, and reorder-point and base-stock policies for probabilistic demand. The chapter then explains the limitations of applying these single-item inventory models in a multiple-item production environment, and hence the need for studying the Economic Lot Scheduling Problem (ELSP). Finally, the chapter reviews some important research work that addresses the ELSP.

After this overview of the ELSP, Chapter 3 describes the manufacturing company where an instance of the ELSP was solved for developing its production planning policies. This chapter introduces the company and its product family, which is the subject of this work; and then illustrates the production process and the production planning processes currently in use. Understanding the facets of the production and the planning processes is important for defining the problem that needs to be solved.

Chapter 4 presents the mathematical model of the problem. The chapter first highlights the characteristics of the problem being modeled, and lists the assumptions made in developing the model. The mathematical model of the problem is then presented. Finally, the chapter describes the heuristic procedure developed to solve this problem.

Chapter 5 demonstrates the application of the heuristic procedure to generate production planning policies for the manufacturing company, and reports the results from a simulation study. The first section of the chapter describes the data collected and the subset of data used in development of policies. Next, the chapter presents the method used to segment the individual stock keeping units (SKU's) produced by the company into product groups. The chapter then gives a step-by-step description of how to apply the heuristic developed in Chapter 4 to generate production plans for the product groups formed. Effectiveness of the production plans thus generated using the heuristic procedure needs to be evaluated when the demand is stochastic. This is done by testing the production plans using a simulation experiment. Chapter 5 illustrates the design of this simulation experiment and details out its results.

Chapter 6 discusses two important issues related to implementation of the solution at the company: generation of SKU-level production schedule based on production plan for product groups, and selection of basic planning period. Finally, Chapter 7 summarizes the work conducted in this research study. The chapter also highlights some key aspects of the work done as well as its limitations, and concludes by providing a few recommendations for future work.

Chapter 2 Inventory Planning: Literature Overview

This chapter presents an overview of the fundamental inventory planning models relevant to the topic of this thesis. Besides the review, it also introduces standard terms and notations that are used throughout this thesis. The overview of inventory planning models begins with two models for single items with deterministic demand: the Economic Order Quantity (EOQ) model and the Economic Production Quantity (EPQ) model. This is followed by a review of two models for single items with probabilistic demand: continuous-review reorder-point policy and periodic-review base-stock policy. The chapter then explains the limitations of these single-item inventory planning models in a multiple-item production environment. This necessitates the study of a multiple-item single-processor production planning problem, also known as the Economic Lot Scheduling Problem (ELSP). The last section of this chapter defines the ELSP, states the necessary and sufficient conditions for a feasible ELSP solution, and reviews a few ELSP heuristics including an important one by Dobson (1987).

2.1 Purpose of Inventory Planning Policies

The objective of an inventory policy is to provide guidelines for making inventory planning and replenishment decisions so that the desired level of customer service is provided at the lowest cost. More specifically, an inventory policy defines for a certain item how much and where inventory should be held, when it should be replenished, and what the replenishment quantity should be. Taylor (2004) provides a good intuitive explanation of inventory planning policies, and Silver, Pyke, and Peterson (1998) provide an excellent technical review of many inventory planning models.

2.2 Inventory Planning for Single Items with Deterministic Demand

There are two fundamental inventory planning models for single items with deterministic demand: Economic Order Quantity (EOQ) and Economic Production Quantity (EPQ). The EOQ model is used when an item is procured from an external supplier and its availability either is instantaneous or has a fixed lead time. The EPQ model is used when an item is manufactured internally by the company and hence it becomes available at a rate equal to its production rate. Both the models assume that the demand rate is fixed and known in advance.

For item i, the following notations are used:

D_i : Demand rate (units/time)

A_i : Ordering or setup cost ($/order or $/setup)

s_i : Setup time (time/setup)

h_i : Inventory holding cost ($/unit/time)

Q_i^* : Economic Order Quantity (EOQ) (units)

T_i^* : Period (time between consecutive orders or production) based on EOQ (time)

TRC_i^* : Total relevant cost of EOQ policy ($)

2.2.1 Economic Order Quantity (EOQ)

Figure 1 below shows the behavior of inventory level over time in an EOQ model. The demand rate is known and steady, and the replenishment is instantaneous.

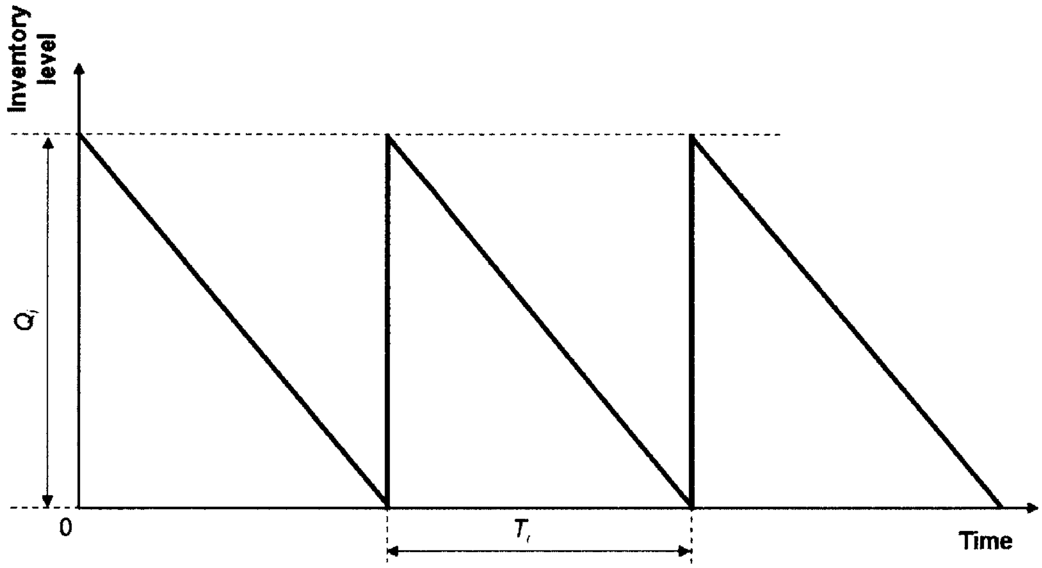

Figure 1: Inventory Behavior in EOQ Model

The total relevant cost per unit time is made of ordering cost and inventory holding cost:

$$TRC_i = \frac{A_i}{T_i} + \frac{Q_i}{2} h_i$$

$$= \frac{A_i}{(Q_i / D_i)} + \frac{Q_i}{2} h_i \qquad = \frac{A_i D_i}{Q_i} + \frac{Q_i}{2} h_i$$

Differentiating this wrt Q_i and equating to 0 to find Economic Order Quantity gives:

$$Q_i^* = \sqrt{\frac{2 A_i D_i}{h_i}} \qquad \text{(Eq. 1)}$$

$$T_i^* = \frac{Q_i^*}{D_i} = \sqrt{\frac{2 A_i}{h_i D_i}} \qquad \text{(Eq. 2)}$$

$$TRC_i^* = \sqrt{2 A_i D_i h_i} \qquad \text{(Eq. 3)}$$

2.2.2 Economic Production Quantity (EPQ)

Unlike in the EOQ model, inventory replenishment in the EPQ model is not instantaneous, but takes place at rate p_i per unit time. In a production environment, p_i would be the production rate of item i. The inventory level based on the assumption of a finite production rate with the known and steady demand rate is shown in Figure 2. The maximum inventory level in the EPQ model is less than that in the EOQ model. This is because it takes Q_i / p_i units of time to completely replenish the order, and the inventory level goes down by $(Q_i / p_i) D_i$ in this time. Thus, the maximum inventory in the system at any time is $Q_i - (Q_i / p_i) D_i = Q_i (1 - D_i / p_i)$. Based on this inventory level, the total relevant cost in the EPQ model is given by:

$$TRC_i = \frac{A_i D_i}{Q_i} + \frac{Q_i (1 - D_i / p_i)}{2} h_i$$

Differentiating this wrt Q_i and equating to 0 gives Economic Production Quantity of:

$$Q_i^* = \sqrt{\frac{2 A_i D_i}{(1 - D_i / p_i) h_i}} \qquad \text{(Eq. 4)}$$

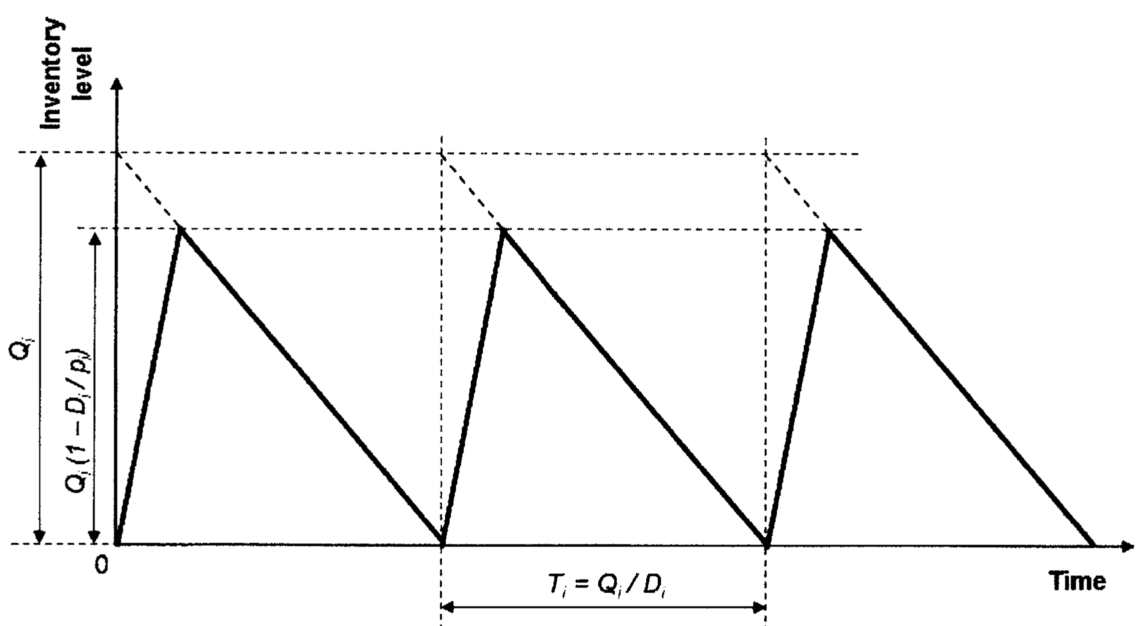

Figure 2: Inventory Behavior in EPQ Model

Both the models described above assume that the lead time for fulfilling the demand is zero, but a non-zero lead time can be easily modeled. With non-zero lead time L, the replenishment orders are placed (or the production is started) at time $(T_i - L)$ in each cycle, so that the items start arriving exactly when the inventory level reaches zero. The exact time when the inventory level reaches zero is known with certainty since the demand rate is deterministic.

2.3 Inventory Planning for Single Items with Probabilistic Demand

The EOQ and the EPQ models described in section 2.2 are applicable only when the demand rate is deterministic or has very little variation. When the demand rate is probabilistic, above models are inadequate because the exact time when the inventory level reaches zero is not known with certainty. Because of this, some safety stock needs to be maintained to accommodate the variability in demand over the lead time.

There are two types of inventory planning models for individual items with probabilistic demand. The first type of models assumes that the inventory level is continuously monitored and an order can be placed as soon as the inventory level reaches a predefined reorder point. The other type of models assumes that the inventory level is reviewed only at some predetermined periods and an order is placed based on the inventory level observed at the time of the review. One model of each kind is described in the following sections.

2.3.1 Continuous-review, Order-point, Order-up-to-level (s, S) Policy

As the name states, the inventory level is continuously reviewed in this policy. As soon as the inventory level drops to or below a preset reorder point (s), an order is placed to restore the inventory to a predetermined order-up-to level (S). Figure 3 shows an example of the behavior of the inventory level over time. Since the inventory is managed using the minimum (s) and the maximum (*S*) levels of inventory, the policy is also known as the "min-max policy" (Silver et al., 1989. p. 238)

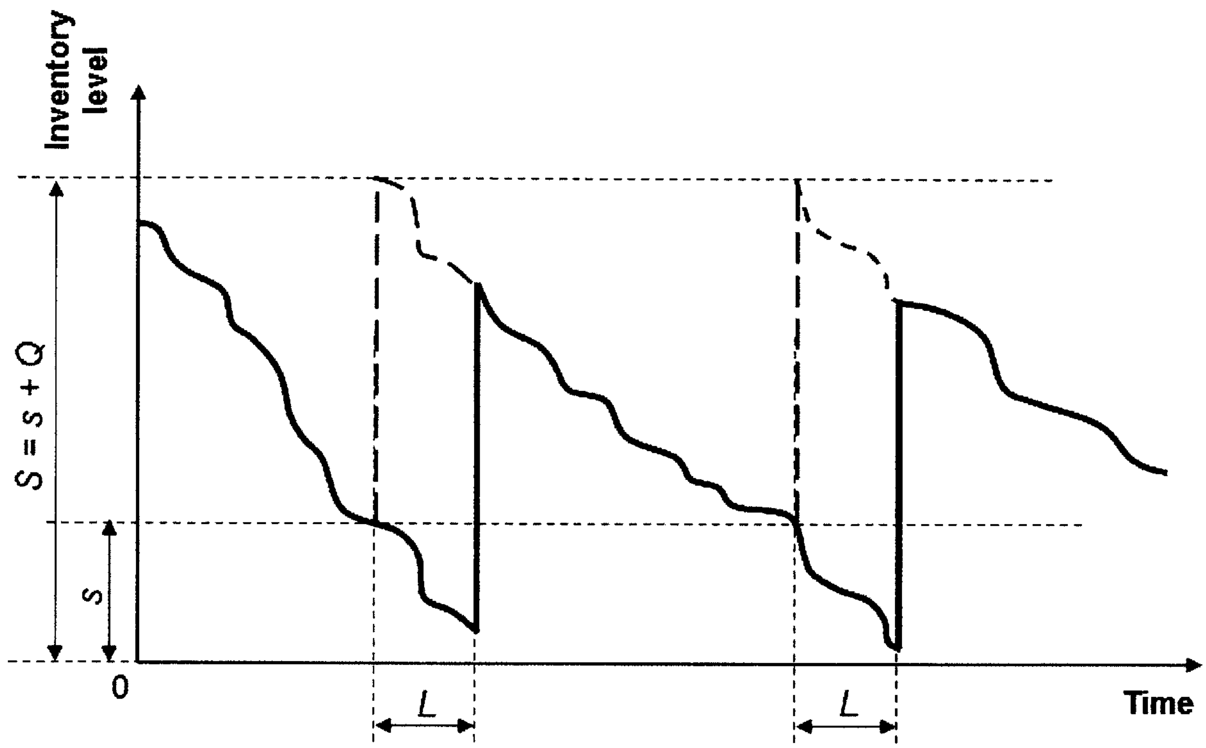

Figure 3: Inventory Behavior in (s, S) Model

The reorder point is based on the average demand in the lead time period, standard deviation of the forecast error (or standard deviation in the demand rate if information about forecast error is not available), and the desired customer service level. The order-up-to-level (S) is the sum of the inventory level at the reorder point and the Economic Order Quantity (Q). The equations used for calculating the safety stock, the reorder point, and the order-up-to-level are shown below.

Given,

Q^* : Economic Order Quantity (EOQ)

$\overline{x}_L$: Average demand over lead time L

σ_L : Standard deviation of the forecast error over L

k : Safety factor (based on the desired customer service level)

SS : Safety stock $= k\sigma_L$

$\therefore$ $s = \overline{x}_L + k\sigma_L$ and

$$S = s + Q^* = (\overline{x}_L + k\sigma_L) + Q^* \qquad \text{(Eq. 5)}$$

2.3.2 Periodic-review, Order-up-to-level (R, S) Policy

In a periodic review policy, the inventory level is reviewed only after certain predetermined time intervals (R). At the time of review, an order is placed to restore the inventory level to a predetermined order-up-to or base-stock level. For this reason, (R, S) policy is also known as the "Base Stock Policy." The behavior of inventory level over time in this policy is shown with an example in Figure 4.

According to Silver, et al. (1998, pp. 239-240), this policy is very commonly used in industry as it does not require continuous monitoring of the inventory level and thus makes it easy to manage inventory, especially where computerized systems are not used for inventory planning. This is also a preferred policy when several different items need to be ordered together, for reasons such as reducing transportation costs by ordering full truckload quantities or ordering sufficient quantity to fill a shipping container when ordering goods from overseas suppliers.

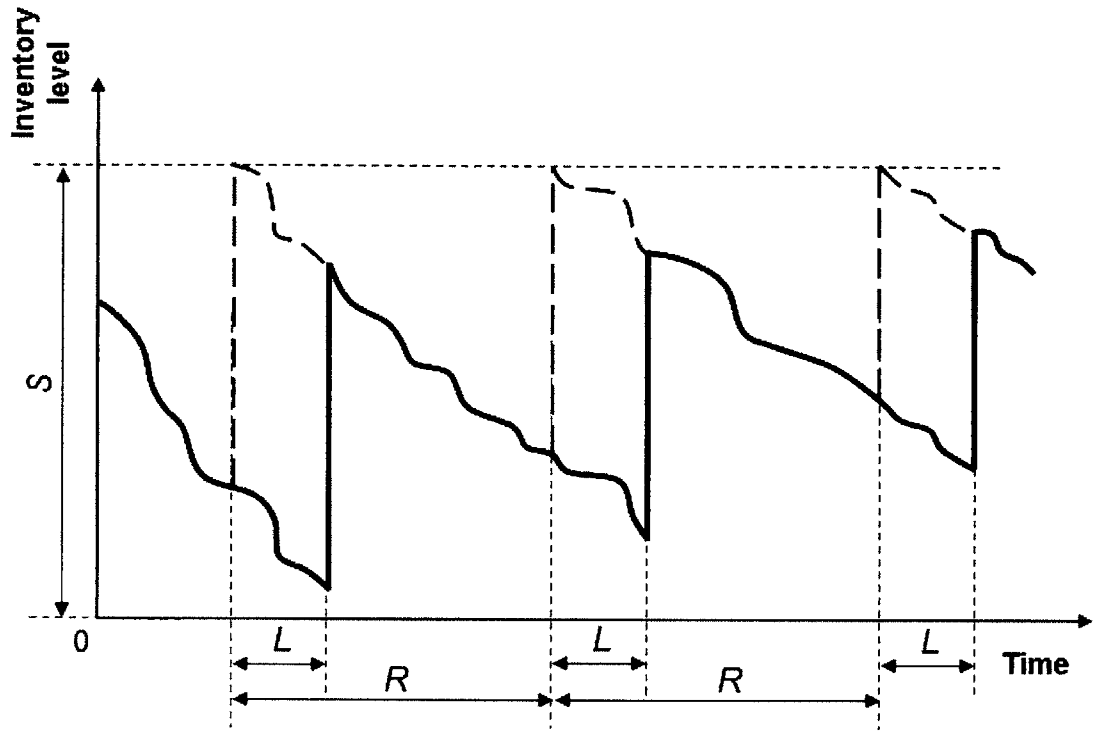

Figure 4: Inventory Behavior in (R, S) Model

The parameters of the (R, S) policy are determined as follows:

R: Review period (determined in advance)

$\overline{x}_{R+L}$: Average demand over time $R+L$

σ_{R+L}: Standard deviation of forecast error over $R+L$

SS: Safety stock $= k\sigma_{R+L}$

$\therefore$ $S = \overline{x}_{R+L} + k\sigma_{R+L}$ (Eq. 6)

2.3.3 Limitation of Single Item Inventory Policies

When several items need to be manufactured at a common production facility, the single-item policies described in previous sections are not adequate for the following reasons:

- The EPQ model may suggest a non-integer optimal order period that cannot be implemented in practice (for example a policy with order period T=12.37 days).

- Optimal order periods for several items may overlap and an item may need to be produced when the production process is already engaged in production of another item.
- If single-item (R, S) policy is used to overcome above limitations, it may lead to a situation where capacity required to produce all items in a certain period is greater than the available production capacity.

Because of the above limitations, the single-item inventory models studied above cannot be independently extended to develop inventory policies for a group of products at a production facility. The Economic Lot Scheduling Problem (ELSP) avoids these limitations. Section 2.4 provides an overview of the problem and some important solutions developed over time.

2.4 Economic Lot Scheduling Problem (ELSP)

The Economic Lot Scheduling Problem (ELSP) is also known as the "single-machine multiple-product lot scheduling problem". It has been studied extensively and literature addressing the problem exists dating as far back as 1958 (Eilon, 1958; Rogers, 1958). The inventory planning problem addressed in this thesis is of the same nature as the ELSP, and the following sections review some key research works that address this problem.

2.4.1 ELSP: Problem Definition and Assumptions

Graves (1979) defines the ELSP as the problem of *finding a feasible schedule to produce a set of items with constant demand rates on a single processor that operates at a fixed processing speed for each item, with the objective of minimizing total cost. The total cost consists of setup cost incurred before production for every item and linear inventory holding cost incurred for items held in inventory, from where the demand is met.*

Elmaghraby (1978) provides a good review of the research work on the ELSP, and several authors (Gershwin, 2002; Graves, 1979; Davis, 1990; Dobson, 1987; etc.) refer to this paper for the preliminary review of the ELSP literature. Listed below are the assumptions that the ELSP is based on:

- Multiple items need to be produced on a single processor and the processor can produce only one item at a time
- Demand rate for each item is known and constant, and demand is fulfilled from inventory
- Production rate for each item is known and constant
- Setup time & setup cost for each item is fixed and independent of the production sequence
- Inventory holding cost is linearly proportional to the inventory level on hand

Based on these assumptions, researchers have defined the ELSP in different ways. Elmaghraby (1978) defines the ELSP as the problem of finding a cyclical production schedule to minimize the total setup and inventory holding cost. Dobson (1987) defines the ELSP as the problem of deciding length of the production cycle that can be repeated indefinitely and defining the production sequence to be followed within that cycle, so that demand can be satisfied at the lowest total cost without allowing backorders.

2.4.2 ELSP: Difficulties and Solution Approaches

As pointed out by several researchers (Elmaghraby, 1978; David 1990; etc), the primary difficulty in compiling an ELSP schedule from individual item solutions based on the Economic Production Quantity model is the possibility of "interference", where two or more items are required to be produced at the same time on the processor that can produce only one item at time. This may happen because of two reasons: the total workload on the processor exceeds the capacity available, or the production of an item needs to be started at a time when the processor is still producing another item. Both these reasons result in the inability to meet demand for the item whose production cannot be started.

Elmaghraby (1978) reports that researchers have used two different approaches to achieve feasible solution, namely Common Cycle approach and Basic Period approach. The Common Cycle approach employs identical cycle time for all items, and the objective is to find an optimal production cycle. In the Basic Period approach, a production period of sufficient length is chosen so as to accommodate production of all items, and the objective is to determine the production frequency and the lot size for each product to be produced.

Figure 5 shows an example of how the two approaches may be applied to the same set of products with deterministic demand rates and instantaneous replenishment. The top section of the figure shows demand for two products: Demand for product-1 is shown with a dotted line, and that for product-2 is shown with a solid line. The slope of each line represents the demand rate for the corresponding product. The abscissa of each demand line represents the length of the replenishment cycle and the ordinate represents the replenishment quantity. The central section of the figure shows an application of the Common Cycle approach; here the length of the replenishment cycle is identical for both products. The bottom part of the figure shows an application of the Basic Period approach. Here, the basic period is equal to the replenishment cycle of product-2, and the replenishment cycle for product-1 is one third the size of the basic period. That is, product-1 is replenished three times during the basic period and product-2 replenished only once.

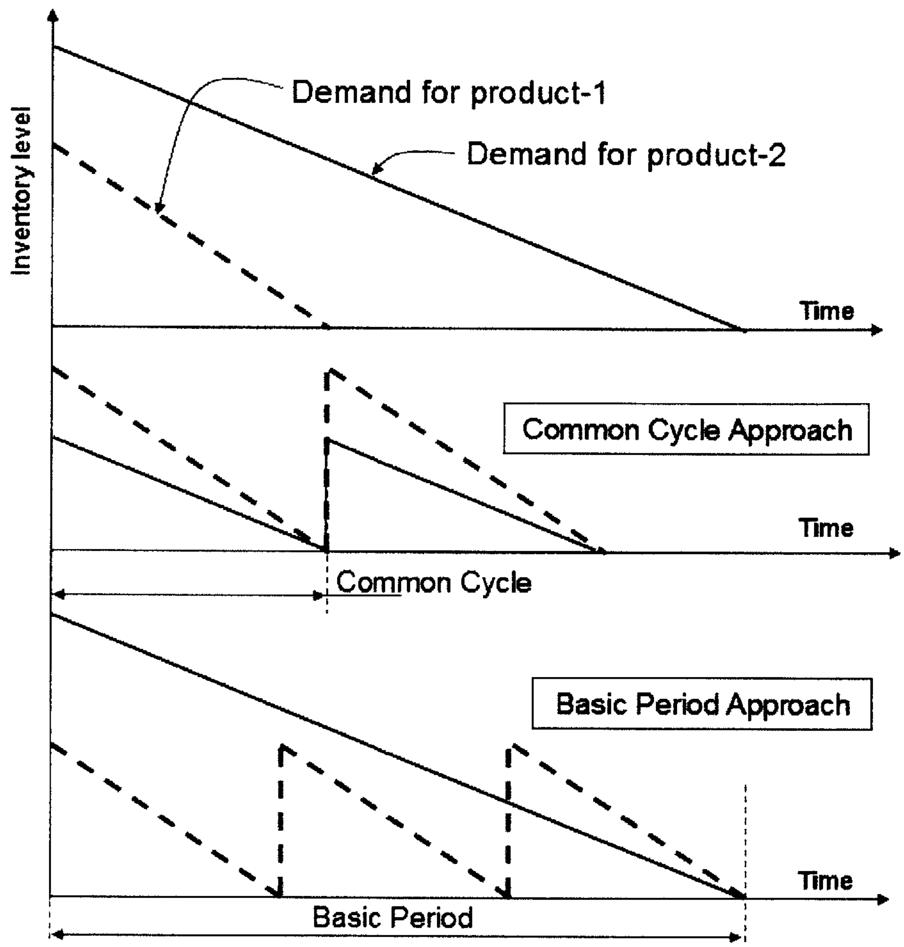

Figure 5: Examples of Basic Period and Common Cycle Approaches to ELSP

The ELSP is a very hard problem and even a restructured version of the problem has been shown to be NP-complete (Hsu, 1983). Hence, the research work on the ELSP has focused on finding heuristics that produce good solutions. Section 2.4.3 reviews some of the heuristics developed over the years.

2.4.3 ELSP Heuristics

Elmaghraby (1978) provides his own heuristic based on the basic-period approach, and compares performance of the heuristic against four others by testing it with a dataset used by Bomberger

(1966). One of the well-known ELSP heuristics is developed by Dobson (1987) and does not use a basic period; this procedure is described in section 2.4.3.2. Before describing Dobson's heuristic, section 2.4.3.1 first describes the necessary and sufficient conditions for achieving a feasible ELSP solution.

2.4.3.1 Necessary and Sufficient Conditions for Feasibility of ELSP Solution

Elmaghraby (1978) also provides necessary and sufficient conditions for a feasible ELSP solution. An ELSP solution defines a production schedule for a set of items (denoted by i in the equations used below). The schedule consists of three time-elements for each item: setup time, production time, and period. These time-elements for one item are graphically presented in Figure 6. Each item is consumed steadily over the period. The quantity of each item produced during the production time is equal to its demand over the entire period.

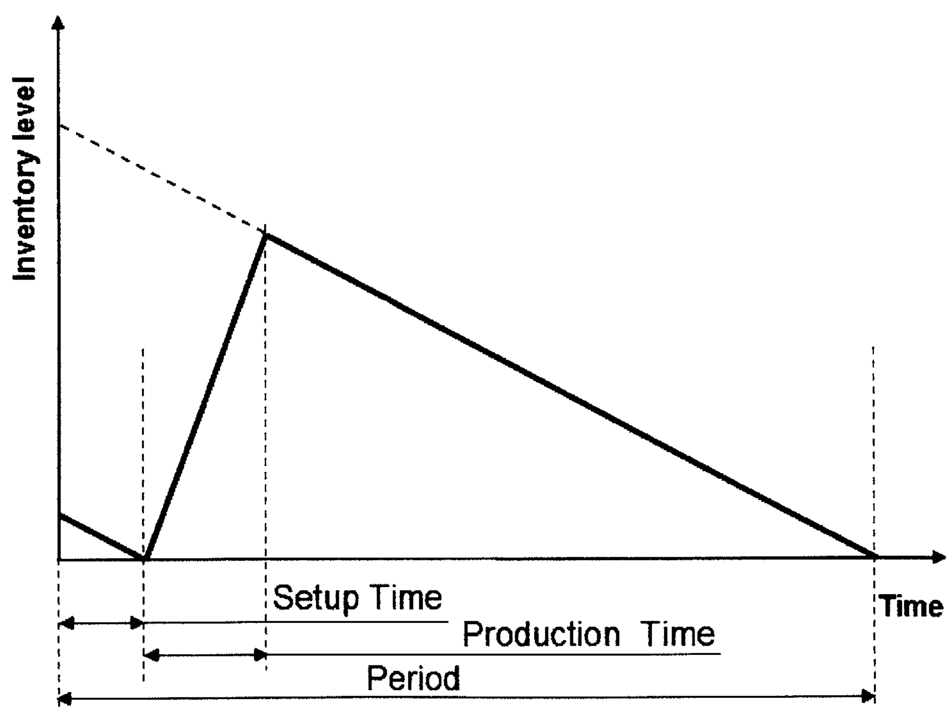

Figure 6: Time Elements Related to One Item in an ELSP Schedule

Necessary condition:

The condition necessary for an ELSP solution to be feasible is that the sum of the ratios of the total of setup and production time to the period for all items be no greater than 1 (Eq. 7).

$$\sum_{i}\left(\frac{(\text{Setup} + \text{Production Time})_{\text{product i}}}{\text{Period}_{\text{product i}}}\right) \leq 1 \qquad \text{(Eq. 7)}$$

The sum of setup and production time for an item is the amount of time the processor is engaged in production-related activities for that item. The ratio of this time to the period of that item represents the portion of the item's period during which the processor is engaged in a production-related activity (setup or production) for the item. This means that for the rest of the time, the processor is available for the activities related to production of other items. If the sum of these ratios for all items to be produced at the processor is greater than one, the processor does not have sufficient capacity to produce all items. Thus, for an ELSP schedule to be feasible, it is necessary that it must be less than one.

Sufficient condition:

The sufficient condition for an ELSP solution to be feasible is that the sum of the total setup and production times for all products be not greater than the period for any individual product (Eq 8).

$$\sum_{\text{i}}(\text{Setup} + \text{Production Time})_{\text{product i}} \leq \min_{i}\left\{\text{Period}_{\text{product i}}\right\} \qquad \text{(Eq. 8)}$$

Satisfying this condition means that the sum of setup and production times for all the products to be produced is no greater than the shortest period among all items. This guarantees sufficient capacity to produce all items, and hence is a sufficient condition to guarantee feasibility of an ELSP schedule.

2.4.3.2 Dobson's ELSP Heuristic

Dobson (1987) provides a formulation for the Economic Lot Scheduling Problem, and then provides a heuristic based on the power-of-two policy. The objective in Dobson's formulation is to minimize total setup and inventory holding costs. Setup costs & setup times, production rate, demand rate, and inventory holding costs for all items are inputs to the problem. The heuristic defines the length of the production cycle, produces a production sequence for that cycle, and determines production lot sizes and idle times between consecutive lots for the given set of items. The formulation assumes that the setup times are independent of the production sequence.

Dobson's heuristic develops a power-of-two policy (Jackson, Maxwell, & Muckstadt, 1985): it calculates integer frequency of production for each item, where each frequency is a value of some power of two (e.g. 1, 2, 4, 8, 16...), and then evenly spaces the production of lots within the production cycle. Thus, if production frequency of an item is 2, it could be produced in periods 1, 3, 5, 7,... or in periods 2, 4, 6, 8,.... The length of the production cycle is equal to the highest production frequency among all the items. For determining production sequence, Dobson points out that the problem of assigning the items to individual production periods and sequencing within each period is analogous to the parallel machine scheduling problem with the number of machines equal to the length of production cycle. He proposes a heuristic based on the Longest Processing Time (LPT) rule, in which items are ordered by their production frequency first and then in the decreasing order of their processing times. The sequences for individual machines thus produced are then concatenated to produce the production sequence for the entire production cycle.

Dobson tests this heuristic with random data (uniform distribution for a given interval) where machine utilization is at least 0.8, and finds that the cost of heuristic is within 8% of the lower bound. Finally Dobson mentions that the improvement due to a better sequence is unlikely to be dramatic, and hence use of LPT as a scheduling rule is adequate.

2.5 Summary

This chapter has presented an overview of some fundamental inventory planning models that are relevant to the research work presented in this thesis. The chapter described two basic single-item deterministic-demand inventory planning models, namely Economic Order Quantity model and Economic Production Quantity model, and two single-item stochastic-demand models, namely Min-Max policy and Base Stock policy. The chapter then described the limitations of these models in multi-item production environment, and how the Economic Lot Scheduling Problem (ELSP) can be used instead. The last section of the chapter pointed out a few important insights about structure of the ELSP.

After presenting relevant literature in this chapter, I will describe the industrial environment where the thesis work was conducted in the next chapter. Theoretical insights gathered from Chapter 2 will then be combined with the understanding of the industrial environment described in Chapter 3 to develop a model and a heuristic to solve the ELSP in the industrial setting in Chapter 4.

Chapter 3 Company-X: Background

This chapter describes background of the manufacturing company where the work performed in this thesis was applied. The names of the company, product line, and facility where the study was conducted are changed to Company-X, Product-Y, and Location-Z, respectively to protect identity. The chapter provides an introduction to the company and the product line studied. Following the introduction, various processes involved in making and delivering the product are described. This includes description of the production process as well as the information-related processes such as knowledge of demand and forecasting, and production planning & scheduling. Finally, important performance measures used to monitor the process are provided.

3.1 Company Background

Company-X is a leading chemical manufacturing company that makes products in three different segments: films and glass products, high-performance specialty products (such as heat-transfer and hydraulic fluids), and nylon fibers. This project work is done at Company-X's North American manufacturing facility at Location-Z, which makes an interlayer glass film (referred to as "Product-Y" in this document). Product-Y film is used in automotive windshields, sandwiched between two glass panes under heat and pressure, to serve as a barrier to the UV rays, heat, noise, and to prevent glass splinters from flying into and around the vehicle in case of an accident. Product-Y is the leading product in the global market for automotive interlayer films and is purchased by all automakers in the world. The current North American supply chain network of Company-X consists of three production facilities and eight distribution centers (Company-X, 2006).

3.2 Product Description

Product-Y film is made from polyvinyl butyral (PVB) and is clear in color. After production, the film is wound on a core and shipped as a roll. An adhesive is applied to the film so that the film can be glued and sandwiched between two layers of glass. Some of the film rolls may have a colored gradient band on one end, as seen on top of many automotive windshields. The film comes with four primary adhesives and in four primary colors for the gradient band. Thus, the film is produced in sixteen primary adhesive-color combinations. Location-Z facility produces products of all sixteen combinations regularly and some additional combinations as needed.

The roll comes in two standard lengths: 250 meter and 500 meter. There are some standard roll widths; however customers typically order the rolls in custom-sized widths, and the facility produces the rolls to the exact width specified. Customers also specify different widths of the gradient band. Since the film can have a gradient band along only one side of its width, the production facility can simultaneously produce two different films of the same or different roll widths and of the same or different gradient band widths, on the same extrusion line as long as both films use the same adhesive and have the same color for the colored band. The production process is described further in section 3.3. The result of producing two rolls on the same line is that the rolls get wound differently with regards to the orientation of the gradient band (clockwise and anti-clockwise with the colored band on top). Thus, within each adhesive-color combination, each roll is further distinguished by following four parameters:

- Roll length {250 meter, 500 meter}
- Roll width (any width between 47cm and 183cm in 1 cm increments)
- Width of the gradient band (any width between 12cm and 30cm)
- Unwind direction of the roll with gradient band on top {clockwise, counterclockwise}

3.3 Description of Production Process

All products are produced on a single extrusion line that operates continuously. The products are made of polyvinyl butyral (PVB), which is fed through a hopper at the beginning of the line. From there, PVB passes through several extrusion rolls and is formed into a film of the desired thickness. The speed of the line depends on the type of the film being produced: the line operates at 112.5 ft/minute (approx. 34.29 m/min) for producing clear film, and at 121.5 ft/min (approx. 37.04 m/min) for producing colored film[1]. At the other end of the line, the film is cut to the desired width and wound into rolls. Two rolls of the same adhesive-color combination can be produced simultaneously as long as the combined width of the two rolls is not more than 2.05 meters. The widths of the two rolls can be different, and roll widths can be adjusted as needed. The rolls are produced in lengths of 250 meter or 500 meter. Once produced each roll is sealed individually and stored in a climate-controlled warehouse.

3.3.1 Periodic Maintenance and Setup Changeovers

The actual production capacity available at the extrusion line is less than the maximum available capacity due to three reasons: line shutdown for planned periodic maintenance, unplanned breakdown of line due to mechanical or technical problems, and setup changeovers. The explanation of each of these is given below and a summary is presented in Table 1.

The extrusion line needs to be shut down approximately once every three weeks for replacing filters and conducting other routine maintenance. The shutdown typically lasts for one day. This time also includes approximately six hours of film production where the film produced does not meet quality specifications, and needs to be shredded and recycled back into the hopper.

---

[1] The production speeds shown here and elsewhere in this thesis are disguised to protect confidentiality of data.

The production process may experience unplanned downtime for two reasons: it may suffer operational failure due to equipment breakdown or it may need to be stopped for an unscheduled changeover. Currently, only information about the process availability is that the average unplanned downtime is 17.6% of the total available capacity.

When the line is producing film, two types of setup changeovers are possible: changeover from one adhesive-color combination to another, and changeover from production of film of a certain width, roll length, and gradient band width to another. Production of each adhesive-color combination is called a "Campaign". The first type of changeover takes place when the line is switched from producing one campaign to another. Campaign changeovers can take anywhere from 45 minutes to 12 hours based on the adhesives and colors of the films produced before and after the changeover[2]. The second type of changeover is much faster; it takes less than 10 seconds to change film width and 12-14 minutes to change width of the gradient band. The line is continuously producing film during both these types of changeover, and the material produced during the changeover is shredded and recycled back into the process. Thus, the changeovers not only expend the productive capacity of the line (time), but also consume resources (material, energy) used in producing the film.

Table 1 summarizes these different types of capacity losses experienced at the production line. It shows the frequency and magnitude of the capacity loss and also states the duration for which the resources (e.g. material and energy) used for producing the film are lost.

---

[2] 45 minutes to 12 hours of changeover time between campaigns is based on the minimum and maximum changeover times. Expected changeover times are somewhere between 45 minutes and 12 hours. Exhibit 2 shows the expected changeover times between various adhesive-color combinations.

Type of Capacity Loss	*Frequency*	*Magnitude*	*Type of Loss*
1. Periodic maintenance (PM) to change filters	Every 21 days	Approx 1 day	Time (24 hours) & material (6 hrs)
2. Unplanned breakdown	Unknown	17.6% of avail. capacity	Time and material
3. Setup changeovers:			
(a) Setup changeover between campaigns	4-6 times between consecutive PM's	Sequence dependent. Up to 12 hours for color change. 45 minutes to 6 hours for adhesive change within the same color.	Time and material (both lost for entire duration)
(b) Changeover within a campaign (film and/or gradient band width)	Multiple times per campaign	From 12-14 min (500m) to 75-80 min (3000m) to change width of band	Time and material (both lost for entire duration)

Table 1: Various Types of Setup-related Capacity Losses on Production Line

3.3.2 Quality Test

After change of adhesive, the film is tested for quality of adhesion. This test currently requires a wait time of about 20 hours. For this reason, Company-X schedules to run each campaign for at least 24 hours (if there is sufficient demand to justify the production quantity). If the film produced does not meet quality specifications, necessary modifications can be made in the existing campaign itself without incurring additional inter-campaign changeover losses.

3.4 Master Production Scheduling

Company-X makes production planning and scheduling decisions in accordance with its Master Scheduling Policy (Company-X, 2001a) developed to meet Oliver Wight Class-A performance expectations. Given below is a description of the production planning procedure currently in use.

The Master Production Schedule (MPS) shows general production plans over an 18-month rolling horizon. The MPS is based on Sales & Operations Plan (S&OP) developed by Company-X's Supply Chain leaders, which is taken as a non-negotiable input for developing the MPS. The MPS is managed everyday and reconciled with the production plan for each product family at least once a week. MPS provides guidelines for making production scheduling decisions by defining three parameters: time zones, safety stock levels, and campaign-level production lot sizes. These three parameters are described in the following sections.

3.4.1 Production Time Zones

Three different time zones are defined for each of the three different schedule domains: Fixed Zone, Firm Zone, and Open Zone. The schedule domains and respective time zones are listed in Table 2 below (adapted from Company-X, 2001b).

Schedule Domain	Fixed Zone	Firm Zone	Open Zone
Site Production and Inventory Plan (SPI)	Current month	2-3 months	4-18 months
Campaign schedule	Current campaign	2 weeks	Week-4 and beyond
SKU schedule	24 hours	2-7 days	Week-2 and beyond

Table 2: Time Zones for Different Scheduling Decisions

The Fixed Zone is closest in time to the actual production activity. Any changes to the schedule within this zone require an approval from high-level authorities and a change is allowed only in the most urgent cases. Currently, schedule changes within the Fixed Zone happen only once or twice a year. Schedule changes are permitted in the Firm Zone as long as they are within the specified tolerance range, and the changes need to be approved by the designated authority. Currently, the tolerance for a schedule changes in the Firm Zone at the campaign schedule level is 10%. Schedules can be changed in the Open Zone without needing any high-level approvals.

3.4.2 Safety Stock

Currently, safety stock levels are calculated for each Stock Keeping Unit (SKU) to provide 95% or better on-time delivery. On-time delivery for each order is measured against the due date requested by the customer while placing the order. Safety stock levels are calculated for all SKU's made by a production facility independent of other production facilities. Initial values of the safety stock are calculated in two different ways based on demand history for each SKU:

- For SKU's with forecast and sales data for at least 12 months, safety stock is calculated to provide a 95% Customer Service Level (CSL) using the following formula:

  Safety stock, $SS = k\sigma\sqrt{LT}$ (Eq. 9)

  where,

  k = Safety Factor (=1.65 for 95% CSL assuming normal distribution)

  σ = Standard deviation of forecast error

  LT = Cycle Time for an SKU (in months)

- For SKU's with less than one year of sales data, the safety stock is set to be equal to one week of average demand, until 12 month's of sales and forecast history is built.

Safety stock levels for all SKU's are reviewed every six months (in June and December) and modified as needed. The safety stock for each SKU produced at the Location-Z facility is physically maintained at only one location: either at the plant or at the distribution center. The company has promised some of its customers the maintenance of a minimum quantity for certain SKU's. For these SKU's, safety stock as well as minimum maintenance quantity requirements are also taken into account for making production decisions.

3.4.3 Campaign-level Production Lot Size

Current order fulfillment policy (Company-X, 2001a) provides some rule-of-thumb guidelines to determine production lot sizes. These guidelines are aimed at minimizing setup changeover times at the production line, and are listed below.

- Produce all colors except blue in 5-7 day runs every 6-8 weeks.
- Adhesive changes within blue (hardest color to change from) are done every 4-5 days.
- Produce each campaign for at least 24 hours. This is done because of the lead time involved in obtaining results from quality tests as mentioned in section 3.3.2. Based on this, minimum sizes are set for each campaign in the company's business system.

Nature of the demand has changed since these guidelines were developed in 2001. So, many times these guidelines cannot be followed and need to be overridden. Currently, the Master Scheduler does not have a tool to evaluate how deviating from (or following!) these guidelines affects performance of the plant. Due to the lack of such a tool, the Master Scheduler has to rely on these guidelines for determining production lot sizes.

3.5 Demand Forecasting

The demand for each SKU is forecasted by the Demand Managers based in Company-X's North American headquarters. The forecasts are sent to individual production facilities, and each facility develops its Master Production Schedule based on these forecasts. Almost all of the SKU's in Product-Y family are made to stock, and hence forecasts are developed for each SKU individually. The demand is forecasted in unit area (square meters) of the film to produce. Accuracy of the forecasts is measured monthly. Currently, the forecasts are about 50% accurate at the SKU-level and 78~98% accurate at the formulation-level.

3.6 Performance Metrics

The Master Production Scheduling Policy states that the objective of the planning & scheduling process is to provide 95% or better on-time delivery while reducing the overall cost. Currently, on-time delivery is the primary performance metric used for evaluation of inventory policy.

3.7 Summary

This chapter described attributes of the production environment and the production planning processes currently used at Company-X's production facility at Location-Z. Based on the understanding of the actual production environment presented in this chapter and knowledge of the past research work presented in Chapter 2, a mathematical model is built to solve the problem. Chapter 4 will present the mathematical model and the heuristic procedure developed to solve it.

Chapter 4 General Problem: Definition and Solution

Chapter 3 described the production and planning environment at Company-X, the elements of which are used to define the industrial application of this thesis. This chapter develops a mathematical model for the production planning problem faced by the company. The chapter first defines the problem and highlights its important facets. The following sections list the assumptions made in developing the model and then present the model. Finally, the heuristic procedure developed to solve the problem is described.

4.1 Problem Definition and Characteristics

As mentioned in section 3.6, the goal of the production planning process is to provide at least 95% availability of the product from the finished goods inventory with minimal total setup and inventory holding costs. The objective of the problem discussed in this chapter is to develop a production plan that allows the Production Planning department at Location-Z to meet this goal. The problem has the following characteristics:

(1) The production facility has a single processor (server).

(2) The server needs to be shut down periodically (every three weeks) for maintenance. Production plans are typically made for each 3-week period.

(3) The server operates continuously between two consecutive periodic maintenance activities except for occasional mechanical breakdowns. The average capacity loss due to the mechanical breakdowns is known.

(4) Each SKU or item is produced at a constant and known rate.

(5) The demand for each item is stochastic with a known average and standard deviation.

(6) The production is made-to-stock and demand is fulfilled from the finished goods inventory.

(7) Changeover of the server from production of one item to another incurs setup changeover costs, and changeover costs are sequence-dependent.

(8) Holding costs are incurred for all finished goods inventory in stock.

(9) Production planning has to guarantee a minimum of 95% availability to meet demand.

(10) The objective is to minimize total costs made of setup cost and inventory holding cost.

4.2 Production Planning Model

This section presents the mathematical model of the problem. The model is based on some simplifying assumptions described in the section below.

4.2.1 Simplifying Assumptions Made in Production Planning Model

(1) Setup times and setup costs are assumed to be independent of the production sequence contrary to the reality. This is done for two reasons:

   a. Considering sequence-dependent setup times adds complexity of the Traveling Salesman Problem to the already complex ELSP. (See Elmaghraby, 1978)

   b. In reality, there is a pattern in the setup changeover times in relation to the adhesive-color combination of the items produced immediately before and after the changeover, and estimated changeover time to a particular adhesive-color combination (called "product group" and is described in section 5.2) can take only a few possible values. (See Exhibit 2) The minimum of these values for a particular product group is used as its sequence-independent setup time.

(2) Holding costs are assumed to vary linearly with inventory level.

(3) The heuristic uses the Basic Period approach as described in section 2.4.2 and Figure 5. The basic period is assumed to be a known parameter. Since production plans are made for each 3-week period between two consecutive maintenance-related planned shutdowns, three weeks is used as the basic period in this model.

(4) The production lot size of an item remains the same every time it is produced.

4.2.2 Problem Statement

The problem described in section 4.1 is a stochastic programming problem since the demand is probabilistic. Given below is the deterministic equivalent of the problem based on the above assumptions. Relaxations to this problem will be used to develop a solution for the production planning problem faced by Company-X.

Let,

T^B: Basic period

m_i: Multiplier of the basic period to get the optimal period for item i

That is: $(1/m_i T^B)$ is the optimal production frequency of item i

D_i: Demand rate for item i

p_i: Production rate for item i

A_i : Setup cost for item i

s_i : Setup time for item i

h_i : Inventory holding rate for item i

C : Total cost

Problem P1:

Minimize $$C=\sum_i \frac{A_i}{\left(m_i T^B\right)}+\sum_i \frac{1}{2} h_i D_i \left(m_i T^B\right)\left(1-\frac{D_i}{p_i}\right) \qquad \text{(Eq. 10)}$$

st

$$\sum_i \left(\frac{s_i}{m_i}+\frac{T^B D_i}{p_i}\right) \leq T^B \qquad \text{(Eq. 11)}$$

$$m_i \in \mathbb{Z}^+ \quad \forall i \qquad \text{(Eq. 12)}$$

$$\{X\} \qquad \text{(Eq. 13)}$$

Figure 7 below depicts the behavior of the inventory level of a single item in the problem formulated above and shows the relationship between basic period and period for that item.

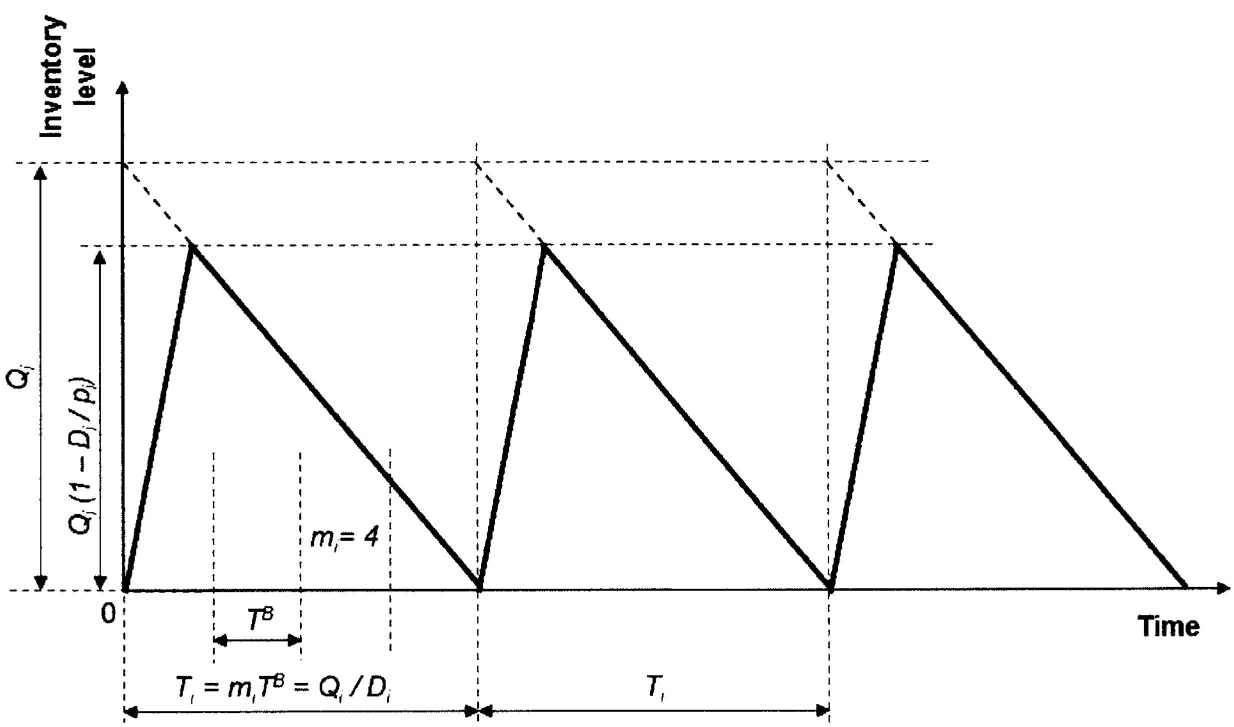

Figure 7: Inventory Behavior for Item-i Described in Problem P1

The formulation assumes that the basic period (T^B) is fixed. The objective function (Eq. 10) minimizes the total cost of setup and holding the inventory. The production lot size for an item is the same every time it is produced and is equal to $D_i m_i T^B$. The first constraint (Eq. 11) checks for feasibility of the total capacity. The second constraint (Eq. 12) restricts m_i to only positive integer values. The third constraint (Eq. 13) defines that only one item can be produced at a time, and hence checks for feasibility against simultaneous production of more than one item. This constraint is used in the same way as done by Rajaram and Karmarkar (2004); the constraint is not defined here because it is checked for in the solution procedure. Besides using a fixed basic period, this formulation is also different from that given by Dobson (1987) (discussed in section 2.4.3.2) in that it does not provide a production sequence.

4.3 Heuristic Procedure

A heuristic procedure is developed to solve the problem defined in section 4.2.2 and is described below. There are two reasons for developing a heuristic: As mentioned in section 2.4.2, even a restricted version of the deterministic ELSP problem mentioned above is NP-complete, and thus it is hard to solve for the optimal solution. Furthermore, the problem **P1** stated above is a deterministic equivalent of the stochastic problem actually faced at Company-X. The heuristic described below takes this into account and finds a solution in two stages. In the first stage, it solves a relaxed version of the problem **P1**, and chooses the best power-of-two multiple of the basic period as the production period for each item. It then allocates items to different production periods within the production cycle to balance the load on total production capacity. In the second stage, a base-stock policy is developed for each item to provide the desired customer service level under stochastic demand. The two stages are described below.

4.3.1 Heuristic Stage-1: Deterministic Solution to Relaxed Problem P1

(1) Define or select the basic period.

(2) Define production cycle (T) as the longest period allowed for any item. Since periods for all items are power-of-two multiples of the basic period (T^B), production cycle (T) defines the largest power of two to be used.

(3) Relax the integrality constraint in problem **P1** and solve it to identify optimal period for each item i.

(4) For each item, find the greatest power-of-two multiple of the basic period (T_i^L) not greater than the optimal period, as well as the smallest power-of-two multiple of the basic period not smaller than the optimal period ((T_i^U)).

$$T_i^L = \sup\{m_i T^B \le T^* \quad : m_i \in 2^k, k \in \mathbb{N}\} \tag{Eq. 14}$$

$$T_i^U = \inf\{T^* \le m_i T^B \quad : m_i \in 2^k, k \in \mathbb{N}\} \tag{Eq. 15}$$

(5) For each item, find the total cost if production periods were T_i^L and T_i^U. Choose the period with the lower cost (C^E) as the period for that item (T_i^E). This is also illustrated in Figure 8. For a power-of-two heuristic, this lower cost is no more than 6% of the optimal cost (C^*). If period (T_i^E) for an item is greater than the production cycle (T), choose production cycle as the period for that item. For every item, calculate production lot size (Q_i^E) based on its selected power-of-two period.

Let,

C^* : Cost of the optimal (EPQ) policy

$C^E :=$ $\min\{C(T = T_i^L), C(T = T_i^U)\}$

then,

$C^E \leq$ $1.06C^*$

$Q_i^E = D_i T_i^E$

If $T_i^E > T$, set $T_i^E = T$

(6) Once the production periods for all items are found, assign items to different periods so that the load on capacity is leveled. This is done by solving problem **P2** stated below. The objective function in problem P2 attempts to minimize the difference between the maximum and minimum loads on production capacity in all periods of a production cycle.

Let,

T : Length of production cycle

i : Index for items

j : Index for periods within production cycle $= \{1, 2, ..., T\}$

k: Number of basic periods in production cycle

s_i : Setup time for item i

x_{ij} : 1 if item i is produced in period j

0 otherwise

U, L : Maximum and minimum loads, respectively, on the production capacity in any period within the production cycle

Problem P2: Minimize $U - L$

st

$$\sum_i s_i x_{ij} + \left(Q_i^E / p_i\right) x_{ij} \le U \qquad \forall j$$

$$\sum_i s_i x_{ij} + \left(Q_i^E / p_i\right) x_{ij} \ge L \qquad \forall j$$

$$\sum_j x_{ij} = T / T_i^E \qquad \forall i$$

$$x_{ij} = x_{i\left(j+T_i^E\right)} \qquad \forall i, \quad \forall j \le T - T_i^E$$

x_{ij} is binary

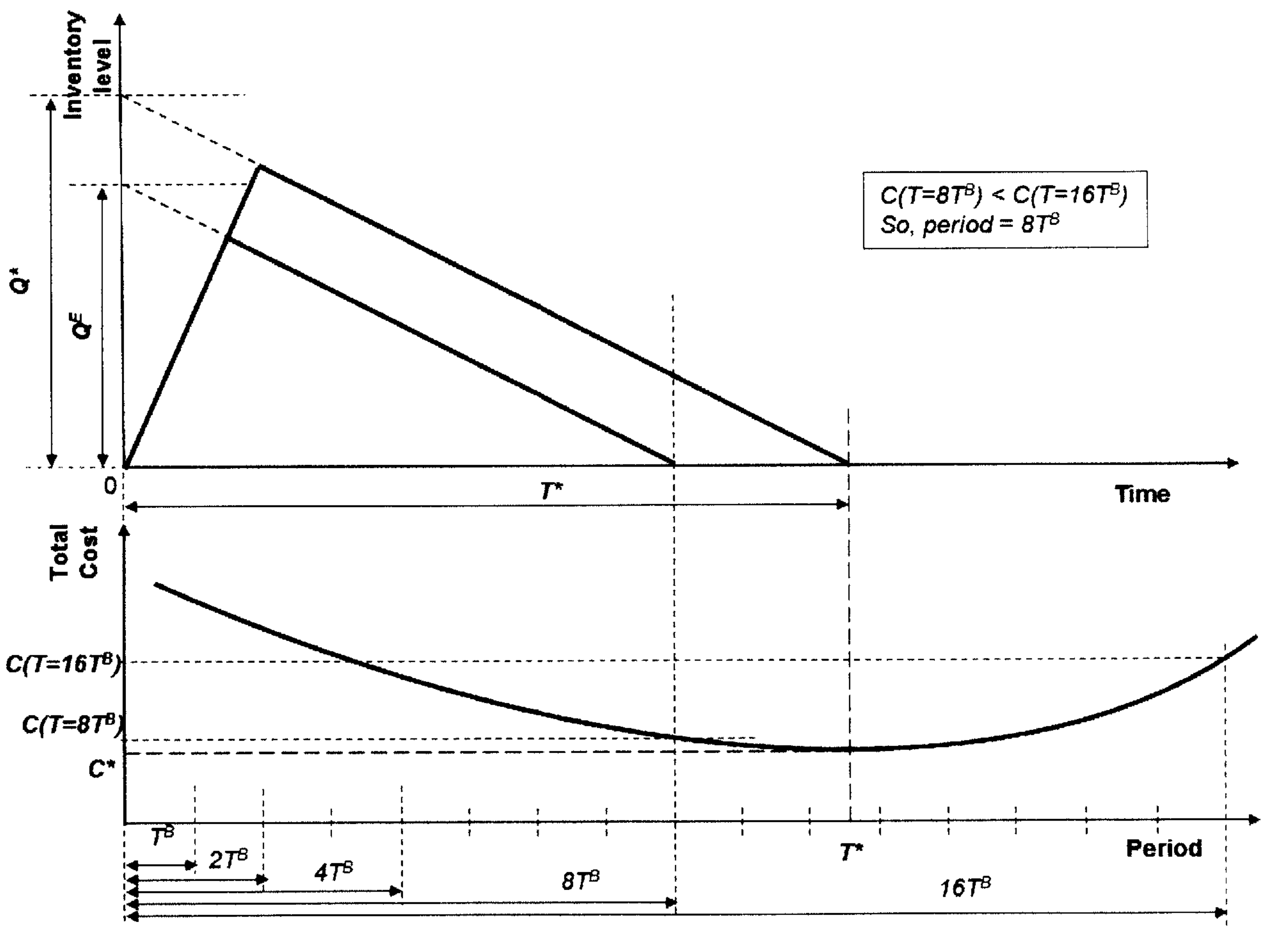

Figure 8: Choosing Best Power-of-Two Period Based on Optimal Period and Cost

4.3.2 Heuristic Stage-2: Base Stock Policy Based on Deterministic Solution

(7) For each item, calculate standard deviation in demand for the duration of that item's period (T_i^E) calculated in stage-1.

Let,

σ_i^t : Std deviaiton in demand over period t for item i

σ_i : Std deviaiton in demand for item i over its production period (T_i^E)

then,

$$\sigma_i = \sigma_i^t \sqrt{T_i^E / t}$$

(8) For each item, calculate safety stock (SS_i) based on distribution of demand and the desired customer service level. Then calculate base stock by adding safety stock to the production lot size (Q_i^E).

Let

SS_i : Safety stock for product i

S_i : Base stock for product i

$f(x)$: Normalized demand distribution for product i

c : Desired custmer service level

k : Safety factor

then,

Find k such that $\int_{-\infty}^{k} f(x)dx = c$

$$SS_i = k\sigma_i$$

$$S_i = Q_i^E + SS_i$$

(9) END.

4.4 Summary

This chapter provided a formal definition and the mathematical model of the production planning problem faced by Company-X's manufacturing plant at Location-Z. The chapter also listed all the assumptions made in building the model and later in developing the solution. Finally, the heuristic procedure developed to solve this problem is described. Next, this heuristic is applied to the data collected at Company-X; Chapter 5 provides a step-by-step illustration of the application of this heuristic to Company-X and presents the results.

Chapter 5 Data and Analysis

This chapter presents the application of the heuristic developed in Chapter 4 to the production planning problem faced by Company-X's Location-Z described in Chapter 3. The chapter is organized in five sections. The first section provides information about the data collected for and used in the analysis. It describes the logic behind choosing a subset of the collected data for use in the analysis. The second section describes the method used for grouping various products into product groups. Demand data is gathered for these product groups, and section 5.3 describes the preliminary calculations performed with this demand data. This section also presents the production rates for various product groups. Section 5.4 provides a step-by-step illustration of the application of the heuristic procedure described in Chapter 4 to develop production plans for Company-X. This section presents the production plans and discusses how sequence-dependent setup times affect the production policy. The production plans developed in section 5.4 are then tested using simulation. Section 5.5 describes the design of the simulation experiments and presents the results.

5.1 Data Collected

Three types of data were collected for developing the production and inventory planning policies: demand, production process characteristics, and parameters used for inventory planning. The type of data collected and its description are given below:

Monthly demand data of three years (between Jan 2004 and Dec 2006) for all SKU's belonging to product family Product-Y was collected. In the first phase of the analysis, SKU's are segmented into product groups for making inventory policies; monthly demand for each product group is the sum of the demands of individual SKU's belonging to that product group. (Inventory segmentation is discussed in section 5.2). After initial analysis of the demand data, I decided to use demand information from Jan-06 through Dec-06 period for further analysis. The reason for choosing the demand from this particular period is given in section 5.3.1. Exhibit 1 shows the monthly demand information for all product groups for year 2006 used in the analysis.

The production process parameters include processing speed and setup changeover times. The process operates at two different speeds based on the color of the film being produced. As mentioned in section 3.3, a colored film is produced at 121.5 ft/minute and a clear film is produced at 112.5 ft/minute. The production line can produce two rolls simultaneously as long as the combined width of the two rolls is up to 2.05 meters. The setup times are sequence-dependent. Setup times required for changing the production over from one product group to another are much longer than those to changeover from one SKU to another within a product group (see section 3.3.1 for details). Since production plans are developed for product groups and not for SKU's, setup times used in the analysis are based on changeover times between different product groups. Exhibit 2 lists the changeover time when process is switched from producing product group listed in the column to the one listed in rows.

Finally, the three parameters used in inventory planning are listed in Table 3 below.

Parameter	**Value**
Inventory holding cost	$0.105 per square meter per month
Setup cost	$10,000 per hour of setup time
Desired customer service level	95% or better availability

Table 3: Data Used for Inventory Planning

5.2 Inventory Segmentation

Before applying the production planning methods discussed in Chapter 4 to Company-X, individual items are segmented into product groups. Production plans are developed for each product group and not an individual item. The similarity in product characteristics as represented by setup changeover times is used for forming product groups. There are six differentiating factors for each film roll produced: adhesive, color, length of the roll, width of the roll, width of the colored band, and orientation of the roll. As described in sections 3.2 and 3.3.1, changing the process over from production of one campaign (combination of adhesive and color) to another takes the longest time, whereas changing the production within a campaign is very quick (see Table 1). Therefore, each adhesive-color combination is chosen as a product group.

5.3 Analysis of Demand Data

This section presents the analysis performed on the demand data before using it to develop production plans. This analysis is done for three reasons: to determine which subset of the historic demand information is appropriate to use for developing production planning policies for future use, to calculate average width of the film roll ordered so that demand information can be converted from square meters to meters (since production rate is in meters per unit time), and to calculate average and standard deviation of demand for the basic period for calculating safety stock and base stock levels.

5.3.1 Selection of Demand Data for Use in Analysis

Figure 9 compares the average values and variability in monthly demand (expressed in square meters) of 21 product groups based on three years (2004 to 2006) and one year of data (2006).

	P01	P11	P12	P13	P14	P15	P21	P22	P23	P24
Summary (monthly demand from Jan 2004 to Dec 2006)										
Average	3,602	401,058	369,640	26,468	141,670	498	25,800	187,005	160,882	67,281
StDev	6,493	227,837	115,666	8,086	42,356	675	43,280	74,796	41,113	16,303
COV	1.80	0.57	0.31	0.31	0.30	1.36	1.68	0.40	0.26	0.24
Summary (monthly demand from Jan 2006 to Dec 2006)										
Average	10,529	579,400	474,359	29,374	115,242	837	15,131	156,697	123,306	65,195
StDev	7,394	246,675	75,088	9,399	27,075	584	21,606	69,805	32,445	17,950
COV	0.70	0.43	0.16	0.32	0.23	0.70	1.43	0.45	0.26	0.28

	P31	P32	P33	P34	P41	P42	P43	P44	P51	P52	P53
Summary (monthly demand from Jan 2004 to Dec 2006)											
Average	16,242	104,123	39,828	12,413	119,366	237,664	110,733	93,624	5,503	12,911	7,734
StDev	22,137	69,787	25,152	16,384	58,058	88,459	34,288	28,607	8,384	11,964	6,253
COV	1.36	0.67	0.63	1.32	0.49	0.37	0.31	0.31	1.52	0.93	0.81
Summary (monthly demand from Jan 2006 to Dec 2006)											
Average	30,604	115,658	45,321	12,002	161,291	165,460	81,431	78,866	13,685	13,350	4,440
StDev	28,164	99,602	24,497	19,913	47,539	31,993	31,006	12,960	9,094	5,613	2,814
COV	0.92	0.86	0.54	1.66	0.29	0.19	0.38	0.16	0.66	0.42	0.63

Figure 9: Average and Variability of Monthly Demand (in SQM)

The high-demand low-variability product groups – viz. P11, P12, P14, P22, P23, P24, P41, P42, P43, and P44 – are the same in both datasets. These products are ordered regularly and have high volumes. Similarly, the low-demand high-variability product groups – viz. P01, P15, P21, P31, P33, P34, P51, and P53 – are the same in both datasets. Thus, demands for most product groups have the same characteristics in both datasets. For this reason, as well as based on insights of plant personnel about demand characteristics, it was decided that demand data for 2006 was a better source to develop production planning guidelines for future. The analysis presented in this chapter from this point onward is based on the 12-month demand data from year 2006.

5.3.2 Determination of Average Roll Widths

Table 4 shows the average width of each product group ordered based on demand information available in square meters and total roll length.

Calculation of Average Roll Width (m)			
Prod Group	Total SQM	Total length (m)	AvgWidth (m)
P01	94,763	51,728	1.83
P11	5,214,598	5,586,499	0.93
P12	4,269,232	4,932,140	0.87
P13	264,367	273,676	0.97
P14	1,037,180	1,119,087	0.93
P15	7,532	7,420	1.02
P21	136,177	135,675	1.00
P22	1,410,271	1,518,006	0.93
P23	1,109,751	1,140,292	0.97
P24	586,758	603,266	0.97
P31	275,440	297,360	0.93
P32	1,040,922	1,088,721	0.96
P33	407,889	421,142	0.97
P34	108,014	116,883	0.92
P41	1,451,615	1,519,733	0.96
P42	1,489,144	1,566,222	0.95
P43	732,882	712,242	1.03
P44	709,791	766,158	0.93
P51	123,163	139,275	0.88
P52	120,150	115,650	1.04
P53	39,956	41,850	0.95
	20,629,594	22,153,024	0.931

Table 4: Calculation of Average Roll Width for Each Product Group

The average width of each product group calculated in this table is used for converting the demand and forecast data, which is expressed as area in square meters, into length of the film to produce. This is done to express demand in the same units as the production rate, which is known in length per unit time (ft/min or m/min).

5.3.3 Average and Standard Deviation of Demand for Basic Period

Figure 10 shows the average and the standard deviation of demand for each product group expressed in monthly and basic-period time buckets. The basic period used here is three weeks. The average demand for the basic period is 0.7 (= 21/30) times the monthly demand, and has standard deviation of $\sqrt{21/30} = 0.837$ times that for the monthly demand.

	P01	P11	P12	P13	P14	P15	P21	P22	P23	P24
Statistics of monthly demand (in SQM)										
Average	7,897	434,550	355,769	22,031	86,432	628	11,348	117,523	92,479	48,896
StDev	5,545	185,007	56,316	7,049	20,306	438	16,205	52,354	24,334	13,462
COV	0.70	0.43	0.16	0.32	0.23	0.70	1.43	0.45	0.26	0.28
Statistics of demand for 3-week basic period (SQM)										
Average	5,528	304,185	249,039	15,421	60,502	439	7,944	82,266	64,735	34,228
StDev	4,639	154,788	47,117	5,898	16,989	367	13,558	43,802	20,359	11,263
COV	0.84	0.51	0.19	0.38	0.28	0.83	1.71	0.53	0.31	0.33

	P31	P32	P33	P34	P41	P42	P43	P44	P51	P52	P53
Statistics of monthly demand (in SQM)											
Average	22,953	86,743	33,991	9,001	120,968	124,095	61,073	59,149	10,264	10,013	3,330
StDev	21,123	74,701	18,373	14,935	35,654	23,995	23,254	9,720	6,821	4,210	2,110
COV	0.92	0.86	0.54	1.66	0.29	0.19	0.38	0.16	0.66	0.42	0.63
Statistics of demand for 3-week basic period (SQM)											
Average	16,067	60,720	23,794	6,301	84,678	86,867	42,751	41,404	7,184	7,009	2,331
StDev	17,673	62,500	15,372	12,495	29,830	20,076	19,456	8,132	5,707	3,522	1,766
COV	1.10	1.03	0.65	1.98	0.35	0.23	0.46	0.20	0.79	0.50	0.76

Figure 10: Conversion of Demand Characteristic from Monthly to Basic Period

5.3.4 Determination of Production Rate

As mentioned in section 2.4.3.1, the necessary condition for an ELSP schedule to be feasible is that the sum of the ratios of the production rate to the demand rate for all products be less than 1. As mentioned previously in sections 3.3 and 5.1, the speed of the production line is a function of the color of the film being produced. Also, the line is capable of producing two rolls simultaneously, provided that the combined width of the rolls is not more than 2.05 meters. Rough cut production capacity of the line and the production rate can be determined for each product group based on its color and average roll width. Figure 11 below shows the production rate calculated for each product group based on the color and the average roll width.

	P01	P11	P12	P13	P14	P15	P21	P22	P23	P24
Film Color	Clear	Clear	Color	Color	Color	Color	Clear	Color	Color	Color
Line Speed (m/min)	34.29	34.29	37.04	37.04	37.04	37.04	34.29	37.035	37.035	37.035
Line Speed (m/hr)	2057.4	2057.4	2,222	2222.1	2222.1	2222.1	2057.4	2222.1	2222.1	2222.1
Avg Roll Width (m)	1.83	0.93	0.87	0.97	0.93	1.02	1.00	0.93	0.97	0.97
# of simult. rolls	1	2	2	2	2	2	2	2	2	2
Effect. prod rate (m/hr)	2057.4	4114.8	4444.2	4444.2	4444.2	4444.2	4114.8	4444.2	4444.2	4444.2

	P31	P32	P33	P34	P41	P42	P43	P44	P51	P52	P53
Film Color	Clear	Color	Color	Color	Clear	Color	Color	Color	Clear	Color	Color
Line Speed (m/min)	34.29	37.04	37.04	37.04	34.29	37.04	37.04	37.04	34.29	37.035	37.035
Line Speed (m/hr)	2,057.4	2,222.1	2,222.1	2,222.1	2,057.4	2,222.1	2,222.1	2,222.1	2,057.4	2,222.1	2,222.1
Avg Roll Width	0.93	0.96	0.97	0.92	0.96	0.95	1.03	0.93	0.88	1.04	0.95
# of simult. rolls	2	2	2	2	2	2	1	2	2	1	2
Effect. prod rate (m/hr)	4114.8	4444.2	4444.2	4444.2	4114.8	4444.2	2222.1	4444.2	4114.8	2222.1	4444.2

Figure 11: Determination of Production Rate for Each Product Group

5.4 Application of Heuristic to Develop Production Plans

This section describes the application of the heuristic presented in section 4.3 to Company-X in a step-by-step fashion. The data used for calculating individual item economic production quantities (EPQ) and economic production periods is shown in Figure 12. Demand is expressed in meters, and production and demand rates are expressed in meters per hour. The production rate for each product group is taken from Figure 11. The sum of the demand rate to production rate ratios for all product groups (shown in Figure 12) is 0.616 < 1.

	P01	P11	P12	P13	P14	P15	P21	P22	P23	P24
Average demand for Basic Period (m)	3,017	325,879	287,708	15,964	65,280	433	7,914	88,550	66,517	35,191
Demand rate (m/hr)	6.0	646.6	570.8	31.7	129.5	0.9	15.7	175.7	132.0	69.8
Production rate (m/hr)	2057.4	4114.8	4444.2	4444.2	4444.2	4444.2	4114.8	4444.2	4444.2	4444.2
Demand Rate / Production Rate	0.003	0.157	0.128	0.007	0.029	0.000	0.004	0.040	0.030	0.016
Minimum setup time (hrs)	6.00	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Minimum setup cost ($)	$60,000	$7,500	$7,500	$7,500	$7,500	$7,500	$7,500	$7,500	$7,500	$7,500

	P31	P32	P33	P34	P41	P42	P43	P44	P51	P52	P53
Average demand for Basic Period (m)	17,346	63,509	24,567	6,818	88,651	91,363	41,547	44,693	8,124	6,746	2,441
Demand rate (m/hr)	34.4	126.0	48.7	13.5	175.9	181.3	82.4	88.7	16.1	13.4	4.8
Production rate (m/hr)	4114.8	4444.2	4444.2	4444.2	4114.8	4444.2	2222.1	4444.2	4114.8	2222.1	4444.2
Demand Rate / Production Rate	0.008	0.028	0.011	0.003	0.043	0.041	0.037	0.020	0.004	0.006	0.001
Minimum setup time (hrs)	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Minimum setup cost ($)	$7,500	$7,500	$7,500	$7,500	$7,500	$7,500	$7,500	$7,500	$7,500	$7,500	$7,500

Figure 12: Parameters for Calculating Economic Production Quantities

Step-1: Three weeks is used as the basic period. This is done because the production process runs continuously for three weeks between two consecutive planned shutdowns for periodic maintenance, and production plans are made for each three-week period.

Step-2: The longest period allowed for any product is taken as 48 weeks. The reason for choosing 48 weeks is that it corresponds to fourth-power-of-two multiple of the basic period (48 = 3 x 2^4) and roughly equals one year. And if there was demand for a product in the 12-month period in 2006, the product could be demanded and manufactured at least once in a year.

It is difficult to determine the setup cost for each product group since setup time, which determines the setup cost, is sequence-dependent and production sequence is not known before the initial calculations of the economic production quantity (EPQ). Therefore, the setup cost for a particular product group is taken to be the least time required to change the process over to produce that particular product group.

Steps 3 & 4: Figure 13 shows the economic production quantity (EPQ) and the economic production period for each item. For each item, the power-of-two periods immediately smaller and immediately greater than the economic period are selected as two alternative periods. Two exceptions to this rule are when economic period is longer than the longest period allowed (in this case, it is 16 basic periods) or less than one. In case of former, both alternatives equal to largest period allowed and in case of latter both are 1.

	P01	P11	P12	P13	P14	P15	P21	P22	P23	P24
EPQ (in meters)	70,191	280,499	259,186	57,202	116,976	9,386	40,209	136,973	118,112	85,297
Period (hours)	11,723.9	433.8	454.0	1,805.9	903.1	10,929.7	2,560.6	779.6	894.9	1,221.6
Period (days)	488.5	18.1	18.9	75.2	37.6	455.4	106.7	32.5	37.3	50.9
Period (# of basic periods)	23.3	0.9	0.9	3.6	1.8	21.7	5.1	1.5	1.8	2.4
Integer period options for Basic Period										
Period (Opt-1)	16	1	1	2	1	16	4	1	1	2
Period (Opt-2)	16	1	1	4	2	16	8	2	2	4
Prod Quantity (Option-1) (m)	48,279	325,879	287,708	31,929	65,280	6,925	31,658	88,550	66,517	70,381
Prod Quantity (Option-2) (m)	48,279	325,879	287,708	63,858	130,560	6,925	63,315	177,101	133,034	140,762
Costs ($/basic period) of optimal and integer period options:										
EPQ	$5,159	$17,427	$16,651	$4,186	$8,371	$692	$2,952	$9,697	$8,448	$6,188
Opt-1	$5,524	$17,623	$16,741	$4,918	$9,836	$724	$3,037	$10,635	$9,879	$6,303
Opt-2	$5,524	$17,623	$16,741	$4,212	$8,422	$724	$3,262	$10,019	$8,507	$6,981

	P31	P32	P33	P34	P41	P42	P43	P44	P51	P52	P53
EPQ (in meters)	59,663	115,331	71,097	37,306	137,281	139,223	93,705	96,333	40,741	37,164	22,301
Period (hours)	1,733.6	915.3	1,458.6	2,757.7	780.5	768.0	1,136.7	1,086.4	2,527.4	2,776.5	4,604.1
Period (days)	72.2	38.1	60.8	114.9	32.5	32.0	47.4	45.3	105.3	115.7	191.8
Period (# of basic periods)	3.4	1.8	2.9	5.5	1.5	1.5	2.3	2.2	5.0	5.5	9.1
Integer period options for Basic Period											
Period (Opt-1)	2	1	2	4	1	1	2	2	4	4	8
Period (Opt-2)	4	2	4	8	2	2	4	4	8	8	16
Prod Quantity (Option-1) (m)	34,692	63,509	49,133	27,273	88,651	91,363	83,095	89,385	32,498	26,985	19,530
Prod Quantity (Option-2) (m)	69,384	127,017	98,266	54,545	177,302	182,726	166,190	178,770	64,995	53,970	39,060
Costs ($/period) of optimal and integer period options:											
EPQ	$4,361	$8,260	$5,183	$2,741	$9,686	$9,844	$6,651	$6,959	$2,991	$2,723	$1,642
Opt-1	$5,018	$9,774	$5,541	$2,877	$10,628	$10,730	$6,699	$6,979	$3,068	$2,864	$1,656
Opt-2	$4,411	$8,298	$5,457	$2,942	$10,005	$10,210	$7,773	$8,332	$3,324	$2,915	$1,907

Figure 13: Periods and Cost of Optimal and Power-of-Two Policies

Step 5: Figure 13 also shows the total cost of the EPQ policy as well as both power-of-two alternatives. For each product group, the alternative with the lower cost of the two options and the corresponding power-of-two period are highlighted. These periods highlighted and corresponding production quantities will be used for those product groups.

The total cost of all items in the EPQ policy is \$140,812 and that for the best power-of-two options for all items is \$143,636, which is 2.01% greater than the optimal cost.

Step 6: After calculating the best production period as a power-of-two multiple of the basic period for each item, product groups are assigned to periods within the production cycle by solving problem P2, as shown in Table 5.

Period	P01	P11	P12	P13	P14	P15	P21	P22	P23	P24	P31	P32	P33	P34	P41	P42	P43	P44	P51	P52	P53
Period	16	1	1	4	2	16	4	2	2	2	4	2	4	4	2	2	2	2	4	4	8
1		1	1						1				1		1	1	1				
2		1	1	1	1			1		1		1		1				1			
3		1	1						1		1				1	1	1				1
4		1	1		1		1	1		1		1						1	1	1	
5		1	1						1				1		1	1	1				
6		1	1	1	1			1		1		1		1				1			
7	1	1	1						1		1				1	1	1				
8		1	1		1		1	1		1		1						1	1	1	
9		1	1						1				1		1	1	1				
10		1	1	1	1			1		1		1		1				1			
11		1	1						1		1				1	1	1				1
12		1	1		1		1	1		1		1						1	1	1	
13		1	1						1				1		1	1	1				
14		1	1	1	1			1		1		1		1				1			
15		1	1			1			1		1				1	1	1				
16		1	1		1		1	1		1		1						1	1	1	

Table 5: Assignment of Product Groups to Production Periods

Figure 14 shows the loads on production capacity with and without leveled production. If production were not leveled by assigning product groups to different periods as shown in Table 5 above and all product groups were produced in the periods that are integer multiples of their production periods, the variability in load on the production capacity is very high. This is shown with a dashed line in Figure 14. The load on production capacity in a period varies between 0.553 million SQM and 2.119 million SQM. The coefficient of variation of the load on production capacity in this case is 0.569. Besides the high variability, the unleveled production plan also violates the capacity constraint in some periods. In Figure 14, these periods are where the dashed line crosses a thick solid line, which represents the approximate productive capacity[3] available at the plant (1.547 million square meters). The unleveled production depicted with the dashed line in Figure 14 is the worst-case scenario.

After assigning product groups to different periods as shown in **Error! Reference source not found.**, the variation in load on the production capacity is significantly reduced. Production capacity needed in each period with this leveled production is shown with a thin solid line in Figure 14, and it varies between 1.183 million SQM and 1.264 million SQM. The coefficient of variation in load on production capacity is reduced to 0.014.

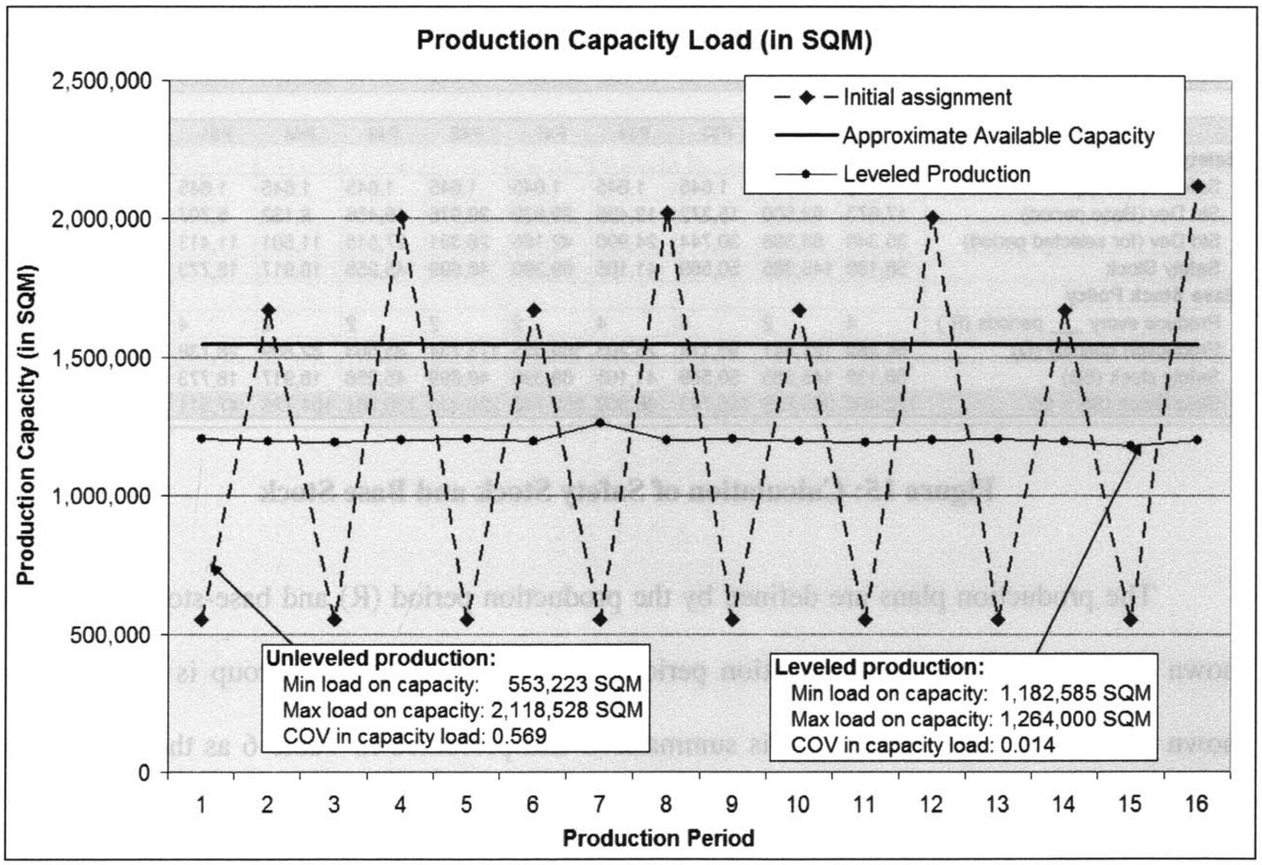

Figure 14: Load on Production Capacity in Unleveled and Leveled Production Plans

[3] The "approximate productive capacity" is based on average film width of 0.931 meters and expected process uptime of 82.4%.

<u>Steps 7 & 8:</u> Figure 15 below shows the calculation of safety stock and base stock. Safety stock is calculated to provide 95% or better material availability. We assume that the demand for each product group is normally distributed (therefore, safety factor = 1.645). The standard deviation is adjusted from the basic period to that for the actual production period for each product group.

	P01	P11	P12	P13	P14	P15	P21	P22	P23	P24
Safety Stock Calculations										
Safety factor (k)	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645
Std Dev (Base period)	4,639	154,788	47,117	5,898	16,989	367	13,558	43,802	20,359	11,263
Std Dev (for selected period)	18,558	154,788	47,117	11,796	24,027	1,466	27,116	61,946	28,792	15,929
Safety Stock	30,525	254,603	77,501	19,403	39,520	2,412	44,602	101,892	47,358	26,201
Base Stock Policy										
Produce every ___ periods (R)	16	1	1	4	2	16	4	2	2	2
Production quantity (Q)	88,445	304,185	249,039	61,686	121,004	7,030	31,775	164,532	129,471	68,455
Safety stock (SS)	30,525	254,603	77,501	19,403	39,520	2,412	44,602	101,892	47,358	26,201
Base Stock (SS + Q)	118,970	558,788	326,539	81,088	160,525	9,442	76,376	266,423	176,829	94,656

	P31	P32	P33	P34	P41	P42	P43	P44	P51	P52	P53
Safety Stock Calculations											
Safety factor (k)	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645
Std Dev (Base period)	17,673	62,500	15,372	12,495	29,830	20,076	19,456	8,132	5,707	3,522	1,766
Std Dev (for selected period)	35,346	88,388	30,744	24,990	42,186	28,391	27,515	11,501	11,413	7,044	4,994
Safety Stock	58,139	145,385	50,569	41,105	69,390	46,699	45,258	18,917	18,773	11,587	8,215
Base Stock Policy											
Produce every ___ periods (R)	4	2	4	4	2	2	2	2	4	4	8
Production quantity (Q)	64,269	121,441	95,174	25,203	169,355	173,734	85,503	82,809	28,738	28,035	18,646
Safety stock (SS)	58,139	145,385	50,569	41,105	69,390	46,699	45,258	18,917	18,773	11,587	8,215
Base Stock (SS + Q)	122,408	266,826	145,743	66,309	238,746	220,433	130,761	101,726	47,511	39,622	26,861

Figure 15: Calculation of Safety Stock and Base Stock

The production plans are defined by the production period (R) and base-stock levels (S) shown in Figure 15 and the production periods in which each product group is produced as shown in Table 5. This information is summarized and presented in Table 6 as the Production Plans for Company-X's Location-Z Production Facility.

Prod Group	Base Stock (S)	Period (R)	Produce in periods showing "1"															
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
P01	118,970	16							1									
P11	558,788	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
P12	326,539	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
P13	81,088	4		1				1				1				1		
P14	160,525	2		1		1		1		1		1		1		1		1
P15	9,442	16															1	
P21	76,376	4				1				1				1				1
P22	266,423	2		1		1		1		1		1		1		1		1
P23	176,829	2	1		1		1		1		1		1		1		1	
P24	94,656	2		1		1		1		1		1		1		1		1
P31	122,408	4			1				1				1				1	
P32	266,826	2		1		1		1		1		1		1		1		1
P33	145,743	4	1				1				1				1			
P34	66,309	4		1				1				1				1		
P41	238,746	2	1		1		1		1		1		1		1		1	
P42	220,433	2	1		1		1		1		1		1		1		1	
P43	130,761	2	1		1		1		1		1		1		1		1	
P44	101,726	2		1		1		1		1		1		1		1		1
P51	47,511	4				1				1				1				1
P52	39,622	4				1				1				1				1
P53	26,861	8			1								1					

Table 6: Production Plans for Company-X's Location-Z Production Facility

5.4.1 Evaluating Setup Times after Assigning Products Groups to Periods

Once the product groups are assigned to production periods, one knows which products are produced in each period and can develop a sequence in which product groups are produced within each production period. Once a production sequence is developed for each period, the actual setup times for each product group become known, and they could be different from the setup times assumed in the Economic Production Quantity (EPQ) calculations.

One could possibly develop a procedure to reiterate steps 3 through 6 of the heuristic until setup times after sequencing remain the same as those used in EPQ or some other stopping criteria, such as number of iterations, is met. This issue is not addressed in this thesis, and I will instead only mention how the change in setup cost from that assumed in the EPQ calculation will affect the inventory policy.

One example of a possible production sequence for each of 16 production periods and the corresponding changeover times is shown in Table 7. Out of the 21 product groups used in the example, the actual setup times of 16 product groups are same as the ones used in the EPQ calculations in all their production instances in the 16-period production cycle. For the remaining five product groups, viz. P01, P12, P13, P15, and P53, the actual changeover times deviate from the ones used in the EPQ calculations. The cells showing location of these products groups within each of the 16 production sequences and the corresponding changeover times are highlighted in grey cells in Table 7. The product groups are sequenced within each period such that all production instances of the five "deviant"[4] product groups require the same changeover time in the production cycle.

Production sequence:											Expected changeover time (hrs) between jobs:									Total c/o
Period	1	2	3	4	5	6	7	8	9	10	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	Hours
1	P11	P41	P43	P23	P33	P12	P42				0.75	0.75	0.75	0.75	3	0.75				6.75
2	P11	P44	P34	P24	P14	P13	P12	P22	P32		0.75	0.75	0.75	0.75	4	3	0.75	0.75		11.5
3	P11	P31	P41	P43	P23	P53	P12	P42			0.75	0.75	0.75	0.75	4	3	0.75			10.75
4	P51	P11	P21	P24	P44	P14	P12	P22	P32	P52	0.75	0.75	0.75	0.75	0.75	3	0.75	0.75	0.75	9
5	P11	P41	P43	P23	P33	P12	P42				0.75	0.75	0.75	0.75	3	0.75				6.75
6	P11	P44	P34	P24	P14	P13	P12	P22	P32		0.75	0.75	0.75	0.75	4	3	0.75	0.75		11.5
7	P01	P11	P31	P41	P23	P43	P12	P42			3	0.75	0.75	0.75	0.75	3	0.75			9.75
8	P51	P11	P21	P24	P44	P14	P12	P22	P32	P52	0.75	0.75	0.75	0.75	0.75	3	0.75	0.75	0.75	9
9	P11	P41	P43	P23	P33	P12	P42				0.75	0.75	0.75	0.75	3	0.75				6.75
10	P11	P44	P34	P24	P14	P13	P12	P22	P32		0.75	0.75	0.75	0.75	4	3	0.75	0.75		11.5
11	P11	P31	P41	P43	P23	P53	P12	P42			0.75	0.75	0.75	0.75	4	3	0.75			10.75
12	P51	P11	P21	P24	P44	P14	P12	P22	P32	P52	0.75	0.75	0.75	0.75	0.75	3	0.75	0.75	0.75	9
13	P11	P41	P43	P23	P33	P12	P42				0.75	0.75	0.75	0.75	3	0.75				6.75
14	P11	P44	P34	P24	P14	P13	P12	P22	P32		0.75	0.75	0.75	0.75	4	3	0.75	0.75		11.5
15	P31	P41	P11	P23	P43	P15	P12	P42			0.75	0.75	0.75	0.75	4	3	0.75			10.75
16	P51	P11	P21	P24	P44	P14	P12	P22	P32	P52	0.75	0.75	0.75	0.75	0.75	3	0.75	0.75	0.75	9

Table 7: Production Sequence for Each Period and Changeover Times

[4] "Deviant" is not a technical term and used here for convenience to refer to the product groups whose actual setup times differ from the ones assumes in the EPQ calculations.

Product Group	Setup Time		Production Period	
	Original	Actual	Original	Actual
P01	6	3	16	16
P12	0.75	3	1	2
P13	0.75	4	4	8
P15	0.75	4	16	16
P53	0.75	4	8	16

Table 8: Change in Setup Times and Production Period for "Deviant" Product Groups

Table 8 shows the setup times assumed in the EPQ analysis and actual setup times (in hours) for the five "deviant" product groups. This table also shows whether and how the power-of-two production period (as number of basic periods) would change for each "deviant" product group if their economic production periods were to be recalculated based on the new setup times (and hence, setup costs).

5.5 Testing Production Plans Using Simulation

The production plan described above is tested using simulation to determine average inventory levels and percentage of stock-outs in stochastic demand. This section describes the design of the simulation experiment, explains the mechanics of implementation of the production plans, and then presents the results.

5.5.1 Design of Simulation Experiment

Given below are the design features of the simulation experiment.

- Number of simulation runs: 30
- Number of periods in each simulation run: 1600 basic periods (= 100 production cycles)
- Warm-up period in each simulation run: 32 basic periods (= 2 production cycles)

5.5.2 Mechanics of Implementation of Production Plans

Given below is a description of how the production plans are implemented in the simulation experiment.

- At the beginning of each period, Production Planning reviews the inventory level of all the product groups.
- Based on the inventory level of each product group observed at the beginning of the period, Production Planning determines the quantity to produce for the product groups that are to be produced in that period. For each product group, the quantity to produce is equal to the difference between its base stock level and current inventory level including any backorders. That is,

$$\begin{pmatrix} \text{Production} \\ \text{Quantity} \end{pmatrix} = \begin{pmatrix} \text{Base Stock} \\ \text{Level} \end{pmatrix} - \begin{pmatrix} \text{Inventory} \\ \text{Level} \end{pmatrix} + (\text{Backorders})$$

  The base stock levels and production periods for each item are provided in Table 6

- Demand is fulfilled at the end of the period from the inventory on hand. The inventory on hand at the end of the period includes the inventory carried forward from the previous period plus any amount produced in the current period.
- If demand is greater than available stock, all the available stock is used to fulfill the demand and a backorder is placed for the unmet demand.

5.5.3 Simulation Results and Summary

The results of the simulation experiment are summarized in three tables and a figure below. The tables show, for each product group, the number of occasions when the inventory level was negative, then number of occasions when the inventory level was below the safety stock level, and the average inventory level. Figure 16 shows the capacity utilization (in square meters) in each production period. The results are based on 1568 production periods (1600 periods – 32 periods used as warm-up period for a simulation run) from each simulation run.

Table 9 below shows the average, standard deviation, minimum, and maximum of the number of stockout occasions (i.e. production periods in which the inventory was insufficient to meet demand and a backorder was placed) for each product group in any simulation run. The average availability of any product group is given as:

$$\text{Average availability} = 1 - \frac{\text{Avg number of stockout occasions}}{(1600 - 32)}.$$

The average availability for all product groups considered together was 98.3%.

	P01	P11	P12	P13	P14	P15	P21	P22	P23	P24
Average	9.6	78.4	76.9	18.8	39.5	9.1	29.3	0.1	38.4	38.8
Std Dev	4.6	6.7	7.2	4.5	7.5	4.6	5.4	0.3	6.3	5.6
Min	0	66	61	11	23	1	17	0	28	27
Max	20	94	92	27	52	19	37	1	50	49
Avg Availability	0.994	0.950	0.951	0.988	0.975	0.994	0.981	1.000	0.975	0.975

	P31	P32	P33	P34	P41	P42	P43	P44	P51	P52	P53
Average	23.6	39.5	0.0	29.7	0.0	0.0	39.9	39.9	21.2	19.5	13.2
Std Dev	5.4	5.9	0.0	8.1	0.0	0.0	5.7	5.9	4.1	3.7	4.7
Min	10	29	0	17	0	0	28	30	14	11	4
Max	33	52	0	51	0	0	53	51	31	26	22
Avg Availability	0.985	0.975	1.000	0.981	1.000	1.000	0.975	0.975	0.986	0.988	0.992

Table 9: Simulation Results: Number of Stockout Occasions and Availability

For instance, in Table 9 above for product group P23, the number of production period where inventory level dropped below zero varied between 28 and 50 in 30 simulation runs. The average number of stockout occasions among all simulation runs was 38.4 with a standard deviation of 6.3. Based on the average of 38.4 stockout occasions in 1568 production periods, P23 was available in 97.5% periods.

Table 10 below shows the average, standard deviation, minimum, and maximum of the number of production periods when inventory level dropped below the safety stock level. This result also includes the occasions when inventory position was below zero as reported in Table 9.

	P01	P11	P12	P13	P14	P15	P21	P22	P23	P24
Average	172.0	785.2	783.5	222.0	389.6	163.5	538.1	48.1	391.4	397.7
Std Dev	17.3	17.9	25.6	9.1	9.5	20.6	21.2	7.6	14.6	13.8
Min	128	737	711	203	366	104	500	34	355	370
Max	200	837	849	239	408	200	579	66	441	419
Avg below SS	0.110	0.501	0.500	0.142	0.248	0.104	0.343	0.031	0.250	0.254

	P31	P32	P33	P34	P41	P42	P43	P44	P51	P52	P53
Average	387.3	541.4	11.6	580.3	3.8	0.0	402.9	394.0	313.2	247.6	207.1
Std Dev	17.6	19.8	3.7	25.4	2.0	0.0	12.1	16.2	16.6	17.0	19.9
Min	348	507	5	538	0	0	384	362	275	216	158
Max	422	581	19	648	8	0	426	423	339	273	233
Avg below SS	0.247	0.345	0.007	0.370	0.002	0.000	0.257	0.251	0.200	0.158	0.132

Table 10: Simulation Results: Occasions when Inventory Level Below Safety Stock

For instance, the inventory level for product group P23 was below its safety stock level on average of 391.4 times, or about 25% of the time. On average, there were a total of 6980.3 production periods in which the inventory level for any of the 21 product groups was below its safety stock level in 1568 periods. Thus, on average 21.2% of the time (= 6980.3 / (21 x 1568)), the inventory level for a product group was below its safety stock level, including the occasions of stockout. Table 11 lists the average inventory levels in square meters for every product groups, and the combined average inventory on-hand for all product groups is 1,742,725 SQM.

	P01	P11	P12	P13	P14	P15	P21	P22	P23	P24
Average	69,519	256,323	78,346	42,571	70,198	5,551	50,562	183,852	80,180	43,304
Std Dev	993.6	3,452.9	1,453.3	341.4	555.4	88.0	631.2	1,247.7	878.8	465.5

	P31	P32	P33	P34	P41	P42	P43	P44	P51	P52	P53
Average	78,312	168,361	109,600	44,642	154,343	133,584	66,679	39,703	28,978	22,073	16,045
Std Dev	886.8	1,992.2	653.6	660.0	618.4	537.3	691.7	308.3	360.3	256.0	205.7

Table 11: Simulation Results: Average Inventory Levels (in SQM)

In the simulation experiment, a product group is produced in every period it is scheduled to be produced according to the production plan presented in Table 6, and the quantity is equal to the difference between a product group's base stock level and inventory position (including backorders) at the beginning of the period. So, it is important to know the distribution of the total capacity required for producing all product groups in any period and whether it exceeds the available capacity in any period. Figure 16 shows a histogram of the production capacity used by the average number of periods in each simulation run.

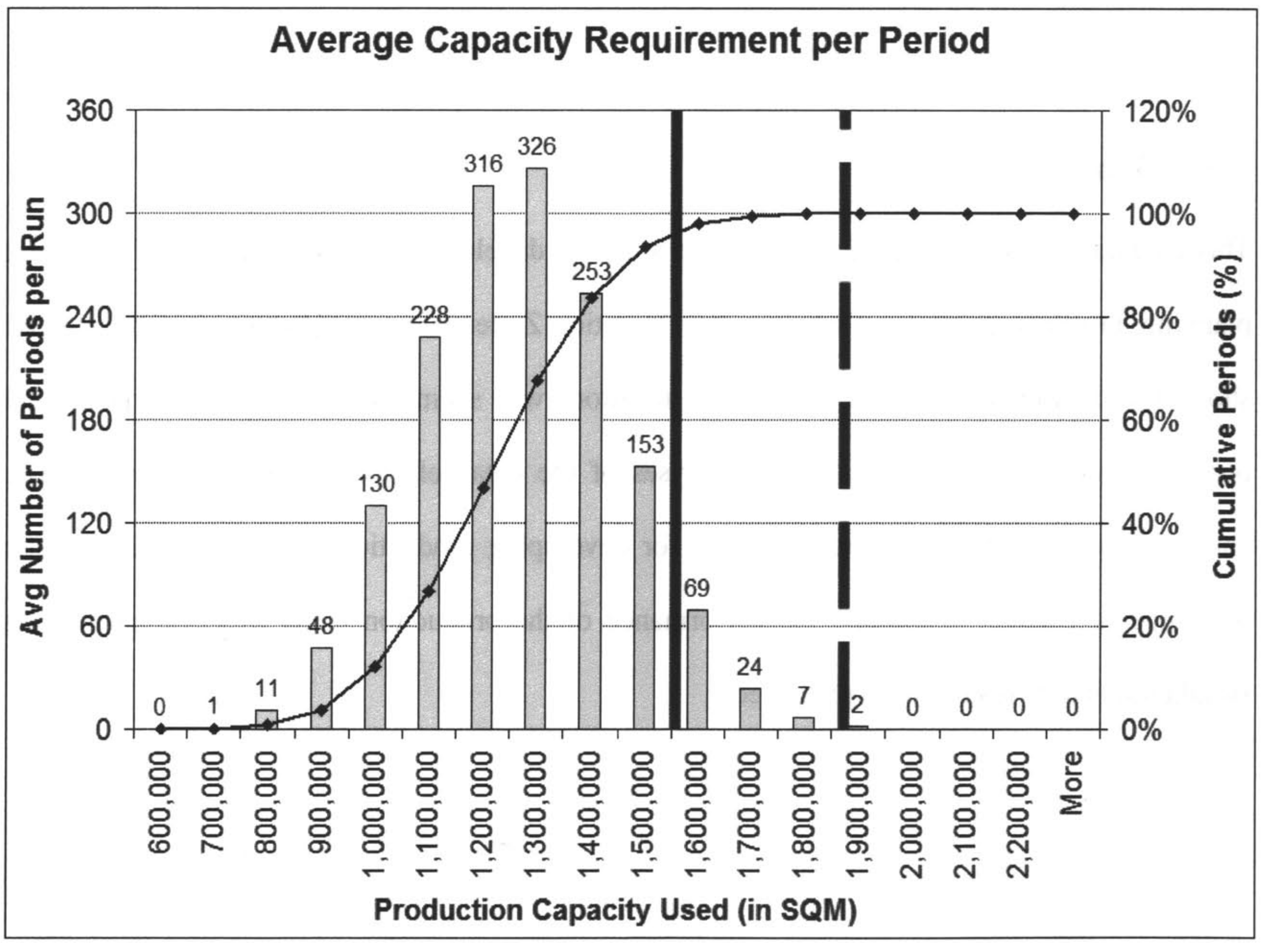

Figure 16: Capacity Requirement per Production Period (in SQM)

The vertical thick solid line in Figure 16 shows the approximate availability of production capacity (1.547 million square meters) based on average film width of 0.931 meters and current process uptime of 82.4%. This capacity is sufficient to meet production demand in 98% of the periods. The vertical think dotted line (capacity: 1.887 million square meters) shows the approximate productive capacity based on average film width of 0.931 meters and 100% uptime. At this capacity level, the production plant has sufficient capacity to meet demand in almost 99.87% (1566 out of 1568) of periods. This is a crude estimate of production capacity in the current operating conditions, and further analysis is needed to understand the behavior of actual availability of the productive capacity.

5.6 Summary

This chapter presented an application of the heuristic developed in Chapter 4 to the production planning problem faced by Company-X's Location-Z described in Chapter 3. The chapter showed what data was collected and how inventory was segmented into product groups, and presented some preliminary statistical analyses of the data before applying the heuristic. The chapter then illustrated the procedure used for developing production plans using the heuristic presented in Chapter 4. Finally, the performance of the production plans was evaluated using simulation and its results were presented.

Chapter 6 Implementation Guidelines

Till now this thesis work has described the theoretical background of the production planning problem studied and then showed how that understanding can be applied to an industrial setting to develop production planning policies for a manufacturing facility of Company-X. There are two important issues related to the implementation of the solution developed in Chapter 5 that require further treatment in this chapter. The two issues are: generation of an SKU schedule from the production plans developed for product groups, and understanding the effect of selection of a different basic period than one selected in Chapter 5.

6.1 Generating SKU Schedule from Production Plans for Product Groups

The production plans developed in Chapter 5 define a production schedule for product groups, but do not describe how SKU schedules should be generated. The information provided by the production plans for the product groups can be extended to scheduling the SKU's. This section presents some ideas about extending the methodology to scheduling SKU's. The ultimate choice of one or more of the methods presented below depends on Company-X's product strategy.

6.1.1 Standardize SKU's and Postpone Differentiating Operations

The most desirable solution for implementing the proposed scheduling method is to standardize the SKU's offered. The production planning method described in this thesis can then be applied to each individual standardized SKU's instead of applying to a product group.

If standardization of SKU's is not possible, Company-X may postpone the production processes that differentiate the SKU's. As described in section 3.2, much of the SKU proliferation results from a very high variety of roll widths offered by the company. It is technologically possible (and most likely feasible) to produce rolls to a standard width or to an assortment of standard widths, and cut the standard roll to the desired width later based on the actual demand. This option will allow Company-X to produce the product groups as described in Chapter 5 while offering the same range of SKU's differentiated by roll widths.

6.1.2 Segment Product Mix into Make-to-Order and Make-to-Stock

In the solution described in Chapter 5, Company-X's product offering was segmented into 21 product groups based on the adhesive-color combination of each SKU. Instead of using adhesive-color combination, product mix can be segmented into make-to-order (MTO) and make-to-stock (MTS) categories based on the repeatability of demand for each SKU. The heuristic developed in this thesis can be used directly for the make-to-stock SKU's.

The make-to-order (MTO) SKU's can be managed by forming subgroups of the MTO SKU's based on the adhesive-color combination, and then scheduling these MTO product groups along with the MTS items using the heuristic procedure described in this thesis. The primary source of SKU proliferation at Company-X is the variation in roll width, and there exist a few standard roll widths (see section 3.2 for details). When an MTO product group is scheduled to be produced, a SKU with actual demand can be produced. If there is no demand for an actual SKU, one with the standard width may be produced.

6.1.3 Use Product Group Schedule to Reserve Capacity

The cyclical ELSP schedule generated by the heuristic can be seen as a calendar showing the allocation of production capacity in various time periods for different product groups and items. Company-X can segment its product offering into make-to-stock and make-to-order categories as described in section 6.1.2 above, and schedule the MTS items using the heuristic described in Chapter 5. The production period and production capacity (based on production quantity) allocated to an MTO product group can be seen as a reservation of the production capacity for manufacturing any of the MTO items from that particular product group. When a customer places a new order and requests a quote for the expected delivery date for an MTO item, Company-X could provide the expected delivery date using the knowledge of the next production period allocated to the MTO product group to which the ordered item belongs. Thus, the cyclical schedule generated using the heuristic provided in this thesis can be used as a placeholder for make-to-order SKU's.

6.1.4 Summary of Methods for Generating SKU Schedules

Preceding sections provide three different ways of generating the SKU schedule using the methods described in this thesis. Company-X can choose one of these methods or a combination of them to extend the production scheduling method describe in this thesis to schedule SKU's. The choice of the method depends on Company-X's product and operations strategy.

6.2 Selection of a Different Basic Period

The production plans developed in Chapter 5 assume the basic period of 21 days. Company-X may choose a different basic period. Table 12 shows how the production plans change by changing the basic period and the length of the maximum period allowed for any product group. The table shows base stock level (in square meter), production period (in number of basic periods), and the cost of the production policy compared to the cost of the economic production quantity (EPQ) policy for four different options:

- 7-day basic period with longest period allowed to be 16 basic periods (approx. 4 months)

- 7-day basic period with longest period allowed to be 32 basic periods (approx. 8 months)
- 14-day basic period with longest period allowed to be 16 basic periods (approx 8 months)
- 28-day basic period with longest period allowed to be 8 basic periods (approx. 8 months)

Basic Period Max Period	7 days 16 basic periods		7 days 32 basic periods		14 days 16 basic periods		28 days 8 basic periods	
Product Group	Base Stock sq meter	Period basic periods	Base Stock sq meter	Period basic periods	Base Stock sq meter	Period basic periods	Base Stock sq meter	Period basic periods
P01	27,451	16	44,578	32	64,232	16	103,541	8
P11	429,183	4	429,183	4	564,377	2	834,763	1
P12	200,174	4	200,174	4	310,858	2	532,226	1
P13	49,820	16	49,820	16	77,236	8	132,068	2
P14	99,414	8	99,414	8	153,194	4	139,828	1
P15	2,174	16	3,532	32	5,094	16	8,218	8
P21	65,624	16	101,078	32	79,746	8	107,990	4
P22	190,779	8	190,779	8	156,319	2	229,444	1
P23	112,228	8	112,228	8	169,770	4	153,753	1
P24	103,635	16	103,635	16	91,103	4	151,952	2
P31	95,697	16	95,697	16	124,261	8	104,599	2
P32	221,850	8	221,850	8	275,824	4	226,654	1
P33	100,692	16	100,692	16	83,589	4	125,889	2
P34	58,666	16	89,528	32	69,867	8	92,270	4
P41	155,394	8	155,394	8	131,926	2	207,195	1
P42	131,139	8	131,139	8	115,345	2	192,560	1
P43	149,908	16	149,908	16	128,262	4	204,264	2
P44	58,648	8	58,648	8	95,452	4	89,054	1
P51	34,450	16	56,201	32	47,222	8	72,767	4
P52	25,839	16	43,841	32	38,299	8	63,219	4
P53	10,851	16	17,773	32	26,060	16	42,634	8
(Policy cost) / (EPQ cost)	1.1436		1.0528		1.0485		1.0537	

Table 12: Effect of Choosing Different Basic Periods

It can be seen from Table 12 that for the first option of 7-day basic period with maximum16 periods allowed, more than half the products have period of 16 basic periods. Thus, their optimal periods are likely to be longer than 16 7-day periods. The cost of this policy is quite high (1.14 times the cost of single-item EPQ policy) compared to the other three options. The third policy with 14-day basic period with 16 basic periods as the longest period allowed performs quite well. Its cost is within 5% of the cost of the single-item EPQ schedule, which is a lower bound on the cost of the optimal solution. This type of analysis can be performed to compare the effect of choosing different basic periods.

6.3 Summary

This chapter discussed two important issues related to implementation of the production planning methods developed in this thesis. The first issue dealt with using the solution described in this thesis to generate an SKU schedule. Three different methods are suggested for addressing this issue and they need to be considered in conjunction with the product strategy of Company-X. The second issue discussed the effect of choosing different basic periods. The analysis presented in section 5.4 can be performed with different basic periods to see how the choice of period affects the production policy.

This chapter concludes the discussion about application of the production planning heuristic developed here to Company-X. In Chapter 7, I will summarize the work presented in this thesis.

Chapter 7 Review and Conclusions

This chapter summarizes the work presented in this thesis. The chapter is organized into three sections: The first section provides a complete summary of the research work done and also describes how this information is organized in this document. The second section highlights some important characteristics of this work, which are organized into two groups: key contributions and limitations. Finally, the last section points out some opportunities for extending this work in future.

7.1 Summary of Work

This thesis presents the development of a heuristic to generate production planning policies for a continuous-process make-to-stock chemical manufacturer (Company-X) of an interlayer film (Product-Y) used in automotive windshield and architectural glass panes. The industrial application of this work was done at one of the company's North American manufacturing facilities (Location-Z). The objective of the production policies here is to schedule the production of multiple items on a single processor with the goal of reducing total setup and inventory holding costs while providing customer service at or above a preset standard under stochastic demand. After understanding the production environment of the manufacturer, it became clear that the manufacturer faced a stochastic production planning problem whose deterministic version is known as the Economic Lot Scheduling Problem (ELSP). The ELSP is known to be an NP-hard problem, so the goal of this research work was to develop heuristic procedures that can be used to plan production. This was done in three steps: understanding the problem and getting acquainted with the research work done in past to address similar problems;

development of a heuristic procedure; and application of the heuristic procedure to the actual problem & testing effectiveness of the production policies developed by the heuristic.

The initial work focused on becoming familiar with the fundamental inventory and production planning models including research work on the ELSP, and understanding the facets of the production and planning environment at Company-X's Location-Z production facility. A review of a few inventory and production planning models that are relevant to the problem studied in this thesis is taken in Chapter 2, and the industrial setting where this problem was studied is described in Chapter 3.

Based on the understanding of the theoretical and the practical aspects of the production planning problem studied here, a heuristic procedure was developed to generate production schedules. Chapter 4 presents a mathematical model of the problem observed and the heuristic developed to solve it.

The heuristic procedure presented in Chapter 4 is applied to Company-X, and the application is illustrated in Chapter 5. This chapter describes the type of data collected and used for applying the heuristic. The heuristic was applied to product groups formed by segmenting inventory items based on the similarity of their production characteristics. Chapter 5 describes how inventory was segmented, and then provides a step-by-step illustration of using the heuristic procedure to develop production planning policies for Company-X. Once the production planning policies are developed, they are tested using simulation; the design of the simulation experiment and its results are also described in this chapter.

Finally, Chapter 6 addresses two issues related to the implementation of the methods presented in this work at Company-X. This chapter gives guidelines about how production plans based on product groups can be extended to generate an SKU schedule. The chapter then briefly discusses how selection of different basic periods affects the production plans.

7.2 Highlights of the Work

This section highlights some important attributes of this research work. They are organized into two sections: key contributions and limitations.

7.2.1 Key Contributions

Given below are some of the key contributions of this research work:

- This work presents a formal way to schedule production at Company-X, something which it currently does not have.
- This work identifies the production planning problem faced by Company-X to be the Economic Lot Scheduling Problem (ELSP), and develops a method for generating production plans based on what is known from the research on the ELSP.
- The method developed here uses a spreadsheet application and does not require any high-end optimization software, and still produces good solutions as measured by (i) the cost of the production plan compared to a lower bound on the cost of the optimal schedule and (ii) balancing of the load on production capacity.
- Guidelines are provided for how this work can be applied to Company-X's production facility at Location-Z

7.2.2 Limitations of the Work

Any work has a limited applicability. It is important to point out the limitations of the work for at least two reasons: to inform the readers what conditions must exist for the methods developed in this work to be applicable so that they are not incorrectly applied where they should not be, and to provide some guidelines for the future work.

- This work is applicable in production settings where goods are typically made to stock, and the production process is characterized by long setup times. The work is applicable only where assumptions in the economic lot scheduling problem are valid.
- The heuristic developed does not provide a systematic way to schedule products with sequence-dependent setup times.
- We assume that the fixed amount of production capacity is available. Probabilistic availability of production capacity is not modeled.
- Effect of poor quality, especially due to long lead time associate with getting results of the quality test, is not studied.

7.3 Recommendations for Future Work

Given below are some recommendations for the future work. Most of these recommendations are based on the limitations of the work observed in section 7.2.2.

- Extend the heuristic procedure to generate ELSP schedules by considering sequence-dependent setup times.
- Model the suggestions provided in section 6.1 to extend the product-group level schedules to SKU-level schedules.
- Model probabilistic availability of production capacity based on frequency of mechanical process breakdowns and mean time required to repair the process.
- Model of the effect of poor quality to study whether the long lead time associated with the quality tests affects the way production plans are developed.

Chapter 8 Summary of Notations Used

For item i, the following notations are used:

D_i : Demand rate (units/time)

p_i : Production rate (units/time)

A_i : Ordering or setup cost (\$/order or \$/setup)

s_i : Setup time (time/setup)

h_i : Inventory holding cost (\$/unit/time)

Q_i^* : Economic order quantity (EOQ) (units)

Q_i^E : Best order quantity based on power-of-two period (EOQ) (units)

T_i^* : Period (time between consecutive orders or production) based on EOQ (time)

T_i^E : Best period as a power-of-two multiple of basic period (time)

TRC_i^* : Total relevant cost of EOQ policy (\$)

TRC_i^E : Total relevant cost of best power-of-two policy (\$)

L : Lead time

R : Inventory level review period

$\overline{x}_L$: Average demand over lead time

$\overline{x}_{R+L}$: Average demand over review period plus lead time

σ_L : Standard deviation of forecast error (or demand variability) over lead time

σ_{R+L} : Std deviation of forecast error (or demand var.) over review period plus lead time

k : Factor of safety

SS : Safety stock

s : Reorder point or minimum inventory level in min-max system

S : Order up to level or maximum inventory level in min-max system

Notations used in the production schedule:

T: Length of production cycle

T^B: Basic period (time)

m_i: Multiplier of the basic period to get the optimal period for item i

That is: $(1/m_i T^B)$ is the optimal production frequency of item i

j: Index for periods within production cycle $=\{1,2,......,T\}$

k: Number of basic periods in production cycle

x_{ij}: $1-$ if item i is produced in period j; $0-$ otherwise

U, L: Maximum and minimum loads, respectively, on the production capacity in any period within the production cycle

Bibliography

Bomberger, E. (1966). A dynamic programming approach to a lot size scheduling problem. Management Science, 12(11), 778-784.

Company-X. (2001). NA Product-Y: Films order fulfillment (MRP II). 5-8 SAF.

Company-X. (2001). Product-Y business policy. pp 1-6.

Company-X. (2006). Current and proposed distribution network. Company-X Presentation.

Davis, S. G. (1990). Scheduling economic lot size production runs. Management Science, 36(8), 985-998.

Dobson, G. (1987). The Economic Lot-scheduling Problem: Achieving feasibility using time-varying lot sizes. Operations Research, 35(5), 764-770.

Eilon, S. (1958). Economic batch size determination of multi-product scheduling. Operational Research Quarterly, 10, 217-227.

Elmaghraby, S. E. (1978). The Economic Lot Scheduling Problem (ELSP): Review and extensions. Management Science, 24(6), 587-598.

Gershwin, S.B. (2002). Manufacturing Systems Engineering. Cambridge, MA: MIT

Graves, S. C. (1979). On the deterministic demand multi-product single-machine lot scheduling problem. Management Science, 25, 276-280.

Hsu, W. (1983). On the general feasibility test for scheduling lot sizes for several products on one machine. Management Science, 29(1), 93-105.

Jackson, P., Maxwell, W., & Muckstadt, J. (1985). The Joint Replenishment Problem with a power-of-two restriction. IIE Transactions, 17(1), 25-32.

Rajaram, K., & Karmarkar, U. S. (2004). Campaign planning and scheduling for multiproduct batch operations with applications to the food-processing industry. Manufacturing & Service Operations Management, 6(3), 253-269.

Rogers, J. (1958). A computational approach to the economic lot scheduling problem. Management Science, 4, 264-291.

Silver, E. A., Pyke, D. F., & Peterson, R. (1998). Inventory management and production planning and scheduling. New York: John Wiley & Sons

Simchi-Levi, D., Chen, X., Bramel, J. (2005). The logic of logistics: Theory, algorithms, and applications for logistics and supply chain management (2nd ed.). New York: Springer

Taylor, D. A. (2004). Supply chains: A manager's guide. Boston: Addison-Wesley

Appendix A

Monthly Demand in Square Meters

	P01	P11	P12	P13	P14	P15	P21	P22	P23	P24
Jan-06	0	216,314	300,747	19,513	67,602	675	0	164,997	99,617	54,682
Feb-06	4,968	243,171	295,217	17,314	78,349	450	3,393	173,993	88,817	59,063
Mar-06	0	153,748	271,598	12,234	69,563	675	4,410	136,305	79,533	56,439
Apr-06	9,696	318,487	398,930	22,123	139,483	918	232	197,901	77,774	43,826
May-06	7,861	505,098	356,240	16,031	71,511	0	7,776	148,840	118,802	60,431
Jun-06	8,499	618,750	353,176	29,248	89,790	0	9,234	131,364	140,526	73,487
Jul-06	8,853	453,186	342,165	18,115	65,998	689	2,808	29,675	66,665	24,014
Aug-06	3,541	793,690	482,101	22,297	101,911	0	2,808	48,490	88,292	55,429
Sep-06	17,705	554,945	391,865	26,036	80,815	918	0	108,034	94,955	39,724
Oct-06	14,164	436,850	379,177	37,922	95,691	1,371	16,380	124,308	117,158	38,126
Nov-06	14,164	549,284	372,993	16,773	87,219	918	44,087	63,947	86,751	45,374
Dec-06	5,312	371,075	325,022	26,761	89,248	918	45,050	82,418	50,864	36,165

	P31	P32	P33	P34	P41	P42	P43	P44	P51	P52	P53
Jan-06	16,542	22,815	37,197	0	142,551	139,811	42,156	64,789	19,877	12,245	7,934
Feb-06	14,364	33,516	34,101	0	97,902	129,070	68,963	57,468	16,938	12,987	5,252
Mar-06	10,854	36,121	26,379	4,668	81,603	122,980	52,126	52,596	19,539	12,272	5,535
Apr-06	1,908	38,860	13,419	0	173,448	138,899	75,139	64,529	13,408	13,752	2,624
May-06	14,508	36,122	19,710	2,948	166,311	171,732	88,763	60,976	15,840	11,192	3,825
Jun-06	63,638	61,776	13,482	10,493	166,395	136,279	78,296	51,839	11,318	13,482	3,132
Jul-06	19,343	53,523	13,559	1,743	77,770	123,664	93,238	64,435	5,099	16,182	2,390
Aug-06	7,751	45,497	29,466	978	123,527	119,741	59,864	58,822	6,944	7,448	3,389
Sep-06	5,607	171,506	51,850	32,740	95,301	101,311	80,755	60,161	3,978	7,313	2,480
Oct-06	16,920	157,779	53,466	1,943	126,090	101,098	35,899	41,621	7,659	4,059	1,229
Nov-06	62,208	123,316	44,525	5,913	124,389	75,779	33,955	51,479	2,106	5,805	0
Dec-06	41,796	260,089	70,734	46,588	76,328	128,781	23,731	81,077	459	3,416	2,169

Exhibit 1: Monthly Demand (in SQM) for Various Items (of Product Group Product-Y)

To:	Setup changeover times (in minutes) Changeover from: P01	P11	P12	P13	P14	P15	P21	P22	P23	P24	P31	P32	P33	P34	P41	P42	P43	P44	P51	P52	P53	Chageover Time (hrs) Min	Mode
P01	0	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
P11	3	0	2	2	2	2	0.75	2	2	2	0.75	2	2	2	0.75	2	2	2	0.75	2	2	0.75	2
P12	3	0.75	0	3	3	3	0.75	0.75	3	3	0.75	0.75	3	3	0.75	0.75	3	3	0.75	0.75	3	0.75	3
P13	3	0.75	5	0	4	4	0.75	5	0.75	4	0.75	5	0.75	4	0.75	5	0.75	4	0.75	5	4	0.75	0.75
P14	3	0.75	6	4	0	0	0.75	6	4	0.75	0.75	6	4	0.75	0.75	6	4	0.75	0.75	6	0.75	0.75	0.75
P15	3	0.75	6	4	0	0	0.75	6	4	0.75	0.75	6	4	0.75	0.75	6	4	0.75	0.75	6	0.75	0.75	0.75
P21	3	0.75	2	2	2	2	0	2	2	2	0.75	2	2	2	0.75	2	2	2	0.75	2	2	0.75	2
P22	3	0.75	0.75	3	3	3	0.75	0	3	3	0.75	0.75	3	3	0.75	0.75	3	3	0.75	0.75	3	0.75	3
P23	3	0.75	5	0.75	4	4	0.75	5	0	4	0.75	5	0.75	4	0.75	5	0.75	4	0.75	5	4	0.75	0.75
P24	3	0.75	6	4	0.75	0.75	0.75	6	4	0	0.75	6	4	0.75	0.75	6	4	0.75	0.75	6	0.75	0.75	0.75
P31	3	0.75	2	2	2	2	0.75	2	2	2	0	2	2	2	0.75	2	2	2	0.75	2	2	0.75	2
P32	3	0.75	0.75	3	3	3	0.75	0.75	3	3	0.75	0	3	3	0.75	0.75	3	3	0.75	0.75	3	0.75	3
P33	3	0.75	5	0.75	4	4	0.75	5	0.75	4	0.75	5	0	4	0.75	5	0.75	4	0.75	5	4	0.75	0.75
P34	3	0.75	6	4	0.75	0.75	0.75	6	4	0.75	0.75	6	4	0	0.75	6	4	0.75	0.75	6	0.75	0.75	0.75
P41	3	0.75	2	2	2	2	0.75	2	2	2	0.75	2	2	2	0	2	2	2	0.75	2	2	0.75	2
P42	3	0.75	0.75	3	3	3	0.75	0.75	3	3	0.75	0.75	3	3	0.75	0	3	3	0.75	0.75	3	0.75	3
P43	3	0.75	5	0.75	4	4	0.75	5	0.75	4	0.75	5	0.75	4	0.75	5	0	4	0.75	5	4	0.75	0.75
P44	3	0.75	6	4	0.75	0.75	0.75	6	4	0.75	0.75	6	4	0.75	0.75	6	4	0	0.75	6	0.75	0.75	0.75
P51	3	0.75	2	2	2	2	0.75	2	2	2	0.75	2	2	2	0.75	2	2	2	0	2	2	0.75	2
P52	3	0.75	0.75	3	3	3	0.75	0.75	3	3	0.75	0.75	3	3	0.75	0.75	3	3	0.75	0	3	0.75	3
P53	3	0.75	6	4	0.75	0.75	0.75	6	4	0.75	0.75	6	4	0.75	0.75	6	4	0.75	0.75	6	0	0.75	0.75

Exhibit 2: Sequence-dependent Setup Changeover Times