Cycle Time Reduction and Strategic Inventory Placement Across a Multistage Process

by

William B. Hetzel
B.S. Chemistry – Yale University (1988)

Submitted to the Sloan School of Management and the Department of Chemical Engineering
In Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Management

and

Master of Science in Chemical Engineering

in conjunction with the Leaders for Manufacturing Program at the Massachusetts Institute of Technology
June 1993

© 1993 Massachusetts Institute of Technology

Signature of Author

MIT Sloan School of Management
MIT Department of Chemical Engineering
May 1993

Certified by

Stephen C. Graves
Professor of Management Science

Certified by

George Stephanopoulos
Arthur D. Little Professor of Chemical Engineering

Accepted by

Jeffrey A. Barks
Associate Dean, Sloan Master’s and Bachelor’s Programs
Cycle Time Reduction and Strategic Inventory Placement
Across a Multistage Process

by

William B. Hetzel

Submitted to the Sloan School of Management and the Department of Chemical Engineering in Partial Fulfillment of the Requirements for the Degrees of Master of Science in Management and Master of Science in Chemical Engineering

ABSTRACT

This thesis project examines cycle time and inventory reduction, which are central thrusts of Eastman Kodak’s corporate strategy. The project shows that these reduction efforts cannot be addressed in isolation. Instead, they represent the outcome that results from improving the fundamental manufacturing processes across the supply chain.

Through a series of three case studies, the project applies academic models to real situations at the Eastman Kodak Company. The models quantify the relationships between cycle time and inventory reduction and the following manufacturing process issues:

- setup time
- product sequencing
- supply and demand variability
- supply chain structure
- customer service

The case studies build in scope from a detailed examination of one product in one manufacturing stage to a high level view across the entire film supply chain.

The first case study develops a specific lot size and inventory strategy at the product level. It quantifies and prioritizes setup time improvements and process variability reductions.

The second case study extends the analysis to the machine level for multiple products. It incorporates capacity constraints and product sequencing issues critical to Kodak’s manufacturing processes.

The third case study covers the entire film supply chain. It determines where the minimum safety stocks can be placed at each stage to attain a desired level of customer service. It also addresses supply chain issues of information flow and asset utilization.

The thesis project ultimately develops a strategy and quantifies the benefits for cycle time and inventory reduction at three levels of detail. It demonstrates the value of broadening the scope of analysis to cover the entire supply chain. Together, the three case studies provide an annual savings potential up to $7 MM.

Thesis Advisors:
Anthony L. Spatorico, Eastman Kodak Company
Professor Stephen C. Graves, MIT Sloan School of Management
Professor George Stephanopoulos, MIT Department of Chemical Engineering

3
ACKNOWLEDGMENTS

I would like to thank all the people at Kodak who welcomed me with such enthusiasm and encouragement. Special thanks go to my advisors Tony Spatorico at Kodak and Steve Graves and George Stephanopoulos at MIT for their support and guidance. Many people at Kodak provided tremendous assistance and resources: Tim Cilano, George Daddis, Ed Hoffman, Andy Piotrowski, Bill Poole, Laurie Stefanski, the Roll Coating Division, the Black & White team, the HSD team, and the SCOT team.

I gratefully acknowledge the support and resources made available to me through the Leader For Manufacturing Program, a partnership between MIT and major U.S. manufacturing companies.

Finally my deepest appreciation to my wife Jennifer for accompanying me in person and in spirit during this experience.
# TABLE OF CONTENTS

Title Page ........................................................................................................ 1
Abstract ........................................................................................................... 3
Acknowledgments ............................................................................................ 4
Table of Contents ............................................................................................ 5
List of Figures ................................................................................................ 6
List of Tables .................................................................................................. 7

Chapter I. Introduction
   1.1. Value of Cycle Time Reduction ............................................................. 8
   1.2. Industry Background ............................................................................ 13
   1.3. Thesis Overview .................................................................................. 21

Chapter II. Single Product Analysis
   II.1. Goals .................................................................................................... 25
   II.2. Methodology ....................................................................................... 27
   II.3. Results .................................................................................................. 30
   II.4. Implementation .................................................................................... 38

Chapter III. Single Machine Analysis
   III.1. Goals .................................................................................................. 41
   III.2. Methodology ....................................................................................... 42
   III.3. Results ................................................................................................ 45
   III.4. Implementation .................................................................................... 48

Chapter IV. Supply Chain Analysis
   IV.1. Goals .................................................................................................... 51
   IV.2. Methodology ....................................................................................... 54
   IV.3. Data Collection ................................................................................... 58
   IV.4. Results .................................................................................................. 60
   IV.5. Implementation .................................................................................... 67
   IV.6. The Springboard Effect ...................................................................... 69
   IV.7. The Downward Production Effect ....................................................... 74

Chapter V. Conclusions
   V.1. Summary ............................................................................................... 81
   V.2. Recommendations ................................................................................ 82
   V.3. Opportunities for Future Work ............................................................. 85

Chapter VI. Appendices
   VI.1. Single Product Analysis ................................................................. 87
   VI.2. Single Machine Analysis ................................................................... 95
   VI.3. Supply Chain Analysis ...................................................................... 98

Chapter VII. Bibliography ................................................................................ 105
LIST OF FIGURES

Figure I-1  Systematic Impact of Long Cycle Times ................................. 10
Figure I-2  Definitions of Cycle Time and Lead Time ............................... 13
Figure I-3  Roll Coating ESTAR Process ............................................. 14
Figure I-4  Concentration of ESTAR Items ........................................... 15
Figure I-5  Roll Coating - ESTAR Scheduling Systems ............................. 16
Figure I-6  Simplified Version of Film Manufacturing Supply Chain ............. 17
Figure I-7  The Sensitized Film Manufacturing Supply Chain ................... 18
Figure I-8  "Optim" Diagram of Film Manufacturing Supply Chain .............. 20
Figure I-9  Potential Annual Savings from the Thesis Projects .................. 23

Figure II-1  Lot Sizing Method ........................................................... 26
Figure II-2  Specific Operational Recommendations .................................. 31
Figure II-3  Potential Savings from the Single Product Analysis ................ 32
Figure II-4  Setup Time Impact on Production and Inventory Patterns .......... 33
Figure II-5  Sensitivity to Setup Time .................................................... 34
Figure II-6  Service Level Impact on Production & Inventory Patterns .......... 35
Figure II-7  Sensitivity to Service Level .................................................. 36
Figure II-8  Pareto of Savings Potential of 50% Setup Time Reduction ......... 39

Figure III-1  Single Machine Analysis Production Sequence ...................... 46
Figure III-2  Single Machine Analysis Production Patterns ........................ 47

Figure IV-1  Economic Drivers of the Supply Chain Analysis ...................... 52
Figure IV-2  The Supply Chain Optimization Team Scope .......................... 55
Figure N-3  Supply Chain Analysis Case Study ...................................... 57
Figure IV-4  Results from the Supply Chain Analysis -" SIP" ....................... 61
Figure IV-5  Representative Inventory Calculation .................................... 62
Figure N-6  Surge Requirements Example for Support 1 ........................... 66
Figure N-7  The Springboard Effect for Different Forecast Increases ............ 72
Figure IV-8  The Downward Production Effect .......................................... 76

Figure VI-1  Single Product Analysis Sample Printout ............................. 93
Figure VI-2  The Covariance Matrix ....................................................... 99
Figure VI-3  Sample of 10 five-week Forecasts ...................................... 100
Figure VI-4  Differences From Actual for 1-Week Out Forecasts ................ 101
Figure VI-5  Differences From Actual for 3-Week Out Forecasts ................ 101
Figure VI-6  The Weight Matrix ............................................................. 103
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>II-1</td>
<td>Inputs and Outputs for the Single Product Analysis</td>
<td>29</td>
</tr>
<tr>
<td>III-1</td>
<td>Inputs and Outputs for the Single Machine Analysis</td>
<td>43</td>
</tr>
<tr>
<td>III-2</td>
<td>Three Part Matrix of Sequencing Data</td>
<td>44</td>
</tr>
<tr>
<td>IV-1</td>
<td>Factors Impacting Safety Stock Placement</td>
<td>52</td>
</tr>
<tr>
<td>IV-2</td>
<td>“SIP” Inputs Required for Each Item in Each Stage</td>
<td>59</td>
</tr>
<tr>
<td>IV-3</td>
<td>Supply Chain Analysis – Sensitivity to Service Level</td>
<td>63</td>
</tr>
<tr>
<td>IV-4</td>
<td>Supply Chain Analysis – Sensitivity to Lead time</td>
<td>64</td>
</tr>
<tr>
<td>IV-5</td>
<td>Supply Chain Analysis – Sensitivity to Forecast Variability</td>
<td>65</td>
</tr>
<tr>
<td>IV-6</td>
<td>The Springboard Effect: 50% Demand Increase Scenario</td>
<td>71</td>
</tr>
<tr>
<td>IV-7</td>
<td>Analysis of Variance for Downward Production Regression</td>
<td>77</td>
</tr>
</tbody>
</table>
Chapter I Introduction

Studying how organizations control their inventory is equivalent to studying how they achieve their objectives by supplying goods and services to their customers. Inventory is the common thread that ties all of the functions and departments of the organization together.¹

In today’s competitive marketplace, achieving manufacturing excellence has become critical for success. This thesis addresses a key element of manufacturing strategy, the ability to compete on cycle time, and it addresses a fundamental measure of progress against that strategy, inventory levels. Inventory levels reflect how every aspect of the business is performing: Is the supply chain tightly coupled; is the setup time short; is the process reliable; is the response to change fast; and finally, is the customer satisfied? The goal of this thesis is to provide specific examples of how to reduce cycle time and its inventory component. The examples cover three different levels of scope and draw from a 6-month internship experience at Eastman Kodak Company. The methodology and results of this work should assist organizations in their pursuit of competitive advantage through manufacturing excellence.

1.1. Value of Cycle Time Reduction

1.1.1 Competitive Advantage

The sensitized film industry has changed over recent years, and competitors threaten in almost every market. Worldwide capacity expansion is outstripping growth in

---

demand, which is creating pricing and service pressure especially in the consumer films. If Kodak cannot supply the desired product at the desired time, a competitor will. In this new environment, cycle time reduction provides a key competitive advantage.

Reduced cycle time can translate into increased customer satisfaction. Quick response companies can launch new products earlier, penetrate new markets faster, meet changing demand, and can deliver rapidly and on time. They can also offer their customers lower costs because quick response companies have streamlined processes with low inventory and less obsolete stock. According to empirical studies, halving the cycle time (and doubling the work-in-process inventory turns) can increase productivity 20% to 70%. Moreover, quartering the time for one step typically reduces costs by 20%.

With reduced cycle times, quality improves too. Faster processes allow lower inventories which, in turn, expose weaknesses and increase the rate of improvement. After eliminating non-value added transactions (as opposed to value added transformations), there are fewer opportunities for defects. Fast cycle time organizations experience more rapid feedback throughout the supply chain as downstream customers receive goods closer and closer to the time they were manufactured. Philip Thomas terms this entire improvement effect “cycles of learning”:

Responsive [low cycle time] businesses enjoy an important advantage: namely, increased opportunities to learn from the feedback of experience, which I call Cycles of Learning.

---


2For a complete description of the strategic implications of cycle time reduction, see Christopher P. Papouras, Lead Time and Inventory Reduction in Batch Chemical Manufacturing, MIT Master’s Thesis, 1991, pp. 6-8.


4ibid.

Conscientious use of such feedback will, in turn, accelerate results, with positive impact on market share, profit, return on assets, and quality, even as costs decline.\(^7\)

On the other hand, businesses that do not pursue cycle time reduction do not merely stand still. They face the opposite of cycles of learning. Figure 1-1 illustrates a common example of the systematic impact of long cycle times. When a company cannot manufacture quickly enough to respond to customer orders, they must institute forecasts. The longer the cycle time, the further out and less accurate the forecast becomes.

Figure 1-1: Systematic Impact of Long Cycle Times\(^8\)

Forecast errors cause expediting to meet unexpected demand, and the disruption adds to queuing and missed deliveries. The entire production process becomes asynchronous with high lead time variability and rising safety stock needs. The cycle time grows even longer, thus forcing a longer forecast horizon and even less forecast accuracy. This type of feedback cycle can grow throughout the organization without a focused effort toward cycle time reduction.

---


1.1.2. Cycle Time Reduction at Kodak

Eastman Kodak Company has recognized these benefits of cycle time reduction and has instituted programs throughout the organization in its efforts toward continuous improvement. Top management launched a program in 1990 called KP4 (Kodak Perfect Process, Perfect Product) which calls for major improvement thrusts in 5 areas: cycle time, invariance, cost, benchmarking, and new products.

A group of leaders for each area have responsibilities ranging from worldwide sharing of successes to presenting an annual KP4 quality conference. The vision of Kodak management is revolutionary, not evolutionary improvement. Therefore, they have mandated 25% improvement per year on key performance measures, which cannot be attained without radically rethinking the business.

Despite these successes, the current pressure for improvement in the KP4 areas is stronger than ever. In 1991, Kodak’s long-term debt to equity ratio increased from 1.0 to 1.2 which included $600 MM in new borrowings.9 Hence, the company’s debt structure is constraining all capital expenditures and is highlighting the opportunity cost of funds tied up in inventory. Cycle time and inventory reduction have become ingrained concepts across the organization. The result is that this thesis is focused on some of the most critical issues facing Kodak today.

---

9 From the Eastman Kodak Company 1991 Annual Report:

<table>
<thead>
<tr>
<th></th>
<th>1991</th>
<th>1990</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-Term Borrowings ($MM)</td>
<td>7,597</td>
<td>6,989</td>
</tr>
<tr>
<td>Shareowners’ Equity ($ MM)</td>
<td>6,104</td>
<td>6,748</td>
</tr>
<tr>
<td>Debt-to-Equity Ratio</td>
<td>1.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>
1.1.3. Definitions

Up to this point, the discussion of cycle time improvements has been general. Cycle time equates to speed, and faster is better. However, for the remainder of this thesis, a distinction will be drawn between “cycle time” and “lead time.” In his 1921 treatise on manufacturing, Henry Ford wrote,

The time element in manufacturing stretches from the moment the raw material is separated from the Earth to the moment when the finished product is delivered to the ultimate customer.\textsuperscript{10}

This description matches Kodak’s definition of cycle time, which is the time from ordering of raw materials through to customer delivery. If one could follow an individual particle, one would measure cycle time from the time that particle entered the plant, through transformation, through inventory holding, all the way until it reached the customer. Cycle time includes time in inventory.

In contrast, lead time is defined as the time from when the customer fixes an order until the customer receives the product. In the scheduling area, lead time measures the offset from when the order is dropped into the system until the goods are delivered. Typically, lead times are written into the internal customer-supplier contracts within Kodak. Lead times are a function of the following:

* manufacturing speed  
  • service level  
  • amount of inventory on hand

For example, if manufacturing cannot respond quickly and if a high service level is desired, then the organization must either keep high inventory or lengthen the promised lead time. Figure I-2 shows how the definition of cycle time includes the lead time and time spent in inventory.

1.2. Industry Background

1.2.1. The Roll Coating Division

The Roll Coating Division (RCD) is located in the Kodak Park manufacturing site in Rochester, NY. RCD produces film base (often called film support) which is subsequently sensitized with photographic emulsion. The polyester film base (trade name ESTAR) is used in rigid products such as microfiche, x-ray, and graphic arts films.

The Roll Coating ESTAR process has several key features:

- ESTAR production is a continuous process that runs 7 days per week, 24 hours per day
- ESTAR machines are highly capital intensive
- Several machines produce hundreds of items
- Product changeovers create waste and the amount varies with sequence

These features mean that every minute not producing salable product is a minute of revenue lost forever, valued at full opportunity cost. As early as 1921, Henry Ford recognized the importance of this time dimension when he wrote,

"Time waste differs from material waste in that there can be no salvage. The easiest of all wastes, and the hardest to correct, is the waste of time, because wasted time does not litter the floor like wasted material. In our industries, we think of time as human energy. If we..."
buy more material than we need for production, then we are storing human energy - and probably depreciating its value.11

Each of the Roll Coating - ESTAR machines in Rochester are several stories tall, a few hundred feet long, and several feet wide. Figure I-3 shows a schematic of a typical machine. Hot polyester resin is extruded and cast on to a large coating wheel which begins the cooling process. A web of material forms, which can then be heated and stretched both lengthwise and widthwise ("drafting and teetering"). Finally, the web is heat treated and wound in a roll several feet wide and several thousand feet long. Production teams of operators and engineers are dedicated to each machine, and they staff the equipment around the clock.

Figure I-3: Roll Coating ESTAR Process

With hundreds of products to manufacture on only a few machines, setups represent an critical part of ESTAR production. Setups can take anywhere from several minutes to several hours. During that time, the machine must be running (and creating waste) in order to bring up all the processes in control. Therefore, the setup cost includes waste material as well as lost capacity and flexibility.

Sequencing is also critical in how long a setup takes. Width, thickness, color, and coating features can all be changed, but products often share several of these characteristics. Therefore, sequences of product that differ by only one characteristic at a time can have faster setups than sequences of radically different products. Some products may have features that only certain machines have the capability to manufacture. Moreover, the high volume products may have weekly orders, while others may only have one order each year (See Figure I-4). As a result, how to dedicate machines (if at all) and how to schedule product sequences and lot sizes become a critical part of asset utilization, inventory management, and the overall manufacturing strategy. These decisions, in turn, affect the ESTAR department’s cycle time and impact the entire film supply chain.

Figure I-4: Concentration of ESTAR Items
A planning department schedules the shop floor in response to the previously discussed constraints:

- Machine capability
- Machine capacity
- Machine speed
- Product sequencing benefits
- Customer orders and lead times
- Lot sizing
- Inventory management
- Scheduled machine maintenance

The Roll Coating planning systems include the International Plant Order (IPO) system for receiving worldwide orders, the AMAPS Materials Resources Planning (MRP II) system for matching customer orders to inventory and production, the Master Production Scheduling (MPS II) system for scheduling production at the item level, the Aquarius system for shop floor data collection, and the Roll Coating Film Electronic Data System (RC FEDS) system for tracking rolls in inventory (see Figure 1-5) Roll Coating - ESTAR serves worldwide Kodak internal customers as well as several outside customers.

Figure I-5: Roll Coating - ESTAR Scheduling Systems
1.2.2. The Film Manufacturing Supply Chain

The Roll Coating Division plays a vital role in the film manufacturing supply chain. It transforms the raw chemicals into a roll of film base. Figure I-6 shows a simplified version of the subsequent steps which include coating the film base with silver halide emulsion (Sensitizing) and cutting and packaging the sensitized rolls (Finishing).

The structure of the supply chain includes 3 important characteristics:

- An explosion of items as different coatings, sizes, and packages are introduced downstream
- An explosion of value as high cost materials and processes are added
- A gradual decrease in lead time, especially in Finishing where multiple relatively low cost pieces of equipment are available and dedicated to a specific business

Roll Coating and Sensitizing are both highly capital intensive operations with one basic manufacturing path, while Finishing less capital intensive with different "slit and chop" paths and different packaging configurations.

Figure I-6: Simplified Version of the Film Manufacturing Supply Chain

From the days of its founder, George Eastman, Kodak has been a highly vertically integrated company. That tradition remains apparent today as shown in Figure I-7 which
Figure I-7: The Sensitized Film Manufacturing Supply Chain

KEY

- Forward Material Flows
- Recycled Material Flows
expands the simple supply chain picture shown in Figure I-6. Many of the raw materials for the film making process come from a Kodak-owned sector called Eastman Chemical Company. As Figure I-7 illustrates, Kodak’s Imaging sector then transforms the raw chemicals all the way to finished film packed in the familiar gold boxes and located in regional warehouses. Often, this entire transformation process takes place at one site, Kodak Park in Rochester, New York, where everything from the power to the packaging is produced on location. Furthermore, as all the dashed arrows indicate, much of the material flows in a closed recycle loop around the site.

Figure I-7 illustrates several key points:

- Eastman Chemical and Synthetic Chemicals\(^\text{12}\) (with some outside purchases) supply the raw materials
- Polyester polymer and chemicals supply Roll Coating ESTAR which makes film base (excluding the acetate process)
- Silver halide and other chemicals supply emulsion manufacturing which makes the sensitized film coating
- Roll Coating’s film base and the emulsion supply Sensitizing which coats the film, creating what is called a “wide roll” of sensitized film
- Finishing then slits and chops the “wide roll” and packages it in gold boxes for distribution

The third case study in this thesis (Chapter IV, The Supply Chain Analysis) covers the part of the of Figure I-7 that is in bold.

Another way to view the supply chain from a cycle time perspective is to use a common tool at Kodak called an "Optim" diagram. Figure I-8 shows such a diagram for the ESTAR supply chain. The horizontal axis represents the cycle time in days for an item to be manufactured, stored in inventory, and transported to the next stage. The vertical axis represents delivered unit cost or cumulative value added for each stage. The area of each block shows the time-value of the stage and serves as a pareto chart of improvement opportunity. The bigger the area, the bigger the potential savings.

\(^{12}\)Four previous Leaders for Manufacturing internships took place in the Synthetic Chemicals Division in 1990 and 1991. See the theses of Christine N. Jutte, Bradley A. Koetje, Theresa Lai-Hing Mock, and Christopher P. Papouras.
Sometimes a very long cycle time item of low value such as “Syn Chem Inventory” can be a lower priority (smaller area block) than a fast item of high value such as “Finishing” (see Figure I-8). However, there may also be systematic effects embedded in the diagram. For instance, the long Syn Chem cycle times may create a need for longer forecast horizons, which in turn may make the forecast less accurate and may force downstream stages to hold extra inventory. The slanted lines on some of the boxes represent the time and value of the actual transformation. A straight vertical line implies that at a broad level of detail, the item can be treated as though it were bought at a point in time and held in inventory.

Figure I-8: "OptimDiagram of the Film Manufacturing Supply Chain

Note: Diagram box sizes are not to scale and do not represent the real data.
In short, this background on the Roll Coating business and on the film manufacturing supply chain provides the context necessary for the three case studies in this thesis. The description should help relate the case studies to each other and show why they represent critical areas for Kodak and for manufacturing in general.

1.3. Thesis Overview

1.3.2. Problem Scope

This thesis addresses the key manufacturing issue of cycle time along with its inventory component. The thesis makes a progression from detailed, limited scope analysis all the way to high level, broad scope analysis. The problem addressed is always “How can cycle time be reduced at this particular level?” The approach is always “How can this work be implemented in a practical business situation’?”

The problem scope continually expands the definition of the system being analyzed. It escalates from a single product all the way to an entire supply chain. The approach involves three case studies:

- The Single Product Analysis
- The Single Machine Analysis
- The Supply Chain Analysis

The thesis shows that as the scope of the analysis grows broader, the level of detail diminishes. The conclusion will be that the approach, the analytic tools, and the solution must be tailored to the breadth of the problem. Therefore, the definition and scope of each case study is critical.
1.3.3. **Problem Approach**

The Single Product Analysis addresses the trade-off between lot size and inventory level for just one product at a time. Because it is limited to a single product, the analysis can include the effects of demand variability and lead time variability. It can account for the volume sold while the machine is in the process of manufacturing the product. Moreover, its simplicity allows it to model many products and many sensitivity scenarios very quickly and easily. Thus, it can be used to build process intuition about the effect and sensitivity of various parameters such as setup time, supply variability, and service level. Also, it can be used to prioritize improvement efforts for every ESTAR product.

The Single Machine Analysis addresses a broader problem. By looking at a collection of products that run on one machine, it can incorporate the impact of capacity constraints and setup sequencing efficiencies. It does not include the detailed variability issues of the Single Product Analysis, but it can take the perspective of a whole machine. The Single Machine Analysis can create an optimum schedule of products, both sequence and lot size, over multiple periods for an ESTAR machine.

The Supply Chain Analysis addresses how product and machine decisions in one department can affect the upstream suppliers and downstream customers. It determines how inventory can be strategically re-positioned across the supply chain to minimize cycle time and cost for the company as a whole. The scope of the Supply Chain Analysis extends well beyond the Roll Coating Division to include both the Sensitizing and the Finishing operations. It does not provide the detail of the previous two case studies, but it does provide the most comprehensive look at the cycle time and inventory issue. As a result, the Supply Chain Analysis provides the most leverage and the most cost savings of the three case studies.
1.3.4. Conclusions

The estimated value of the three case studies is over $7 million in annual cost savings (see Figure 1-9). The first column shows the savings that have firm implementation plans due by the end of 1993 or earlier. The second column of “case study savings” shows just the savings shown by representative case studies that were actually modeled. The third column shows the effect of rolling out those case studies across all ESTAR products. Note that the Supply Chain Analysis shows negative $0.5 million in this column. That figure represents an investment in inventory that would

Figure 1-9: Potential Annual Savings from the Thesis Projects

<table>
<thead>
<tr>
<th>Terms are $MM</th>
<th>Implemented Savings in ’93 (Supply Chain)</th>
<th>Case Study Savings (Supply Chain)</th>
<th>Total Potential Savings (Estar Dept only)</th>
<th>Total Potential Savings (Estar supply Chain)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROJECT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Product Analysis</td>
<td>0.5</td>
<td>1.3</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>– Lot Sizing &amp; Inventory</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Machine Analysis</td>
<td>0.0</td>
<td>0.1</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>– Capacity &amp; Sequencing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Chain Analysis</td>
<td>0.1</td>
<td>0.8</td>
<td>(0.5)</td>
<td>4.4</td>
</tr>
<tr>
<td>– Strategic Inventory Placement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>2.2</td>
<td>2A</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Note: Inventory Reductions are evaluated at 35% annual savings

---

13 The 1993 implemented savings for the Single Product Analysis were pledged independency of this work, but include waste and inventory savings addressed by the model. The 1993 implemented savings for the Supply Chain Analysis represent a pilot program that directly resulted from this thesis work.
result in a net cost reduction if the whole supply chain were considered. That is precisely what the last column does. It shows that the $7 million savings potential comes from implementing all three case study analyses throughout the Rochester ESTAR department and its associated supply chains. It represents a stretch goal and indicates the order of magnitude of this thesis work on bottom-line cost savings.

The conclusion of this thesis is that the nature of the problem dictates the appropriate level of detail, but there is tremendous value in looking across the entire supply chain. Cycle time reduction represents a key corporate strategy that affects not just each department, but also all of the interconnections. For some organizations, this becomes the most important theme in the business:

The overriding goal [at Toyota] is to never [sic] inconvenience downstream customers.14

The vision involves becoming a “supply chain leader.”15 As the supply chain cycle time is further and further compressed, the utmost limit becomes zero inventory between stages. At this point, the stages are coupled and lead time and capacity are synchronized. The supply chain has reached its ultimate cycle time goal of being directly tied to the customer.

---


Chapter II. Single Product Analysis

Because the Roll Coating - ESTAR department has few machines that produce almost 200 distinct items, frequent product changeovers and setups are necessary. Therefore, lot sizing and inventory trade-off issues become critical both on the shop floor and in the planning arena. The Single Product Analysis addresses this cross-functional trade-off with a data driven model. The model suggests that Roll Coating - ESTAR could save up to $2 MM annually at current capability by adjusting operating policies on all their products. Moreover, they could save an additional $0.5 MM annually if they could also reduce setup times by 50%.

The reason for introducing the model is that the ESTAR department determines lot sizes without considering inventory costs. The product engineers calculate the average setup waste for a product, and from that, the average setup cost. Then they balance the setup cost with the product’s profit per foot (net of the running waste). once enough salable feet are produced for the profit to equal the waste, the product reaches “break-even,” and the minimum lot size is established (see Figure II-1). The minimum lot size is implemented by entering it into the MPS II scheduling system (see Figure I-5).

This lot sizing scheme does not factor in the cost of inventory holding.16 One hypothesis for this is that performance measures influence the calculation. The product engineers, who have responsibility for setting lot sizes, are evaluated on waste but not on inventory. Responsibility for the inventory lies with a separate planning department.

---

16This section represents what the author learned from word-of-mouth interviews with Kodak employees who actually set lot sizes. Later comments suggest that written procedures differ from actual practice.
11.1. Goals

The ultimate goal for the Single Product Analysis is to create a simple model reflecting the macro-drivers of the business. Related to the discussion above, one clear purpose of the model is to incorporate inventory costs into the lot sizing strategy.

Other objectives of the Single Product Analysis include:

- Providing concrete, implementation-oriented outputs
- Prioritizing lot size and setup reduction opportunities for the top few ESTAR products that constitute most of the annual volume
- Quantifying sensitivity to setup time, supply variability, and service level
- Providing process intuition for both the engineers and the planners

The Single Product Analysis focuses on setup time reduction because it is the key to unlocking Roll Coating - ESTAR’S production constraints. The model translates faster setups into decreased lot sizes and increased run frequencies by providing specific
If one product retains a long setup time, then the economics mandate long, infrequent runs. This constraint will in turn affect the other products which must run on the same machine. They must wait for the long-running product, and as a result, they become more difficult to schedule and require more safety stock. In contrast, fast setup products can justify frequent changeovers with short runs, and this capability frees the machines to respond quickly to swings in demand or production problems. The final result is improved customer response and service which can provide a distinct advantage in the competitive film market.

11.2. Methodology

The methodology behind the Single Product Analysis is a lot size, reorder point system. This type of system utilizes specific process data to generate detailed results for one product at a time. This methodology has a fundamental trade-off. Although the outputs are specific and operational, they may not be optimal or even feasible when all the products in the department are looked at together.

The single product analysis does not specify how to reduce setup times. It values and prioritizes setup time improvements and specifies how to cash out the benefits. In Estar Roll Coating, methods to reduce setup times include:

- Organizational emphasis, measurement, and rewards focused on the issue
- Choreographing setups in advance using an experienced team
- Performing some tasks off-line before the changeover
- Moving tasks from series to parallel


The general strategy behind Single Minute Exchange of Dies involves 4 stages:

0. Dissecting the setup in detail using videotape to identify every step and whether it is “internal” or “external”
1. Ensure that only “internal” steps are performed when the machine is down
2. Convert “internal” steps to “external” ones by breaking old habits
3. Streamline, standardize, simplify every “internal” step remaining
   - One-turn screws
   - Visible, calibrated settings
   - Special jigs and part holders

This is sometimes called an iterative (Q,R) procedure, see for instance Thomas E. Vollmann, William L. Berry, and D. Clay Whybark, Manufacturing Planning and Control Systems. (3rd ed. Homewood, IL: Business One Irwin, 1992), pp. 728–729.
There are several key features in the Single Product Analysis that take it beyond a simple Economic Order Quantity calculation including:

- Input of supply variability in the form of a mean lead time and its standard deviation (i.e., a lead time of 2 weeks ± 1 week)
- Input of demand variability in the form of a mean demand per time and its standard deviation (i.e., a demand of 1,000 feet per week ± 200 feet per week)
- Calculation using finite production time to manufacture an order (versus instantaneous arrival as if purchasing from the outside)
- Calculation of an imputed stockout cost to quantify the costs and benefits of selecting a particular customer service level

In specific detail, Table II-1 lists the model inputs and outputs. The appendix (section VI.1) elaborates on the calculations used and shows sample model outputs.

Although this methodology represents a general approach applicable to a wide variety of situations, there are two features unique to Kodak and film manufacturing:

- Discrete run frequency possibilities
- Correlation of waste to the entire lot

Discrete run frequency possibilities mean that there are only a finite number of choices (weekly, hi-weekly, monthly, etc.) for how often Kodak can run a batch. This is because in Roll Coating - ESTAR and in Sensitizing operations, there is capital intensive, capacity constrained equipment that causes scheduling competition for resources. Using only a finite number of frequencies provides scheduling convenience and allows coordination with other parts of the production process. The implications are that 1) run frequent y analyses do not need to be precise to the day, and 2) this paradigm may need to be challenged as manufacturing processes become more flexible. Correlation of waste to the entire lot

---

19 Simple Economic Order Quantity analysis assumes the order arrives instantaneously and that there is neither supply nor demand variability. If this the case, one can set the inventory holding cost equal to the setup cost and solve directly for the quantity without using any calculus. See for instance Barry Renden and Ralph M. Stair, Jr., Qualitative Analysis for Management, 4th ed., (Boston, MA: Allyn and Bacon, 1991).

20 As defined in section 1.1.3, this leadtime represents how long it takes to get the product on the machine including raw material procurement and competition for resources by other products. The lead time here is not the “touch time.”
Table II-1: Inputs and Outputs for the Single Product Analysis

**Units**

**INPUTS**
- Demand (mean & std. deviation) .................. KLF*/Week
- Lead Time (mean & std. deviation) ............... Weeks
- Setup Cost ........................................ $/Setup
- Unit Cost ........................................... $/KLF
- Inventory Holding Cost ........................... Annual %
- Machine Speed ..................................... KLF/Week
- Yield .............................................. %
- Desired Service Level .............................. % of KLF met from stock

**OUTPUTS**
- Lot Size ........................................... KLF Or Days
- Reorder Point ...................................... KLF
- Avg Time Between Runs ............................ Weeks

**Calculations**
- Total Inventory Cost .............................. $/Year
- Total Setup Cost .................................. $/Year
- Imputed Cost of Shortfall ........................ $/KLF
- Safety Stock ....................................... KLF Or Days
- Average Inventory ................................. KLF Or Days

*KLF* means Thousands of Linear Feet in length, generally on a roll several feet wide

entire lot means that in film manufacturing, product defects and waste are not always random occurrences, but instead are often associated with a particular setup. Generally when any rolls are discarded, the entire lot is discarded. The importance of this is that “lot-correlated” waste is an additional factor besides inventory costs that drive Kodak toward smaller lot sizes.
11.3. Results

The Single Product Analysis identified specific operating changes that could lower Roll Coating - ESTAR’S inventory and setup costs by 45%. The potential savings do not require any manufacturing process improvements or major investments. The actions involve changing only lot sizes, run frequencies, and safety stock levels at current capabilities. Because the model recommends more frequent setups for some products and less frequent setups for others, the overall time spent on setups does not change dramatically, and there is enough capacity on the machines in aggregate.\textsuperscript{21} The results are based on an analysis of the top few ESTAR products, which account for most of the department’s production volume. The model also shows that inventory and setup costs could be reduced an additional 10% (for a total of 55%) if the setup times for all products can be reduced by an average of 50%.

The model looks at products in detail one at a time, and, as a result, it can provide concrete, implementation-oriented outputs for each product. Figure II-2 shows recommended changes in lot size and average inventory for a sample of 10 ESTAR products.

\textsuperscript{21} As discussed later, the Single Product Analysis has a fundamental weakness that it looks at each product separately. The next chapter on the Single Machine Analysis will address this weakness.
**Figure II-2**: Specific Operational Recommendations of the Single Product Analysis\(^{22}\)

<table>
<thead>
<tr>
<th>Change in Lot Size</th>
<th>Change in Avg Inv</th>
</tr>
</thead>
<tbody>
<tr>
<td>200%</td>
<td>150%</td>
</tr>
<tr>
<td>100%</td>
<td>50%</td>
</tr>
<tr>
<td>0%</td>
<td>-50%</td>
</tr>
<tr>
<td>-100%</td>
<td>-200%</td>
</tr>
</tbody>
</table>

---

**Figure II-3** shows the bottom line dollar value of making the recommended operating changes. Notice that for products 2 – 5, when the lot sizes are reduced, the corresponding setup costs are increased. The result of this small investment in smaller lots and more frequent runs is a dramatic reduction in inventory holding costs. The model’s capability to offset small setup waste increases with large inventory cost decreases in the face of supply and demand variability is critical for the Roll Coating Organization. The simultaneous trade-off of waste and inventory challenges a paradigm of keeping the two issues separate at Kodak. The model results force a re-thinking of the current organization where production is responsible for waste and a separate planning department is responsible for inventory.

\(^{22}\)The reason that lot size can increase while inventory simultaneously decreases (products 1, 6, 7, 8, 9, and 10) is that these changes represent differences from current actual figures. That is, if the lot sizes stayed the same as they are currently (or decreased), the inventory reductions would be even greater than those shown in Figure II-2.
The Single Product Analysis can also quantify the value of improvement activities. One of the key improvement thrusts for Roll Coating is setup time reduction. Not only does every minute of a setup consume precious asset capacity (see Figure I-1), but it also creates material waste. In response to these costs and the Kodak-wide initiative to reduce cycle times by 25% per year, Roll Coating created across-functional team of operators and engineers from each machine to work on setup time reduction. The teams are called “pit crews” (as in racing car crews working together to change tires in seconds), and their charter is to “choreograph” each product change in advance.

The Single Product Analysis brings new insight and motivation to the “pit crew” effort. The model precisely quantifies the dollar value of the less obvious benefits of setup time reduction. Faster setups can justify more frequent runs of smaller lot size, lower inventories, and more rapid lead times for improved customer response. Small lot
sizes can be extremely important because defects tend to be associated with an entire run of one product. As previously mentioned, when rolls need to be re-worked or discarded, usually the entire lot “is involved, so smaller lots can help reduce that cost.

Figure II-4 shows the effect of setup times on production and inventory patterns. Note that the longer setup (scaled to 100 minutes) requires longer runs and higher inventories to attain the minimum cost operation. The shorter setup (scaled to 17 minutes) can justify more frequent runs. The shorter setup requires higher safety stock levels to achieve the same level of customer service because it is at the low end of its inventory cycle more often. (This model does not capture the fact that more frequent runs

Figure II-4: Setup Time Impact on Production and Inventory Patterns

![Graph showing the effect of setup times on production and inventory patterns.](image-url)
have a shorter planning horizon, and thus less demand variability. This effect can be large enough actually to have lower safety stock with more frequent small batches.23)

Figure II-5 shows the sensitivities of cost, lot size, and average inventory to the spectrum of setup times. Because the relationships are not linear, the model proves very useful in setting specific lot size quantities and cost targets for each product. Moreover, the model demonstrates the real dollar values of waste and inventory for each setup improvement, which can provide new process intuition.

Figure II-5: Sensitivity to Setup Time

---

The Single Product Analysis can quantify operational sensitivity to many other parameters besides setup time. These parameters include service level, demand variability, lead time variability, and inventory holding cost. For example, Figure II-6 shows how different service level targets affect production and inventory patterns. Service level here is defined as the percentage of demand in linear feet met from stock. Note that higher service requires just slightly more frequent runs and higher safety stock. In the case of Roll Coating - ESTAR, service levels below 90% tend to require zero safety stock under normal operating conditions.

Figure H-6: Service Level Impact on Production and Inventory Patterns

---

Figure II-7 shows the sensitivity of the model outputs to different service levels. As higher service levels are desired, at current manufacturing capability, the total cost rises much faster than linearly. This cost and the expected number of stockouts at a given service level can be used to calculate the cost per stockout to a customer. The model outputs include this imputed stockout cost, and it can help in setting service levels that optimize the trade-off between responsiveness and cost. Basically, the model can provide a quantitative answer to the question, “What does it cost to provide a service level of X?” This cost can then be balanced against what the customer is willing to pay to receive that service level.

Figure II-7: Sensitivity to Service Level

![Graph showing sensitivity to service level](image-url)
The Single Product Analysis can provide detailed, operational outputs in response to different improvement efforts and planning decisions. It can quantify and prioritize actions based on their contribution to the bottom line. It can even provide process understanding and intuition about inter-relationships among different operating parameters.

The Single Product Analysis, however, has one serious limitation: it can examine only one product at a time. The key to controlling lead time variability and the resulting queues and missed due dates is the proper choice of lot sizes. Furthermore, queuing is a joint effect of multiple items competing for limited resources. The whole system of products, not one single product, determines the lead time variability. The model outputs for lot size and run frequency for each ESTAR product calculated individually maybe impossible to schedule when combined due to machine capacity and capability issues. The facility is a 24-hour, 7-day operation running at high utilization. Certain products can only be run on certain machines. The lot size and run frequency of one product cannot be determined in a vacuum.

The analogy of traffic driving through an intersection works well here. Unless volume is very small, a four-way stop, which takes each car (or product) separately, will create large queues. A traffic light should meter flow according to overall load. Accounting for all the waiting cars as a whole, the light should have short cycles (small batches) when lightly loaded and long cycles (large batches) when heavily loaded. It is not an individual car (or product) that determines the travel time, but rather the whole flow of traffic.

All this is not to say that the Single Product Analysis cannot be useful. The following section on implementation shows how it can be utilized in a practical fashion.

---

However, this shortcoming, and indeed the theme of this thesis, points out the value of expanding the problem treatment to a more global basis. The next section, which covers the Single Machine Analysis, addresses the fundamental limitation of examining just one product. There is a cost, though. As the scope of the analysis grows, the level of detail diminishes. The Single Product Analysis provides the most comprehensive output of any effort in the thesis.

11.4. Implementation

The Single Product Analysis is in the process of being implemented in Roll Coating - ESTAR. While it is being used to help with the annual planning cycle and with developing process intuition, its main use is in driving setup time reductions. The benefits of setup time improvement activities can be analyzed and prioritized using outputs from the Single Product Analysis. In particular, the top few Roll Coating - ESTAR products were put in a pareto chart ranked on the benefit of reducing setup time by 50%. The “pit crew” teams could then prioritize their setup time efforts and select the one or two highest value opportunities for their machine with a definite financial target. The model determines the overall value of setup time improvements by blending factors such as annual volume, material cost, current setup time, and yield. Note that the pareto chart in Figure II-8 also shows the combination of waste and inventory savings that minimize overall cost. Making both the waste and inventory targets visible is important because the production department has an incentive to reduce only waste. At the extreme, setup time reductions could be used solely to lower waste if run frequencies and inventories remained constant. While this strategy would make the production department’s measures look the best, it would not minimize cost for the company.
Moreover, the Single Product Analysis assumes a “unit” demand for products (constant, continuous use by customers each week). For low-volume products, this is often not the case. Batch operations downstream occasionally call for a fairly large, single lots of low-volume product. When this is the case, using the Single Product Analysis to set small, frequently manufactured lots maybe inefficient. It maybe more cost effective to try to predict these occasional demand spikes and produce to a forecast for low-volume products.

One of the ESTAR department’s goals is to make setup time reduction an important priority for each machine team The Single Product Analysis will be implemented to aid this effort. The model identified and quantified the top products for each machine in terms of setup time reduction value. Managers now can use these top
product opportunities to set numerical goals for each machine team’s performance matrix. The performance matrix, in turn, is used in employee evaluations that determine promotions and compensation. In this way, the engineers and operators associated with each machine will know that their priorities are aligned with the corporate vision for cycle time reduction.

The most important result from the Single Product Analysis is the expansion of Roll Coating’s lot size thinking to include inventory considerations. Further opportunities to reduce setup times, optimize lot sizing, and change limited performance measures will always exist. The single product model represents the first step in this direction.
Chapter III. Single Machine Analysis

Because the lot size and run frequency for one product cannot be determined in a vacuum (see section 11.3), the scope of the Single Product Analysis was increased to include the dynamics of an entire ESTAR machine at once. The Single Machine Analysis covers all the products that are run on one machine for a given period of time. Given the order due dates, setup times, and the capacity constraints, the Single Machine Analysis produces the minimum cost, feasible schedule. On one ESTAR machine alone, the model determined a schedule that could save thousands of dollars per year.

111.1. Goals

The goal of the Single Machine Analysis is to expand the scope of the product analysis and make the results more implementable across the ESTAR department. Specifically, by looking at the problem at a machine level, the analysis can include:

- Sequencing effects on setup times
- Capacity limits

The sequencing effects arise because the time required to setup a given product is not fixed. It depends on which product precedes it. As previously mentioned, this is because each product has a number of parameters such as width, thickness, color, and coating features which might or might not be the same as the preceding product. Changing shades of blue may take on the order of minutes while changing thickness can

---

26 The current literature often refers to “the single machine case,” but it differs greatly from the Single Machine Analysis. The literature does not account for sequencing; it assumes product sequence does not affect setup time, which is not the case in ESTAR Roll Coating. In addition, the literature does not minimize cost, but tends to minimize average time in the system, average number of jobs in the system, WIP, or average job lateness. The standard algorithm is “Shortest processing Time” (SPT) which means do the shortest job first and the longest job last. See Thomas E. Vollmann, William L. Berry, and D. Clay Whybark, Manufacturing Planning and Control Systems, (3rd ed. Homewood, IL: Business One Irwin, 1992), pp. 535-536.

27 The single product analysis uses a freed setup time based on the most common sequence of products.
take substantially longer. **Current practice in Roll Coating is to follow a sequence of**
products on each machine that smoothes the changeovers and prevents the setups from extreme, back-and-forth patterns. This fairly rigid sequence, however, does not vary with loading. When utilization is low, Roll Coating might be missing an opportunity to reduce inventory or reduce lead times by changing the setup sequence. The Single Machine Analysis optimizes the sequencing relative to the load. When capacity is full, the minimum time sequence is used. When capacity is not full, the minimum overall cost sequence is used. This variable sequencing challenges the current paradigm in Roll Coating where breaking the standard order of products is considered an extraordinary event that hurts the waste performance measure.

The Single Machine Analysis also improves on the Single Product Analysis by including a capacity constraint. The model can limit the hours per week of setup and production time.

### 11.2. Methodology

The Single Machine Analysis addresses the basic problem of how Roll Coating - ESTAR should schedule one machine to minimize the cost of meeting demand. The analysis models the simplest machine in the department. The analysis covers four weekly buckets of demand and assumes no backordering is allowed (100% service level). Table III-1 lists the required data inputs and model outputs.
### Table III-1: Inputs and Outputs for the Single Machine Analysis

<table>
<thead>
<tr>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUTS</td>
</tr>
<tr>
<td>- Demand (byproduct with weekly due dates), KLF*/Week</td>
</tr>
<tr>
<td>- Capacity, Hrs/Week</td>
</tr>
<tr>
<td>- Machine Speed, KLF/Hour</td>
</tr>
<tr>
<td>- Inventory Holding Cost (by product), $/KLF/Week</td>
</tr>
<tr>
<td>- Starting Inventory (byproduct), KLF</td>
</tr>
<tr>
<td>- Ending Inventory (by product), KLF</td>
</tr>
<tr>
<td>- Setup Time (byproduct &amp; predecessor), Hours</td>
</tr>
</tbody>
</table>

| OUTPUTS |
| - Production (byproduct by week), KLF |
| - Product Sequence |

**Calculations**

- Inventory Level (byproduct by week), KLF
- Total Inventory Cost, $/Week
- Total Setup Cost, $/Week

*KLF means Thousands of Linear Feet in length, generally on a roll several feet wide

The Single Machine Analysis uses a mixed integer programming model to minimize setup and inventory costs subject to the following constraints:

- Production and inventory balance with demand for each product and for each week
- Setup time plus production time do not exceed capacity in any week
- A product must be setup before being produced
- Every week must have a feasible sequence of products
- The production net of demand must tie to the beginning and ending inventory inputs (which reflect safety stock goals and seasonal production smoothing)

The most critical feature of the model is its treatment of sequencing. Table III-2 shows the three part matrix of data that feeds the model. The model has a variable representing

---

Table III-2: Three Part Matrix of Sequencing Data for the Single Machine Analysis

<table>
<thead>
<tr>
<th>SETUP TIME:</th>
<th>To Product</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Hours)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.0</td>
<td>0.5</td>
<td>1.0</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td><strong>0.3</strong></td>
<td><strong>0.0</strong></td>
<td><strong>0.8</strong></td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>0.5</td>
<td>0.0</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>6.0</td>
<td>5.5</td>
<td>3.5</td>
<td>0.0</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WASTE PER SETUP:</th>
<th>To Product</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Thousands of linear Feet)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>8</td>
<td>15</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>0</td>
<td>12</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>8</td>
<td>0</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>90</td>
<td>83</td>
<td>53</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>COST PER SETUP:</th>
<th>To Product</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>($000)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$0</td>
<td>$2</td>
<td>$4</td>
<td>$19</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$1</td>
<td>$0</td>
<td>$3</td>
<td>$16</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$4</td>
<td>$2</td>
<td>$0</td>
<td>$13</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>$23</td>
<td>$19</td>
<td>$14</td>
<td>$0</td>
<td></td>
</tr>
</tbody>
</table>

Note: Sample calculations have been included for instructive purposes. The numbers used in these calculations are not representative of actual manufacturing data.

each possible setup permutation in each week. That variable equals one if the setup takes place or zero if the setup does not take place in the minimum cost schedule. If the

29. representative setup permutation would be S_{423} which would mean setup product 4 from product 2 in week 3.
variable equals one, then the model adds the waste cost of the setup to the final cost. The appendix on the Single Machine Analysis (section VI.2) provides full detail on the model and its constraints.

The Single Machine Analysis does suffer some limitations relative to the Single Product Analysis. That is the trade-off for broadening the scope and including capacity constraints. The Single Machine Analysis does not allow any viability in demand or lead time. The model fills the order requirements for each week and must be re-run if a customer changes the amount. The model reserves 10% of the hours in each week for slack, but then assumes product will emerge from the machine at the rated speed without any variability. Finally, the model completes each order with 100% service and does not handle the situation where demand exceeds capacity.30

III.3. Results

The Single Machine Analysis outputs were compared to the actual schedule for four-week periods on one machine. On average, the model schedules cost 10% less than the actual schedules. If these results are extrapolated to all of the ESTAR machines, they show a potential annual savings of substantial size. The savings would not be additive with the previously identified savings from the Single Product Analysis.

Figure III-1 shows the week by week production sequence for a representative four-week period using the data inputs from Table III-2.

---

30The situation where demand exceeds capacity could be easily incorporated into the Single Machine Analysis. The cost of not meeting demand could be added to the objective function, and this would ensure optimal allocation of resources.
Figure III-1: Single Machine Analysis Production Sequence

<table>
<thead>
<tr>
<th>WEEK</th>
<th>Product 1 (52 KLF)</th>
<th>Product 2 (148 KLF)</th>
<th>Product 3 (0 KLF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Product 3 (1,147 KLF)</td>
<td>Product 4 (111 KLF)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Product 4 (160 KLF)</td>
<td>Product 1 (1,103 KLF)</td>
<td>Product 2 (0 KLF)</td>
</tr>
<tr>
<td>4</td>
<td>Product 2 (1,222 KLF)</td>
<td>Product 1 (49 KLF)</td>
<td></td>
</tr>
</tbody>
</table>

Note: Sample numbers have been included for instructional purposes. The numbers in these calculations are not representative of actual manufacturing data.

Figure III-2 shows the pattern of demand orders, production, and resulting inventories in linear feet for each product. In short, what the model does is determine the size and timing of the gray production bars given inputs of the white demand bars and the starting and ending inventory points. The model also sequences the gray production bars by product within one week. The middle points of the inventory line are free to flex anywhere above zero and are dependent upon the demand and production. The model makes all these decisions not just to find a feasible solution, but to find the minimum cost solution.
The model makes many decisions that make sense intuitively, but would be difficult to calculate manually. Although product 1 in this example has zero demand in week 1, it turns out to be efficient to make 52 KLF right away because the model starts
the machine setup on product 1. Also in week 1, just enough product 2 is manufactured to last until week 4, leaving zero inventory for 2 periods. At the end of week 1, the model sets up for product 3 but does not begin producing it until week 2. This allows the fastest setup sequence to product 3 (see Table III-2) without creating any product before it is necessary. Even though product 3 has demand every week, it is produced only once because that optimizes the trade-off between setup cost and inventory cost.

There are two additional lessons about the overall operating policies that come from the Single Machine Analysis. First, the sequencing is not a fixed rotation across all the products. Rather, it is a smooth transition in response to a particular demand load and inventory requirement. Second, there is no concept of fixed lot size. The model sizes each batch dynamically to meet demand within the capacity limits. The expansion of the single product to the single machine model enabled the analysis to incorporate sequencing and capacity, precisely the issues that inspired these two lessons. Moreover, the concepts of flexible sequencing and flexible lot size challenge the existing organizational mental models and scheduling systems. The Single Machine Analysis provides a tool for developing insight about which operating policies should be considered fixed and which should be considered variable.

111.4. Implementation

The Single Machine Analysis was not implemented on any continuing basis, but the reasons behind this decision are instructive. The most important reason why Roll Coating did not incorporate the model into the scheduling or operating processes is that it does not have a broad enough scope. Because the model cannot schedule all of the ESTAR machines at once, it cannot allow products to be manufactured on more than one machine. Like the Single Product Analysis, it is inherently sub-optimum.
Moreover, when there is excess capacity, the model does not schedule the machine. Although less than 24-hour usage could challenge current Roll Coating policies, for the most part the nature of the process makes short shutdowns uneconomical. Once the extruder shuts off and the machine cools down, the process requires a significant number of hours and waste production to bring all the sections back up and in control. An area for further research might be to add shutdown constraints and costs to the model, perhaps treating them like an additional product.

Finally, there are several practical reasons why the Single Product Analysis was not permanently implemented. It was too complex. The potential savings were not enough to justify the effort of systematizing the model to schedule each machine each week. Also, the model uses computer power inefficiently. Just modeling four products in four weekly buckets required 100 constraint equations and took an hour to compute using the branch and bound method\textsuperscript{31} on a powerful personal computer.

The purpose for including the single machine model even though it was not permanently implemented is that it helps build process understanding about variable sequences and lot sizing. It represents a logical stepping stone in the progression between the Single Product Analysis and the complete supply chain analysis that follows. And finally, it offers an example of how academic technology must be applied judiciously to provide practical benefits.

Chapter IV. Supply Chain Analysis

The third step in the expanding scope of this thesis incorporates the supply chain from Roll Coating through to Finishing. (See Figures I-7 and I-8 for a description of the process flow.) Although this analysis cannot provide recommendations down to the level of detail of the Single Product Analysis, it can utilize a more systematic approach to the entire manufacturing process. For instance, instead of just lowering inventory at every stage without considering the impact on other stages, the supply chain analysis determines appropriate safety stock levels looking at the simultaneous contributions of all stages together. The analysis determined that inventories for one set of products from a case study could be reduced by 20%. This would translate to annual inventory cost savings for all ESTAR supply chain products of up to $4.4 MM.

A recent trade journal article advocates this supply chain approach. It claims that, Step one is fully understanding the complete flow of materials and services that add value as perceived by the consumer. . . . [One needs to] develop a strategic plan to achieve a competitive advantage by managing the resources of the entire supply chain.

Figure IV-1 shows a simplified version of the value-added chain for film manufacturing, and it details some of the economic drivers that influence inventory strategy.


Figure IV-1: Economic Drivers of the Supply Chain Analysis

Table IV-1 lists factors that the model considers when determining inventory placement strategy. Note that in Kodak’s case, both the item explosion and the value explosion as the process moves downstream indicate that inventory should be held as far upstream as the lead times and other process parameters will allow. Section IV.4 on results will show that this is indeed the case.

Table IV-1: Factors Impacting Safety Stock Placement

<table>
<thead>
<tr>
<th>Parameters Favoring Upstream or Lower Safety Stocks</th>
<th>Parameters Favoring Downstream or Higher Safety Stocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Item explosion</td>
<td>• Forecast error</td>
</tr>
<tr>
<td>• $ Value explosion</td>
<td>• Production smoothing</td>
</tr>
<tr>
<td>• Short leadtimes</td>
<td>• Information delays</td>
</tr>
<tr>
<td></td>
<td>• High service levels</td>
</tr>
</tbody>
</table>
IV.1. Gods

The goal of the supply chain analysis is to determine the optimum safety stock levels between each stage in the film making supply chain. The underlying concept is that looking at one stage of the supply chain in isolation is inherently sub-optimal. The production speed and quantity of each stage impacts upstream suppliers and downstream customers. All the stages in the supply chain are interconnected by information flows. In short, the inventory and production policies that are best for one stage may not be optimal for the supply chain as a whole.

The supply chain analysis attempts to address this situation. Its calculated inventory levels differ from those in the single product and single machine analyses because here the goal is to reach a global, system-wide optimum. As a result, the recommendations challenge the conventional targets and performance measures for individual divisions. For example, Roll Coating currently faces a corporate-wide mandate to lower inventories. However, the supply chain analysis recommends actually raising some Roll Coating inventories in order to minimize the overall inventory cost of supply chain. This effect occurs because when Roll Coating holds more inventory, downstream stages can hold less, resulting in a net savings for the corporation. This example highlights the importance of considering the entire supply chain when setting inventory and production policies.

Another goal of the supply chain analysis is to address other policy issues that arise from considering one department at a time in isolation. Those policy issues include:

- The “Springboard” Effect
- The “Downward Production” Effect

---

34Here safety stock refers to any inventories used for unplanned events. This excludes cycle stocks (often due to lot sizing) and pipeline stocks (often due to transport times). For a more detailed definition of safety stocks and a literature review on calculating them, see Stephen C. Graves. “Safety Stocks in Manufacturing Systems” (New York, NY: Elsevier Science Publishing Co., Inc., 1988).
The Springboard Effect describes how forecast changes at the customer end can get amplified as the information is passed upstream. The Downward Production Effect is a cycle of declining production throughout the year with a sharp rise in January, presumably due to individual departments trying to meet year-end inventory targets. The supply chain analysis resolves these policy issues by looking across the entire product flow with an analytical model. The details behind the policy issues and the solutions are discussed in sections IV.6 and IV.7.

IV.2. Methodology

The methodology behind the supply chain analysis involved 3 main components:

1. Using a team approach
2. Applying a representative case study
3. Interpreting and implementing the results from a model

Using a team approach for the supply chain analysis was critical. The team (called “SCOT” for Supply Chain Optimization Team) represented each major stage of the supply chain for a product group. Figure IV-2 illustrates the scope and multinational nature of this supply chain. The team approach enabled us to have experts describe the process flow inside and between each stage. The shared learning became important because each stage began to understand how its policies could affect its suppliers and customers. Moreover, it built the trust and laid the groundwork necessary to increase the inventory at some stages to a level exceeding departmental targets. The strong team was willing to bring its case to upper management and change performance measures in order to benefit the supply chain as a whole. The SCOT team consisted of production managers, planners, and forecasters with authority to make inventory decisions. Thus, when the team met, it was empowered to change the entire supply chain
on the spot. Finally, the team approach expedited and simplified the data collection from each stage (See section IV.3).

Figure IV-2: The Supply Chain Optimization Team Scope

The second component of the methodology involved using a case study. This approach allowed quick data acquisition, model testing, and process learning. Furthermore, it generated the results needed to implement a pilot program. The supply chain analysis focused on a single ESTAR film support item. That single support item becomes three different sensitized film codes because it can be coated with three different emulsions. Those three film codes can be finished (slit, chopped, and packaged) into 24 different finished good items. Figure IV-3 illustrates the supply chain analysis case study. This particular product “tree” was chosen because it is high volume, it has relatively few end items (24 total), and it represents a “typical product” which the team felt would make a useful pilot program.
It is important to note that the case study does establish arbitrary bounds on the supply chain. The case study starts with the creation of a roll in Roll Coating and excludes the upstream raw material stages such as chemical, gelatin, and polymer production (see Figure I-8). The case study ends with the Finishing process and arrival at the Central Distribution Center. Kodak has an extensive domestic and international distribution system of warehouses that were not included in the model because other planning tools exist specially designed for that end of the supply chain.35 Besides being bounded at both ends, the case study supply chain is also simplified. In reality, the sensitizing and finishing stages have materials flowing into them such as emulsion and packaging components (see Figure I-8). Even though these materials require inventory management, they are assumed to be available with 100% service and are not explicitly incorporated into the model.

---

35 Kodak uses a system called Distribution Resources Planning (DRP) to manage its domestic network of 5 regional distribution centers (RDC’s) and one central distribution center (CDC). Basically, the Supply Chain Analysis treats the CDC as the end of the supply chain and uses the demand and forecast variance at that level. Additional information on DRP systems can be found in Andre J. Martin, Distribution Resources Management: Distribution Management’s Most Powerful Tool, (Englewood Cliffs, NJ: Prentice-Hall, 1991).
Figure IV-3: Supply Chain Analysis Case Study

Roll Coating Safety Stock  Sensitizing Safety Stock  Finishing Safety Stock

- Finished Item 1
- Finished Item 2
- Finished Item 3
- Finished Item 4
- Finished Item 5
- Finished Item 6
- Finished Item 7
- Finished Item 8
- Finished Item 9
- Finished Item 10
- Finished Item 11
- Finished Item 12
- Finished Item 13
- Finished Item 14
- Finished Item 15
- Finished Item 16
- Finished Item 17
- Finished Item 18
- Finished Item 19
- Finished Item 20
- Finished Item 21
- Finished Item 22
- Finished Item 23
- Finished Item 24

Increasing $ value

Various waste percentages

Various existing inventory levels

Typical leadtimes
The third component of the methodology involved using a model called Dynamic Requirements Planning developed by Professor Stephen C. Graves of MIT’s Sloan School of Management. In broad terms, the model calculates the demand and variance of inventory (safety stock) for each stage in a supply chain. It optimizes the trade-off between production smoothing and inventory variability given the dynamics of the supply chain. The software model can operate either in analytic or in simulation mode. It can be used at an aggregate level (including all of the volume flowing through each stage) or at the item level (as with the case study product “tree” illustrated here). Advanced versions use simulation to model push or pull systems, discrete batching, and shipping consolidation. The team nicknamed the model the “SIP” model for Strategic Inventory Placement. Section IV.3 and the appendix (section VII.3) provide details about the model.

**IV.3. Data Collection**

Data collection represents a critical part of the supply chain analysis. Not only does the model require detailed figures for each stage, but also the data itself can identify potential problems in the supply chain. Once again, the team approach to the data gathering process was essential, and team members gained a more global perspective on their role in the supply chain.

The “SIP” model requires 4 major types of data inputs:

1. **Item definition**: Each item in the product “tree” requires the inputs listed in Table IV-2.

2. **Item linking**: Each “branch” must be established linking items across the different stages. As in a bill of materials, each “branch” includes the waste factor for the square feet that are lost upon conversion. The resulting “tree” structure inputs the item explosion into the model.

---

36 Todate, there are no publications detailing the model. Mr. David Kletter, a graduate student at MIT, wrote the software and assisted with the model development.
3. Forecast variance: As described in the appendix (section VII.3), each end item has an associated “covariance matrix.” This input represents the variance of the forecast from actual demand. It details forecast accuracy 1 week ahead, 2 weeks ahead, and so on out to the planning horizon (which is included in the Table IV-2 inputs).

4. Production smoothing: As described in the appendix (section VII.3), each item (not just end items) has an associated “weight matrix.” This input translates when downstream demand fluctuations are actually produced upstream. (Thus this input is also a “wait” matrix.)

Table IV-2: “SIP” Inputs Required for Each Item in Each Stage

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leadtime</td>
<td>weeks</td>
</tr>
<tr>
<td>Unit Cost</td>
<td>$/KSF*</td>
</tr>
<tr>
<td>Inventory Holding Cost</td>
<td>Annual %</td>
</tr>
<tr>
<td>Manufacturing Frequency</td>
<td>I/Weeks</td>
</tr>
<tr>
<td>Demand by End Item</td>
<td>KSF/Week</td>
</tr>
<tr>
<td>Planning Horizon by End Item</td>
<td>Weeks</td>
</tr>
<tr>
<td>Desired Service Level</td>
<td>% of periods with no stockout*</td>
</tr>
</tbody>
</table>

* KSF means Thousands of Square Feet
**This is commonly referred to as Type II service

Using team participation to collect data from every stage not only proved to be very efficient, but it also identified some potential problems in the supply chain. For example, the model requires collection and analysis of forecast data. In the course of using these figures, the team discovered that the forecasts contained systematic errors that revealed potential problems with the forecasting process. Another side issue that the data collection effort identified was a discrepancy in the Annual Operating Plan volumes between sensitizing and finishing. The waste-adjusted numbers for the case study product “tree” showed that Finishing intended to use more of one item than Sensitizing planned to manufacture for it. As a result, the team learned that the annual planning process was not connected between the two stages and relied on completely separate
inputs. The team subsequently formed sub-groups charged with resolving both of these problems that the data had revealed.

IV.4. Results

The supply chain analysis showed the potential to lower inventory across the case study product “tree” by 20%. The general intuitive principles discussed earlier were shown to hold true, and the “SIP” model quantified the results as shown in Figure IV-4. Note that in general, inventories can be pushed upstream where they are in a strategic position because:

- The inventory is common to the greatest number of finished end items desired by the customer
- The inventory is at its lowest value added and thus at its lowest carrying cost

In fact, the inventory levels of Roll Coating’s “Support 1” actually need to increase to provide savings for the supply chain as a whole. This does not necessarily contradict the Single Product Analysis which might suggest lowering inventory. For one thing, the Single Product Analysis does not consider the effects of the rest of the supply chain. But more importantly, the Single Product Analysis is designed to quantify and prioritize setup time reduction opportunities. Subsequently, any setup time reductions can be used to drive the “SIP” model, which then can determine the best inventory policy for the supply chain.

37 This solution was found using the “SIP” model. Service levels were set at 95% for each stage. The weight matrices were not optimized and were set to reflect each stage’s lead time and manufacturing frequency. In order to reflect Kodak’s current scheduling systems, there was no production smoothing across weeks.
The definition of “inventory” as it is used in this results section is important. The inventory changes and comparisons in Figure IV-4 represent average inventories. Average inventory for each item includes the safety stock calculated by the “SIP” model plus the cycle stock from aggregation needs plus the pipeline stock from transport needs. Figure IV-5 illustrates a representative calculation for a single item. Using average inventories to show potential reductions proved critical in convincing the Supply Chain
Figure IV-5: Representative Inventory Calculation for One Finished Good Item

Assume:
- Average Demand (KSF*/Wk) 100
- 1992 Average Inventory (Days**) 38
- 1992 Average Inventory (KSF) 750

![Figure IV-5 Diagram]

Safety Stock + Cycle Stock + Pipeline Stock

(Calculated from “SIP” model taking into account entire supply chain)

<table>
<thead>
<tr>
<th></th>
<th>Avg Lot Size (KSF)</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truckload Quantity (KSF)</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Total Accumulation (KSF)</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>(Avg cycle stock= half of 700)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety Stock (Days)</td>
<td>5</td>
</tr>
<tr>
<td>Safety Stock (KSF)</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle Stock (Days)</td>
<td>18</td>
</tr>
<tr>
<td>Cycle Stock (KSF)</td>
<td>350</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipeline Stock (Days)</td>
<td>9</td>
</tr>
<tr>
<td>Pipeline Stock(KSF)</td>
<td>180</td>
</tr>
</tbody>
</table>

Transit to Next Stage (Days) 4
System Update Time (Days) 1
Order Processing Time (Days) 3
Location Setting Time (Days) 1
Pipeline Stock (Days) 9
Pipeline Stock(KSF) 180

Total Average Inventory (Days) 32
Total Average Inventory (KSF) 630

Total Inventory Reduction (Days) 6
Total Inventory Reduction (KSF) 120 (-16%)

*KSF means thousands of square feet
**Kodak convention converts weeks to days on the basis of 5 day work weeks
Note: Pipeline times are measured in days, not hours, because the computer system updates once each night in a batch run

Sample calculations have been included for instinctive purposes. The numbers used in these calculations are not representative of actual manufacturing data.
Optimization Team to trust the model results. The production managers and planners on the team could relate to average inventory numbers, especially when expressed in days, because that is the way they are used to thinking of inventory. The team could compare actual average inventories for 1992 with the “SIP” model’s average inventories and feel comfortable with the magnitude of the proposed reductions. Viewed in isolation, some of the potential reductions in safety stock were quite dramatic (60% to 80%) and prompted one manager to comment, “These results bring acid to my stomach.” Adding the cycle and pipeline stocks helped dilute the safety stock reductions and gave the team confidence to implement a pilot program based on the “SIP” model outputs.

In order to implement the “SIP” model recommendations, the team needed to feel confident in the results. Therefore, multiple scenarios were run to test the sensitivity to various parameters. Table IV-3 shows the sensitivity to different service level scenarios. As service level goals at each stage are increased, the required inventory across the supply chain must increase. This is not a linear relationship, but rather follows the standard normal cumulative distribution function (as you approach 99.9% of the area under the unit normal curve, you need to go out many standard deviations).

### Table IV-3: Supply Chain Analysis - Sensitivity to Service Level

<table>
<thead>
<tr>
<th>Service Level</th>
<th>95%</th>
<th>97%</th>
<th>99%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential $ Inventory Reduction Across the Supply Chain</td>
<td>21%</td>
<td>18%</td>
<td>13%</td>
</tr>
</tbody>
</table>

Note: Results are based on the case study product “tree.” Service levels apply to all stages.
Table IV-3 applies the same service level across all three stages in any given scenario. This reflects Kodak’s current way of thinking, but it is not a requirement either for the “SIP” model or in reality. The conclusions of this thesis (Chapter V) discuss some of the benefits and areas for future study that involve different service levels for each stage of the supply chain.

Table IV-4 quantifies the sensitivity to different lead time scenarios. When the lead time of any stage is reduced, the required inventory across the supply chain can also be reduced. The “SIP” model proves very useful for translating the effect of cycle time/lead time improvements at one stage on other stages both upstream and downstream.

Table IV-4: Supply Chain Analysis – Sensitivity to Lead time

<table>
<thead>
<tr>
<th>Potential $ Inventory Reduction Across the Supply Chain</th>
<th>Basecase</th>
<th>50% of Standard Lead time</th>
<th>150% of Standard Lead time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Standard Lead time</td>
<td>Standard Lead time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24%</td>
<td>21%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16%</td>
<td></td>
</tr>
</tbody>
</table>

Note: Results are based on the case study product “tree.”
Finishing lead time is not halved in the 50% Lead time scenario due to integer limitations in the model.

Table IV-5 shows the sensitivity to different forecast variance scenarios. As the forecast variance is reduced (improved forecasting), the inventory can be reduced. Forecast variance here is completely independent of demand variability. That is, the important issue is how well can demand swings be predicted, not how much is demand fluctuating. In this particular case study, a 50% reduction in forecast variance (Table IV-5) helps to lower inventory levels more than a 50% reduction in lead time (Table IV-4). However, it may be artificial to run scenarios on these parameters separately because, in
general, reduced lead times will allow shorter planning horizons, and hence improved forecasts over the lead time.

**Table IV-5: Supply Chain Analysis – Sensitivity to Forecast Variability**

<table>
<thead>
<tr>
<th></th>
<th>Basecase</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50% of Current Forecast Variance</td>
<td>150% of Current Forecast Variance</td>
<td></td>
</tr>
<tr>
<td>Potential $ Inventory Reduction Across the Supply Chain</td>
<td>27%</td>
<td>21%</td>
<td>17%</td>
</tr>
</tbody>
</table>

Note: Results are based on the case study product “tree.”
Taking 50% of the variance is equivalent to taking the standard deviation divided by the square root of 2

Besides the required safety stocks, the “SIP” model also provides information on the induced demand variance at each stage of the supply chain. This demand variance can be used to determine the surge capability needed for any item. The calculated demand variance is based on forecast variance, production smoothing, lead times, and the degree of commonality for upstream items. For instance, in the case study product “tree,” 24 end item sources of variability offset each other as they get translated upstream into the demand for one common ESTAR support item. Figure IV-6 illustrates how the “SIP” model outputs can be used to determine the surge requirements for that one support item.
Figure IV-6: Surge Requirements Example for Support 1

<table>
<thead>
<tr>
<th>Typical Model Outputs</th>
<th>Required* Surge Capability (KSF/Wk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scaled Demand (KSF/Wk)</td>
<td>Demand Std. Dev. (KSF/Wk)</td>
</tr>
<tr>
<td>1,000</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,494</td>
</tr>
</tbody>
</table>

Note: KSF stands for thousands of square feet
*Assumes surge capability covers 959° (or 1.645 standard deviations) of the expected demand

No model is perfect, and no description of a model is complete without a list of shortcomings. The "SIP" model has three weaknesses:

- It does not account for lead time variability
- It assumes stationary average demand over time
- It cannot accommodate a large product explosion

The model assumes deterministic lead times. Once an order is placed, a finished product appears exactly one lead time later, no earlier and no later. The long-run average demand is fixed so that the model would have to be re-run over time to accommodate steady increases, declines, or seasonal effects. New versions of the model incorporate actual forecasts using simulation which can help average out these effects. Finally, the current version of the model cannot easily handle a product “tree” that splits into more than 25 end items. However, in most practical situations, a team should probably not be working at any greater level of detail than this. Keeping the model at a high level both reinforces the fundamental guiding principles and also makes decisions on implementation simpler.
IV.5. Implementation

Once all of the supply chain analysis requirements were complete, the stage was set to implement a pilot program. To recap, the preparation that was in place included:

- An experienced team with representatives from each stage and function
- A complete set of data inputs validated by the team
- A "basecase" set of recommended inventory levels for each stage that the model calculated
- A set of actual inventory data to compare to the "basecase"
- A series of “aggressive” and “conservative” inventory scenarios to test the model’s sensitivity
- A surge requirement analysis for each stage’s capacity

Armed with these data, the Supply Chain Optimization Team gathered for an all-day session to discuss the results and decide if they felt confident enough to try the strategic inventory placement. The team added local intelligence about specific customers and manufacturing issues for each item that could not be captured by the model. After reaching an understanding about how all of the model’s proposed changes would impact the supply chain, the team decided to implement a pilot program. They chose to follow the most conservative scenario as a starting point with the intention of moving to the "basecase" if there were no service problems. Like a case study approach, the pilot program could be used to test the validity of the model on a small scale with a minimum amount of risk.

The Supply Chain Optimization Team implemented a plan for the case study product that only involved the inventories of three items. The plan raised the one Roll Coating item’s inventory by 20% (all safety stock), and it lowered two Sensitizing items’ inventories, each by 60%. This provided a net, one-time inventory reduction of close to $400 K and an annual savings of close to $100 K. The plan was implemented in early 1993 so that the increase in Roll Coating inventory would not affect 1992 end-of-year targets. The savings were captured in the 1993 Annual Operating Plan for the case study
line of business. As of the end of April, 1993, not a single end customer order had been missed on the pilot product due to stockouts or inventory shortages.\textsuperscript{38}

The main barrier that the team had to overcome in reaching the implementation stage was understanding how the “SIP” model works. The following tools helped them build up the necessary confidence and trust in the model:

- Running different scenarios, especially conservative ones
- Displaying all the input data and its sources for validation
- Explaining how the model used the input data
- Comparing the model results \textit{versus} current inventory levels
- Showing the required surge capacity
- Exposing all of the model’s shortcomings

Finally, the manner and conviction with which the results are presented have a big impact on whether an academic model and a vision of rapid customer response through the supply chain can become a practical business reality.

The next step for the Strategic Inventory Placement model involves transferring the methodology to other supply chains in other lines of business. The results of the pilot test and subsequent expansion of the program can be publicized through Kodak worldwide forums including plant cycle time coordinator conferences, the worldwide cycle time newsletter, and the hi-weekly supply chain (“Macro-flow”) leaders meetings. Any supply chain with a strong team, a focused set of products, and a willingness to reduce inventory would provide a ripe environment for trying the strategic inventory placement approach. The annual value of implementing “SIP” programs across all of the Roll Coating - ESTAR supply chains could exceed $4 MM.

\textsuperscript{38}Phone call to the Supply Chain Optimization Team leader on 4-27-93.
IV.6. The Springboard Effect

Another goal for the Supply Chain Analysis was to assess the impact of various department level policies on the entire system. The Strategic Inventory Placement model addresses this type of issue by analyzing the supply chain as a whole, and this approach in turn highlighted an inventory management policy that has been termed the “Springboard Effect.” In order to run the” SIP” model and interpret its results, the team needed to understand the upstream information flows as well as the downstream material flows. One result of studying the information flows was the discovery about the systematic impact of setting safety stocks in weeks.

The Springboard Effect describes the way a change in downstream demand is transmitted up the supply chain at Kodak. Basically, any forecast and demand noise is amplified as the information is passed upstream. Demand increases trigger larger and larger production levels upstream, and demand declines leave component inventories stranded without orders. For example, a small increase in demand for one finished good item might launch a growing response moving upstream in the supply chain until finally a raw material supplier may end up doubling or tripling its production levels. Basically there are 2 root causes behind the Springboard Effect:

1. Current scheduling algorithms set safety stocks in forward weeks of supply
2. Demand information is passed upstream department to department

The first root cause is that safety stock targets are measured and thought of as a certain number of weeks. The number of weeks is translated into a real quantity based on the immediate future demand. That is, if the safety stock target is 2 weeks and the forecast demand is 100 in week 1, 50 in week 2, and 10 thereafter, then the target safety stock quantities will be 150 in week 1, 60 in week 2, and 10 thereafter. There is a rationale behind this logic that says measuring targets in weeks of forward supply covers supply variability by always producing products before they are needed. The logic builds
in safety time. However, the implication of the first root cause is that forecast changes cause safety stock quantity changes.

The second root cause is that at Kodak, upstream stages only receive updated demand information when their downstream customer passes it back to them. The rationale behind this process is that each stage shifts the timing of orders around to meet its own capacity limitations and inventory goals, and then it passes on the “filtered” changes upstream. The implication of the second root cause is that upstream departments do not have visibility of the actual finished goods demand changes; they only “see” a filtered version at a later time.

These two root causes lead to the following scenario (see Table IV-6): Marketing says finished goods demand for item Z is increasing by 50%. Because the finished goods inventory aim is measured in weeks of forward supply, its inventory quantity must also increase by 50%. So Finishing must now produce 50% of what it currently has in inventory. Finishing then dutifully passes along this information to Sensitizing. Now Sensitizing, who also measures its inventory in forward weeks of supply, must increase its own inventory quantity by 50% because of the demand change. Plus, it must produce enough to cover Finishing’s inventory increase too. Therefore Sensitizing must now produce 83% of what it currently has in inventory, 50% for itself and 33% for downstream inventory. The springboard has started!

Sensitizing then passes on its demand upstream to Roll Coating. Roll Coating must now produce enough to cover its own inventory increase, as well as that of Sensitizing and that of Finishing. Now Roll Coating must produce a colossal 125% of what it currently has in its inventory. The springboard continues to amplify this demand

---


change at ever increasing levels as information is passed upstream. Table IV-6 illustrates the effects of this 50% demand increase scenario.

Table IV-6: The Springboard Effect: 50% Demand Increase Scenario

<table>
<thead>
<tr>
<th>Hypothetical Data:</th>
<th>Finishing</th>
<th>Sensitizing</th>
<th>Roll Coating</th>
<th>Chemicals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inv Aim (Inv Wks)</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>15</td>
</tr>
<tr>
<td>Waste Factors (BOM)</td>
<td>1.00</td>
<td>1.20</td>
<td>1.44</td>
<td>1.58</td>
</tr>
</tbody>
</table>

Demand increase by 50%:

<table>
<thead>
<tr>
<th>Original Inventory (SF)</th>
<th>100</th>
<th>180</th>
<th>288</th>
<th>594</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inventory Increase (SF)</td>
<td>50</td>
<td>90</td>
<td>144</td>
<td>297</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Production for own Inv</th>
<th>50</th>
<th>90</th>
<th>144</th>
<th>297</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production for Downstream</td>
<td>0</td>
<td>60</td>
<td>216</td>
<td>571</td>
</tr>
</tbody>
</table>

| Total Production      | 50 | 150 | 360 | 868 |

| Production/Original Inv | 50% | 83% | 125% | 146% |

Note: The above numbers are included for instructional purposes and are not representative of actual manufacturing data. The waste factors, for example, are just 20% compounded.

Figure IV-7 expands this single scenario to show the results of all different forecast increases on each stage of the supply chain. If the demand for an item doubles (a common occurrence at Kodak especially on new items), the graph shows that the fourth stage upstream will actually have to produce triple the amount it currently has in inventory.
Figure IV-7: The Springboard Effect for Different Forecast Increases

Note: The above numbers are included for instructional purposes and are not representative of actual manufacturing data. The lines were generated from the hypothetical data in Table IV-6.

Of course the forecast does not always increase. When the forecast is decreased, the Springboard Effect occurs, but in the opposite direction. Each stage’s inventory targets go down, and upstream stages are left with inventories that will have no demand until each downstream stage has drained its own inventories. To summarize the Springboard Effect:

- **Forecast Up** means upstream stages spring to fill inventory targets throughout the supply chain
- **Forecast Down** means stranded inventory will be slow to drain out of the supply chain
Finally, it is important to note that delays in the information flow and long lead times serve to dampen the Springboard Effect. This is because the upstream stages may not receive the changing demand information quickly, and they may not have the production speed to respond to the new inventory targets. However, Kodak has strong improvement thrusts in both of these areas and ironically, as Kodak improves its response speed, the Springboard Effect will grow worse.

Actual data that demonstrate the Springboard Effect are difficult to find. The reasons are that there are delays in relaying the forecast upstream and that upstream inventories often service multiple end customer items. Nevertheless, in the course of researching forecast data for the Strategic Inventory Placement model, one strong example was uncovered. In this one case, a large order due in 10 weeks for a high-volume finished good item was moved forward by 2 weeks. One week later, Sensitizing scheduled production for 1.2 times the demand change. One week after that, Roll Coating scheduled production for 1.4 times the demand change. Because the demand change involved just moving the timing, not a permanent increase, the Springboard Effect was seen afterwards, too. After the order due date, Roll Coating was left with inventory to support the end item that was 25% higher than its year-to-date average.

The Strategic Inventory Placement model corrects for the Springboard Effect because the model treats safety stock as a distribution of actual inventory quantities (thousands of square feet in this case), not in weeks of forward demand. If a demand spike occurs, the model assumes that some stages will have to dip into safety stock. In contrast, using the logic behind the Springboard Effect, the planning system would respond to a demand spike by changing the inventory quantities.

Nevertheless, the Strategic Inventory Placement model cannot replace a planning system. The model is designed to analyze the supply chain, run “what-if” scenarios, and provide insight about the process. Kodak’s current Master Production Scheduling (MPS
II) and Materials Resources Planning (MRP II) systems are more appropriate for managing inventones on a detailed level across the plant. One potential solution for reducing the Springboard Effect without totally rewriting the existing inventory systems involves redefining the way “forward weeks of supply” are counted. Instead of having a 1-week safety stock target refer to the actual next 1 week of demand, the system could have it refer to an average rate of demand. The average rate could define a week of safety stock as 1/52 of the year’s demand in the case of a flat market, or the average rate could cover shorter periods if the market is seasonal. In any case, the effect on safety stock levels of a one week demand spike would be dampened out by a factor of 1/52 or 1/season. With steadier safety stock targets, the production rates across the supply chain could be scheduled more smoothly. Demand noise would then be dampened, rather than amplified, moving up the supply chain.

In summary, there would be two advantages to altering the definition of “forward weeks of supply” in this way. The first advantage is that the production swings from the Springboard Effect could be eliminated without discarding the current systems. The second advantage is that the safety stock targets would still change, albeit more gradually, in response to forecast demand trends. If an absolute safety stock quantity were fixed for each item, then manual intervention would be required whenever any item’s long range demand changed. Identifying and addressing issues such as the Springboard Effect represent an important part of supply chain management, and it illustrates the value of extending the scope of examination across the entire system.

IV.7. The Downward Production Effect

Another department level policy issue that the Supply Chain Analysis addressed was the “Downward Production Effect.” This effect describes a situation in many Kodak manufacturing departments where the highest production rate occurs in January. The rate
gradually declines throughout the calendar year until December when the production rate reaches its minimum. Suddenly, during the following January, the production rate jumps again, reaching a new annual peak.

The Downward Production Effect could have adverse effects for two reasons:

- Poor asset utilization
- Poor use of labor

Basically, the effect imposes an artificial seasonality on the manufacturing process. Capital intensive assets like the Roll Coating machines could go unused in the latter half of the year. New customers cannot be brought in because they could not be serviced in the early part of the year when capacity is stretched to the limit. Moreover, enough labor must be hired and trained (and often paid overtime) to run at full load early in the year, and then later in the year the department becomes over-staffed.

**Figure IV-8** illustrates the Downward Production Effect in a single production area for 1990 and 1991 by using regression analysis, (1989 and earlier data were unavailable, and 1992 could not be calculated without a full year of actual results.) The X-axis shows one data point for each month. The Y-axis shows production as a percentage of the monthly average for the year. Basically the Y-axis is a specific month’s production divided by the monthly average for the year. The production rates are adjusted for number of days in the month. The production area operates 24 hours per day, 7 days per week, so weekends and holidays were included. Major mechanical

---

41The adjustment for different numbers of days in the month worked in the following way:

\[
\text{[Adjusted Production Rate]} = \left( \frac{1}{\text{Days in Month}} \right) \cdot \left( \frac{365}{12} \right) \cdot \text{[Actual Production Rate for Month]}
\]

For example, if 100 units were actually produced in February. then

\[
\text{[Adjusted Production Rate for February]} = \left( \frac{1}{28} \right) \cdot \left( \frac{365}{12} \right) \cdot \{100\}
\]

\[
= 109 \text{ adjusted units / month}
\]
repairs on machines were excluded. The actual production rates for the years can be different because the analysis normalizes for different absolute quantities.

**Figure IV-8: The Downward Production Effect**

![Graph showing the Downward Production Effect](image)

- **Slope** = -1.7% per month
- **R-Squared** = 42%
- **p-value** = 0.05%

Note: Monthly production is adjusted for the number of days in the month. Each year is normalized by the average daily rate. The numbers in this chart are for instructive purposes and are not representative of real manufacturing data.

The meaning of **Figure IV-8** is that production rates in a particular department showed a statistically significant decline of 1.7% per month over the course of each year for two years running. The data verifies that the Downward Production Effect is real for certain areas. A simple regression model showed a slope of 0.017 with an F-ratio of 16 (see **Table IV-7**). Any F-ratio higher than 7.9 (for these degrees of freedom) indicates
that the non-zero slope has greater than 99% significance\(^2\). Indeed, the p-value was calculated to be 0.0005 which means that we can reject the hypothesis that the slope equals zero with 99.95% confidence.\(^3\) The \(R^2\) value shows that the regression model explains 0.09/0.20 or 42% of the variability.

### Table IV-7: Analysis of Variance for the Downward Production Regression

<table>
<thead>
<tr>
<th>Degrees Freedom</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F-Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>1</td>
<td>0.09</td>
<td>0.087</td>
</tr>
<tr>
<td>Residual</td>
<td>22</td>
<td>0.12</td>
<td>0.005</td>
</tr>
<tr>
<td>Total</td>
<td>23</td>
<td>0.20</td>
<td></td>
</tr>
</tbody>
</table>

All of the above statistics highlight the value of gathering actual data. Production and planning personnel suspected that production was dropping each year only to rebound again each following January. But there was no real evidence or hard proof. With the actual data in hand, and with the supporting statistics to demonstrate significance, the particular department could be convinced that the Downward Production Effect was real.

\(^{42}\)An F distribution describes the ratio of 2 chi-square random variables and is often used to compare variances of two independent normal distributions. In the simple regression model presented here, the two variables being compared are the mean squares for the regression and the residual in Table IV-7:

\[
F = \frac{MS_{Regression}}{MS_{Residual}} = \frac{0.087}{0.005} = 16
\]

If the F-ratio is large enough, then the null hypothesis (that the slope is zero) can be rejected at a certain significance level. In this case, with 1 degree of freedom for the regression and 22 degrees of freedom for the residual, a “large” F-ratio is 7.9 at the 99% significance level. This value can be found in almost any set of statistical tables as \(F(99\%; 1, 22)\). For further details about the F-ratio and for statistical tables, see Robert V. Hogg and Johannes Ledolter, *Engineering Statistics*, (New York, NY: Macmillan Publishing Co., 1987), pp. 162, 281, and 399.

\(^{43}\)The p-value was calculated using a regression add-in package with Microsoft’s Excel 4.0. The p-value represents the probability of obtaining a sample exactly matching the 1990 and 1991 Roll Coating production figures if the slope were in fact equal to zero (no significant downward production).
Furthermore, additional research showed that more than one department was experiencing this effect. In fact, in 8 out of 14 areas sampled across the supply chain, there was a Downward Production Effect with at least a 90% significance level.

At this time, the exact causes of the Downward Production Effect have not been determined, and it remains an opportunity for further research. However, there are two major hypotheses:

- End of year point inventory reduction targets drive down replenishment orders throughout the supply chain.
- Inventory build-ups preceding mechanical shutdowns occur all during the year up and down the supply chain, but are rarely scheduled during the November–December holiday season.
- Sales targets are systematically high.

Either of these two causes, or a combination including the Springboard Effect is possible. The important point is that Downward Production is a supply chain wide phenomenon. Its damaging effects on labor and asset utilization spread when downstream stages transmit ever-decreasing orders upstream. The role of the supply chain analysis in this case is to manage the inventory across all the stages and to communicate clearly all of the strategies for change. If inventories need to be reduced, then the supply chain can work together to execute the change without disrupting production or creating detrimental cycles. The Downward Production Effect represents yet another instance where taking a broad perspective across the supply chain is critical.

Once the cause of the Downward Production Effect has been determined, prospective solutions can be developed. If end-of-year point inventory targets are indeed driving down production throughout the year, then at least two potential solutions exist:

1. Use a moving monthly average rather than an end-of-year point in performance metrics
2. Use a supply chain-wide measure of inventory rather than measuring each department separately
The first potential solution might measure say the average daily inventory for the last 2 months. Although improvements might take awhile to appear, this type of moving average would eliminate some of the “game playing” that can be used to make a point measure of inventory lower. The second potential solution would remove the incentive to cancel orders from upstream suppliers just before the measurement date in order to make a single department’s own books look good. In the long run, it is far more beneficial to the company to have rapid and smooth supply chain production than a single snapshot of low inventory.  

\[44\]

\[44\] It is public knowledge that bond rating services such as Moody’s and Standard & Poor’s still use conventional end-of-year point inventories as part of their rating process. Until they change their methods, companies may have a legitimate reason to lower their production at year end to reduce inventories artificially. Companies could potentially avoid a bond rating downgrade that would increase their real cost of capital.
Chapter V. Conclusions

V.I. Summary

Cycle time represents a vital competitive dimension for the Roll Coating Division and for Eastman Kodak Company as a whole. Through a series of three case studies that gradually expand in scope, this thesis has addressed cycle time reduction at every level of detail. Each case study examined the concept of inventory levels and their effect on production, scheduling, and cost. Inventory fundamentally reflects the way the business is being run and how well it is performing against the competition. As Karmarkar suggests, “[This] question of how to determine inventory levels cuts quickly to the basics of manufacturing in an age of intense global competition.”

The central themes that unite the case studies in their efforts to reduce cycle time include:

- The need to understand the fundamental manufacturing process and incorporate that knowledge into the problem solving approach
- The importance of finding the right level of detail to address the problem at hand
- The value of looking across the entire supply chain and recognizing the effect that one department’s decisions can have across the system

Every case study required process understanding. Without a detailed grasp of what an ESTAR machine setup entails, there would be no way to quantify the effect of setups on cycle times. Every case study provided a different level of detail to answer a different question. The Single Product Analysis could incorporate supply variability and the Single Machine Analysis could incorporate product sequencing, but both at the cost of not considering the impact on upstream and downstream stages. The Supply Chain Analysis, on the other hand, lacked those fine points, but could address the broader issue of what inventories should link the stages together. Finally, looking across the entire

---

supply chain provides tremendous leverage and global thinking toward which actions will benefit the company as a whole.

**V.2. Recommendations**

On a broad level, the recommendation is to maintain and promote Kodak’s corporate emphasis on cycle time reduction. Rapid cycle times provide a competitive weapon for satisfying the customer, reducing cost, and improving quality. Each business, each division, and each machine team needs to translate how the company’s cycle time vision applies to their scope of activities. Then analysis and models such as those presented in this thesis can help assess the impact of particular actions and prioritize improvement opportunities.

One important obstacle that hinders cycle time improvement throughout Kodak is the Materials Resources Planning (MRP II) system. The recommendation is to evaluate constantly the need to have a system which constrains thinking to weekly buckets and to fixed lead times. How can the company encourage, measure, and reap savings from cycle time reductions of less than a week if the systems only schedule in terms of weeks? What incentive is there for operators or engineers to work on speeding up every setup if the next stage is not scheduled to consume that item until a fixed lead time has elapsed? Thus, the recommendation is that management create greater incentives for cycle time reduction because the whole structure of the scheduling system creates disincentives.

On a more focused level, the recommendation is to expand on the three critical areas discussed in the thesis case studies. For the Single Product Analysis, the benefits of setup time reduction and lot sizing can be emphasized and encouraged by applying the

---

46Conflicting evidence has arisen recently that part of the system is not constrained to weekly buckets. This thesis is based on data from interviews with the master planners and their supervisors, and it represents their perception of the scheduling system’s capabilities.
model results to each machine team’s performance matrix. Roll Coating can also re-
energize the “pit crew” concept of choreographing setups in advance and stressing quick
changeovers. Setup time reduction appears to be the next major frontier on Kodak’s
corporate cycle time reduction strategy. Ultimately, Kodak might consider measuring
production employees on inventory as well as on waste to encourage actions that address
both issues simultaneously.

For the Single Machine Analysis, Roll Coating can always seek new ways to
optimize capacity and sequencing. New custom-designed detailed scheduling tools are
being introduced constantly and could be integrated with the existing scheduling systems
(see Figure 1-6).47 Most important, though, is to educate ESTAR employees about the
process intuition that the model provided, including the implications of

- Running at capacity
- Sequencing of products
- Speed of setups
- Flexibility of machines

Another recommendation is to resist the temptation to have a fixed product sequence and
a fixed lot size for each product. The Single Machine Analysis showed that these
parameters should remain flexible and respond to the entire load on the system. Finally,
the concept of increased flexibility, (any machine running any product without long
setups), could provide a fundamental solution that removes the scheduling complexity
instead of merely coping with it.

For the Supply Chain Analysis, the recommendation is to roll out the results of the
pilot program across the entire product line of business studied. Moreover, the concept of
strategic inventory placement could be applied to other film lines and even Kodak’s other

47 For a review of detailed scheduling packages, see Uday S. Karmarkar and Milind M. Lele, “The Marketing/
Manufacturing Interface: Strategic Issues.” University of Rochester Center for Manufacturing & Operations
non-photographic businesses. The Supply Chain Analysis involved a cultural shift where the team was focused on their role as members of a product “flow” serving the end customer. This supply chain allegiance challenges many companies’ traditional organizational focus on functions or single departments. A recommendation would be to expose everyone associated with products, operators and engineers, to the business unit goals and the other members of their supply chain.

Another supply chain recommendation is to gather and publicize some of the data that the SCOT team collected even if it is not going to be input into the “SIP” model. The forecast variance data can detect systematic forecast process problems, and the comparison of each stage’s demand data can pinpoint any disconnects in the Annual Operating Plan.

To combat the Springboard Effect, the recommendation is to communicate end item demand changes to every stage in the supply chain without delay. Also, with a small systems change, safety stocks could be based on demand rates of a year or a season, rather than on immediate forward weeks of supply. These actions would help dampen out the demand noise amplification that currently causes large swings in upstream production requirements.

For the Downward Production Effect, if it is indeed caused by end-of-year point inventory targets, then the measurements should be changed. Using moving average inventories and supply chain-wide totals might eliminate the inefficient production declines that occur throughout the year.

One final recommendation would be to make the critical cycle time issue explicit in the Roll Coating Division’s Vision and Mission statements. Although the statements cover quality, teamwork, and continuous improvement, there is no mention of speed or response time. Top management commitment is required to drive major change within the organization, and cycle time improvement is no exception.
V.3. Opportunities for Future Work

The ultimate cycle time vision foresees a supply chain capable of blasting goods through to respond to customer needs with the barest amounts of inventory between each stage. Opportunities for future work all involve ways of transforming this vision into reality. One paradigm worth challenging is the idea that Roll Coating, Sensitizing, and Finishing all need to be separate functions de-coupled with inventory. Perhaps a future state would couple these stages and provide a synchronous manufacturing process. A similar alternative might involve a hybrid push-pull system where inventories could be “pushed” to a strategic de-coupling point and then “pulled” rapidly through the supply chain in response to specific customer orders.

Another opportunity across the supply chain would be to explore the benefits of differentiated service levels. Rather than providing 95% service at every stage, a strategy could be to provide lower service levels upstream and higher service levels downstream to the end customer. The “SIP” model provides an ideal tool for simulating the effect of different service level strategies on cost and delivery performance throughout the supply chain.

Other opportunities for future work on the topics addressed by this thesis include:

- Incorporating more aspects unique to Kodak into the Single Product Analysis. These would include discarded product being correlated with lots, waste learning curves associated with each run, and sequencing effects.
- Adding lead time variability to the Supply Chain Analysis
- Finding other data-driven examples of the “Springboard Effect” and running simulations to test different safety stock strategies
- Testing the “Downward Production Effect” correlation to different factors to determine its precise cause

---

48 Or a point at which product proliferation occurs
Another opportunity for future work is to put the responsibility for cycle time reduction in the hands of the operators. As the people closest to the detailed work, they are in the best position to eliminate non-value added transactions, streamline procedures, and improve production techniques. They can then control other cycle time areas such as work-in-process inventory and work queues:

Let’s stress it again. The setting of a buffer [inventory] length involves the most fundamental managerial decision—the trade-off between the measurements. When choosing long buffers it directly impacts the level of time-related INVENTORY (work-in-process and finished tasks). . . . Choosing short buffers directly impacts . . . THROUGHPUT (unreliable delivery). Who should make this decision, who should establish the length of the TIME BUFFERS? In most companies, it’s not the top manager or even the scheduler, it’s the forklift driver.49

The goal of this thesis was to address the critical issue of cycle time and its related inventory component. The final measure of its success will be if it stimulates the reader to think of future opportunities to apply this work to practical business situations.

Chapter VI. Appendices

VI.1. Single Product Analysis

The Single Product Analysis uses a Lot Size–Reorder Point system to determine optimum operating policies\(^{50}\). In short, this type of system determines operating policies by specifying when to order and how much to order. Those two pieces of information can be used to calculate the expected manufacturing frequency, average inventory, safety stock, and other parameters.

In the model, both the periodic demand and the lead time are taken as variable, and their distributions are combined to determine the resulting distribution of demand over the lead time. The overall technique involves calculating an initial lot size using an Economic Production Quantity formula. Then that value is used to calculate the reorder point, which, in turn, can be used to calculate a more accurate lot size. The Single Product Analysis repeats this iterative process once because in most cases the values quickly converged to less than a 10% spread.

The first part of the model transforms raw data into the inputs needed to calculate the lot size and reorder point. This first part involves four steps:

1. Calculating the expected demand during the lead time and its standard deviation
2. Calculating the cost per setup
3. Calculating the inventory holding cost
4. Calculating the net production rate

1. 
\[ \delta = D \cdot \tau \]
\[ \delta = \sqrt{\tau \cdot \sigma_D^2 + D^2 \cdot \sigma_T^2} \]

\( \delta \) = Expected demand during the lead time in KLF

\( \sigma_D \) = Standard deviation of demand during the lead time in KLF

\( D \) = Mean periodic demand in KLF / Week

\( \tau \) = Mean lead time in Weeks

\( \sigma_D \) = Standard deviation of periodic demand in KLF / Week

\( \sigma_T \) = Standard deviation of lead time in Weeks

*KLF symbolizes thousands of linear feet

2. 
\[ S = t \cdot M \cdot C_u \]

\( S \) = Setup cost in $ / setup

\( t \) = Setup time in minutes

\( M \) = Machine speed in linear feet/ minute

\( C_u \) = Unit cost in $ / linear foot

3. 
\[ C_I = 1,000 \left( \frac{C_H}{52} \right) \]

\( C_I \) = Inventory cost in $/ KLF / Week

\( C_H \) = Annual inventory holding cost as a % of unit cost

\( C_u \) = Unit cost in $/ linear foot
Note that determining $C_H$ is a calculation requiring multiple inputs that may vary depending on the exact situation. For the Single Product Analysis, the following holding cost factors were included:\textsuperscript{51}

- Weighted cost of capital
- Taxes
- Insurance
- Spoilage
- Theft
- Obsolescence
- Warehouse employee costs
- Warehouse space and utility costs
- Warehouse supplies including light-tight boxes
- Cores at the center of the rolls of ESTAR film base
- Variable inventory management costs (systems and employees)

4.

$$P = Y \cdot M \cdot \left[ \frac{60 \cdot 24 \cdot 7}{1,000} \right]$$

$P$ = Net production rate in KLF / Week  

$Y$ = Yield off of machine in %  

$M$ = Machine speed in linear feet/ minute

Once these 4 quantities have been calculated, the model begins the second stage, an iterative process of determining lot size and reorder point. To get started, the Economic Production Quantity formula is used to calculate a lot size:

\[ Q_0 = \sqrt{\frac{2SD}{C_i(1-\frac{P}{D})}} \]

\( Q_0 \) = Starting Economic Production Quantity (lot size) in KLF
\( S \) = Setup cost in $ / setup
\( D \) = Mean periodic demand in KLF / Week
\( C_i \) = Inventory holding cost in $ / KLF / Week
\( P \) = Net production rate in KLF / Week

This value for \( Q_0 \) can then be used to calculate the necessary statistics needed to determine the reorder point.

\[ L(z) = \frac{Q_0(1-\beta)}{\theta_{\delta}} \]

\( L(z) \) = The standardized loss function

\( L(z) = \int_z^\infty \phi(t) \, dt \) where \( \phi(t) \) is the standard normal density

\( \theta \) = Desired service level (% of demand met from stock)

\( \delta \) = Standardized variate found by looking up \( L(z) \) in a table
Once the first iteration values of \( Q \) and \( R_0 \) have been calculated, they can be used to determine statistics needed for another lot size iteration.

\[
n(R) = Q_4(1 - \beta) \]

\( n(R) = \) Expected number of stockouts per manufacturing cycle \hspace{1cm} (IV)

\[
n(R) = \int_{R}^{\infty}(x - R)f(x)dx \text{ where } f(x) \text{ is the normal density function} \]

\[
F(z) = \text{Standard normal cumulative distribution function} \hspace{1cm} (V)
\]

(The probability of being to the left of \( z \))

These statistics allow the model to calculate the second (and final) iteration values for lot size and reorder point.

\[
Q_i = \frac{n(R)}{1 - F(z)} + \sqrt{Q_0^2 + \left(\frac{n(R)}{1 - F(z)}\right)^2} \hspace{1cm} (VI)
\]

\[
L_i(z_i) = \frac{Q_i(1 - \beta)}{\theta_\delta} \hspace{1cm} (VII)
\]

\( L_i \) and \( z_i \) represent the new values after iteration

\[
R_i = \delta + \theta_\delta z_i \hspace{1cm} (VIII)
\]

\( R_i = \) Reorder point in KLF after iteration
The values of $Q_i$ and $RI$ now enable the model to calculate the desired operational results in an implementable format.

$Q_i = \text{Lot size in KLF}$

$\left( \frac{Q_i}{P} \right) \cdot 7 = \text{Lot size in days of production}$

$\frac{Q_i}{D} = \text{Avg time between lots in weeks}$

$\left( \frac{SD}{Q_i} \right) \cdot 52 = \text{Annual setup cost in } \$$

$R_i - \delta = \text{Safety stock in KLF}$

$\frac{R_i - \delta}{D} = \text{Safety stock in weeks}$

$(R_i - \delta) + \frac{Q_i}{2} \left( 1 - \frac{D}{P} \right) = \text{Average inventory in KLF}$

$(\frac{R_i - \delta}{D}) + \frac{Q_i}{2D} \left( 1 - \frac{D}{P} \right) = \text{Average inventory in Weeks}$

$\left[ \text{Avg Inv in KLF} \right] \cdot C_i \cdot 52 = \text{Annual inventory holding cost in } \$$
Figure VI-1 shows a sample page of a model printout.

**Figure VI-1: Single Product Analysis Sample Printout**

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>Symbol</th>
<th>Representative Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand</td>
<td>Mean</td>
<td>KLF/wk</td>
</tr>
<tr>
<td>Std Dev</td>
<td>KLF/wk</td>
<td></td>
</tr>
<tr>
<td>Lead Time</td>
<td>Mean</td>
<td>wk</td>
</tr>
<tr>
<td>Std Dev</td>
<td>wk</td>
<td></td>
</tr>
<tr>
<td>1. Demand during LT Mean</td>
<td>KLF</td>
<td>(\delta)</td>
</tr>
<tr>
<td>Std Dev</td>
<td>KLF</td>
<td>(\sigma(\delta))</td>
</tr>
<tr>
<td>2. Setup Cost</td>
<td>Machine</td>
<td></td>
</tr>
<tr>
<td>SU Time</td>
<td>min</td>
<td>(t)</td>
</tr>
<tr>
<td>Mach speed</td>
<td>LF/min</td>
<td>(M)</td>
</tr>
<tr>
<td>Unit cost</td>
<td>$/LF</td>
<td>(C(u))</td>
</tr>
<tr>
<td>Setup cost</td>
<td>$/Setup</td>
<td>(S)</td>
</tr>
<tr>
<td>3. Inventory Cost</td>
<td>Annual %</td>
<td>(C(H))</td>
</tr>
<tr>
<td>Weeks/year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit cost</td>
<td>$/LF</td>
<td>(C(u))</td>
</tr>
<tr>
<td>Inv cost</td>
<td>$/KLF/wk</td>
<td>(C(I))</td>
</tr>
<tr>
<td>4. Production Rate</td>
<td>Mach speed</td>
<td>(M)</td>
</tr>
<tr>
<td>Yield</td>
<td>% yield</td>
<td>(Y)</td>
</tr>
<tr>
<td>Rate</td>
<td>KLF/wk</td>
<td>(P)</td>
</tr>
<tr>
<td>Desired Service Level</td>
<td>(\beta)</td>
<td></td>
</tr>
</tbody>
</table>

**EQUATIONS**

<table>
<thead>
<tr>
<th>CALCULATIONS</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic Order Quantity</td>
<td>KLF I</td>
</tr>
<tr>
<td>Standardized Loss Function</td>
<td>KLF II</td>
</tr>
<tr>
<td>Standardized Z Value</td>
<td>Std Dev.s</td>
</tr>
<tr>
<td>Reorder Point</td>
<td>KLF III</td>
</tr>
<tr>
<td>Expected stockouts per mfg order</td>
<td>KLF IV</td>
</tr>
<tr>
<td>1 - F(z) [Prob of being to right of z]</td>
<td>KLF V</td>
</tr>
<tr>
<td>E.O.Q. (1st iteration)</td>
<td>KLF VI</td>
</tr>
<tr>
<td>New Standardized Loss Function</td>
<td>KLF VII</td>
</tr>
<tr>
<td>New Standardized Z Value</td>
<td>Std Dev.s</td>
</tr>
<tr>
<td>Reorder Point (1st iteration)</td>
<td>KLF VIII</td>
</tr>
<tr>
<td>Value of no shortfall</td>
<td>KLF $/KLF</td>
</tr>
<tr>
<td>Value of no shortfall</td>
<td>$/K sq ft</td>
</tr>
<tr>
<td>Inv level when order placed</td>
<td>KLF</td>
</tr>
</tbody>
</table>
Figure VI-1: Single Product Analysis Sample Printout (Continued)

MODEL RESULTS

<table>
<thead>
<tr>
<th></th>
<th>Equation</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lot Size</td>
<td>KLF</td>
<td>IX</td>
</tr>
<tr>
<td>Lot Size</td>
<td>Days</td>
<td>X</td>
</tr>
<tr>
<td>Avg Time Between Runs</td>
<td>weeks</td>
<td>XI</td>
</tr>
<tr>
<td>Setup Cost</td>
<td>$/year</td>
<td>XII</td>
</tr>
<tr>
<td>Safety Stock</td>
<td>KLF</td>
<td>XIII</td>
</tr>
<tr>
<td>Safety Stock</td>
<td>weeks</td>
<td>XIV</td>
</tr>
<tr>
<td>Average Inventory</td>
<td>KLF</td>
<td>Xv</td>
</tr>
<tr>
<td>Average Inventory</td>
<td>weeks</td>
<td>XVI</td>
</tr>
<tr>
<td>Inventory Holding Cost</td>
<td>$/year</td>
<td>XVII</td>
</tr>
</tbody>
</table>

ACTUAL DATA

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>30 Wk Average Inventory</td>
<td>KLF</td>
</tr>
<tr>
<td>30 Wk Minimum Inventory</td>
<td>KLF</td>
</tr>
<tr>
<td># of Setups</td>
<td></td>
</tr>
<tr>
<td>Production</td>
<td>KLF</td>
</tr>
<tr>
<td># of Weeks</td>
<td></td>
</tr>
</tbody>
</table>

ACTUAL RESULTS (30 Weeks of 1992)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Lot Size</td>
<td>KLF</td>
</tr>
<tr>
<td>Lot Size</td>
<td>Days</td>
</tr>
<tr>
<td>Avg Time Between Runs</td>
<td>weeks</td>
</tr>
<tr>
<td>Setup Cost</td>
<td>$/year</td>
</tr>
<tr>
<td>Safety Stock</td>
<td>KLF</td>
</tr>
<tr>
<td>Minimum Inventory</td>
<td>weeks</td>
</tr>
<tr>
<td>Average Inventory</td>
<td>KLF</td>
</tr>
<tr>
<td>Average Inventory</td>
<td>weeks</td>
</tr>
<tr>
<td>Inventory Holding Cost</td>
<td>$/year</td>
</tr>
</tbody>
</table>

Actual minus Model Setup Cost/yr  -$7,416
Actual minus Model Inv Cost/yr    $77,678
Actual minus Model Total Cost/yr  $70,262

The Single Product Analysis was actually calculated using Microsoft’s Excel 4.0 spreadsheet program on an Apple Macintosh IIi personal computer.
VI.2. Single Machine Analysis

The Single Machine analysis uses integer programming to determine the minimum cost necessary to meet a given demand. The model is formulated as follows:

Definition of Decision Variables:

\[ P_{ik} = \text{Amount of product } i \text{ (in KLF) produced in week } k \]
\[ I_{ik} = \text{Amount of product } i \text{ (in KLF) in inventory at the end of week } k \]
\[ s_{ijk} = \begin{cases} 1 & \text{if product } i \text{ is setup from product } j \text{ in week } k \\ 0 & \text{otherwise} \end{cases} \]

Definition of Data Variables:

\[ c_{ij} = \text{Cost in } \$ \text{ of setting up product } i \text{ from product } j \]
\[ h_i = \text{Holding cost in } \$ \text{ of keeping product } i \text{ in inventory for one week} \]
\[ t_{ij} = \text{Time in hours to setup product } i \text{ from product } j \]
\[ d_{ik} = \text{Demand in KLF for product } i \text{ in week } k \]

Objective Function:

Minimize cost of all setups and inventory holding:
\[
\text{Min} \sum_k \sum_i c_{ij} s_{ijk} + \sum_k \sum_i h_i I_{ik}
\]

Constraints:

1. Production and inventory balance with demand for each product and for each week:
\[
I_{ik} = I_{i,k-1} + P_{ik} - d_{ik} \quad \text{for all } i, k
\]

2. Setup time plus production time do not exceed capacity in any week:
\[
\sum_j \sum_i (t_{ij} s_{ijk} + 0.118 P_{ik}) \leq 150 \quad \text{for all } k
\]
3. If a product is not setup in a given week, that product cannot be produced:
\[ P_{ik} \leq M \sum_j s_{ijk} \quad \text{for all } i, k \]

4. If the machine is setup for a given product, then a different product must be setup that week or the run must continue into the following week:
\[ \sum_j s_{ijk} = \sum_{j+1} s_{ijk} + s_{i,k+1} \quad \text{for all } i, k \]

5. The machine can start the week set on only one product:
\[ \sum_i s_{ijk} \leq 1 \quad \text{for all } k \]

6. The model must generate a feasible sequence of products each week:
\[ s_{ijk} + s_{jik} \leq 1 \quad \text{for all } i \neq j, j \neq i, k \]

7. The starting inventory levels are input:
\[ l_{i0} = \text{constant} \quad \text{for all } i \]

8. Safety stock and seasonal smoothing are set through the ending inventory levels:
\[ I_{it} = \text{constant} \quad \text{for all } i \]

9. The machine starts setup on one product. Here it is product 1:
\[ s_{111} \leq 1 \]

10. The machine does not start setup on any of the other products:
\[ \sum_i s_{ijk} = 0 \quad \text{for all } i \neq 1, k = 1 \]

11. The setup variable must be an integer 0 or 1. Either the setup occurs or it does not:
\[ s_{ijk} = 0,1 \quad \text{for all } i, j, k \]
12. The production and inventory mounts cannot be less than zero:

\[ P_{ik}, I_{ik} \geq 0 \quad \text{for all } i, k \]

The Single Machine Analysis was actually calculated using Schrage’s *LINDO* program\(^5\) on an Apple Macintosh IIxi personal computer.

---

VI.3. Supply Chain Analysis

This appendix will detail how the two matrices in the Strategic Inventory Placement (“SIP”) model are defined, and then it will provide additional information on how the model calculations work.

VI.3.1. The Covariance Matrix

The covariance matrix represents the forecast error entering the supply chain. Each stage 1 end item has a covariance matrix associated with it. Figure VI-2 illustrates a typical covariance matrix used in the Supply Chain Analysis. The matrix is square, and it has 11 rows and columns which reflect the 10 week forecast horizon input for that particular item. (The counting starts with the current week as zero, so 10 weeks plus week zero give 11 rows and columns.) Each element represents the variance or covariance of forecast from actual demand a certain number of weeks in advance. Only diagonal variance elements were used in the Supply Chain Analysis. The off-diagonal elements represent covariances, the correlation of the forecast error in one week to errors in other weeks. The team did not use the off-diagonal columns in the Strategic Inventory Placement analysis because the team felt that this data would not have a large impact on their implementation decision.
Figure VI-2: The Covariance Matrix

<table>
<thead>
<tr>
<th></th>
<th>Variance of Forecast X Weeks Out</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>83 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
</tbody>
</table>
In order to calculate the actual values for the covariance matrix, the following steps need to be taken:

1. A sample of forecasts for the end item must be collected. By definition, these forecasts extend out the same number of periods as the planning horizon. Figure VI-3 depicts a sample of 10 forecasts for one end item with a 5-week horizon.

**Figure VI-3: Sample of 10 five-week Forecasts**

<table>
<thead>
<tr>
<th>Week of Report</th>
<th>Week Being Forecasted</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>A F1 F2 F3 F4 F5</td>
</tr>
<tr>
<td>17</td>
<td>A F1 F2 F3 F4 F5</td>
</tr>
<tr>
<td>18</td>
<td>A F1 F2 F3 F4 F5</td>
</tr>
<tr>
<td>19</td>
<td>A F1 F2 F3 F4 F5</td>
</tr>
<tr>
<td>20</td>
<td>A F1 F2 F3 F4 F5</td>
</tr>
<tr>
<td>21</td>
<td>A F1 F2 F3 F4 F5</td>
</tr>
<tr>
<td>22</td>
<td>A F1 F2 F3 F4 F5</td>
</tr>
<tr>
<td>23</td>
<td>A F1 F2 F3 F4 F5</td>
</tr>
<tr>
<td>24</td>
<td>A F1 F2 F3 F4 F5</td>
</tr>
<tr>
<td>25</td>
<td>A F1 F2 F3 F4 F5</td>
</tr>
</tbody>
</table>

A = Actual demand for that week  
F1 = Forecast for 1 week out  
F2 = Forecast for 2 weeks out  
F3 = Forecast for 3 weeks out  
F4 = Forecast for 4 weeks out  
F5 = Forecast for 5 weeks out
2. Next differences between the current forecast and the prior week’s forecast must be calculated for each number of weeks-out. (Note that for the forecast 1 week out, the prior week’s forecast is really the actual demand that occurred.) Figure VI-4 shows, for forecasts 1 week out, how the differences from actual would be found. Figure VI-5 shows, for the forecasts 3 weeks out, how the differences from 2 weeks out would be found.

**Figure VI-4: Differences From Actual for 1-Week Out Forecasts**

<table>
<thead>
<tr>
<th>Week Being Forecasted:</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
<th>25</th>
<th>26</th>
<th>27</th>
<th>28</th>
<th>29</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Week of Report</td>
<td>16</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td>20</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>24</td>
<td>25</td>
<td>26</td>
<td>27</td>
<td>28</td>
<td>29</td>
<td>30</td>
</tr>
<tr>
<td>1. 16</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. 17</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. 18</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. 19</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. 20</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. 21</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. 22</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. 23</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. 24</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. 25</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure VI-5: Differences From Actual for 3-Week Out Forecasts**

<table>
<thead>
<tr>
<th>Week Being Forecasted:</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
<th>25</th>
<th>26</th>
<th>27</th>
<th>28</th>
<th>29</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Week of Report</td>
<td>16</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td>20</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>24</td>
<td>25</td>
<td>26</td>
<td>27</td>
<td>28</td>
<td>29</td>
<td>30</td>
</tr>
<tr>
<td>1. 16</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. 17</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. 18</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. 19</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. 20</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. 21</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. 22</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. 23</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. 24</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. 25</td>
<td>A</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>F4</td>
<td>F5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3. From step 2, a set of differences has been collected for each forecast, that is, a set of differences from the forecasts 1 week out, a set of differences from the forecasts 2 weeks out, etc. In step 3, the sample variance of the set of differences for each time period must be calculated. For instance, from Figure VI-5, one can obtain a set of 7 differences from actual 3 weeks out. The sample variance of this set of 7 values maybe calculated from the following statistical formula:

\[ S^2_{3 \text{ wks out}} = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 \]

where \( n = 7 \)

\( S^2 \) = the sample variance

\( x_i \) = one of the sample differences

\( \bar{x} \) = the average “difference”

4. Finally, the sample variance, represented as one single number, can be placed in the covariance matrix. In the case illustrated here, the 3-week out forecast variance would be put in as element 3,3 in the covariance matrix.

Gathering forecast variance data such as the inputs required for the “SIP” model would probably have a beneficial side effect in almost any application. The analysis requires an evaluation of past forecasts. In the particular case study business supply chain, the forecast error was not routinely measured. Gathering data for the “SIP” model revealed a systematic bias in the average forecast and an unexpected increase in the variance in weeks 3 and 2 before the due date. The result was that part of the Supply Chain Optimization Team initiated a thorough study of forecast techniques and ongoing performance measures.

VI.3.2. The Weight Matrix

As the Strategic Inventory Placement model was used in this thesis, the weight matrix translates when desired production changes are actually fulfilled. In other words, the weight matrix determines production smoothing. The basic model itself can optimize the weight matrix to achieve the minimum cost trade-off between smoothing production
and avoiding inventory build-ups. As applied to the Supply Chain Analysis, the weight matrix was used to build in delays in responding to demand changes, not for production smoothing.

**Figure VI-6** shows an example of a weight matrix used for one of the Sensitizing items. Each item in every stage has an associated weight matrix. The columns represent the week when a production change is desired, starting with week 0 (the present) and extending out to the forecast horizon minus the sum of lead times of downstream stages. The rows represent when the demand change is actually produced by the factory. For instance, a 1 in column 5 and row 6 means that 100% of the demand change in week 4 will be start production in week 5 (counting starts with week 0). Similarly, a 0.5 in column 8 and row 7 means that 50% of the demand change in week 7 will start production in week 6.

**Figure VI-6: The Weight Matrix**

\[ L.T = 3 \text{ wks} \]

<table>
<thead>
<tr>
<th>Time When Desired Production Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>1 1 1 1 0 0 0 0 0 0</td>
</tr>
<tr>
<td>0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>0 0 0 0 0 1 1 0 0 0</td>
</tr>
<tr>
<td>0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>0 0 0 0 0 0 0 1 1 0</td>
</tr>
<tr>
<td>0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>0 0 0 0 0 0 0 0 1 1</td>
</tr>
</tbody>
</table>

Coated Once
Every 2 Wks
Note that in Figure VI-6, all the rows inside the lead time must be zero. This means that the manufacturing stage cannot accommodate demand changes inside the lead time and must produce any additional requirements at a later time. Also illustrated in Figure VI-6 is a production response delay every other week to represent a manufacturing frequency of once every two weeks. This is only a delay in response to demand changes and does not preclude production in any given week. This zero-one pattern represents the actual inputs used to generate the Supply Chain Analysis. Later versions of the model can handle manufacturing frequency, batch sizing, and shipping consolidation using a simulation approach.

VI.3.3. “SIP” Model Calculations

The Strategic Inventory Model characterizes inventory as a random variable and determines its statistical variance. In particular, the more production is smoothed (i.e. lower production variance), the higher will be the variance of the inventory. The safety stock level is then set to be the mean inventory level for which the probability of stocking out equals one minus the desired service level. As an example, if the variance of inventory is 100, the standard deviation is 10, and the safety stock could be set at 16.45 (1.645 standard deviations) to achieve 95% service. This means the expected value of the safety stock would be 16.45, but it will vary around this mean level. 95% of the time, however, the safety stock should stay above zero (stockout level).
Chapter VII. Bibliography


