Batch Sizing Strategy & Production Load Leveling in a Multi-Step Chemical Manufacturing Process

by

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

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Master of Science in Chemical Engineering

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ABSTRACT

In the last couple of years Eastman Kodak Company went through major changes in its strategic direction. The same disruptive technologies that they helped develop for digital imaging have shaped a new industry, and the market requirements and preferences for photography have changed dramatically. Some of the tightly held complementary assets that gave Kodak a competitive advantage are no longer as critical as were in the past.

Kodak management has set a very strong emphasis on running a lean operation. At the same time, executive management has set very aggressive targets for inventory reduction and productivity increase in the manufacturing units. Demand for chemicals used in film and paper for silver halide-based photography has steadily decreased in the last decade. There is growing pressure to increase inventory turns in production processes that are not as profitable as they were ten to twenty years ago. Management is faced with the need to implement aggressive tactics that minimize inventories and lower costs.

Continuous batch size reduction is one of the lean manufacturing principles that manufacturers of discrete parts have successfully used to drive operational improvements and that Kodak is pursuing as well. This thesis takes a closer look at the differences between discrete and batch chemical manufacturers. It describes the considerations and real challenges in analyzing batch sizing decisions for chemical plants that have been operating for several years. In general, for Kodak's chemical manufacturing processes, large batches are needed to reduce total manufacturing costs. These cases serve as an example for Kodak's management and lays out the steps that have to be taken to support the decision-making process. A tool to support batch sizing strategies that are aligned with inventory objectives is presented. The need for continuous revision of batch sizing policies in the face of declining demand in some products and increased growth in others is emphasized.

Finally, the thesis touches upon the application of production load leveling and its potential benefit in a chemical plant. This concept that has been implemented in several forms within lean factories should be taken very seriously at the chemical plants of Eastman Kodak Company. The example of the work done for one high-volume chemical will support the conclusions on production load leveling.

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INTRODUCTION

Lean manufacturing, developed to a large extent by Toyota under the name of the "Toyota Production System", has been implemented in different countries and industries across the globe in the last fifteen to twenty years. Several companies that have implemented lean production methodologies have experienced huge improvements in quality, cost reduction, and service levels. Lean manufacturing principles do not necessarily work well in all manufacturing settings. High-mix, low-volume manufacturing facilities experience different difficulties, when implementing lean manufacturing, than low-mix, high-volume facilities. In particular, the chemical batch processing industry works with different underlying models than those of discrete manufacturers. Companies that have both discrete manufacturing and chemical batch processing as integral part of their operations have to be careful when implementing lean principles across the organization. Management within each type of operation should select only those tools from the lean manufacturing toolkit that best fit the types of processes they manage. Management in the chemical batch processing industry should also adapt lean principles developed by discrete manufacturers in a way that makes sense for batch-driven processes constrained by physicochemical phenomena. This thesis explores two important aspects of lean manufacturing, batch size reduction and production load leveling, in the context of chemical batch manufacturing.

Motivation for this Thesis

The Synthetic Chemicals department (SynChem) at Eastman Kodak Company has been operating in its current facilities for more than ten years. Throughout the last decade, they have pursued different improvement programs and have worked at increasing efficiency and productivity.

A number of LFM theses written in the past have addressed some areas for improvement in the operations of this same department in different stages of its history. Some of the topics that have been covered are:

a) Reduction of manufacturing lead time[1,2]
b) Reduction of process variability[3]
c) Improvement of batch cycle time[4]

Synthetic Chemicals has pursued all three of these goals and has worked very hard at seizing cost reduction opportunities from its operations.

The topics covered in this thesis became important issues of debate, analysis, and consideration in the Synthetic Chemicals department in 2004, and they are topics that are discussed numerous times within other manufacturing departments within Kodak. Batch size reduction and production load leveling are relevant to SynChem's definitive operations strategy because these policies can affect, both positively and negatively, total manufacturing costs and inventory levels.

This thesis addresses both the technical challenges and opportunities that arise when evaluating batch sizing decisions and production load leveling in a chemical plant. The role of cost accounting methods and other managerial issues that come up when implementing production smoothing and batch size changes will be considered.

Problem Statement

The Synthetic Chemicals department has been implementing lean manufacturing by adopting the Kodak Operating System (KOS), a system created internally at Kodak that builds on many of the principles developed over several decades at Toyota, and in other world class organizations that have implemented lean manufacturing. Two questions have been brought up at SynChem in the last two years of implementation, and they are addressed in this thesis:

1) Should SynChem adopt a strategy of continuously reducing batch sizes of the chemicals they manufacture to remove waste, in the form of inventory, from its operations?
2) Should any form of production smoothing or production load leveling be implemented in the production of chemicals?

Both these questions are relevant to SynChem and to the chemical processing industry (CPI) as their parent organizations try to become leaner and reduce overall inventory levels. Below, we will further explore each of these two topics in more detail and why answering these questions is crucial to SynChem.

Batch Size Reduction Strategy

As pressure to reduce total inventories in dollar terms increased for the Synthetic Chemicals department, and it became more difficult to find opportunities for improvement, the initiative to reduce batch sizes of chemicals manufactured in the department had become more widely accepted. In the first quarter of 2004, before the start of the six-month internship that led to this thesis, SynChem management evaluated the batch size reduction of approximately 20 chemicals. Reducing the batch sizes of such chemicals would cut their cycle stocks dramatically and assist them in meeting ambitious inventory targets. Among the assumptions made during the evaluations in the beginning of 2004 were the following:

- No additional direct labor would be required to sustain the strategy.
- There was sufficient capacity in the form of equipment availability to sustain the strategy.
- Costs from activity based accounting were utilized to calculate inventory savings.

This thesis will address this topic and cover the following points:

- What are the most relevant costs that should be considered in the evaluation of batching policies in Synthetic Chemicals?
- Does the total manufacturing cost really increase or decrease when reducing batch sizes, in order to reduce average cycle stock levels, in a multi-step chemical batch operation?
- Which models can SynChem use to find the optimal batch sizes for some of its chemicals?
- Is continuous batch size reduction a sustainable strategy for SynChem? Is there really a need to move away from the classical batching theory (e.g., economical order quantity) now that the knowledge from KOS is being transferred from discrete manufacturing operations to chemical batch processes within the same company?

What appears to be a reduction of inventory in dollar terms causes, in some cases, an increase in the total manufacturing expenditures. At the same time, what appears to be savings from reduction of inventory holding costs, does not materialize fully.

The more significant tradeoffs, when deciding on a batch sizing strategy, were evaluated. There are mainly two factors that drive the need for larger batch sizes: the high cost of cleaning the equipment and setting it up when switching production of one chemical to another, and the relationship between processing time and the quantity being processed in a chemical reactor.

Production staff in chemical plants also needs to periodically review batching policies for its products when demand for such products is changing considerably (e.g., 15-40% per year). Management also may use excess capacity to reduce inventory levels. Nevertheless, managers need to make the right decisions when selecting those chemicals that they will scale-down, based on criteria that will be covered in this thesis.

Production Load Leveling

Production load leveling has been identified as a way to increase productivity and reduce overproduction.[6, 7] It was not yet clear though, how SynChem should implement production load leveling and why. Lean manufacturing principles have been spreading across Eastman Kodak Company, through a program named Kodak Operating System (KOS). Heijunka, or production smoothing, has been implemented in other departments within Kodak, and SynChem had to evaluate how to adapt these principles to its chemical batch processes.

It is also important to evaluate what the factors are that drive high inventories and especially wasteful inventory or "overproduction" in SynChem.

This thesis will cover the following points:

- How does production load leveling assist SynChem in reducing the complexity in managing the production of their products and reducing process variability?
- How should SynChem define "overproduction" or "wasteful inventory", in the context of an operation that inherently requires inventory to be carried, in order to run in an economically optimal way?
- What are the causes for the types of "overproduction" identified?
- What is the benefit of production load leveling for SynChem, and how should SynChem go about implementing it?

Production load leveling needs to be implemented through pilot trials, at least for those chemicals with high to medium annual production volumes. A set of work centers must be dedicated to the production of these chemicals.

Thesis Outline

This thesis contains five main sections. The first one (Chapter 1) provides an overview of the Synthetic Chemicals department and gives a description of its operations. This section includes a brief assessment of its current state and some of the drivers of high inventory levels that this thesis addresses. Chapter 2 lays out important factors to be considered when making batch sizing decisions in discrete manufacturing and discusses these factors in the context of chemical batch manufacturing. Case studies in Chapter 3 are used to describe models that help quantify the tradeoffs involved when making the decisions in single and multi-step batch processes and to draw general conclusions about a batch size reduction strategy in the chemical batch processing industry. The case studies lead to Chapter 4, where a more broad and higher level approach is described that addresses the need to set more discipline and order regarding batching policies and decisions, specially in an operation that is under constant pressure to reduce overall inventory levels. Chapter 5 covers the topic of production load leveling introduced earlier in the problem statement. As shall be seen in this chapter, production load leveling can be implemented to control inventory levels and drive overall productivity improvements in a chemical plant.

This thesis is the culmination of a six-month internship within the Synthetic Chemicals department, during which analysis on batch sizing considerations and decisions was conducted. In addition to this initiative, work was carried out with a local team to explore production load leveling and to find ways to improve the flow of materials through the factories.

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CHAPTER 1 – UNDERSTANDING OPERATIONS IN SYNTHETIC CHEMICALS

This section provides an overview of the Synthetic Chemicals department. The chapter covers the business context in which Eastman Kodak Company is operating and the role of Synthetic Chemicals within Kodak's current strategy and supply chain. An overview of the department's organizational structure and its operations is provided, followed by an assessment of some of the operational challenges the department is facing.

1.1 Kodak's Business Context

Eastman Kodak Company is undergoing significant changes. These changes are a result of discontinuities in technological developments in the imaging industry and increased competition in the traditional segments in which Kodak has operated in the last thirty years.

Demand for film and paper utilized in traditional silver halide photography has been decreasing steadily in the U.S. and the rest of the world in the last five to ten years. Cameras that used silver halide film are being replaced by digital cameras, digital phones and personal digital assistants that have image-capturing technologies embedded into their architecture. Billions of pictures are being stored in memory chips and billions of pictures printed on paper by developing silver halide film, and by using photochemicals, are being replaced by prints made from digital files utilizing thermal printing technologies. Billions of pictures stored as electronic files will never be printed at all.

1.1.1 Kodak's Shift to Digital Imaging

Eastman Kodak Company has gone through a lot of changes in the last five years. Their stock price increased approximately 52% from record low levels in the fourth quarter of 2003 to its current levels (2Q-2005), after executive management announced a shift in their strategy to move toward digital products and services and executed on that strategy. Of course, this implied that they would manage the decline of products for traditional photography by shrinking the manufacturing and distribution base accordingly and by cutting fixed costs and manufacturing overhead ahead of the decreasing global demand. These actions would allow Kodak to remain a positive cash flow viable business, which could support the transition to the development and commercialization of services and products within the new digital imaging industry.

1.1.2 Traditional Photography Operations in Kodak's New Strategy

Kodak's shift to digital imaging requires a significant reduction in the manufacturing installed base at Kodak Park and elsewhere in the world. In 2003, the executive management at Eastman Kodak Company announced plans to reduce total real estate holdings worldwide by one third by the end of 2006 and to reduce number of employees by 16%. The main objective is to consolidate manufacturing operations into a smaller set of locations, pursue revenue opportunities by selling or leasing property that is no longer utilized, and to reduce manufacturing overhead. Kodak must reduce its fixed costs ahead of the drop in demand for traditional photography-related products in order to maintain a favorable cash position and a healthy return on assets.[5]

Kodak is also trying to improve the cash flow position of this segment of its business. The increased positive cash flow from its operations related to traditional photography is to be used in spending for R&D, marketing, and promotion related to more innovative digital technologies in both commercial and consumer imaging. An imperative to increasing its cash flow position is to trim inventories and reduce the capital tied up in raw materials, labor, and other operational expenses for chemical, film, and paper manufacturing. The Synthetic Chemicals (SynChem) department is assigned the task of slashing its inventories by as much as 20% per year. If SynChem were a manufacturer of discrete parts, this goal might be harder to achieve.

1.2 Synthetic Chemicals in Kodak's Supply Chain

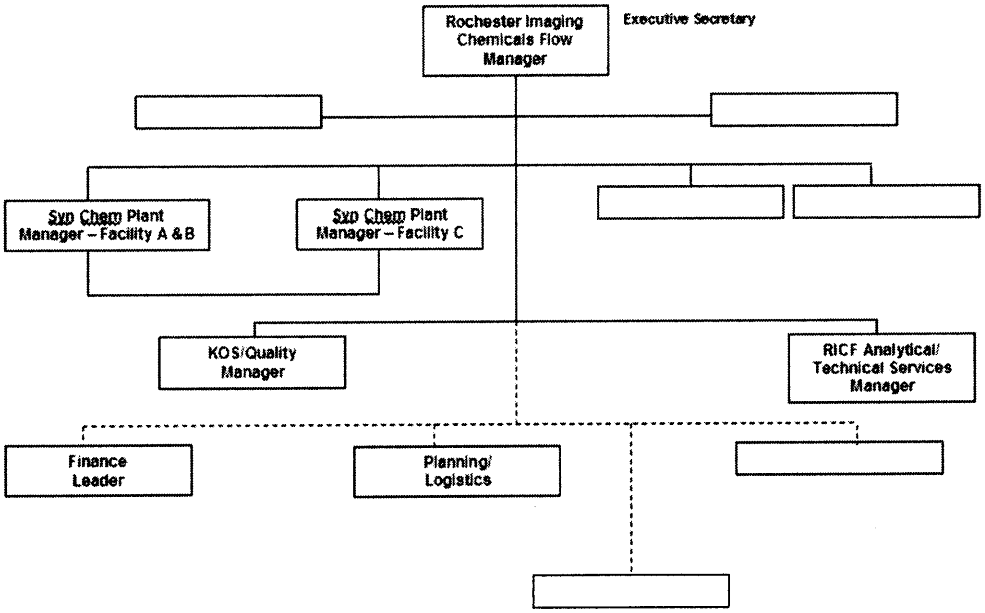
SynChem is part of the larger division named Rochester Imaging Chemicals Flow. This department is based in Kodak Park in Rochester, NY. The department is responsible for the manufacturing of organic dyes, synthetic polymers, and other organic chemicals. These chemicals are utilized in a variety of applications. Examples of uses are: in coating and sensitizing of film and paper used in traditional silver imaging, in the manufacturing of photochemicals used in the silver halide development process, in the manufacture of dyes for thermal media used in thermal printing, small-scale chemicals used in research and development, and in devices utilizing organic light-emitting diodes (OLED's).

As of 2004, SynChem shipped chemicals to film and paper sensitizing plants in Rochester (NY), Colorado, Mexico, Australia, Brazil, Canada, England, and France. It manufactures over 650 chemicals and manages more than 2,000 raw materials and chemical intermediates in its facilities. 85% of the total volume (an estimated 7,800 metric Tons) is produced by SynChem in three facilities in Rochester, New York. SynChem also has a small-scale operation that manufactures chemicals at a bench scale laboratory (e.g., batches of less than 500 g).

1.3 Synthetic Chemicals: Organizational Overview

As mentioned earlier, SynChem is part of a larger organization. Figure 1 shows the key roles that shape the operational strategies for the department and who makes crucial tactical decisions. The empty boxes in the organizational chart represent other supporting roles or other manufacturing departments within the Rochester Imaging Chemical Flow (RICF) that are not relevant to the two topics within SynChem, batch sizing decisions and production load leveling, discussed in this thesis. The people in the roles that are shown in the boxes of the chart constitute a team that drives the decision-making processes within SynChem.

Figure 1 – Synthetic Chemicals – Organizational Overview



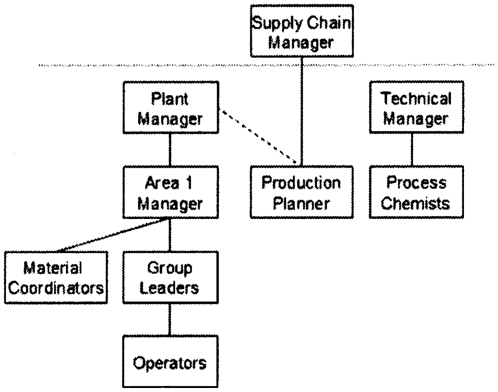
The SynChem plant managers are responsible for the day-to-day operations of the SynChem manufacturing facilities, and their main concern is to meet several company targets for their products, such as service levels, capacity utilization, productivity, headcount targets, inventory targets, and more broadly, all activities that allow them to meet the budget and estimated target expenditures planned in advance during the annual operating plan. Unit manufacturing costs, an accounting measure based on production volumes, manufacturing overhead allocated from support functions, and actual expenditures in the facilities, is an important measure against which plant managers are measured as well.

The planning and logistics function has particularly responsibility for service levels, logistics and its associated costs, and target inventory levels. The KOS and quality manager is the change agent that pursues the implementation of KOS and principles from lean manufacturing in the whole RICF division, driving productivity improvements, and cost reduction projects. The RICF analytical and technical services manager manages technical services for testing and asset management (e.g., reactor maintenance, equipment reliability, Total Productive Maintenance programs, etc.). The finance leader is responsible for managing the financial controls in the department and supports the decision-making processes that involve financial analysis.

All of these members bring important information to the table when making operating decisions in which the tradeoffs of setup costs, change-over costs, material costs, labor, inventory holding costs and logistics, and the understanding of overhead allocation in the unit manufacturing costs.

Figure 2 shows the organization at one of the facilities. These functions run the actual manufacturing operations, making sure the facility meets its required targets.

Figure 2 – Organizational Structure at a Synthetic Chemicals Manufacturing Plant



1.4 Synthetic Chemicals Operations Overview

This section describes general characteristics of SynChem's operations. It defines certain terms that will be used throughout the thesis and provides a basic and general understanding of the equipment and processes that SynChem utilizes to manufacture its products.

1.4.1 Facilities and Work Centers

There are three main facilities where most of SynChem's products are manufactured. These facilities differ slightly in their layout and specific types of equipment.

A typical facility has all reactors, distillers, and centrifuges on a second story and dryers, filters, and pumps on the ground level. A typical plant is divided in 16 to 24 rectangular production areas referred to by production personnel as "bays". Each bay consists, typically, of three reactors and one centrifuge. Each reactor system has another vessel right next to it, called a receiver, which is used to hold the distillate in distillation operations performed in the same reactor. Reactor sizes range from 50 gallons up to 2,000 gallons and are, in the majority of cases, made of glass-lined stainless steel. Reactors and centrifuges are interconnected through a complex system of pipes, valves, and pumps. Reactors are also used as distillation units and as crystallizers.

Each reactor, centrifuge, and dryer is treated as a work center. Reactors with different capacity and operational characteristics (e.g., different internal wall material such as glass lined vs. stainless steel) are treated as different work centers. Manufacturing overhead is allocated to all work centers based on forecasted production volumes, product routings, and total equipment capacity. A burden rate is estimated for each work center in dollars per hour of operation. It is important to note that this burden rate is not the cost of operating the work center per unit of time but is the result of manufacturing overhead allocation based on activity-based cost accounting.

1.4.2 Manufacturing and Processes

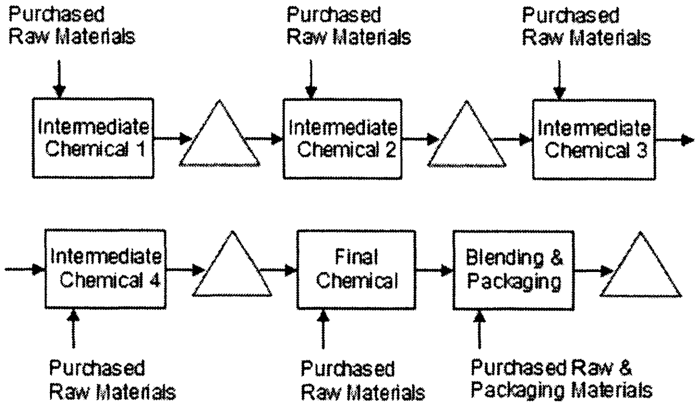
In order to better understand SynChem's manufacturing process, it is useful to define first define terminology, such as "chemical chain", "batch size", and "campaign". It will also be useful to define some of the production steps and to describe a typical manufacturing process.

1.4.2.1 Chemical Chains

A chemical chain consists of all the intermediate chemicals, x_i, that are manufactured in SynChem's facilities, in order to produce a final chemical, *a*, that is shipped to a customer. Chemical chains can be very simple, consisting of zero to one intermediate chemicals (in addition to the final chemical) and as complex as chains consisting of seven intermediates. In some cases, an intermediate that is used to make a subsequent intermediate in one chemical chain might be used to manufacture another intermediate in a second chemical chain. Some chemicals that are synthesized within SynChem are used in more than five chemical chains.

The different chemical chains represent the chemical pathways that research and development for SynChem has found to be the optimal ones to synthesize the final chemicals. Once the chemical pathway is set at the laboratory level, the process is validated and improved in a larger-scale manufacturing plant.

Figure 3 – Diagram of the Steps in a Chemical Chain



1.4.2.2 Batch Sizes

Throughout this thesis, the words batch size, lot size, batch quantity, and run size will be used interchangeable and relatively often. We define batch size as the total amount of material in kilograms (or any other unit of mass) that is produced in one single run. A single run can be defined by specifying when a production process starts and when the production process ends. In all cases within this thesis, the production process will begin when an empty reactor (either clean or not from a previous production run) is prepared (e.g., valves are open or closed, cooling or heating is begun, pressure in the jacket or the reactor is set and checked) and initial materials are added to the empty reactor. The production process will end when the final step in the series of unit operations that conform the production process, such as mixing, reaction, distillation, liquid-liquid separation, crystallization, filtration, etc., ends, and the intermediate chemical is packed and stored for subsequent use. The subsequent use might take place immediately (e.g., two hours) or in a longer interval of time (e.g., months or years).

Yields and the absolute amounts of material produced and isolated, change from unit operation to unit operation throughout the complete production process. Therefore, the amount of mass being transferred from a reactor to a unit where crystallization will take place is different than the amount of mass transferred from the crystallizer to the centrifuge. All batch sizes will be expressed in terms of the average yield of the desired chemical at the very end of the production process. The desired chemical might be an intermediate chemical or a final chemical. All quantities of purchased raw materials and chemicals made "in-house" will be added to the process in stoichiometric proportions established during the development and validation stage.

1.4.2.3 Campaigns

The largest capacity reactors installed in SynChem vary by plant. In one, 2,000 gallons is the largest reactor available; while in other plants, 1,000 or 750 gallon reactors are the maximum available capacity. The economical tradeoffs relevant to sizing and purchasing equipment are not considered in this thesis. Equipment is taken as given and capital costs are considered "sunk costs".

Whenever a quantity larger than the maximum feasible batch size (due to reactor size) is needed, SynChem performs a series of runs or batches in a row of the same chemical without any need for cleaning or setups. A series of runs or batches of the same chemical is called a campaign. Campaigns can be thought of as equivalent to a batch of discrete parts in a discrete manufacturing process. The total processing time of a campaign varies linearly with the number of runs. Campaigns are also used by SynChem to lower the cost of changeovers and setups needed to switch production from one chemical to another within a work center, such as a reactor, crystallizer, or centrifuge.

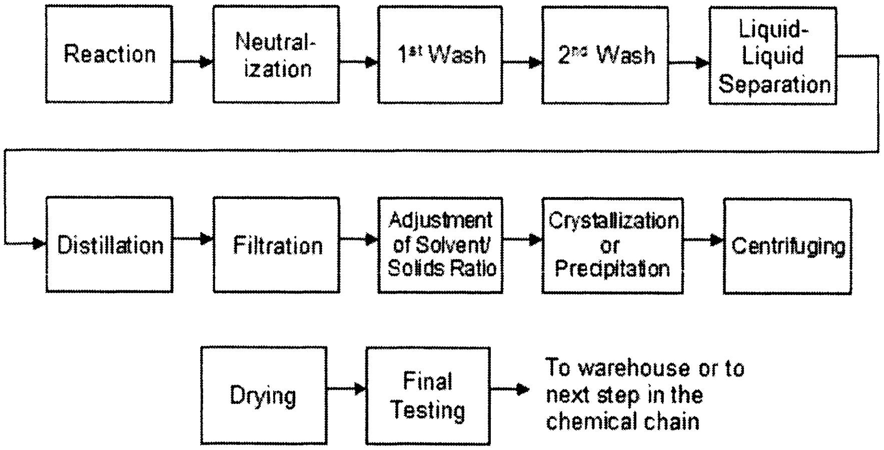
1.4.2.4 Batching Policies

The materials control coordinator, the production planner, the process chemists, the product development chemists (the product development chemists report to the R&D laboratories out of SynChem's organizational structure), and the industrial engineers working for SynChem define the batching policy for all chemicals in the product portfolio. A batching policy consists mainly of the following parameters: 1) the number of runs (batches) that will be made per campaign, 2) the batch size for each of these runs (Note: in the vast majority of cases, all of the runs in one campaign will be of the same batch size). The number of times a campaign will be scheduled in a year will depend upon the total annual production volume.

1.4.2.5 The Manufacturing Process

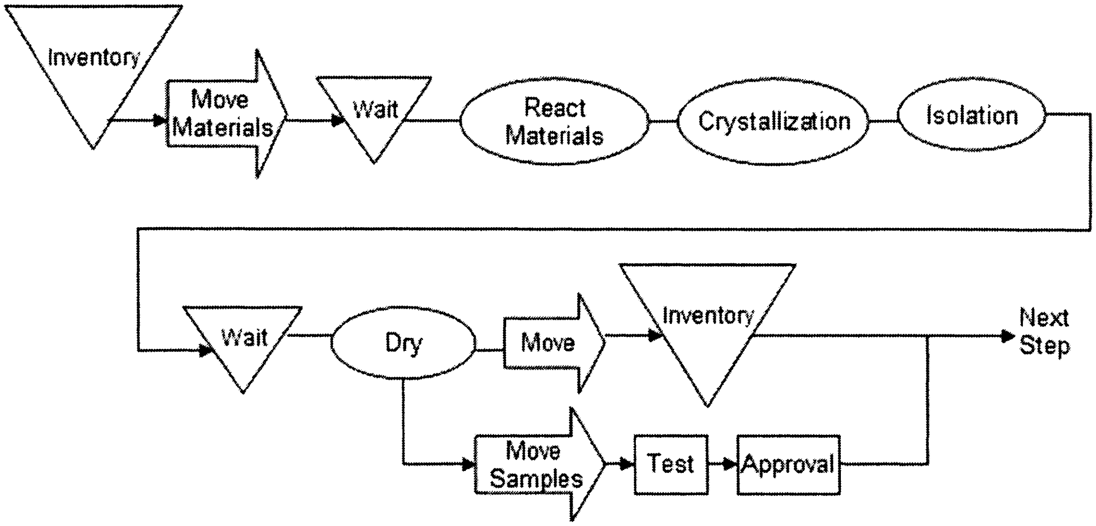
The manufacturing process used in SynChem to make an intermediate or final chemical varies considerably from product to product. One of the many different processes that is representative of a large number of chemicals is the one taken from Mock's[3] thesis and shown below.

Figure 4 – Production Process for One Chemical Made in the SynChem[3]



A more general diagram for the process is also shown in Figure 5, conceptualized by Jutte[2]. She was able to describe the more typical and common steps among all products in one diagram. No two production processes are exactly the same, and these processes vary from chemical to chemical on several dimensions.

Figure 5 – Common Production Steps for an Intermediate Chemical[2]



One common characteristic among all products is that processing times tend to be relatively long. The time required to make one intermediate chemical from the point in time in which preparation of the reactor takes place until the point in time in which the approved dried chemical is moved to the warehouse might range anywhere from one and a half days up to ten days. The dimensions on which processes vary from chemical to chemical are the following:

- The type of equipment that is required to make the product
- The number and type of steps required to make the product
- Time: reaction times, distillation times, heating and cooling times, drying times, etc.
- Yields: % of the expected final chemical that is actually obtained after going through all of the processing steps
- Process parameters, such as pressure, temperature, mixing shear force, pH, etc.
- Safety and environmentally related risks

All these dimensions and the variability of all of them across SynChem's product portfolio make SynChem's operations a very complex one to manage.

1.4.3 Production Scheduling

The production of intermediate chemicals and final chemicals is managed and scheduled based on a Manufacturing Resource Planning (MRP II) system. This system utilizes bill of material information and lead time parameters for each intermediate chemical, in order to calculate the start days for the production of each of the steps in a chemical chain. A material and production planner in each manufacturing area utilizes the start dates established by the MRP II system to create the shop floor schedules. The planner must take into account equipment and labor availability for the next two to four weeks and review the number of reactors and other resources required for each of the chemicals to be manufactured.

SynChem makes many of its chemicals to order. For many of its products, scheduling of production is confirmed and triggered once an order has been received. In other cases, though, production of some intermediates and common chemicals with very long manufacturing lead times (chemicals utilized in several chains) are triggered by a volume forecast.

The production system is a push system, since production is scheduled on the shop floor when an order is received or when a longer-term forecast deems it necessary to begin production of a product or chain. The production schedule and the work centers where the products will be made are decided upon by the material control coordinator and the production planner.

Many scheduling conflicts appear because there are items that are pushed into production through the MRP system at one work center, while at the same time, the manufacturing process for a chemical chain is in its third step at this same work center. Scheduling is, by far, one of the most important tasks in SynChem, as it is in any facility of a batch processing plant that manufactures a large variety of products with shared resources.

In some instances, inventory is held between two steps of the production process for a chemical chain. After synthesizing one intermediate, it is packaged and sent to the chemical warehouse where it sits in inventory until a certain amount of it is required for the production of the next intermediate. In other cases, the material that is synthesized is used immediately in the continuing step for the production of the next intermediate. After completion of the second intermediate, the material is then used in the third intermediate, and so on.

1.4.4 Cost Accounting

Although neither the cost structure for Kodak's chemical products will be provided in this thesis, nor actual costs for any of the chemicals presented in the different case studies in Chapter 3, the cost accounting system used at SynChem will be described briefly.

Like any other capital intensive industry, the chemical processing industry has a large portion of fixed costs and manufacturing overhead. These costs are due to the depreciation charges that are charged to the manufacturing department from the initial capital investment, additional capital expenditures, maintenance, and manufacturing support staff. A large portion of operating costs remains relatively constant across the year, according to the budget that was set the year prior. As long as the total production volume remains relatively constant, operating costs from manufacturing support staff, electricity, steam, cooling water, safety, and pollution abatement equipment remains also relatively constant across the year, regardless of the changes in the product mix. The other two important cost components are material costs and direct labor. Direct labor is defined as the workers that control and operate the manufacturing equipment or the personnel that is involved in other manufacturing support functions related with the flow of products. Material handlers, for example, are considered direct labor.

The Synthetic Chemicals department is treated as a cost center for the purposes of cost accounting at Eastman Kodak Company. The required resources: labor, raw material projections, and equipment capacity, are estimated in the yearly budget-setting process in the annual operating plan. Corporate overhead, charged to the cost center, and manufacturing overhead, generated in SynChem, are allocated to the different work centers (reactors, centrifuges, dryers) based on activity. That is, the overhead is allocated based on the proportion of capacity that a specific work center represents and the total volume that is processed in it. Based on the routings, an estimate of the total amount of hours that the work center will be operating is calculated and used in the allocation of the overhead. There is a burden rate for each type of equipment in dollar terms per hour. It is important to remember that this does not represent the cost of operating the work center for one hour.

Appendix 1 lists several characteristics of SynChem's operations and compares them with the typical discrete-parts manufacturer and with the general chemical processing industry.

1.5 Synthetic Chemicals Current State and Present Challenges

This section will provide an assessment of some of the current challenges faced by the Synthetic Chemicals department. The focus is on the need to lower inventory levels and batching decisions. Overproduction is defined and the main causes for it are described.

1.5.1 The Batch Size Reduction Initiative

Figure 6 shows the end-of-month inventory level for all months in 2004 until October. Planned inventory levels are shown for November and December. SynChem did an outstanding job of eliminating inefficiencies in the material handling and control systems, reducing manufacturing lead times and reducing safety stocks. A portion of the inventory reduction can be attributed to the batch size reduction of several chemicals, both of high and low production volumes. At the time of the internship, several chemicals were still being considered for batch size reduction. The driving force behind the need to lower batch sizes is to lower cycle stock and meet inventory targets.

Figure 6 – End of Month Inventory Level for Synthetic Chemicals - 2004

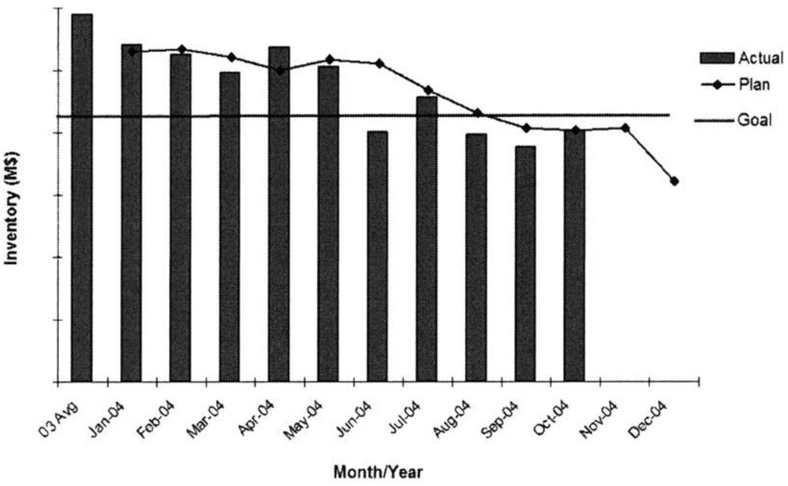
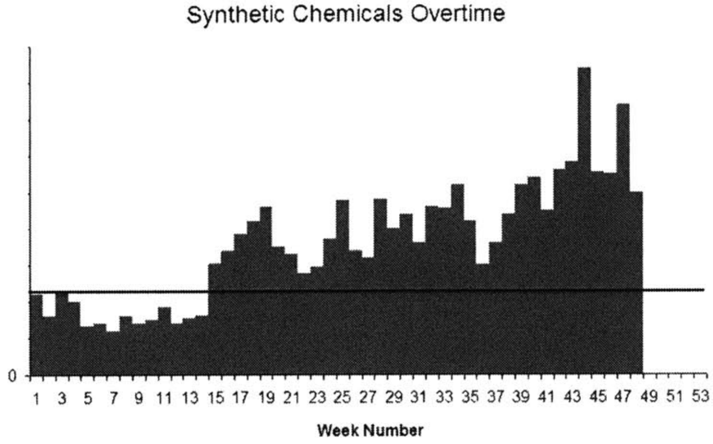


Figure 7 shows the overtime that SynChem's facilities incurred during most of 2004. The horizontal line in the graph represents the budgeted or planned overtime. The metric utilized to monitor overtime can be man-hours, man-days, full-time equivalents, or a similar one. A portion of the overtime can be attributed to increases in production volumes in all three SynChem facilities during the first three quarters of 2004. Another portion of the overtime can be attributed to efforts undertaken to reduce inventories through batch size reduction. Chapter 2 and 3 cover the tradeoffs that have to be evaluated when making batch sizing decisions. These chapters will also explain why reducing batch sizes increases the labor requirements, and thus drives labor overtime.

Figure 7 – Overtime in all Synthetic Chemicals Facilities



Figures 6 and 7 are good illustrations of some of the economic tradeoffs that manufacturing companies must constantly consider when choosing between carrying more inventory or utilizing more capacity and resources.

Over 15 chemical chains were being considered for batch size reduction. These batch size reductions would help to reach the goal shown in Figure 6 and drive inventory levels even lower. As with any cost accounting system in any manufacturing facility, SynChem's cost accounting system does not necessarily capture all the elements that are relevant to evaluate the economics of a batching decision. Chapters 2, 3, and 4 address this issue and provide models to evaluate the economics behind the decisions.

1.5.2 The Complexity in Synthetic Chemicals' Operations

Synthetic Chemicals' operations are complex. They manufacture over 600 different chemicals. The vast majority of these chemicals have subtle differences in their manufacturing processes. Process parameters change for most of the unit operations involved in the synthesis of their compounds. This complexity makes production scheduling very difficult.

A close look into an ABC analysis done by chemical chain for all of the products made in one of the SynChem main facilities reveals some important information. In terms of volume and value, ABC analysis usually has been done in the department at the item level. The number of chemicals to manage is of course, overwhelming. When this same analysis is done by chains, one learns very useful information. First of all, 18 chemical chains account for 80% of the total value in the product bill of this facility. Only six chemical chains account for 50% of the total value that flows through the plant. Figure 8, shows an ABC analysis by chemical chain for one of SynChem's facilities. Figure 9 shows an ABC analysis by compound for the same facility.

Chapter 5 will present a case analysis of a high-volume chemical chain, whose process was re-engineered to simplify scheduling and to utilize less labor and equipment resources that would otherwise be idle. This case underscores the importance of separating the product portfolio, by volume and chains. Simplifying the scheduling of high-volume chemical chains, by dedicating equipment to their production, setting a tact rate at which to manufacture them, and visually monitoring the demand vs. the rate of production, utilizing a system based on CONWIP loops and a visual scheduling tool from the Heijunka toolbox, will greatly simplify the complexity for SynChem operations. Bays within the facility can be assigned to high-volume chemicals only and be run as a flow shop. Planning staff and supervisors can then focus more of their attention on managing and scheduling the production of low-volume chemical chains, which would require a flexible, job-shop-type of system.

Figure 8 - ABC Analysis by Chemical Chains for One Facility from SynChem

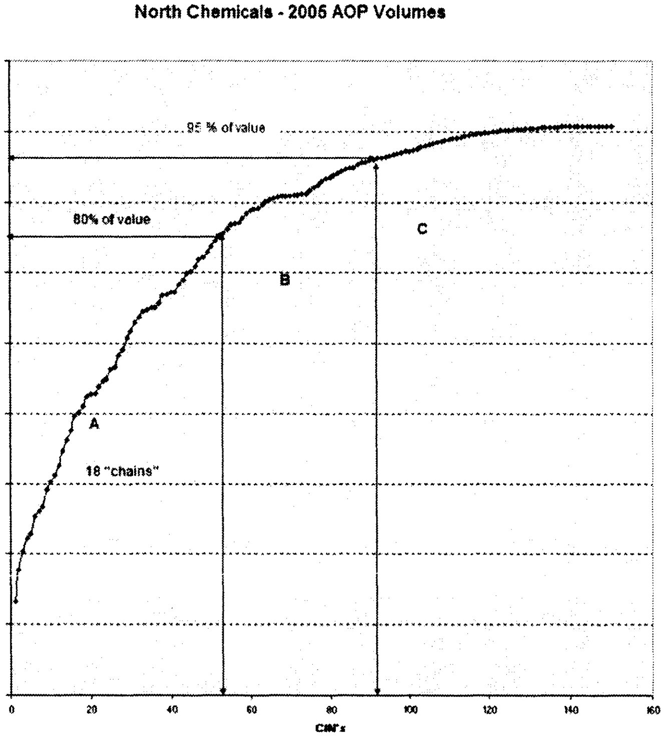
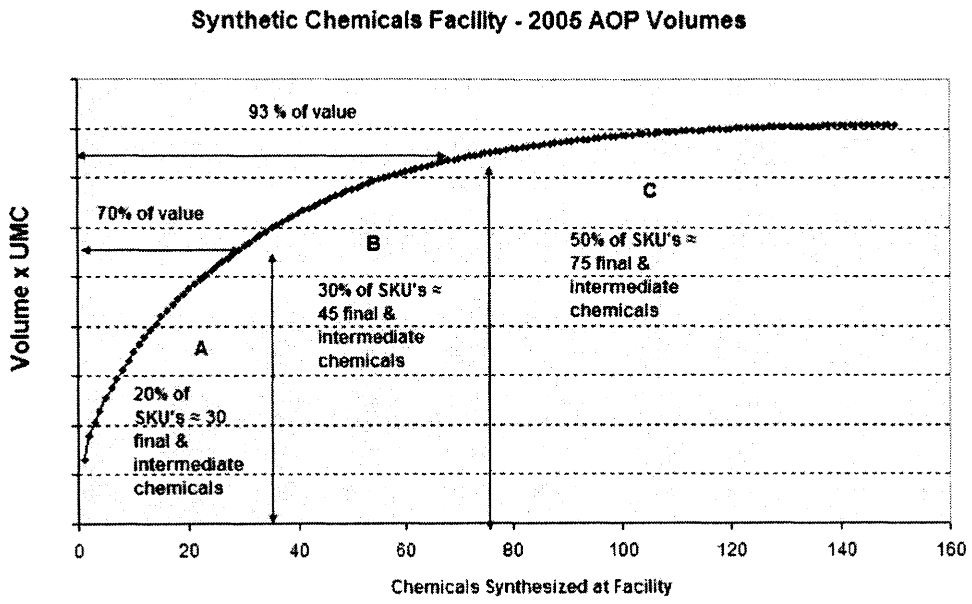


Figure 9 - ABC Analysis by Chemical for One Facility from SynChem



1.5.3 Defining Overproduction

SynChem runs a type of operation that requires significant amount of inventory, if it is to be run in an economically optimal way. It is difficult for SynChem to differentiate the needed inventory from the costly overproduction. The following section categorizes overproduction currently present in SynChem's operations in two segments: 1) overproduction related to scheduling and the MRP system, and 2) overproduction related to synchronicity in the quantities made of each intermediate in a chemical chain. Implementing production load leveling (Chapter 5) would address point 1, by correcting reorder points, based on feedback from demand signals and attempting to manufacture products based on a takt rate. Point 2 is of relevance when considering batch sizing decisions to lower inventories (Chapter 2, 3, and 4).

1.5.3.1 Overproduction Related to Scheduling and the MRP System

Overproduction related to scheduling may be triggered by several factors. Some possible reasons are:

1) Incentive to produce in order to absorb monthly expenses and minimize monthly variances
2) Re-order points that have been incorrectly set
3) Overoptimistic forecasts of future sales (usually in a 6 – 12 month horizon)
4) Utilization of capacity that would otherwise be idle

In all of these cases, products are manufactured in a time when there is more than sufficient inventory on hand to cover from six months up to one year's worth of demand.

Figure 10 (Figures 10-A to 10-C) shows the historic daily inventory across a period of one year for four different final chemicals manufactured by SynChem.

A batch of chemical P and of chemical Q (see ovals in the charts for chemicals P and Q, Figures 10-A and 10-B) was manufactured, even when there was sufficient inventory in place to cover the demand for more than one year.

Chemical R's (Figure 10-C) safety stock was reduced gradually after the first half of the one-year period shown in the graph. Re-order points, and the frequency with which the batch is made, are critical to avoid excessive safety stock.

Figure 10 – Examples of Overproduction

Figure 10-A **Figure 10-B**

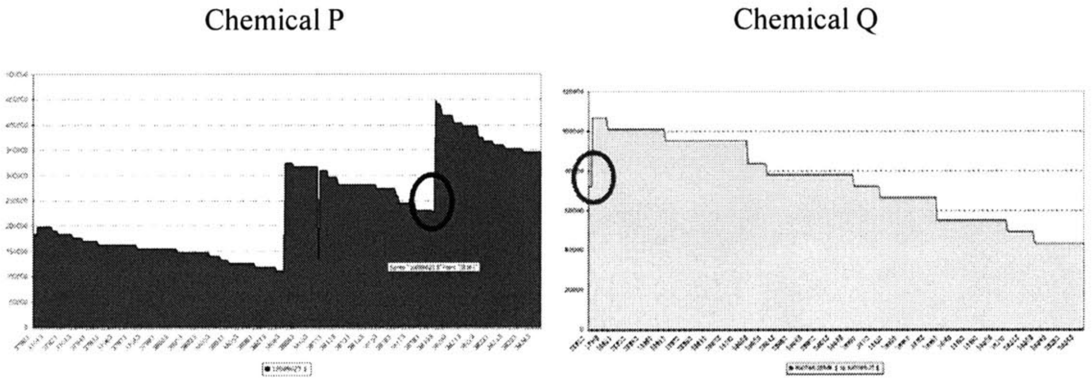
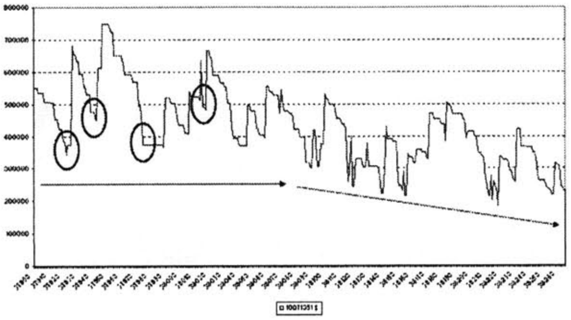


Figure 10-C

Chemical R



1.5.3.2 Overproduction Related to Synchronicity in Chemical Chains

The other forms of overproduction are relatively small leftovers of an intermediate that is not fully consumed in the subsequent process. This leftover of material is generated due to the following reasons:

a) Yield variation in manufacturing process
b) Capacity optimization

1.5.3.2-a Yield Variation

In many cases, the yield of the process to synthesize an intermediate chemical is highly variable. Therefore, when this intermediate will be used to make a subsequent intermediate chemical, the process chemists must make sure that there will be enough material synthesized of the first intermediate to be used in the production of the second intermediate. In many instances, the batch size of a first intermediate would be such that, even if the yield of such batch size is two to three sigma below the average expected yield, the material synthesized would still suffice to make an entire batch of the second intermediate. Obviously, if the yield on a given batch is two to three sigma above the average standard yield, then the leftover material, after the portion needed for the synthesis of the second intermediate has been used, will be significantly higher.

There are many products for which the process chemists have been able to reduce yield variability up to a point in which there is a consistent quantity that is leftover after synthesizing a first intermediate that then is consumed to manufacture a chemical in the next step of the chemical chain. Although process chemists have been able to reduce the variability (or the process simply did not yield variable results as initially expected), the batch size of the chemical has not been revised nor changed. As a result, there is a continuing buildup of intermediate chemical inventory that can not be used in the short term, simply because the amount of the build-up is still less than the amount that is required to make the second intermediate chemical.

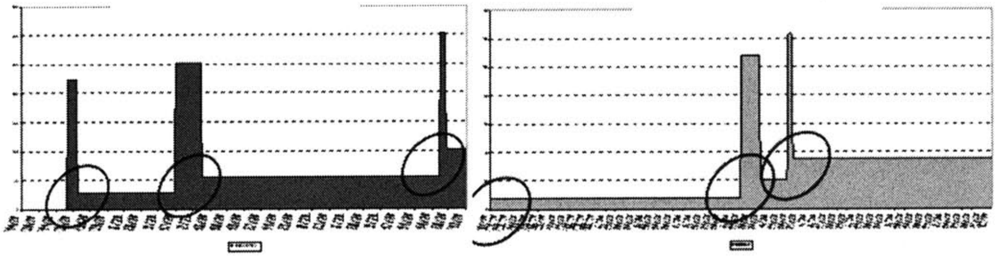
1.5.3.2-b Capacity Optimization

In the chemical batch processing industry, batch sizes are determined largely by capacity optimization models upon design or upon addition of productive assets to a facility.[8] The batch size of the intermediate chemical will be set in a way that minimizes unit manufacturing cost, or in a way that optimizes the total manufacturing costs, among them, the inventory holding costs, considering a long term time horizon (e.g., 10 years). Assume that there is a chemical of batch size $Q_1 = 80$ kg. Assume, furthermore, that a quantity $A_1 = 60$ kg of this chemical is required to make a batch of the next intermediate in the chemical chain. If one batch of the first and of the second intermediate are made once every year, and the model looks four or five years into the future (in the design of a chemical plant, 10 years is a commonly used time horizon), the leftover of material (80 kg – 60 kg = 20 kg every year) after three batches of the intermediate have been made, over a period of three years, would be sufficient to support production of the next intermediate the fourth time it is required. In a four-year horizon, this saves one setup cost and the labor costs associated with one additional batch.

In the reality of the business context that Eastman Kodak Company is experiencing now, and by the time sufficient material has accumulated, the material that has been aggregating up in the inventory might be lost, spoiled, or even obsolete.

Figure 11 and Figure 12 show the historic daily inventory across one complete year for four different intermediates from four different chemical chains in which there is consistently a leftover of product. In these cases, product yields have been relatively consistent. Leftovers will not be used any time soon, as can be seen by the length of the spikes, which show the production of a batch (first vertical line from the left on a spike) and the immediate consumption. There are more than $100,000 tied up in inventory for one complete year (level of this inventory hardly moves) in only these four examples.

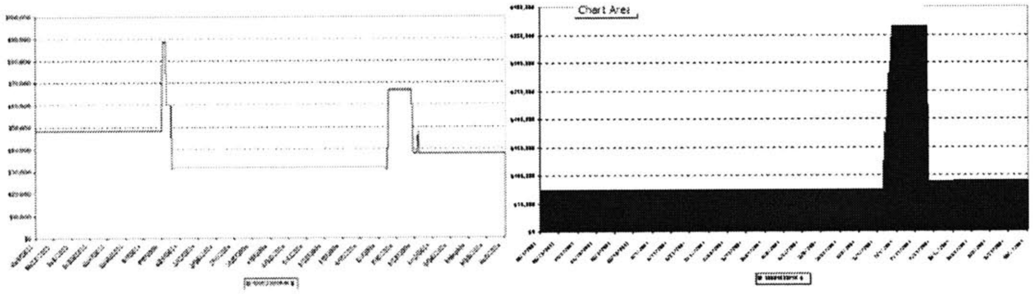
Figure 11 - Historic Daily Inventory of Two Intermediates across One Whole Year



Intermediate used in a chemical chain

Intermediate used in a chemical chain

Figure 12 - Historic Daily Inventory of Two Intermediates across One Whole Year



Intermediate used in one chemical chain

Intermediate used in one chemical chain

Batch sizing decisions should include considerations regarding the two points covered in the last section (*1.5.3.2 Overproduction Related to Synchronicity in Chemical Chains)*. These will be addressed in Chapter 4.

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CHAPTER 2 - BATCH SIZING CONSIDERATIONS

In Chapter 2, the relationships between batch sizes and other important production parameters will be described. These relationships will be discussed in the context of discrete manufacturers and the chemical batch processing industry. First, the chapter explores what should be done in terms of lot sizing when there is excess capacity in a production facility. Then, the importance of setup cost reduction is emphasized, and its impact on batch sizing policy is described. Lead time is also a lever that can be varied by changing lot sizes in a manufacturing plant. Finally, the most important batch sizing considerations for Synthetic Chemicals, and for any batch chemical processing plant conducting similar batch sizing analysis, will be covered.

2.1 Lot Sizing and Excess Capacity

For the purposes of this thesis and any study regarding batch sizing decisions, two types of plant capacity can be considered. First, installed capacity is determined by the total number and types of manufacturing equipment and machinery available at the plant. This installed capacity is also defined by the total available hours in a period of time (e.g., in a year) in which the equipment can be operated, assuming the necessary staff required to operate these assets is available.

Then, we can define an operational capacity, determined by the first set of resources required to determine the maximum installed capacity and by the number of other variable resources, such as direct labor, indirect labor, and materials.

When there is an excess of operational capacity, there is a number of workers and machines that, at different points in time, are idle. When this capacity is used for a productive activity, its cost can be considered to be zero. In other words, the marginal cost of undergoing this extra productive activity is zero or, at most, negligible.[6]

When dealing with the problem of reducing lot sizes, this last consideration is very important. The main purpose of lot size reduction is to reduce the lead time of a unit, the time it takes for one unit to be delivered to the customer after an order has been placed.

"When a general-purpose machine, such as a die press, has excess capacity, it is an advantage to reduce lot size as much as possible, aside from the separate problem of shortening setup time. If the machine still has excess capacity, it is better to continue reducing setup time to utilize it.

When there is an excess of operational capacity, it is fairly simple to conclude, without a cost study, whether a gain or loss will result from one of the following: a lot size reduction, a relocation of workers to perform certain activities when they would otherwise be idle, and the outsourcing of a product. What is of utmost importance is to know at all times whether there is excess capacity. If production managers don't know whether there is extra capacity, they will make mistakes in the decision-making process and, in some cases, they will incur additional expenses."[6]

SynChem should try to extract improvements from their excess operational capacity. If managers can be certain that this capacity exists, they do not need to fear additional costs. Therefore, it is necessary to make the differentiation between operational and installed capacity. Although there might be enough installed capacity for the manufacturing of additional product or to reduce lot sizes, it is possible that there is not enough direct labor to run the equipment for the extra time it is required to operate. In this situation, one (or more) additional workers must be staffed, incurring additional variable costs. If this is the case, an economic analysis must be made to determine whether this is an appropriate action to take.

2.2 Lot Sizing and Setup Cost Reduction

The Kodak Operating System (KOS) draws many of its principles from the Toyota Production System. Early on, after the Second World War, Toyota took a different approach regarding lot sizes, than most mass producers. Toyota's production slogan, as described by Taiichi Ohno, is "small lot sizes and quick setups".

Large lot sizes are needed in many production processes to amortize the high cost of performing a setup or change-over needed to make a different subsequent product and to improve equipment efficiency by running it most of the time. When large lot sizes are preferred, the manufacturer must handle larger quantities of material and generates high inventory levels of components and final products. Toyota's system aims to eliminate the costs associated with workers, land, facilities and capital to manage inventory. Toyota's leaders viewed inventory as waste, since the money invested in managing it doesn't really add any value to the product the customer wants.

The last statement is not necessarily true. In many cases, inventory is needed for a manufacturer to deliver product to a customer on time, when needed, at a cost the producer is willing to cover, and at a price the customer is willing to pay. If both price and on-time delivery matter to the customer, then the inventory the manufacturer needs to hold does add value. Improvements in technology, process improvement, cost reduction in labor, raw materials, or production capacity, allows a firm to reduce its inventory levels, and at the same time, provide the customers with on-time delivery, and at the products' prices they are willing to pay.

Setups are regarded as elements that reduce efficiency and increase costs. At SynChem, this is also the case. Setups are lengthy processes in themselves and have a significant cost. These high costs are due to the organic solvents that must be used to clean equipment and the fact that the setup is a very labor-intensive operation and takes a considerable amount of time (six to twelve hours). There are also two other elements that should be considered and treated as setup cost drivers: quality testing and waste treatment. Every batch must be tested, regardless of the size of the lot. Additionally, there is a significant amount of waste generated with every batch that must be treated or destroyed. Waste consists of co-products generated in the reaction or solvents and salts used for the reaction, distillation, and liquid-phase separation of the materials of interest. Although the amount of waste generated in the chemical reactions are, in most cases, directly proportional to the batch size, the amount of solvents used during the clean-up operations is not. The quantity of cleaning solvents used will depend on the reactor's ratio of volume to surface area, the type of mixing involved and the state of the chemical (slurry, viscous liquid, suspension, solution, non-viscous liquid). Finally, there is also a quantity of the useful product that is not recoverable and is considered scrap. The amount of scrap per batch depends more on the equipment utilized than on the actual batch size. Therefore, regardless of batch size, there are testing and waste treatment costs that will also be amortized by the product made in the batch.

SynChem must make it an objective of development chemists, process chemists, operators, and managers to reduce setup costs. Teaching these employees why it is important to pursue such a lofty goal and how to reduce these costs will require repeated on-the-job training. This might be something new to employees, who are accustomed to class-room-type courses and instruction.

A key component to reduce setup costs is a sense of urgency to generate extra capacity with the available resources, mainly equipment, labor, and raw materials. If this extra capacity is attained, then the batch size of a handful of chemicals done infrequently and stored for long periods of time can be reduced. More capacity must then be generated through productivity improvements to reduce the batch size of another group of chemicals. This is a path of continuous improvement and can only be sustained by changes in the working culture and leadership of Kodak employees.

It is also vital that SynChem operators be the ones to develop the best methods to perform setups and cleanups and to set a standardized process under the guidance of their area managers. Any new process innovation, regardless of how small it is, that reduces the amount of solvents, people, and time a setup takes, should be immediately documented and standardized.

One of the processes within Toyota that benefited from setting setup reduction as an important goal for operators and engineers is the die process. In the 1940s, it took two to three hours to change a die. In the 1950s, setup time dropped from one hour to 15 minutes. In the 1980s, die setups were shortened to three minutes.[6]

Now, let us consider the main differences between discrete manufacturing and chemical batch production, when it comes to reducing lot sizes. In most discrete manufacturing operations, run time varies linearly (with a slope of 1) with run size. Therefore, if a batch of 200 units is processed in two hours, a batch of 100 units can be worked in half the time: one hour. However, in chemical batch manufacturing, this relationship does not hold. There are different physical and chemical phenomena taking place in the transformation of chemicals. The rate at which processing takes place depends, therefore, on chemical kinetics, mass, and heat transfer rates. Therefore, in chemical batch manufacturing, when a batch is reduced in half, processing time, or run time, is not reduced by half. Depending on the main processing steps: distillation, reaction, heating, cooling, filtration, etc, run time will be reduced by 5 – 20%. When the lot size is reduced, the amount of product made per unit of time and unit of labor decreases, reducing productivity.

Because the reduction of lot sizes has little impact on the reduction of processing time, total production lead time is not impacted significantly. The benefit of lead time reduction achieved by constantly reducing lot sizes in a discrete manufacturing operation is not gained in a chemical batch operation.

In discrete manufacturing, in general, if the setup time is reduced to 1/N of the initial time, the lot size could be reduced to 1/N of its initial size without changing the loading rate of the process in question. Again, due to the reasons explained in the previous three paragraphs, this does not hold true in SynChem's operations. Therefore, even setup reduction will not have the same positive impact that it has in a discrete manufacturing operation.

In the Toyota Production System, shortening the processing time without decreasing productivity is attained by reducing setup time and lot size. This is especially effective when many varieties of products are produced. In SynChem's operations, processing time is not reduced by reducing lot size. Actually, productivity is diminished and total processing time does not change (or changes very slightly). Lead times are not shortened significantly and, therefore, safety stock levels have to be very similar to the ones that are required under a standard MRP process and a functional work flow in large batches.

2.3 Lot Sizing and Lead Times

To show the effect on lead times of lot size reduction in both discrete and chemical batch manufacturing, assume that there are three kinds of parts, A, B, and C. Assume the processing time for each unit is one minute, and the setup time between lots of any kind is one hour. Assume further, that the lot sizes of any part A, B, or C is 3,000 units. The lead time to produce all three kinds of parts is, therefore, 153 hours. If the lot sizes are reduced to one-tenth of their original size and the setup time is reduced to one-tenth of its initial time, the total time required to produce all three kinds of parts is 15 hours and some minutes. Because setup time and cost is reduced to one tenth of its original values, productivity, throughput, and total system cost is not impacted negatively.

Although large-lot production can minimize the average unit cost, it will increase the inventory level of each department and also increase the total production lead time. This makes it more difficult for manufacturing plants to adapt to changes in customer orders in the middle of production runs. The last statement is true in discrete manufacturing. In chemical batch manufacturing, production lead time is impacted significantly, when campaign sizes are reduced. Papouras[1] shows in his thesis, how lead times and inventory is lowered in SynChem, when campaign sizes (number of runs per campaign) is decreased.

It is important to note, that for the last argument to be correct, one must assume that the units being manufactured are not moved from one production step to a second production step until the whole batch has been completed. Therefore, when the first 500 units of our previous example are completed, they wait in inventory (probably a pile located at the end of the work station) until the other 2,500 are completed. The 3,000 units are then transported to another step in the production process. In many cases, a complete order is not shipped from a factory until the complete order is finished. If the order consists of a large batch of products, the first products that are produced must sit in inventory until all of the products constituting the batch are processed. In the same fashion, if a small batch of products of size n arrives at a work center that is processing a much larger batch of size N, this small batch of products will sit in inventory, until the remaining units, $N - n$, (in the case in which both precedent and subsequent processes are perfectly synchronized, start and finish at the same time) are processed in the latter stage. By aggregating these effects in an operation driven by large batches, and in which material movement is performed in large batches as well, lead times increase considerably. By making smaller batches at each step, or by transporting material in smaller amounts from process step to process step, lead times are reduced and thus inventory levels required to prevent stock-outs are also reduced.

Safety stocks decline when lead times are reduced. Safety stock is the amount of inventory that a manufacturer needs to keep in his warehouse and in the pipeline to hedge against deviations from average demand during the lead time.[9] The following formulation shows the relationship between the safety stock and the lead time for a continuous review policy model:[9]

Equation 1 – Safety Stock for a Continuous Review Policy

$$\text{Safety Stock} = Z \times STD \times L^{0.5}$$

Where:

Z = safety factor – standard normal variable for a defined probability of stocking out.
STD = standard deviation of the demand or pulls from the inventory per unit of time
L = Lead time

For a periodic review policy, the effect of lead time reduction on safety stock is less dramatic:[9]

Equation 2 - Safety Stock for a Periodic Review Policy

$$\text{Safety Stock} = Z \times STD \times (r + L)^{0.5}$$

The new term, r, introduced in this expression represents the length of the review period.

In chemical batch manufacturing, lead time is not impacted significantly, when **lot sizes** are reduced (note that there is an advantage described previously of reducing **campaign size**). Average unit costs increase in all cases and lead times remain relatively the same, making a decrease of lead times and safety stocks infeasible. The reason why this is so will be covered later in the next chapter in more detailed.

Since the Toyota Production System is one of the principal models for the KOS, it is important to note that several processes within the Toyota supply chain are still manufactured in small to relatively large lot sizes. Casting, sintering, forging, stamping, and plastic molding of interior parts are still manufactured in lots, and the size of the lots is driven by the economics of the processes and the physical or chemical constraints that are reached when trying to reduce run times.

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CHAPTER 3 – CASES STUDIES ON BATCH SIZE OPTIMIZATION

This chapter is broken down into two parts. The first part deals with the different factors that have to be considered and quantified when evaluating the tradeoffs involved in the batch sizing decisions at Synthetic Chemicals. The second part of the chapter presents case studies on four different chemicals that were among a larger group of chemicals analyzed during the six-month internship that preceded this thesis. In general, large batches, constrained only by reactor sizes, are more advantageous due to the high setup and changeover costs. Productivity and capacity decreases significantly as batches are scaled down beyond a certain threshold. This threshold is unique for each chemical. Savings on inventory holding costs are more than offset by these caveats.

The steps to analyze each chain are the same, regardless of the number of intermediates in the chain, the recipes, the routings, and the costs associated with changeovers and holding inventory.

The main cost components are described in the following sections.

3.1 Setups

The term *setup* is defined in numerous ways, depending on the context in which it is being used. Across industries, companies, and manufacturing processes, the term might have different meanings. In this thesis, setup is regarded as the group of all activities that have to take place every time production is switched from one chemical to another. These setup activities are also characterized by the fact that they are done once per batch. Setup activities include:

- Cleaning up all of the equipment (reactors, centrifuges, filters, pipelines, pumps, valves) after a chemical has been made, leaving surfaces free of traces from dyes, solvents, powders, particulates, etc.
- Setting up the equipment after it has been cleaned, connecting fittings, pipelines, closing and opening appropriate valves, checking pressure and temperature in cooling or heating systems, etc.
- Testing during the entire process and at the very end of the run. Because testing has to be done on a "per-batch basis", regardless of the amount of material in kilograms that are made per batch, it is included in the setup costs.

When considering a batch of an intermediate chemical, setup costs entail all setup activities necessary in all work centers through which the materials will flow, from the reactor, through grinding and packaging of the chemical.

3.2 Setup Costs

a. Labor: Cleaning and preparing the reactors, filter-presses, and centrifuges are labor-intensive activities. A person must be dedicated to the task and disassemble piping lines, clean valves, fittings, press filters, pumps, and add cleaning components to the reactors and centrifuges.

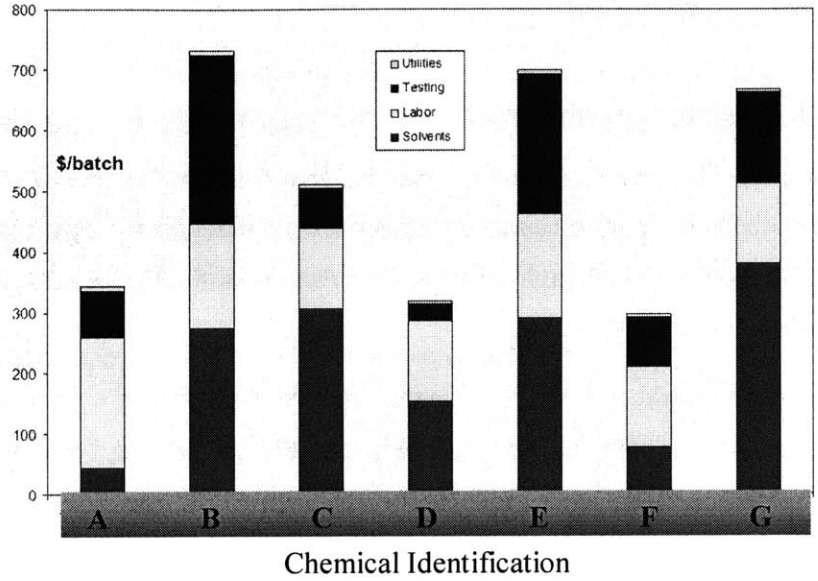
b. Cleaning materials: Organic chemicals are required to clean the equipment when a reactor will stop being used to make a chemical A and will be used to make chemical B. Because a certain amount of materials is needed to clean a reactor of a given size, regardless of the level up to which the reactor was filled with reacting material, this quantity will remain constant for a given reactor size, even if the batch size changes between corresponding ranges.

c. Testing: Quality tests must be performed for every lot, regardless if only one kilogram of material is prepared per batch or if two metric tons are made. For every intermediate or final compound, there are different tests that are conducted either throughout the process or at the very end, right before sending the product to the warehouse.

d. Utilities: The costs associated with utilities, such as steam, cooling water, and electricity are very hard to estimate. The amounts of steam, cooling water, and electricity utilized per batch will not change significantly with the batch size. These costs can also be assumed to remain relatively constant, month to month. For this study, these costs have been assumed constant (fixed costs), and their effect on the outcome of the study is considered minimal. Therefore, these costs have been ignored.

It is important to note that these cost components will vary considerably from chemical to chemical. This is one of the reasons why batch sizing decisions at the SynChem should be considered on a case-by-case basis, when there are no capacity constraints. In these case studies, infinite capacity was assumed. Due to the high cost of change and the fact that capacity is already determined, it is current policy that batch size changes will only be done on a case-by-case incremental basis. Figure 13 shows the different setup costs for several chemicals, labeled with letters from A to G for confidentiality purposes. Both intermediate chemicals and final chemicals appear in the chart.

Figure 13 - Setup Costs per Batch for Seven Different Chemicals



3.3 Variable Manufacturing Costs

a) Material Costs: The material cost component is the most straightforward element to incorporate into the calculations. The material costs are the purchased prices of the materials required to make one kilogram of the chemical of interest. The stoichiometric proportions for the reaction and the separation processes (e.g., distillation, liquid-liquid separation, filtration, etc.) remain constant for a given process, regardless of the batch size. If there is an intermediate in the recipe of a final chemical, the cost of the intermediate per kg will be calculated from the material costs only, excluding the "value-added" cost elements, such as labor and manufacturing overhead. On average, material costs constitute about one fourth to one half of the total unit manufacturing cost for a final chemical.

b) Labor Costs: Labor costs are calculated by multiplying the average labor rate (includes employee benefits) times the number of hours of labor required to make a batch. The reader must be aware that an operator might actually work directly with a batch only 20 to 70 % of the time that it takes to make the batch. The actual time an operator spends working on a batch varies significantly from product to product. There are times in which the operator is not required to be in the work center, and the process has not stopped. For example, in some cases, a mixture might have to be mixed for one hour (while a chemical reaction is taking place).

As the way SynChem utilizes its operators in its facilities changes, the implications of labor costs on variable manufacturing costs will differ. Many years ago, SynChem dedicated one or two operators to each bay. Therefore, it was relatively simple to allocate the labor costs to the chemical made in the bay. In most cases, one operator is capable of running up to two different chemicals in one single bay. Although running three chemicals in one single bay is possible, it is not very common.

As SynChem's operators and staff learn to run the chemical processes in a more team-integrated format (e.g., a team of four operators overlooking production in eight bays) and learn to automate and standardize tasks, labor productivity increases. If the operator works only 70% of the chemical's processing time at the work center, and is empowered and able to work the other 30% of the time performing productive tasks in another work center (e.g., adding material to another reactor in a different bay), then the labor costs to make the batch should be 70% of the initial cost. If, in the other hand, the operator is not able to engage in other productive activities, the resource is idle and the cost of being idle should be integrated in the variable manufacturing cost of the chemical that is being analyzed.

As will be described in subsequent sections, reducing the batch size of a chemical will not reduce the labor requirements in a linear or proportionate way. Whether the operator spends 30% of the processing time at the work center or 70% of it, once the batch size is reduced, the operator will still spend a very similar amount of time at the work center. This will be covered in subsequent sections.

3.4 Inventory Holding Costs

It is common in the literature that covers operations theory to treat inventory holding costs as a variable cost. For example, in some cases, the annual inventory holding cost is a percentage of the unit manufacturing cost of a product, usually a value between 10 and 35%. If the cost of a unit is $100, and the annual inventory holding cost is 24% (a value found in the literature for the chemical process industry), it is assumed that the inventory holding cost per unit is $24/year.

Table 1 - Inventory Holding Costs Relative to Total Manufacturing Costs

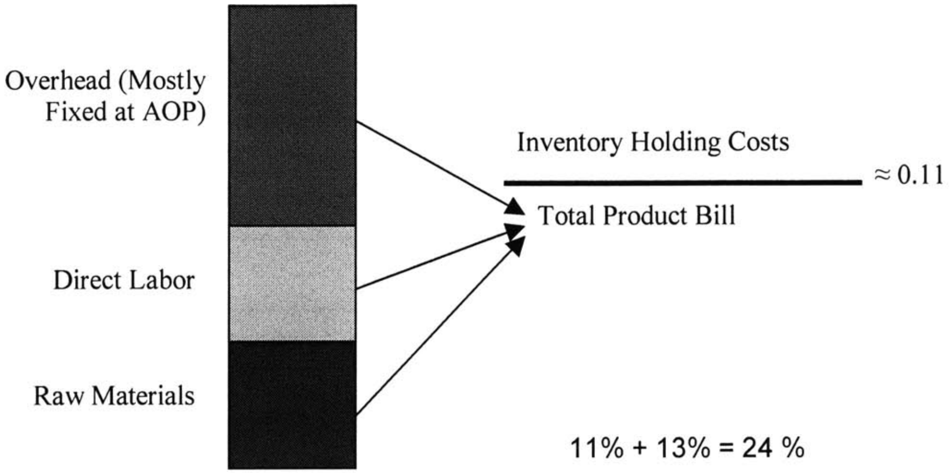
Cost Driver	Resource	Cost
Opportunity Cost of Capital	Kodak's Cost of Capital	13%
Storage/Building Cost	Rent, Depreciation, Utilities, Insurance, Taxes	4%
Obsolescence Related Cost	Mfg waste, re-testing, obsolete/defective inventory	3%
Planning/Scheduling Cost	25% of labor, benefits, supplies, related with admin staff	2%
Warehousing Cost	Labor, benefits, and supplies for warehouses	2%
Internal Transportation	Terminal handling, trucking to/from port, freight, demurrage, bill of landing, port handling…	2%

Note: Values have been modified and do not necessarily reflect actual values.

In practice, as happens at Eastman Kodak Company, it is very difficult to quantify the true inventory holding cost that is incurred due to the inventory management associated with one single chemical or even for a finite group of products. An estimate of the total inventory holding cost as a percentage of total manufacturing costs (both fixed and variable costs) for some of the plants within the department is shown on Table 1.

Figure 14 represents how these numbers are actually calculated.

Figure 14 – Method to Estimate Inventory Holding Costs



AOP: Annual Operating Plan

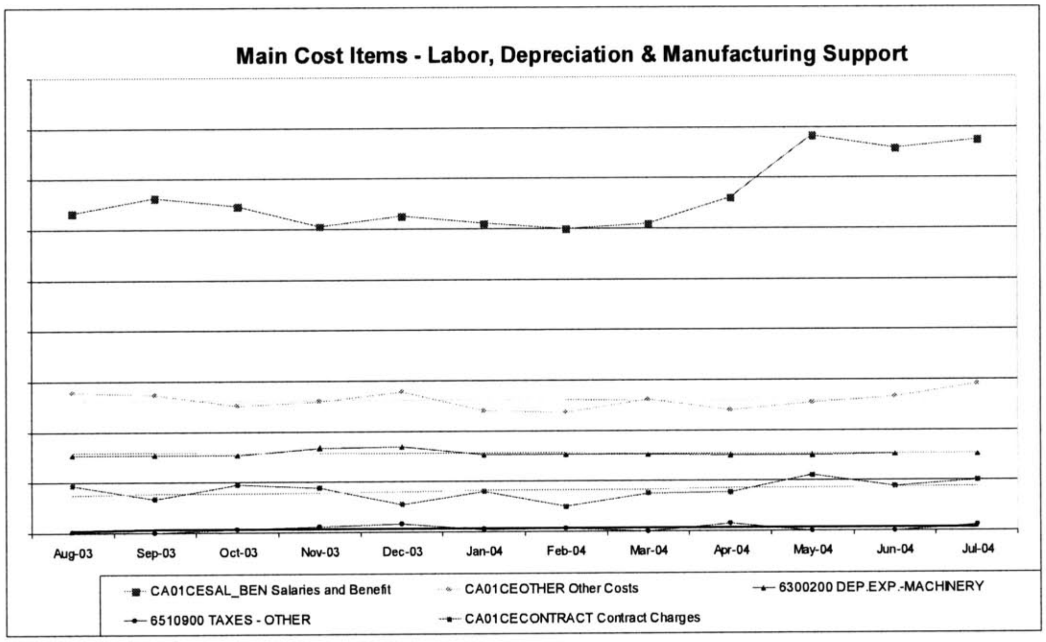
Kodak's estimated cost of capital: 13%

The inventory holding cost has several components, but a large portion of them are actually fixed costs. If, for example, we were to reduce the average inventory of a chemical, which throughout the year uses an average of seven rack spaces in the warehouse, to an amount that would utilize two or three rack spaces less, the fixed costs associated with managing and handling the material will not be reduced at all. The plant still expenses the same amount for the property, labor, equipment leases, etc. Therefore, for this case in isolation, the marginal cost of holding extra inventory is zero. If inventory levels for this one single chemical are reduced by half, the department would have gained no savings whatsoever in the fixed-cost portion of the costing equation. It is only when the department has reduced inventory levels by a significant amount, that some of these fixed costs can be shed from the system.

3.5 Other Cost Considerations

From the preceding discussion, we might be tempted to state that the only true variable portion of the inventory holding cost in a marginal analysis is the opportunity cost of capital, as determined by Kodak's capital structure and established and well-accepted hurdle rates. In discrete manufacturing it is easier to cost the material management and handling expenses in a "per unit" term. In fact, the utilization of forklift trucks, labor, space, planners, and managers can be related to volume (in units) with a linear function. The same applies to the opportunity cost of capital. If the plant needs to make larger batches of discrete parts, the money invested in labor, and even a large portion of the overhead tied now into inventory, will increase in a proportionate linear way. If the plant has higher inventory turns and lower average inventory levels, it will have less of such capital tied up in inventory; and therefore, a lower opportunity cost of the capital employed to support such operations.

Figure 15 - Fixed Expenses for a SynChem Facility throughout One Year



This is not the case when fixed costs are a large proportion of the total costs. In SynChem, a large portion of cost is manufacturing overhead, which is relatively constant over time. Regardless of the batching policies and inventory levels, the plan requires having these expenditures in order to support continuing operations. Figure 15 shows all of the expenditures incurred by one of SynChem's facilities across time (in months). The labor expense shows a significant increase in May, and this was due to increasing production volumes and use of overtime, increasing as batch sizes of several chemicals were reduced.

The only noticeable exception in the short- and perhaps medium-term is labor cost. Labor expenses plotted in Figure 15 increased considerably in May at one of the facilities due to both increasing production volumes and more extensive use of overtime.

"The Goal", a book by Goldratt,[10] has been extensively read and disseminated in manufacturing plants across the U.S. In his book, Goldratt suggests cutting batch sizes by half and claims that this measure will render tremendous benefits in the form of lead-time reductions, throughput rate increases, and inventory level reduction. In these assertions, he makes two critical assumptions on the production processes, which he states explicitly in his book:

1. Run time (time it takes to process the complete batch) varies linearly with run size. It takes half the amount of time to make a batch half the original size.
2. Batch sizes are to be reduced in non-bottleneck resources, where there is idle capacity that can absorb the increased amount of time spent on setups.

For SynChem, both assumptions do not hold:

1. Run time does not vary linearly with the run size.
2. Batch sizes are cut in all steps and unit operations in the process chain. In most cases, when the batch size is reduced, it is also reduced at the bottleneck resources: reactors, and in some cases, depending on scheduling, dryers. Therefore, capacity is reduced at the bottleneck resource when batch sizes are reduced. How critical this is will depend on the utilization of the bottleneck resource at that point in time.

3.6 Process Characteristics that Affect Cost

In chemical batch manufacturing, one important consideration is the relationship between the transformation time (or processing time) and the quantity of material processed in a batch. In discrete manufacturing, this relationship is linear. In chemical batch manufacturing, this relationship depends upon the following phenomena:

a) ***Chemical kinetics***: Chemical kinetics for the particular chemical reaction set a constraint on how fast a material can be synthesized. If a lot size is reduced by half, and the product is synthesized in a smaller reactor, the reaction time remains constant.

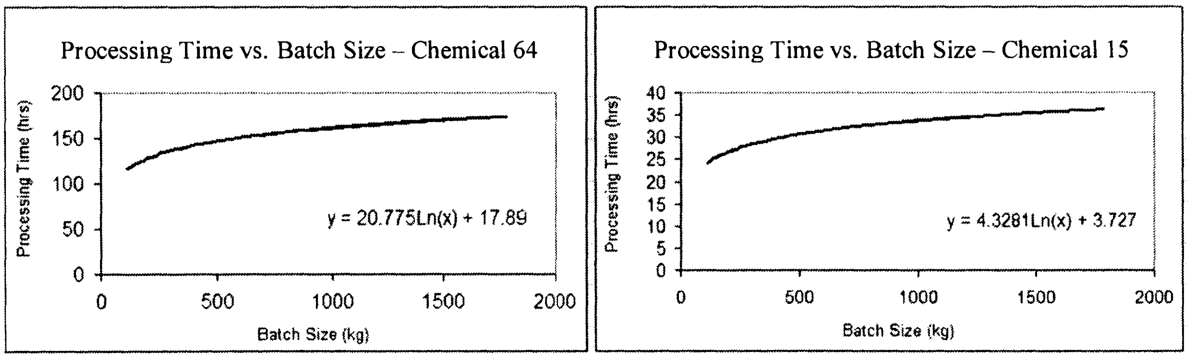
b) ***Mass transfer***: Mass transfer will be determined by the mass transfer coefficient (specific for the materials involved and the system), concentrations of the components, state in which the reaction takes place, molecule sizes, mixing pattern, temperature, and pressure in the reactor.

c) ***Heat transfer:*** Heat is conveyed through the jacket's surface of the reactor to the mixture. Although reactor size does have an impact on the time it takes to heat a mixture, due to the relationship of surface area for heat transfer and working volume of the reactor, there is, nevertheless, a constraint limiting the speed at which a mixture can be heated in a reactor, when going from a large batch down to a smaller batch. Mass and heat transfer constraints are especially important in the distillation and separation (centrifuging and filtration) stages.

d) ***Material addition:*** This is probably one of the few components of the processing time that is linear. The time it takes to add a material into a vessel or to transfer material by using a pump is directly proportional to the quantity added or transferred.

One disadvantage present in evaluating the relationship between batch sizes and processing times is that it is almost impossible to perform trials at the plant in which different lot sizes of a same material are made and their processing times are measured. In order to obtain an estimate of the relationship, the process chemists for the chemicals of interest were interviewed and a curve or fit was created to represent the relationship. These curves are logarithmic functions. In many cases, when evaluating capacity and analyzing batch sizes, the department's staff assumed the processing time to remain constant, regardless of the lot size. We realized that using these logarithmic fits would generate better estimates than assuming fixed processing times independent of batch sizes. Two such curves for two different intermediates in a chemical production chain are shown below:

Figure 16 – Relationship between Batch Size and Processing Times



Processing Time vs. Batch Size – Chemical 64

Processing Time vs. Batch Size – Chemical 15

Such curves were estimated around one or two data points. These data points were historic, either from the current production routings or from routings that were utilized in the past when the lot sizes of the chemical were different.

The following case studies will show the effects of changing the batching policy beyond an optimum point and will also demonstrate how different assumptions, based all in different data from the cost accounting system, provide evidence with several levels of support for the final decision.

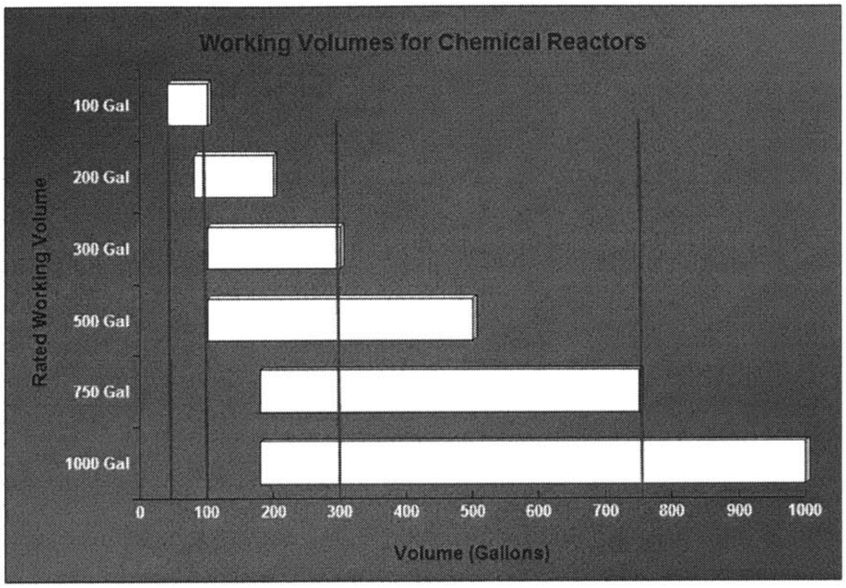
3.7 Feasible Regions for Batch Size Optimization

When determining the optimal batch size and the optimal number of runs per campaigns for all the intermediate and final chemicals in a chemical chain, a feasible region for the decision variables must be predetermined for each of the intermediate chemicals in the chain. In all of these cases, the decision variables are of two forms: either positive continuous variables, which represent the batch size, the amount of kilograms that will be made in each batch, or positive integers, which represent the number of runs per campaign. The feasible region is defined by minimum and maximum constraints set for the batch size in kilograms. Minimum and maximum constraints are set on the amount of kilograms per batch that can be processed. This amount of material in kilograms depends on two main factors: 1) the yield of the desired chemical in kilograms per unit of volume of the total solution needed during the reaction stage (or the stage that takes up the highest volume), and 2) the minimum and maximum volume at which the process can be carried out in the reactor. For example, a process can be carried out in a 750 gallon reactor, even if the reactor is only filled to 30% of its working volume, which is equivalent to approximately 190 gallons of mixture.

Note that a batch can be made in reactors of different sizes, ranging from a 100 gallon reactor up to a 2,000 gallon reactor. The feasible region defined for each analyzed chemical has to take into account the available reactors in the plant in which the chemical is to be manufactured. The figure below shows the working volumes in gallons for all reactor sizes.

When analyzing the cost of different batching scenarios for SynChem's products, the minimum quantity was defined by the minimum amount that could be made in the smallest reactor available at the plant, and the maximum quantity defined as the maximum amount that could be made in the largest reactor in the plant.

Figure 17 – Feasible Working Volumes that Determine Feasible Regions for Batch Size Optimization



3.8 Case I: Chemical 38

The process to manufacture chemical 38 is a one-step process with no intermediates. This chemical is manufactured in relatively low volumes. In 2004, only 134 kg were made, while the forecast for 2005 is 140 kg. This chemical was not manufactured in years 2002 and 2003.

In this case, finding the optimal batch sizing policy is relatively simple. The only difference with the economic order quantity equation, used commonly for discrete parts, is that the unit manufacturing cost is a function of the batch size (the variable we are trying to find). The equation to be minimized is the cost function (objective function) shown below:

Equation 3 – Objective Function for Manufacturing Cost of Chemical 38

$$\Phi(Q) = \varphi\frac{\alpha}{Q} + \left(\varpi + \frac{Q}{2}\right)\left(\beta + \left(\frac{(a\ln Q + b)\varepsilon}{Q}\right)\right)\delta + \alpha\left(\beta + \left(\frac{(a\ln Q + b)\varepsilon}{Q}\right)\right)$$

where:

Q = Batch size (kg/batch)

φ = Testing Cost (\$/batch) + Cleaning Solvents Cost (\$/batch) + Labor Cost (\$/batch) + Utility Costs (\$/batch).

α = Annual Demand (kg)

β = Material Cost (\$/kg) - Raw materials needed to synthesize the chemical

ϖ = Safety Stock = $(Z)(\mathrm{STD})(\mathrm{L})^{0.5}$

a, b = Constants of the logarithmic fits that are used to estimate processing time (or labor hours) as a function of the batch size Q

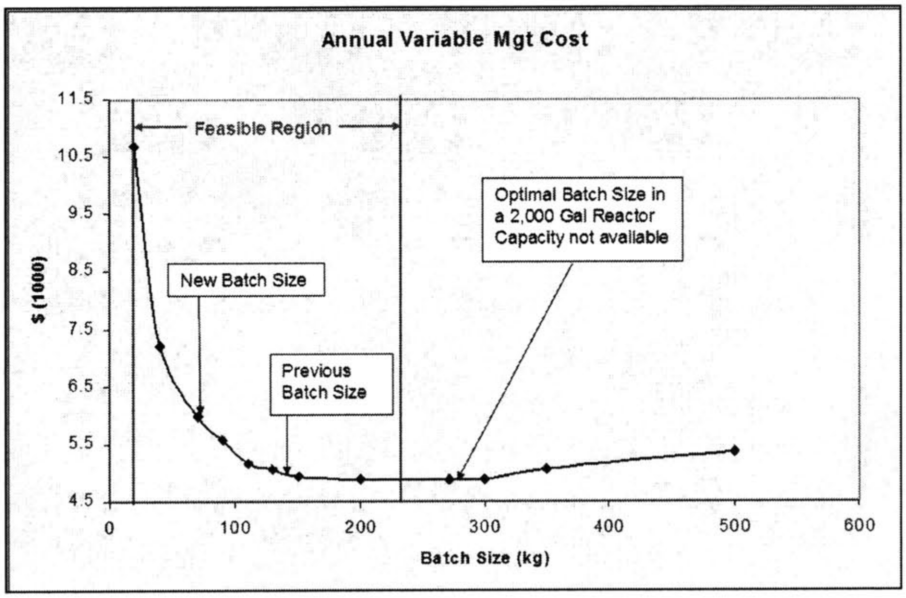
δ = Kodak's opportunity cost of capital (13%)

ε = Labor rate (\$/hr) – Average that includes salary and benefits of direct labor

Note that L, the lead time, should change as a function of the batch size because processing times do change slightly as the production lot size is scaled down. However, the reduction in processing time when cutting the batch size by 25 - 75% is very small, relative to the total lead-time of the final chemical (queuing time + idle time + transportation time + processing time). Therefore, the standard value for the lead time (based on historic information) stored in SynChem's MRP II system was utilized.

The following figure shows the results obtained for this chemical. The curve describes the total variable manufacturing cost relevant to the decision, such as material costs, labor costs, setup costs, and holding inventory costs. Labeled as "Previous Batch Size", is the batch size with which SynChem had been operating in the last two to three years. Labeled as "New Batch Size", is the batch size, which was being considered as a new standard lot size for the production of chemical 38. The "New Batch Size" was set arbitrarily, around 50% of the original value, in order to cut cycle stock by half. In this case, by reducing the batch size by approximately 50%, SynChem is moving up in the variable cost curve, making it more expensive to make the same product and quantity. Note that the optimal batch size of approximately 280 kg would have to be made in a 2,000 gallon reactor. Because this reactor size is not available in the plant in which the product is to be made, the optimal quantity is beyond the feasible region. The optimal batch quantity is, therefore, right at the feasible region, which represents the quantity made in a 1,000 gallon reactor. This product was made in the last years in a 750 gallon reactor. The difference in cost between this option and the option of manufacturing the product in a 1,000 gallon reactor is minimal. On top of that, there are considerably more 750 gallon reactors installed at the plant. Therefore, when taking capacity and equipment availability into account, it is more favorable to manufacture the product in the 750 gallon reactor.

Figure 18 - Annual Variable Manufacturing Cost for Chemical 38

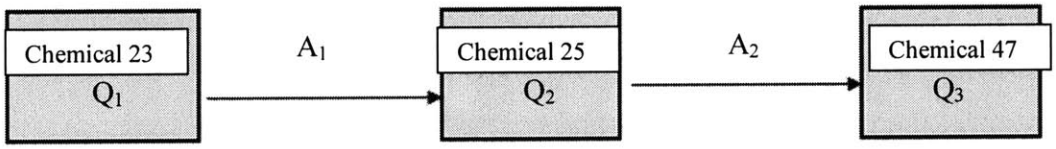


Note: Actual Annual Variable Mgt Costs have been modified and do not reflect actual values. Relationship between the actual values were maintained (relative scale).

3.9 Case II: Chemical 47

The process to manufacture chemical 47 is a three-step process with two intermediates. This chemical is manufactured in very low volumes. In 2004, a little less than 4 kg were required, while the forecast for 2005 is 11 kg. This chemical was not made in 2003; and in 2002, about 12 kg of this chemical were made.

Figure 19 – Synthesis Pathway for Chemical 47



Q_i represents the batch size for each of the intermediates and for the final chemical. The quantity A_i stands for the amount of intermediate that is used to make the next intermediate (or final chemical if that is the case) Q_{i+1}. The quantity A_i is determined by the stoichiometric quantities or proportions developed by the process chemists to make Q_{i+1}. Although A_i will vary with Q_{i+1}, the proportions are fixed. The equation to be minimized is the cost function (objective function) is shown below:

Equation 4 - Objective Function for Manufacturing Cost of Chemical 47

$$\Phi\left(\bar{Q}\right) = \alpha_3\left[\beta_3 + \frac{50}{28}\left[\beta_2 + \frac{110}{30}\Psi_1(Q_1) + \Psi_2(Q_2)\right] + \Psi_{31}(Q_1) + \kappa\right] + \sum_{i=1}^{3}\varphi_i\frac{\alpha_i}{Q_i} +$$

$$+\left(\varpi_1 + \frac{Q_1}{\tau_1}\right)[\beta_1 + \Psi_1(Q_1)]\delta + \left(\varpi_2 + \frac{Q_2}{\tau_2}\right)\left[\beta_2 + \frac{110}{30}\Psi_1(Q_1) + \Psi_2(Q_2)\right]\delta +$$

$$+\left(\varpi_3 + \frac{Q_3}{\tau_3}\right)\left[\beta_3 + \frac{50}{28}\left[\beta_2 + \frac{110}{30}\Psi_1(Q_1) + \Psi_2(Q_2)\right] + \Psi_3(Q_3) + \kappa\right]\delta$$

where the only new terms introduced are:

$$\Psi_i(Q_i) = \frac{(a_i \ln Q_i + b_i)\varepsilon}{Q_i}$$

i = 1, 2, 3 for chemical 23, chemical 25, and chemical 47, respectively

κ = Labor cost (\$/kg) of the finishing and packaging process for the final chemical

τ = Inventory Simulation Parameter

The numeric ratios (50/28, 110/30) are the stoichiometric proportions. For example, in order to make 28 kg of the third and final chemical, 50 kg are needed in the recipe of the second intermediate.

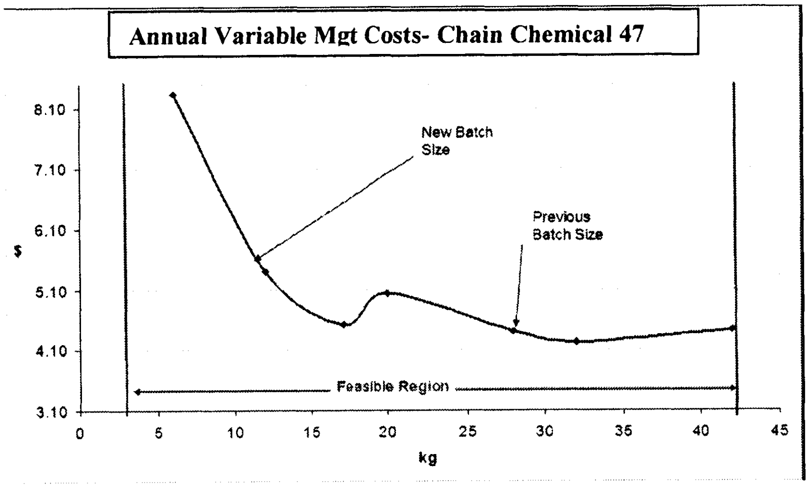
In some instances, as was the case with this chemical, the average inventory term of the intermediates, $\varpi_i + \frac{Q_i}{\tau_i}$, is set to zero. When the volumes required per year of the intermediates are very low, it is to SynChem's best interest to manufacture only the amount of the intermediates that they need for the subsequent processes to avoid having any left-over material that carries a very high probability of becoming obsolete, getting lost, or being damaged when stored for two years or more. In these cases, the safety stock and the average inventory of the chemicals $i = 1$ and $i = 2$ are set to zero.

In other cases, in which we want to evaluate the option of keeping intermediates in inventory, we can assign a value to the inventory simulation parameter, τ, which will be a number between 1 and 3 (see explanation in the following section). This parameter can be set based on the historic inventory profile of the chemical or by comparing the batch sizes of chemicals i and $i+1$ and understanding the way inventory varies across time.

For this particular chemical, no inventories of the intermediate chemicals are carried. This constraint set on the system requires Q_1 and Q_2 to be a function of Q_3. This function is defined by the stoichiometric relationships in the recipes.

The following figure shows the results obtained for this chemical. The curve describes the total variable manufacturing cost as a function of the batch size of the final chemical, Q_3. Labeled as "Previous Batch Size" in the figure, is batch size Q_3, with which SynChem had been currently operating. The batch size that was being evaluated to replace the previous one, in order to reduce cycle stock, is labeled as "New Batch Size" in the figure. By reducing the batch size of the final chemical, Q_3, and thus, the batch sizes of the intermediates, Q_1 and Q_2, which were treated as a function of Q_3, the annual variable manufacturing cost is increasing, and SynChem would be moving up the cost curve.

Figure 20 - Annual Variable Manufacturing Cost for Chemical 47 (Three Step Chemical)



Note: Actual Annual Variable Mgt Costs have been modified and do not reflect actual values. Relationship between actual values were maintained (relative scale).

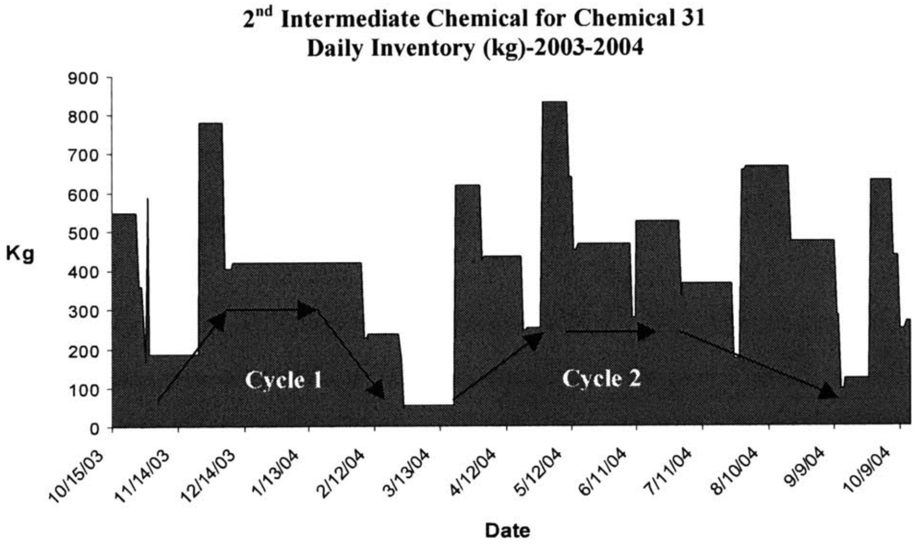
There is a region, between $Q_3 \approx 16$ and $Q_3 \approx 25$ in which the cost curves behaves somewhat differently. If we follow the curve from the right to the left, we can notice how the annual variable manufacturing cost first decreases to a global minimum around $Q_3 = 32$, as the reduction of inventory holding costs is higher than the increase in setup and manufacturing labor costs. Then $\Phi(Q_3)$ starts to increase as the batch size Q_3 decreases, and the setup and labor costs increase at a faster rate than the rate at which the marginal inventory holding costs decrease. When one moves further left along $\Phi(Q_3)$, between $Q_3 = 17$ and $Q_3 = 20$, there is a drop in the value of $\Phi(Q_3)$, before it picks up again and starts increasing very rapidly. This shape in the curve is caused by the increase in labor costs of the second intermediate chemical when Q_3 is between 17 and 20 kg. For $Q_3 = 20$, Q_2 is equal to 36 kg. The maximum amount that can be made in a 750 gallon reactor of the second intermediate is 30 kg. Therefore, to sustain the batching policy of $Q_3 = 20$, two batches of the second intermediate must be made in series (a campaign of two runs), each of 18 kg. To make two batches in a row requires approximately 1.8-1.9 times the total amount of time that is required to make one single batch of a larger quantity. When Q_3 decreases to 17, Q_2 is equal to 30 kg, and this quantity of the second intermediate can be made in one single run in a 750 gallon reactor at the maximum working volume. Therefore, the labor and time it takes to make one batch of 36 kg is considerably lower (see Figure 16, relationship between batch size and processing times) than the labor and time it takes to make two runs, each of 18 kg of the same chemical. The run of 18 kg can be made in a 750 gallon reactor, but it would most probably be manufactured in a 500 gallon reactor.

The last example shows how equipment constraints dictated by working volumes of reactors and the concentration at which the process takes place, in terms of kilograms of final chemical per liter of reacting mixture, are critical factors to take into consideration when selecting the appropriate batching policies for all the intermediate chemicals in a chain. As chains increase in the number of steps, and when inventories of intermediates are allowed, it becomes very difficult to consider equipment constraints and all the interactions involved. This is when modeling becomes very helpful, as was the case in the last example.

3.9.1 The Inventory Simulation Parameter

When the inventory profile for a product, plotted as the actual daily inventory across time, has the shape of saw teeth, the average inventory, assuming no safety stock is present, is half the amount of the batch size ($Q_i/2$). To estimate the average daily inventory in one complete year, or for a longer period of time, one can simply divide the batch size by two and add the safety stock. In SynChem, there are chemicals for which the average daily inventory can not be estimated in this way. In some cases, the average inventory will be 75% of the batch size plus the safety stock, and in other cases, the average inventory might be 33% of the batch size plus the safety stock. This is an effect of batching. Figure 21 provides an example. It shows the daily inventory level in kilograms for the second intermediate of a chain to make chemical 31. The batch size is 553 kg and the amount consumed every time the third and final chemical is manufactured is 190 kg.

Figure 21 – Effects of Batching and Synchronization on Average Inventory



For now, yield variability will be ignored. When the batch size (e.g., 553 kg) is larger than the amounts consumed every time the final chemical is manufactured (e.g., 190 kg), a cycle will be generated in which inventory begins building up and gradually decreases. When two runs of 190 kg each of the final chemical are made, for a total of 380 kg, there is a leftover of the second intermediate that can't be used for another batch of the final chemical. In the example above, the leftover is 553 – 380 kg = 175 kg. In order to make another batch of the final chemical, another batch of the second intermediate of 553 kg has to be made. Inventory begins piling up, but eventually, the leftovers are enough to produce one batch of final chemical without making the second intermediate, and the inventory gradually decreases. This cycle will repeat itself, and the frequency of the cycle depends upon the batch sizes of the intermediate chemical and the final chemical, and the stoichiometric relationships dictated by the recipes. For this particular case, the average inventory is Q/1.3, which means that the average inventory will be 75% of the batch size. If, for example, we reduce the batch size of the second intermediate, from 553 kg to 400 kg, leaving everything else equal, the cycle length of gradual inventory buildup and decline will be smaller, and will contribute less to the average daily inventory. In such a case, the average inventory will be 65% of the total batch size, and the inventory simulation parameter, τ, will be 1.5.

An inventory simulation parameter, τ, of 2.5, would be used in a case in which two assumptions prevail: the amount of material consumed of the intermediate *i* to make the final chemical is very close to the batch size of the intermediate *i,* and the intermediate is made on a very close date to the manufacturing date of the final that requires a portion of the intermediate. When we calculate the average inventory for such a case, we will find that it is, at most, 20 to 30 % of the batch size (Avg Inv = Q_i / 2.5).

The inventory simulation parameter, τ, can be modified in a model in MS's Excel with "IF" statements, as a function of the difference between the batch sizes, which are, in turn, decision variables. It can also be set by the decision maker as a close estimate of the average inventory that he expects to see in the future if he selects batch sizes that are within a reasonable range for the chemicals of interests.

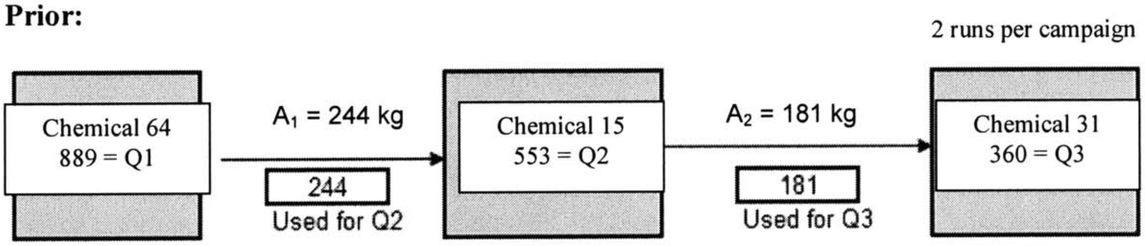
3.10 Case III: Chemical 31

Chemical 31 is a high-volume chemical for which demand has been decreasing rapidly in the last four years. Approximately 5,500 kg were forecast to be made in 2005. This final chemical is also a chain with two intermediates. The most important difference between this chemical and the one we evaluated previously is the demanded quantity. Because the demand for this item is relatively high (among the top 20 items for the department), the average inventory levels of the intermediates is not set to zero. Instead, we allow for the leftovers of the intermediates to be stored in inventory up to two years. The quantities stored are higher and are consumed with higher frequency in a year. In this case, Q_1, Q_2, and Q_3, are all independent decision variables. However, the reason why each of the intermediates can not be treated as a separate single batch product is due to the fact that variable manufacturing cost of the first intermediate will affect the material cost portion of the variable manufacturing costs of the second item. In turn, the resulting manufacturing cost of the second intermediate will affect the variable manufacturing cost of the third and final chemical.

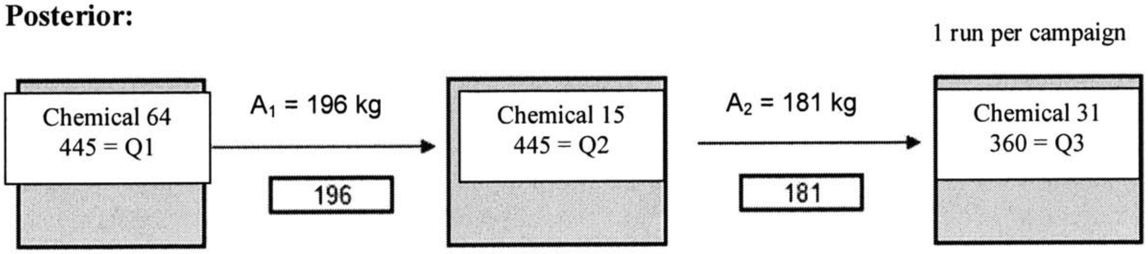
The batching policy that SynChem was utilizing for chemical 31, at the time of the Internship, is shown in the following figure under the label "Prior". The batching policy, under the label "Posterior" is the policy that was being considered for implementation to dramatically cut the inventories of the materials used in the chain for chemical 31. As in our previous example, the quantities Q_1, Q_2, and Q_3 are the batch sizes of the first, second, and final chemical in the chemical chain, respectively. The amounts A_i, are the amounts of chemical *i,* from the batch size Q_i that is used in the recipe to manufacture the next chemical, *i+1,* of batch size Q_{i+1}.

Figure 22 – Synthesis Pathway for Chemical 31

Prior:



Posterior:



The other important difference is the number of batches per campaign that are made whenever production for this item is scheduled. Each series of batches is called a campaign. Because the quantity required per batch of the final chemical is much larger than the maximum amount that can be manufactured in a 750 gallon reactor, there is a need to make several batches (or runs), one after the other, every time production is scheduled. Therefore, in addition to the batch sizes, the numbers of runs per campaign are also decision variables in the objective function. As we move down the chemical chain (from the first intermediate chemical to the final chemical), the value of the inventory increases considerably due to the material and labor invested in producing it. Therefore, it is expected that the model would suggest making large batches for the first one or two steps and holding the material in inventory for a longer period of time, and would suggest making smaller batches and carrying less inventory for the final product. The objective function described for the last case has to be modified to render the following cost function:

Equation 5 - Objective Function for Manufacturing Cost of Chemical 31

$$\Phi\left(\bar{Q},\bar{n}\right)=\alpha_3\left[\beta_3+\frac{181}{360}\left[\beta_2+\frac{244}{553}\Psi_1(Q_1)+\Psi_2(Q_2)\right]+\Psi_{31}(Q_1)+\kappa\right]+\sum_{i=1}^{3}\varphi_i\frac{\alpha_i}{Q_i\times n_i}+$$

$$+\left(\varpi_1+\frac{Q_1\times n_1}{\tau_1}\right)[\beta_1+\Psi_1(Q_1)]\delta+\left(\varpi_2+\frac{Q_2\times n_2}{\tau_2}\right)\left[\beta_2+\frac{244}{553}\Psi_1(Q_1)+\Psi_2(Q_2)\right]\delta+$$

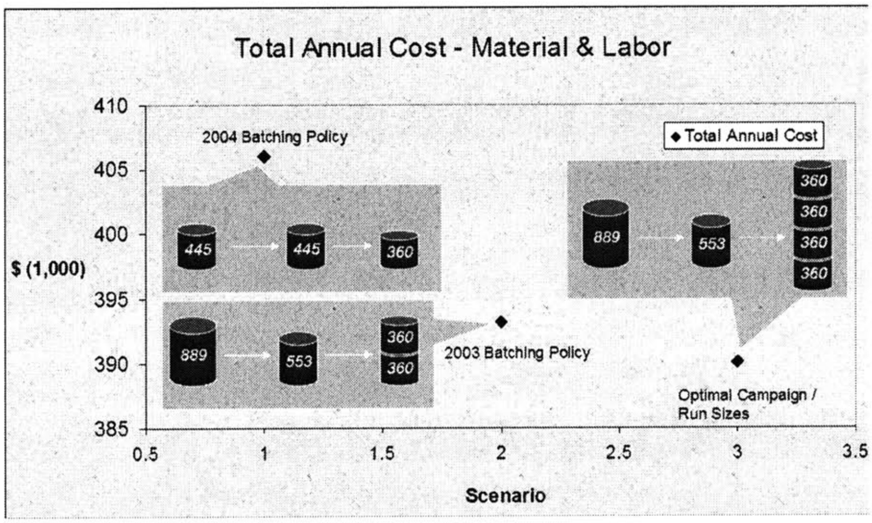
$$+\left(\varpi_3+\frac{Q_3\times n_3}{\tau_3}\right)\left[\beta_3+\frac{181}{360}\left[\beta_2+\frac{244}{553}\Psi_1(Q_1)+\Psi_2(Q_2)\right]+\Psi_3(Q_3)+\kappa\right]\delta$$

Figure 23 shows the results obtained for chemical 31. There are six decision variables in this case, and therefore, instead of drawing a continuous curve, one can show the scenarios of interest as data points.

For each scenario, a vector of six decision variables, the batching policy of the intermediates and the final chemicals is represented in a dialog box. Each cylinder in the dialog boxes represents a run, and the batch size of each run is displayed within the cylinder. For example, for the scenario labeled "2004 Batching Policy", the first cylinder at the far left in the dialog box represents the batching policy for the first intermediate in the chemical chain. Q_1 (batch size for first intermediate) in this case is 445 kg, and whenever the production of this intermediate is scheduled the campaign consists of only one single run. The second cylinder to the right, in the same dialog box, represents the batch size of the second intermediate, Q_2. In this case, the batch size of the second intermediate is also of 445 kg and only one run is scheduled per campaign. The third cylinder to the right, still in the same dialog box, represents the batch size for the third and final chemical, Q_3. In this particular case, the batch size is 360 kg and only one run is scheduled per campaign. As another example, the dialog box labeled as "Optimal Campaign / Run Sizes" depicts a different scenario. The number of cylinders to the far left in the dialog box represents n_1, the number of runs per campaign (1 in this case) for the first intermediate, and 889 represents Q_1, the batch size for the first intermediate. Toward the right, the optimal batch size for the second intermediate, Q_2, is 553 kg, and the optimal number of runs per campaign, n_2, is one. This is represented by a single cylinder. To the far right in the dialog box, the optimal number of runs per campaign, n_3, for the third and final chemical in the chain, is 4, represented by four cylinders with the same optimal batch size, Q_3. In this case, Q_3 is 360 kg. In this scenario, every time a campaign of the final chemical is scheduled for production, 360 kg/run x 4 run/campaign, 1,440 kg of chemical 66831 would be made. Labeled as "2003 Batching Policy", is the batching policy that SynChem was utilizing in 2003 and 2004. Labeled as "2004 Batching Policy", is the policy that was being evaluated in the second half of 2004 to be implemented in order to reduce inventory levels.

The difference between the optimal level and the 2003 batching policy is not significant. Nevertheless, if SynChem would decide to manufacture five or more runs per campaign for this chemical, the inventory holding costs would increase significantly. If SynChem can lower its cost of setups, the 2003 Batching Policy would be the new optimal scenario.

Figure 23 - Annual Variable Manufacturing Cost for Chemical 31

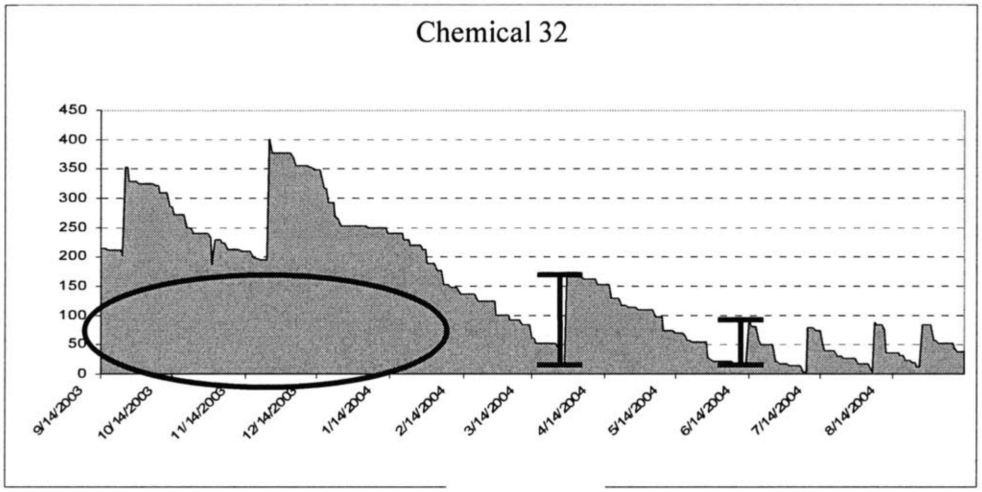


Note: Actual Annual Variable Mgt Costs have been modified and do not reflect actual values. Relationship between actual values were maintained (relative scale).

3.11 Case IV: Chemical 32

The chemical 32 is a good example of a product to which the batch size reduction policy was applied to dramatically reduce average inventory. The annual volume is relatively small, approximately 1 metric ton. Three intermediate chemicals have to be synthesized before making the final product. One product characteristic is that demand is fairly predictable (low coefficient of variation). The historic inventory profile throughout a year is shown in Figure 24.

Figure 24 - Daily Inventory (kg) of Chemical 32



It is obvious that in the first six months of this period there was a significant excess of inventory (marked with an oval). The staff managing the inventory for one of the facilities was able to eliminate this safety stock, generating savings from the inventory holding costs that were avoided, specifically the opportunity cost of the capital (labor and materials) required to support this level of inventory. In an effort to cut the average inventory for this item even further, the batch size (indicated by the vertical line on the inventory profile chart) of the final chemical and two of the intermediates were reduced by 20% to 50%.

It has been discussed in the previous cases that the high cost of changeovers and the relationship between the processing times and processing quantities for most of the chemicals made in SynChem favor the production of chemicals in large batches. Optimizing the objective function described for the second case study in this chapter would determine the optimal batch size for this chemical.

For this particular chemical, there is another piece of information that becomes critical when making decisions on the tradeoffs of using capacity to reduce inventories. In most calculations performed to evaluate the tradeoffs, the opportunity cost of holding inventory is calculated by assuming that the actual capital tied up in the form of products in the warehouse for a series of intermediates and final chemicals isn't tied up elsewhere in the supply chain. If this capital would have to be invested elsewhere in the supply chain of the chemical being considered, then the opportunity cost becomes zero, because there isn't really any other option for using the capital.

Another justification that managers commonly use is that, by reducing the inventory levels of products made in the plant, the inventories of raw materials will also decrease significantly. Unfortunately for SynChem, it is more difficult to reap these benefits from batch size reductions of products made "in house".

The following table shows the list of the most expensive raw materials used to synthesize chemical 32 and the lead times offered by the suppliers. The three materials highlighted in the table represent approximately 42% of the material cost ($/kg). The lead times for materials B, C, and D are very long, around sixty days.

Table 2 - Lead Time and Prices of the Most Expensive Raw Materials for Chemical 32

Raw Material	Price ($/unit)	Vendor LT (days)
A	$ 3.09	14
B	$29.52	60
C	$ 5.66	60
D	$13.69	60
E	$52.00	7

When the pattern of consumption is changed due to a batch size reduction, the same amount of quantity is consumed over a relatively long period of time, such as two months, although the withdrawal quantity and the frequencies of the withdrawals from the inventory in the warehouse have changed. The total amount of inventory of the raw materials B, C, D, and the amounts of such materials that have been used and are now in the form of the intermediate or final chemical (although, physically, these materials have been transformed) has not necessarily changed. If the ordering policies for these raw materials are not changed, all that would happen is that the inventory that has been reduced for the intermediate or the final chemical is now pushed upstream to the raw materials inventory. As a result, the average inventories of the raw materials with long lead times tend to increase in the short term. In a period of one year or more, the inventory levels of the raw materials remain unchanged because consumption rates remain constant or are dependent on demand. Figure 25 and 26 show graphically that as long as the batching policy, Q_{RM}, of the raw material is not changed, the reduction of the batch size of the final chemical has no significant effect on the inventory levels of the raw material. If these raw materials were procured from a local supplier, there would be a significant reduction in the raw material inventories. But for the chemicals in Table 3, which are sourced from southeast Asia and have 60 to 90 days lead times, the reduction of the inventory of raw materials depends more on the economics of the logistics and the shipping costs vs. the inventory holding cost of the raw material. Now, changing the ordering policy requires a review of the contract with the supplier and a close examination of the transportation and ordering costs.

Figure 25 – Hypothetical Case for Effect of Batch Size Reduction on Raw Material Inventory

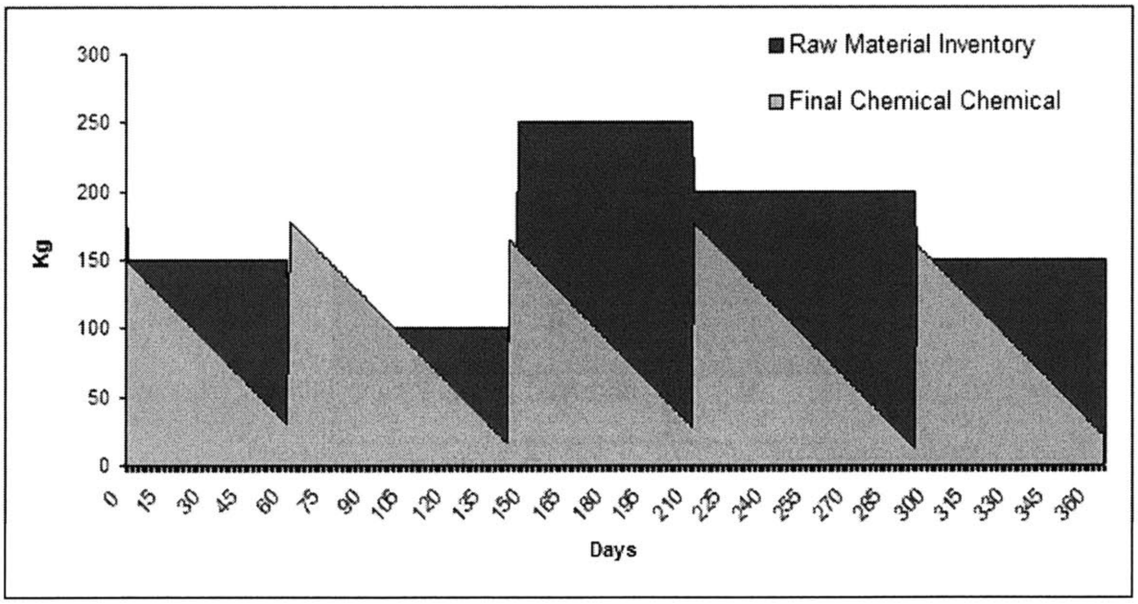
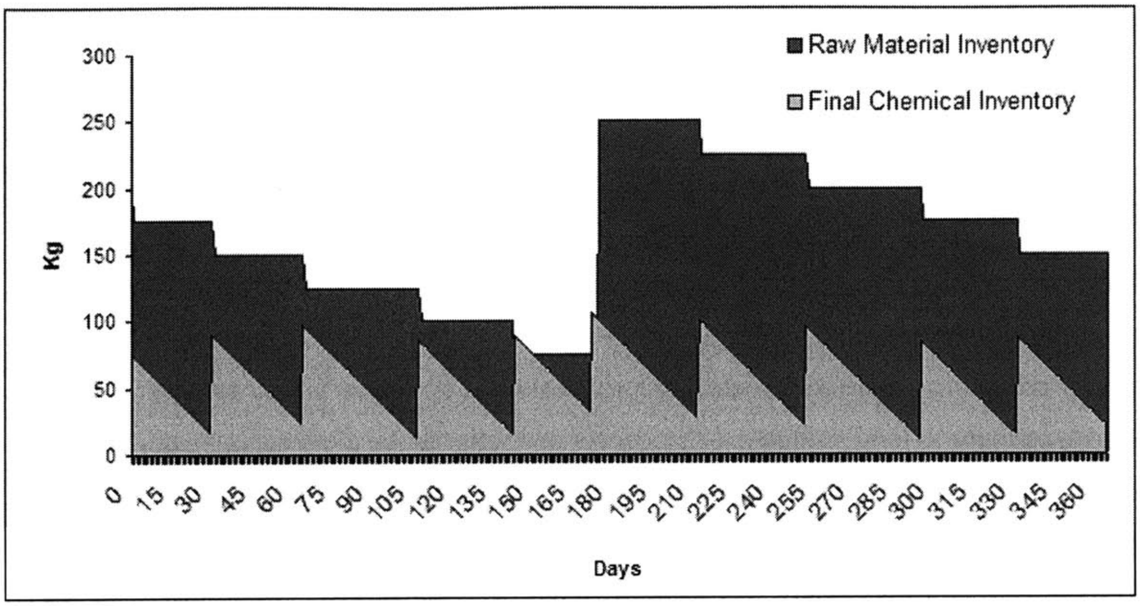


Figure 26 - Hypothetical Case for Effect of Batch Size Reduction on Raw Material Inventory



If less labor is now employed at every batch (proportionate to the amount of quantity made), even if it must be used more frequently, the employer is tying less capital (for the labor expenses) on average to support operations. The employer is tying up almost the same amount of working capital to make one batch of 205 kg of chemical 32 than to make one batch of 80 kg. What happens in the cost accounting system is that, after the change, the chemical becomes more expensive. The quantity of material kept in inventory, on average, has decreased, but the value (or cost) of the material has increased, and the net effect will be that the inventory levels will not appear to have decreased in the financial statements in dollar terms.

One of the timing issues with financial reporting, which operating managers must be aware of, is that there usually is a lapse of time during which unit cost standards are set. Many manufacturing companies monitor their operations by measuring variances against a frozen cost standard. In such cases, in a batch processing chemical plant, inventories indeed appear to decrease when reducing lot sizes, but then, once the revaluation is done at the end of the period on which the costing standards are valid, these same managers will be surprised when they learn that the cost per unit has increased in such a way that the inventory reduction benefits have been wiped out completely, and in some cases, actually increased in dollar terms. This happens as productivity decreases (kg/$-labor), operating costs increases, and the overall production bill of the manufacturing plant increases and is reallocated to the same number of stock-keeping units and production volumes.

3.12 A Note on the Reasons to Reduce WIP

Eliminating work in process (WIP) from an operation does not lead necessarily to financial gains. High inventories are a symptom; they appear in a manufacturing process for a reason. The causes for suboptimal levels of inventory are, as mentioned by Hayes: erratic process yields, unreliable equipment, long production changeover and setup times, ever-changing production schedules, and suppliers who do not deliver on time.[11] Manufacturers should address these deeper problems in order to avoid overproduction. In a batch chemical processing operation, addressing these problems, which require detailed tactical involvement of production staff, will generate financial benefits in the form of lower inventories. Instead, if WIP is to be diminished by reducing cycle stock, operations staff must first evaluate the tradeoffs involved that were discussed in this chapter.

3.13 Summary

This section reviewed important factors to consider and to quantify in order to make batch sizing decisions in SynChem. There are two main drivers for large batches in SynChem's manufacturing operations. One is high setup costs, which can range from $300 up to over a $1,000 per setup (including change-over), and the second is the relationship between processing times and the amount being processed. When there is lack of data, a logarithmic fit can be used to estimate processing time as a function of the batch size. Therefore, only by focusing on reducing setup costs and increasing labor and equipment productivity, can SynChem be able to continuously reduce batch sizes. It was discussed that fixed costs, both related to the facility (e.g., manufacturing overhead) and to the warehouse and inventory management (e.g., real state, leases, material handlers, etc.) should not be used to find the optimal batching policy, and that only variable costs relevant to the decision should be used. Models were developed for one-step and three-step chemical chains with different approaches, depending upon whether they were of high production volume or of low production volume. In all three cases, variable manufacturing costs increased (from $1,500/yr for a low-volume chemical up to $15,000/yr for a high-volume chemical) when batch sizes were reduced in order to cut cycle stock. When aggregating the effect of the increase in variable manufacturing costs of batch size reductions of a group of over 20 chemicals, the increase in costs can be estimated to be over $100,000. Accumulated labor overtime for year 2004 was well above this figure. Batch size reduction is not a sustainable strategy for SynChem, and batch sizing decisions should utilize traditional batch optimization analysis.

Finally, supply chain managers must also consider that by reducing cycle stock alone in their chemical plants, they will not necessarily be able to cut inventories upstream in the pipeline. For materials with very long lead times that are shipped from distant continents, economic order quantities are very important in keeping low costs, and thus, the assumption should not be made that because cycle stocks are reduced, reduction of expensive raw material inventories will immediately follow.

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CHAPTER 4 - BATCH SIZING STRATEGY FOR SYNCHEM

In Chapter 3, an approach to determine optimal batching policies for products made in the Synthetic Chemicals department was presented. SynChem has been able to reduce the number of runs per campaign that they need to manufacture many of their products, and thus, have been able to reduce lead times and inventory levels significantly in the last ten years. As there is increasing pressure to minimize inventory levels, SynChem needs to incorporate the analysis from Chapter 3 in their decisions. At the same time, a broader and higher level approach that addresses the need to set more discipline and order regarding batching policies and decisions is necessary, especially in an operation that is under constant pressure to reduce overall inventory levels. Such an approach is covered in this chapter.

4.1 Batching Decisions at SynChem

In the last ten years, when a product was introduced, the number of runs per campaign and the frequency of campaigns per year were determined by the total volume forecast and the batch size. In order to determine the batch size, the decision makers mentioned in an earlier section (*1.4.2.4 Batching Policies)*, made sure that the following requirements were met successfully: 1) minimize the standard unit manufacturing cost, 2) maximize equipment and capacity availability, and 3) allow the manufacture of a high quality product and the implementation of a safe consistent process.

The standard unit manufacturing cost would, in itself, depend on the quantities of material transformed. The operating and setup costs could be amortized on the quantity made per batch. Therefore, as long as there was capacity available in larger-scale reactors, lot sizes would be picked that maximize the use of such reactor, regardless of the implications on inventory turnover and material leftover.

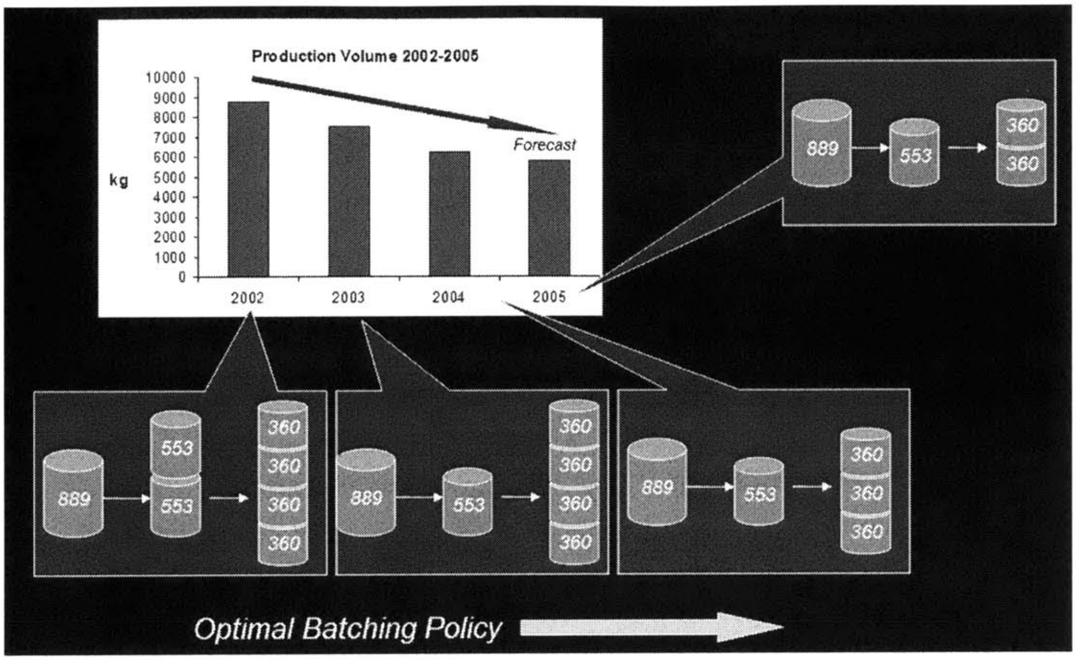
4.2 Adjusting Batch Policies to Changes in Demand

As demand and volumes for SynChem's chemicals either increased or decreased in the last ten years, batching policies have changed ad-hoc, following the judgment of the production planning communities. In many cases, if not in most cases, the batch size has remained constant and the frequency at which the batches are made during a year change according to the total production volumes. For a year in which total demand is 1,000 kg, a chemical that has a batch size of 100 kg will be made ten times. In the following year, when demand drops to 750 kilograms, the chemical will still have a batch size of 100 kg and will be made eight times a year. Although the average inventory during the year will remain relatively constant, the number of setups will change. What might have been an optimal batching policy five years ago might not be an optimal one now, when the production volume has decreased 20 – 40%, as in the case of some chemicals that are used downstream in film and paper production, or increased by 50%, in the case of some of the more recently developed thermal media dyes. The following figure shows how for a given chemical, the optimal batching policy changed from year to year as demand for the chemical dropped. Data was only available from 2002 to 2005. In 2002, the batching policy was as followed: 889 kg of the first intermediate, two runs per campaign for the second intermediate, 553 kg per run, and four runs per production campaign for the final chemical, 360 kg per run. If the same batching policy were used to make the volume forecasted for 2005, SynChem would incur higher total manufacturing costs, which is due to the excessive inventory holding costs. Instead, keeping the same batch size of the first intermediate unchanged, which is the intermediate with the least value added, and thus the least cost, but dramatically reducing the runs per campaign for both the second intermediate and the final chemical, allows SynChem to manufacture the 2005 production volume of the complete chain at an optimal point in which the total variable manufacturing costs for the chain are minimized.

Note that the standard manufacturing cost will indeed increase. Although, according to Eastman Kodak Company's cost accounting practices, the product is more expensive to manufacture, in reality, the total overall system cost for making this chemical is at its optimum.

This same situation applies to several other chemicals made in SynChem. As Kodak manages the transition from traditional photography to digital imaging, operation managers must change their focus and priorities that they once had, as their business was growing. Now that operations at SynChem are mature and volumes for chemicals used in traditional photography are stagnant or dropping, SynChem management must be very disciplined and aggressive in pursuing smaller incremental cost reduction opportunities. Batching policies must be revised more often (e.g.,

Figure 27 - Optimal Batching Policies for a Chemical with Diminishing Demand



every year in current times vs. every five years or more, as it was done in the past). This is justifiable in such a mature industry and operation in which cost advantage will come mainly from continuous incremental improvements in business policies and processes, such as monitoring batching policies, rather than from major breakthroughs.

Monitoring the batching policies year after year for those chemicals for which volumes are increasing or decreasing at relatively high rates every year is a task that SynChem management must undertake.

4. 3 Monitoring Batch Sizes – Lot Size Control Chart

SynChem personnel should also have a way to monitor batch sizes of the chemicals in their portfolio. There are three reasons for this:

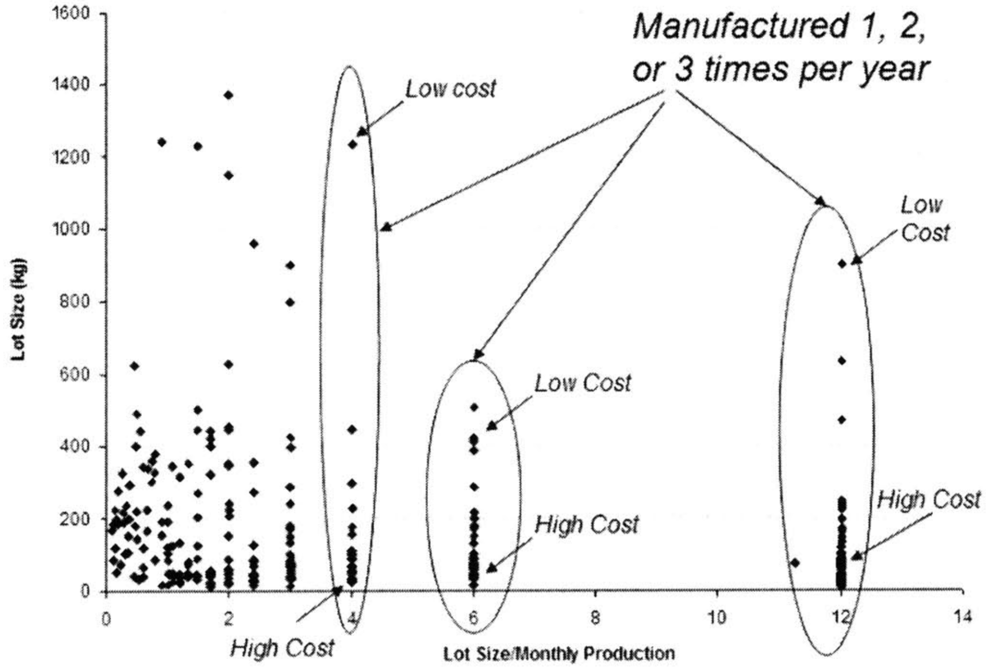
1. Identify for which chemicals they should reduce batch sizes, given that they have excess capacity and idle resources, in order to lower inventory levels.
2. Measure the effect and gains from driving setup cost reduction and productivity improvements on batch sizes and therefore inventory levels.

3. Identify when demand for a chemical is changing and batching policy should be revised.

When there is capacity available and labor productivity improvements, SynChem could be able to actually scale down the lot sizes of certain chemicals to reduce inventory. The justification for doing this has been already discussed in the "Batch Sizing and Excess Capacity" section. One framework that SynChem can use to prioritize the chemicals that are to be scaled down in order to reduce inventory and use excess capacity is one taken from the Toyota Production System.[7]

Figure 28 is a lot size control chart. This chart can include all chemicals manufactured in SynChem or those made by one single facility. This lot size control chart allows SynChem to closely monitor batch sizes for its chemicals. Production staff can add a color code to the dots plotted in the chart, which can differentiate costs, strategic importance, years since it was first introduced, etc. to help them spot trends in changes of inventory coverage or even the batch size proposed by process chemists.

Figure 28 - Lot Size Control Chart for Synthetic Chemicals



Each dot in the x-y plot represents either an intermediate or final chemical. There are approximately 300 chemicals plotted. This chart makes it simple for management to identify the chemicals that they are holding in inventory for longer periods of time by calculating the monthly coverage of the inventory (lot size/monthly production). Three groups stand out as those that are made once a year (its coverage is 12 months), those that are made twice a year, and those that are made three times a year. In the lower left-hand side of the x-y chart, are the chemicals that are made every one or two months. It can be seen that the batch sizes for these chemicals tend to be below 600 kg, the majority of which are below the 300 kg mark. These chemicals should not be considered for batch size reduction, mainly because as has been shown in the case analysis section of this thesis, the total manufacturing cost will inevitably increase. For all the chemicals in this quadrant, the increase in labor and setup (cleaning and testing) costs more than offset the reductions in inventory holding costs. Also, for all chemicals in this quadrant, capacity is dramatically reduced when lot sizes are decreased, because these chemicals tie up considerable amount of resources' availability.

Within each group of chemicals with the same coverage (dots in the x-y plot surrounded by circles), the chemicals that have large sizes (dots at the very top within each circle) are usually the ones that have the lowest cost. Even though, some of these chemicals could be good candidates for a scale-down, the impact on the inventory measured in dollar terms is so small, that it is not worth the energy and time of employees to analyze and implement the changes required for the scale-down. Although there might be considerable space savings from one single item (four to ten rack spaces on average), the savings are negligible, and the impact on the inventory level in dollar terms will not affect the department's financials.

As we move down the x-y plot within one group of chemicals with the same coverage, their value increases. The dots at the very bottom, especially for the groups with coverage of 6 and 12 months, have very high costs per kilogram. The high cost per kilogram for this group of chemicals is driven by three factors: 1) long processing times (up to several days) due to low rates of reaction, several lengthy distillation or liquid-liquid separation stages, etc., 2) labor-intensive steps, 3) small yields (amount of material produced) on which to amortize the manufacturing overhead allocated to the work center (e.g., 100 gallon reactor) per unit of time of activity. The chemicals in this group are also made in the smallest set of equipment available to the manufacturing facility. Therefore, it would be impossible to scale their respective batch sizes even further.

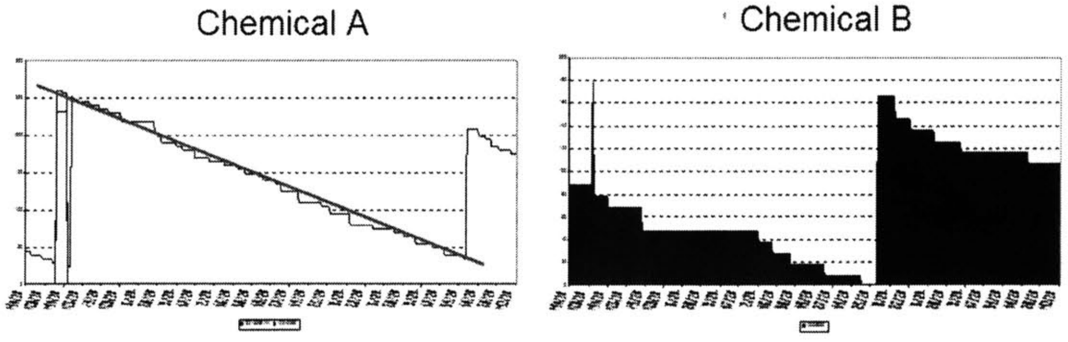
4.4 Criteria to Select Chemicals for Batch Size Reduction

How should SynChem choose the chemicals they will target for batch size reduction to use the spare capacity from "slow" months or quarters and level the load of the plant throughout the year? The criteria for selection are as follows:

1. Batch making frequency
2. Value of inventory (price, cost, etc.)
3. Scale-down feasibility (size of equipment utilized)
4. Pattern of demand (fairly deterministic, variable, single large orders, etc.)

Points one, two, and three are pretty straightforward to understand from the batch size control chart. Point four is less intuitive. If SynChem has found two chemicals that are made infrequently (e.g., once every year), have a high value (e.g., \$800/kg vs. \$3/kg) and that are made in large-sized reactors, but available capacity in the plant will not allow both chemicals to be scaled down, SynChem should scale-down the one that has more variable, unsteady, or cyclic demand. The following figure shows the one-year historic inventory profile (actual inventory in kg vs. actual days) for two chemicals that are made only once a year and are of very high value in dollar terms. Both of these chemicals could potentially be scaled down. If the smaller sized equipment had only enough spare capacity to accommodate production for one of these two chemicals, chemical B should be chosen for such a decision. Chemical B has seasonal demand with higher variability from "pull" to "pull". We define a "pull" as the event describing the retrieval of product in a certain quantity from the producer's warehouse or supermarket. The expected cost of obsolescence for chemical B when demand volumes are decreasing is considerably higher than for chemical A, which has a predictable steady demand.

Figure 29 - Lot Size Control Chart for Synthetic Chemicals



4.5 Synchronizing Batch Sizes in Chemical Chains

In Chapter 1, section 1.5.3.2, a type of overproduction was identified in Synthetic Chemicals operations. This overproduction is related to lack of synchronicity in some chemical chains. One refers to a synchronized chain when the total amount of material made in each campaign of an intermediate *i* in a chain is a multiple of the amount needed for the subsequent intermediate *i +1*. In low-volume chemical chains that are not synchronized, there are leftovers of intermediates that are not used for a long period of time. These leftovers, when aggregated, can add up to a significant amount of inventory in dollar terms. After conducting an analysis on 60% of the chemical chains from one of SynChem's facilities, a total of $700,000 worth of inventory from leftovers that will not be used in a two to five year period, unless actions to do so are taken, was identified. The amount of inventory sitting idle without undergoing any turns could possibly be slightly higher. For high-volume chemicals, synchronicity is less relevant, as explained in the following subsection.

4.5.1 Synchronicity in High-Volume Chemicals

In the case of high-volume chemicals, synchronizing a chain may yield suboptimal batch sizes. If the optimal batch size is, for example, 90 kg, and the amount of the intermediate used in the next step is 75 kg, the leftover, 15 kg, will be stored in the warehouse. After five batches of the intermediate have been manufactured, say, in seven and a half months (at a rate of one batch every six weeks), there is sufficient material in stock from all the leftovers (15 kg x 5 batches) to forego one batch of the intermediate. This saves one setup and variable manufacturing costs, such as labor. These savings are taken into account by the batch optimization model used for the case analyses presented in Chapter 3. Furthermore, by avoiding one batch over a period of one year, SynChem increases its capacity. Because the required annual volumes are relatively high for this chemical, there is a very high probability that the accumulated leftovers will be utilized and will not spoil, get lost, or become obsolete. The inventory profile for such chemicals looks somewhat similar to the profile of the chemical shown in Figure 21 (page 58). There is a cycle consisting of a gradual build-up of material, followed by consumption of the material. This cycle repeats itself consistently in the cases in which demand for the final chemical is not seasonal, but rather stable across time. When there is seasonality in the demand, the cycles have different frequencies.

4.5.2 Synchronicity in Low-Volume Chemicals

Figures 11 and 12 from Chapter 1 show the effect of manufacturing an intermediate with a batch size larger than the amount to be consumed of the intermediate in the subsequent manufacturing step. There were several examples found in SynChem's operations of inventory buildup that will be idle and not consumed for the next three to four years (in some cases, up to six to nine years). The reasons to avoid this material buildup or to eliminate this unnecessary inventory have already been discussed in Chapter 1. There are measures that management can pursue to avoid this overproduction that are described in the two following sections.

4.5.2.1 Recipe Modifications

One way to use up all of the material generated in a step *i,* is to modify the batch size of the chemical manufactured in step $i + 1$. The proportions and stoichiometric relationships in the manufacturing of a chemical are to be left unchanged. Therefore, all of the material requirements and the final batch size of the intermediate $i + 1$, will be calculated as a function of the amount if the intermediate *i* that is to be consumed.

This procedure can be followed as long as the excess of the intermediate *i* made is not significantly large, measured as a percentage of the intermediate *i*'s batch size. If the step $i + 1$ is already being carried out in a reactor at full capacity, and the excess of intermediate *i* requires the batch size of $i + 1$ to increase by about 20%, there will not be any feasible way to synthesize the chemical utilizing the current validated recipe (stoichiometric proportions) in the same work center. If the work center has a 750 gallon reactor for this example, then the batch size $i + 1$ simply can not be scaled up more than 5 – 10%.

Some caveats of the strategy of modifying recipes to use excess material are the following:

1. There would be lack of consistency in the quantities used from batch to batch, and it might lead to operator mistakes in the manufacturing process.

2. As the volume and mass of the material in the reactors and distillers changes slightly from batch to batch, certain parameters will also vary, such as cooling or heating rates, mixing times, reaction holding times, etc. These variations generate noise when performing statistics for process control and may cause noise that affects the operators' ability to interpret the various process parameters.
3. Synthetic Chemicals is moving toward kitting of raw materials that are to be used on the production floor. For those intermediate chemicals that are used immediately in a subsequent step, there might not be sufficient time between packaging of the intermediate chemical and its use in the subsequent step to allow for kitting and transportation of the other required raw materials. These raw materials have to be transported from the chemical warehouse to the production facility and then onto the production floor.

4.5.2.2 Reducing Batch Sizes to Synchronize Chemical Chains

Another approach to avoid leftover material is to reduce the batch size for those chemicals that have had relatively consistent yields in the past, in order to synthesize only the material that is to be used in the subsequent step. Leftovers are to be expected, due to the inevitable variability in the yields, but the leftover material would be considerably lower in volume. The inventory pattern for a chemical intermediate in a synchronized chain would look similar to Figure 30.

Figure 30 – Daily Inventory for a Low-Volume Chemical – Synchronized Chain

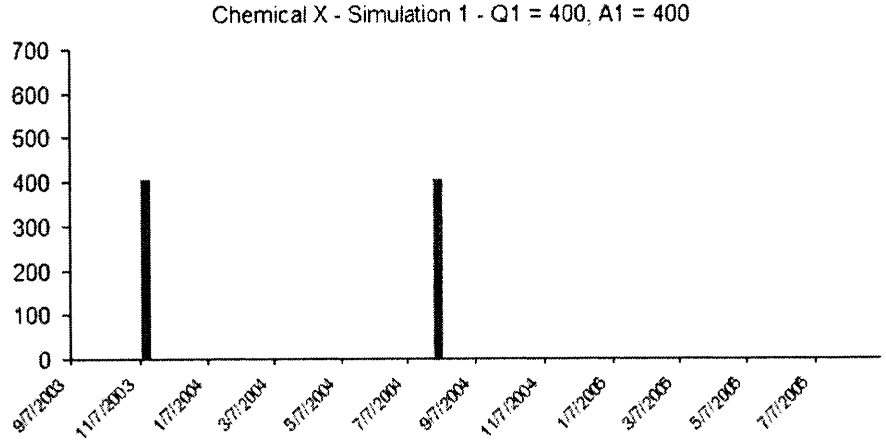


Figure 31 - Daily Inventory for a Low-Volume Chemical – Overproduction

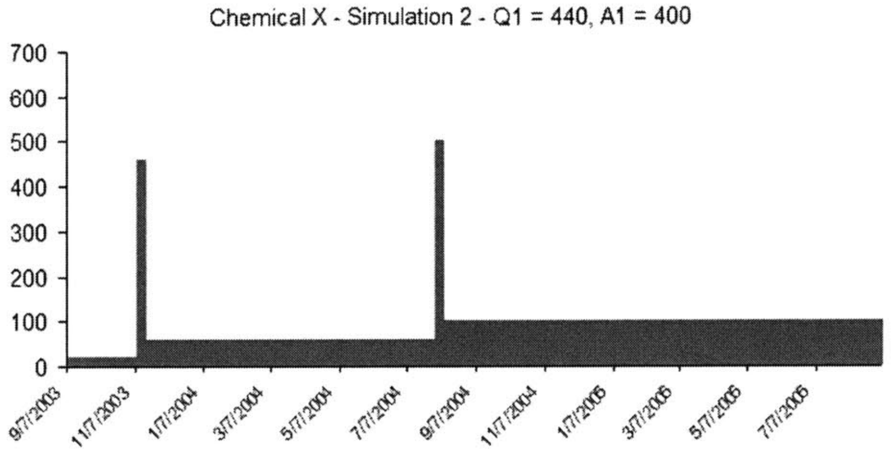


Figure 31 is the daily inventory for the same chemical intermediate with a higher batch size than the amount that is to be used in the subsequent step.

Management can also take into account the possibility of spoilage, loss, and obsolescence in the models used to estimate the optimal batching policy in the previous section. They can assign a probability to the events of spoilage, loss, and obsolescence, and multiply this probability to the unit cost of the material. This cost would be summed to the total inventory holding cost in the optimization model.

4.6 Summary

This chapter puts a lot of emphasis on the fact that the demand for the products made by Synthetic Chemicals is changing very quickly. The demand for some of the chemicals that are used in the value chain for traditional film and paper is dropping rapidly, at rates that range from 5% per year up to 25% per year. On the other hand, demand for other chemicals that support thermal printing is increasing by as much as 50% per year. Synthetic Chemicals should review the batching policies of the chemicals that are undergoing the biggest changes in demand at least once every year. Savings in variable manufacturing costs from changing the batching policy as demand drops about 25% per year for one single chemical may range from $500 up to $4,000 per year depending on the absolute volumes. SynChem may use a lot size control chart to monitor the batch sizes of its products. It can help them identify the materials with low inventory turns and excess inventory.

When there is capacity available (and labor resources that are idle), and the plant load is to be leveled, management may choose chemicals whose batch sizes are to be reduced, by following these criteria: 1) batch making frequency, 2) value of inventory, 3) scale-down feasibility, and 4) variability of chemical's demand.

Synthetic Chemicals might also pursue the goal of synchronizing the chemical chains for low- to medium-volume chemicals. For low-volume chemicals, there are two ways in which overproduction of intermediates can be avoided: 1) modifying the recipes of the intermediates that utilize another intermediate manufactured in a previous step, and 2) reducing the batch sizes of intermediates to make sure that only the material that will be consumed is actually produced. Between $500,000 and $700,000 of intermediate chemicals inventory, which are not to be used in less than two to three years, could be reduced for one of the SynChem facilities, if one of these two strategies were implemented.

For high volume chemicals, synchronizing chemical chains may yield suboptimal batching policies. The batch optimization models utilized in Chapter 3 should be used for such high-volume chemicals.

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CHAPTER 5 - PRODUCTION LOAD LEVELING

As mentioned in Chapter 1, the high number of chemicals in SynChem's product portfolio, and the differences in the processing steps and process parameters for all these products, make scheduling production and managing inventory a complex activity. This chapter introduces the concept of Constant Work in Process (CONWIP) and production load leveling. Then, it presents a case analysis of a project related to a high-volume chemical chain that was carried out at SynChem. Production load leveling was a key factor that drove the project. The case analysis is a first attempt at separating the product portfolio into families, dedicating equipment to such families and leveling the load for the high-volume chemicals. Implementing the latter can increase the factory's efficiency, free up capacity, increase labor productivity and eliminate waste in the form of movement and overproduction.

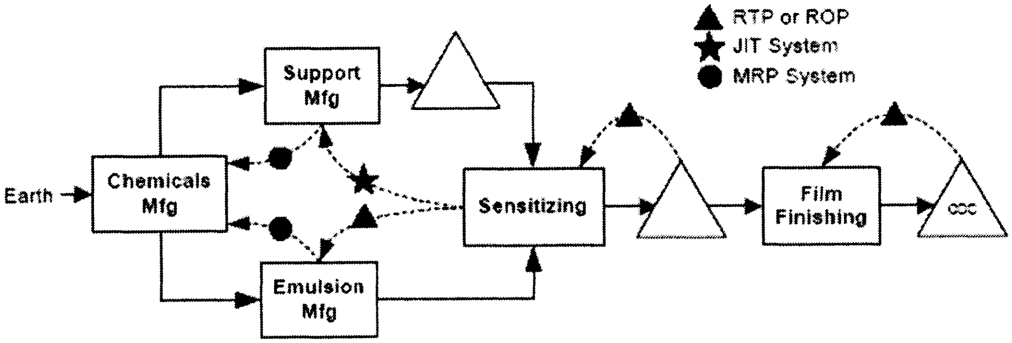
5.1 Systems to Trigger Production

There are mainly four ways in which the production of chemicals can be scheduled or triggered at a manufacturing facility:

1) Pull system
2) Push system (Material Resource Planning - MRP)
3) Constant Work in Process (CONWIP)
4) Make to Order

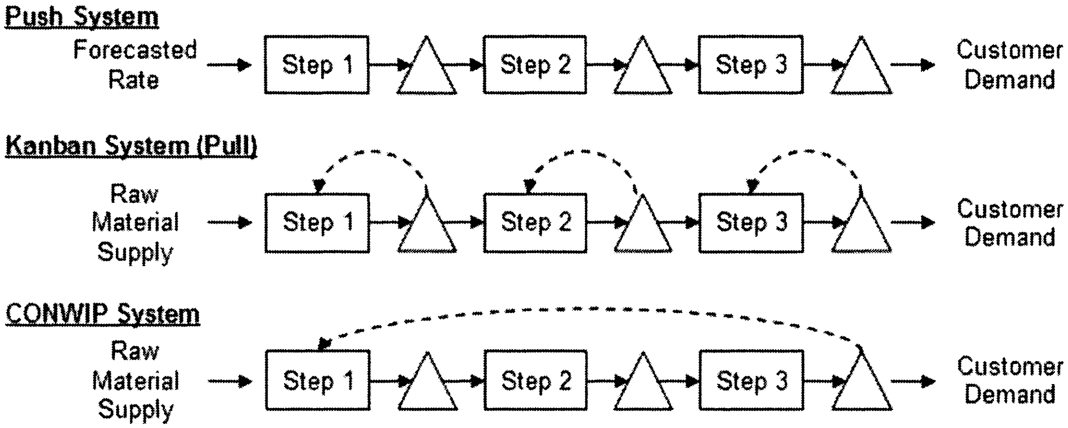
Horn[12] describes one of the supply chains in which SynChem finds itself, the supply chain of film manufacturing utilizing the following figure.

Figure 32 - Supply Chain for Film Manufacturing[12]



Eastman Kodak Company's supply chain group has been trying to reduce its supply chain costs by adopting different types of inventory management policies at each stage of the supply chain. In his thesis, Horn[12] discussed different methods for scheduling processes and signaling production in the supply chain of a film manufacturer. Figure 33, as developed by Horn[12], graphically describes how each of the three systems work. The subsequent sections describe each of these systems.

Figure 33 - Three Production Systems Considered for SynChem[12]



5.1.1. The Push System

A push system initiates production based on demand forecasts. When the product is processed completely in Step 1, it waits in inventory until there is enough material to initiate Step 2 and thus triggers Step 2. In many cases, Step 2 will be triggered by the MRP system, which utilizes also a forecast and the standard routings and standard lead times to estimate when Step 2 should be scheduled. [13] When actual customer demand is known, feedback from the data results in changes in demand. The new adjusted demand rate is built into a new forecast.

5.1.2. The Kanban System (Pull)

An extensive description of the Kanban system can be found in Ohno[6] and Monden.[7] Figure 33 provides a brief description of the concept. Production will be triggered in Step 1, by a signal sent from the posterior step, or from the inventory location between Step 1 and the posterior.

When inventory has reached a certain level of depletion on the material buffer right after Step 1, a signal is sent to the manufacturing step that provides the product to schedule production. Since the work center in Step 1 might be processing another product, the order coming from upstream might have to wait in a queue before production for the material of interest actually begins. Ohno, [6] who is credited for creating the foundations of the Toyota Production System, states that a prerequisite for a Kanban system to work is to have production smoothing and leveled load of production in place.

5.1.2.1 Kanban for Synthetic Chemicals - Challenges

As KOS is implemented in all operating units of the entire organization at Kodak, each manufacturing unit is encouraged to implement a pull system. A true pull system would be very costly for the Synthetic Chemicals department to implement. Such a system can be conceptualized in any of two ways:

1) Inventory between unit operations or work-centers: In this case, the buffer (Kanban) would have to be placed between work centers. The reactor would be processing one batch, and the next equipment, a centrifuge, would be working with a second batch, perhaps of a different product. In a buffer between the two work centers, there would be a batch of material that was processed by the reactor and distiller and is now ready to be centrifuged or filtered. In reality, this is very impractical, because there are several chemicals that need to go into the centrifuge and separation operations immediately after leaving the reaction or distillation steps. Another important issue has its roots in the fact that the processing times, reaction, distillation, etc., are very different from chemical to chemical. Therefore, the types of unit operations, process steps, and processing times of the chemicals that go through a work center vary tremendously (up to 50 - 100% in terms of hours) from chemical to chemical. The length of time and the high cost of changeovers make it also extremely difficult to coordinate the start and finish of the processes with the start and finish of changeovers. A lot of idle time would be generated in each of the work centers. The different routings and recipes would make it also very difficult to operate in a continuous-flow fashion (one product being processed at a work center right after another has left it), because in many instances,

products do not follow the same path through several work centers, and in some instances, processes both converge and diverge at the work centers.

2) Inventory between steps in a chemical chain: If inventory would be placed between each subsequent step of a chemical chain, the total level of inventory across the chain and in the plant (if applied to all the chemical chains) would be extremely high and costly. In such a scenario, production of a second intermediate would only begin after the buffer of the material right before the next step in the process in which the third intermediate is made, is depleted completely or at a pre-specified level. This is a concept easier to visualize with discrete parts making up the buffer. Discrete parts are depleted gradually, and when they reach a certain level, production of the required product is triggered in the previous processing step. But in chemical batch processing, the buffer would have to be a multiple of the required material for the next processing step. Most surely, this multiple would be the exact amount to be used in the next reaction step. In a chemical chain consisting of seven intermediates, there would be inventory of each of the seven chemicals stored in the warehouse. In SynChem, the way chemical chains are scheduled causes the department to carry inventory of all seven intermediates nonetheless, sometimes in suboptimal quantities. But this is the case for only a finite number of chains. These chains are possibly great candidates for a pull system, given that their volume and frequency with which they are manufactured is fairly large. As we will see later, this particular set of chemicals is of a small number.

5.1.3 Constant Work in Process

In the case of a CONWIP system, the demand signal would be generated at the chemicals warehouse, when the final chemical inventory reaches a certain threshold. The information signal would travel to the first step in the process, the processing step for the first intermediate. From then on, the orders for the subsequent intermediates would be pushed. The pushed order for the second and subsequent intermediates can be generated immediately after the processing step of the first intermediate has begun. At this point, SynChem is not scheduling production for the complete chain as a response to a forecast, nor is it making the product for a direct order. Instead, it is maintaining a constant level of work in process for that product, once a signal from the customer has been sent, indicating that more products are required. In SynChem's case, the direct customer is the next process step in the supply chain, for example, the emulsion manufacturer in the film processing supply chain.

Horn[12] described in his thesis the advantages and the disadvantages of a CONWIP system when compared with a pull system and with a push system (MRP). The most important advantages over a push system that he cites are:

a) "The WIP level is directly observable, while the release rate in a push system must be set with respect to the abstract notion of capacity."
b) "It requires less WIP on average to attain the same throughput."

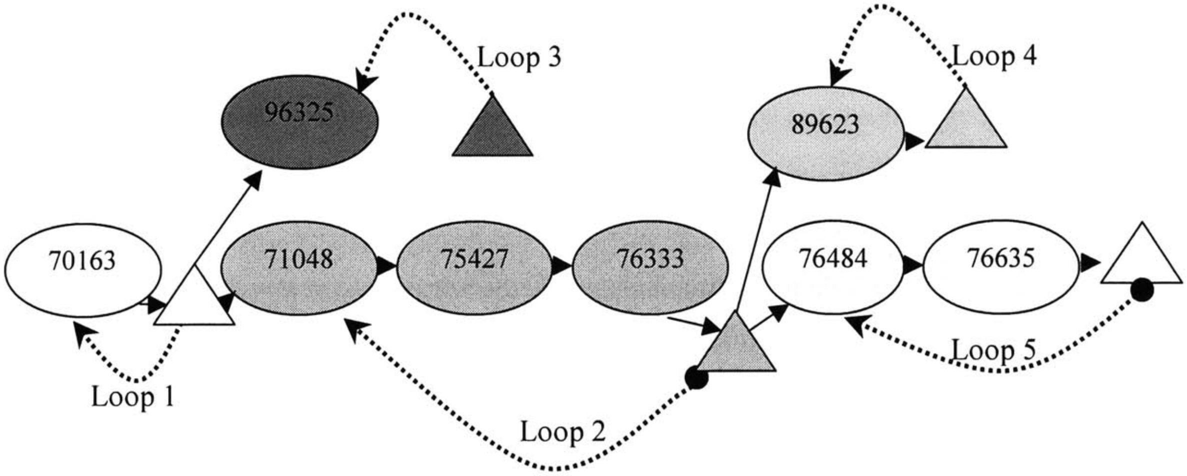
The benefits of CONWIP vs. a pure Kanban system that are the most relevant to SynChem are:

a) "It can easily accommodate a changing part mix."
b) "It can accommodate a floating bottleneck, due to the natural tendency of WIP to accumulate in front of the slowest step."
c) "It introduces less operator stress due to a more flexible pacing protocol."

5.2 CONWIP to Trigger Production of Chemical Chains

There are several chemical chains that look like the one shown below. There are "branches" in the chemical chain that diverge into different products or families of products, or that converge into one same product. Some intermediates appear in the branch or chain of several final chemicals that are not of the same family or otherwise related in any way. To be able to use a CONWIP strategy in the chain shown below, these chemicals that are part of the chain and are raw materials in other chains as well must be held in inventory. The term that lean practitioners, and now, Kodak, likes to use is the term: "supermarket". There has to be a supermarket of all of those chemicals that are used in considerable volumes in three or more different recipes. The example below shows where the supermarkets would be placed and how the CONWIP loop would be placed.

Figure 34 - Chemical Chain for 76635



Synthetic Chemicals is considering implementing CONWIP as an alternative to a strict pull system. This would cap the amount of intermediates in inventory while allowing the manufacture of only what is required.

5. 3 Production Load Leveling

It has been well documented in the literature that covers lean manufacturing and the Toyota Production System that the following condition has to be in place for any strategy similar to a pull system to work properly: smoothing of production, or leveled production.

5.3.1 Importance of Production Load Leveling within Synthetic Chemicals

Smoothing of production has to be applied downstream of the process of interest and a rough-cut plan forwarded to the upstream process. When smoothing of production takes place, the pulls experienced in the upstream processes will follow a more stable pattern and frequency, and the managers in these upstream processes can prepare the required capacity to handle the rate of pulls. Otherwise, there would be instances in which an upstream process doesn't have the capacity to meet the required production orders on time. When applying CONWIP, this becomes even more critical because there will be times in which two or more products have to be processed at the same work center at the same time. A prioritization scheme will be necessary and a backlog will be generated.

For SynChem, the downstream products are constituted of the final packaged chemicals. Ideally, the downstream products should be those, made by SynChem's customers. Because these products are out of the scope of this study, we will state that the final chemicals are the end products of SynChem's value chain.

If each process goes to its preceding process to withdraw the necessary chemicals at the necessary time in the necessary quantities, then, if the subsequent process withdraws amounts in a fluctuating manner in regard to time and quantity, the preceding processes should prepare as much inventory, equipment, and manpower as is needed to adapt to the peak in the variance of the quantities demanded. What is described in this last statement is an issue in discrete manufacturing as well. In a batch chemical processing plant, the effect is amplified due to the longer production lead times and long chemical kinetics.

5.3.2 Defining Production Load Leveling

To better explain what production smoothing is, it is useful to reference Figure 35. One of the main objectives in production smoothing is to keep production rate constant (see Figure 35-C). Because there is inherent variability in the demand for the products (Figure 35-A), inventory levels (Figure 35-B) must be allowed to fluctuate.[14]

Figure 35 – Production Load Leveling

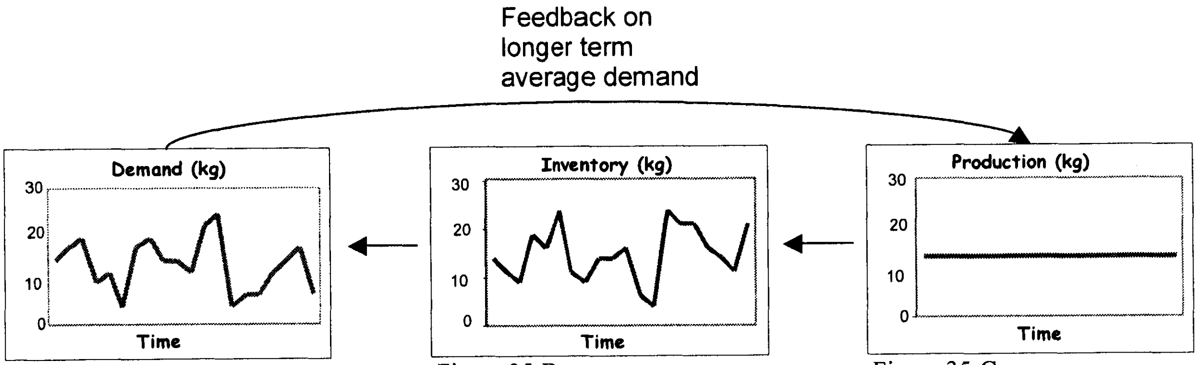


Figure 35-A Figure 35-B Figure 35-C

Production rate is set to be equal to the average demand. The rate can be expressed in different ways, depending on the type of process. A discrete manufacturer might want to express the production rate in units per hour or units per day, and will try to equate this rate of production to the average rate of demand, also expressed in units per hour or units per day. When daily demand increases or decreases the production rate is kept constant. The difference in the rates for a given period of time is absorbed by inventory. Production rates are only modified when the average rate of demand shifts (e.g., after a certain amount of time, average demand is consistently higher or lower than the previous average demand and inventory begins consistently increasing or decreasing over the same period of time beyond pre-established levels). Continuous feedback is supplied from the source of demand to the manufacturer. The new production rate is then set equal, again, to the observed demand rate.

Constant production rates allow operators to become more productive and efficient. It allows for expected cycles of learning, upon which new incremental improvements can be done. The production rate becomes a drumbeat; that is, operators as well as support staff learn to identify when the pace of production has increased or decreased, and it becomes more visible in the plant. Preventive maintenance and personnel training becomes easier to schedule. Asset utilization rates are increased and quality of products is enhanced by the consistency in repetitive processes. Hayes, et al.[11] found that reducing confusion in a production facility enhances productivity and throughput. Among the things that cause this confusion, he mentions: "erratically varying the rate of production, changing a production schedule at the last minute, overriding the schedule by expediting orders, changing the crews (or the workers on a specific crew) assigned to a given machine, haphazardly adding new products to the list of products a work center makes". Hayes found that such complexity affects total factory productivity. Production load leveling attempts to reduce and minimize complexity for factory workers and staff members.

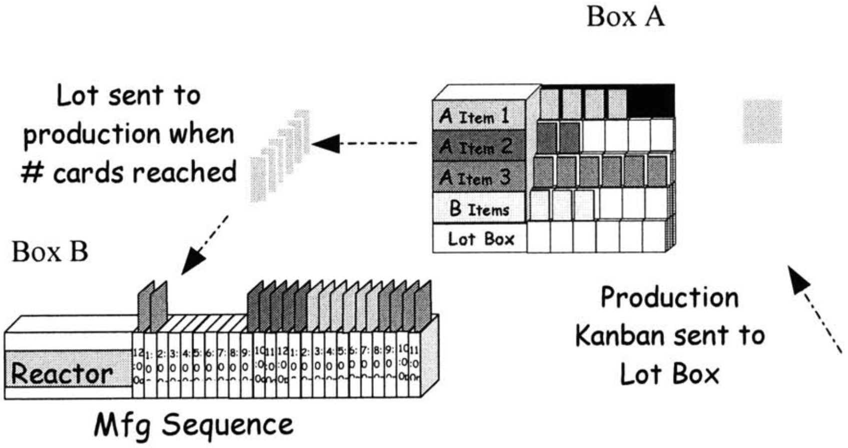
Production is to be kept constant across time. For example, for a given reactor, the production rate could be: one batch of chemical A in the first four days of the week and one batch of chemical B in the next six days (three days of the week when production began for chemical A and the other three days of the following week). Chemical A would then be made again in the last four days of the second week and so on, and the cycle repeats itself. For SynChem, both the production rate and the demand rate would have to be expressed in kg per week or kg per month.

Of course, if production rate is kept constant for chemical A and B, there is a need to allow the inventory level to fluctuate across time with the fluctuations of demand.

5.3.3 Visual Production Scheduling

The initial production rate in production load leveling is based on a forecast, and one could be tempted to state that this is a pure MRP system. Then again, once production has started, the accumulated demand signals are used to adjust the production rate accordingly in a way that does not cause much disruption in the production schedule. One way of doing so is to use one of the tools of a heijunka system. This type of visual planning tool has already been implemented in other Eastman Kodak Company manufacturing units.

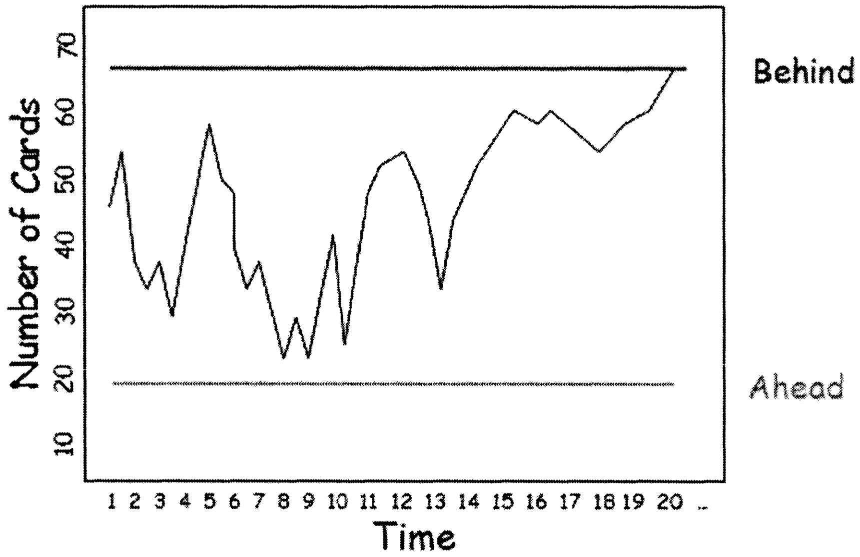
Figure 36 - Visual Planning Tool Used in a Heijunka Implementation



Every time a box of the final chemical (or another larger predetermined amount) is dispatched from the warehouse, a card can be inserted in the respective row of a box similar to the one shown in Figure 36 (box A). Once a certain number of cards are reached (the size of one batch), a production batch card is sent to the production floor to box B, where it will be placed in the queue for the products (or batches) to be made in that reactor. Figure 36 shows many cards going to box B, but all of these cards (representing one box of material each) can be replaced by one production batch card for the total amount equal to one production batch. For high-volume chemicals, the rate at which the production batch card arrives at the production floor should be very close, if not the same, to the production rate for that chemical. If a card arrives before or after (e.g. three days after or one week before) the day production for a new batch is supposed to start, the schedule and the sequence of the chemicals that are being made in the reactor should remain the same. One of the purposes of production load leveling is to avoid over reaction to a change in demand. Only, if the inventory levels drop below a pre-established level, or go beyond the pre-established control limit, should the production rate be increased or decreased as a response to the change in demand (see Figure 37).

In SynChem, production rates should be measured in kg per week or kg per month, depending on the total processing times of each step. It does not make sense for SynChem to work at the day level, as is the case for many discrete parts manufacturers, because most processing steps take up to as much as three to five days.

Figure 37 – Ahead/Behind Control Chart Indicating an Increase in the Number of Production Cards Being Sent to Box B (Figure 36)



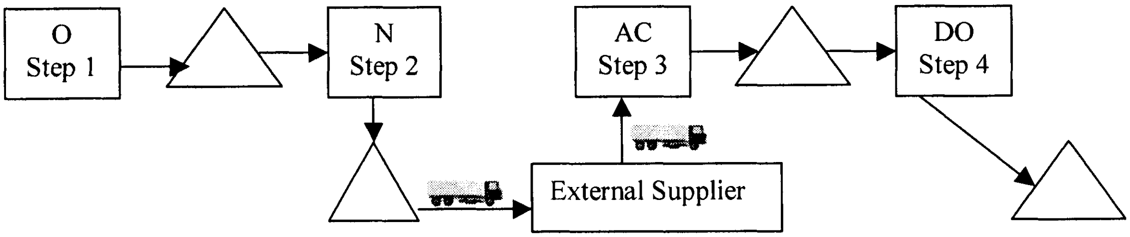
5.4 Case Analysis: A High-Volume Chemical Chain

The chemical chain identified in this section as "DO" is among the most important chemical chains for SynChem. The total volume is approximately 32 metric tons per year (2005 Forecast). This chemical represents approximately 12% of the total value of the products that are made in one of SynChem's facilities.

5.4.1 Material Flow for the DO Chain

A simplified representation of the material flow for this product is shown in Figure 38. Each step (numbered from 1 to 4) represents the complete manufacturing process to make a chemical. The first chemical intermediate will be identified as "O" (Step 1), the second as "N" (Step 2), and the third as "AC" (Step 3). The final chemical made in Step 4 has the same identifier as the complete chain, DO. Each triangle represents inventory, either in a warehouse or on the production shop floor.

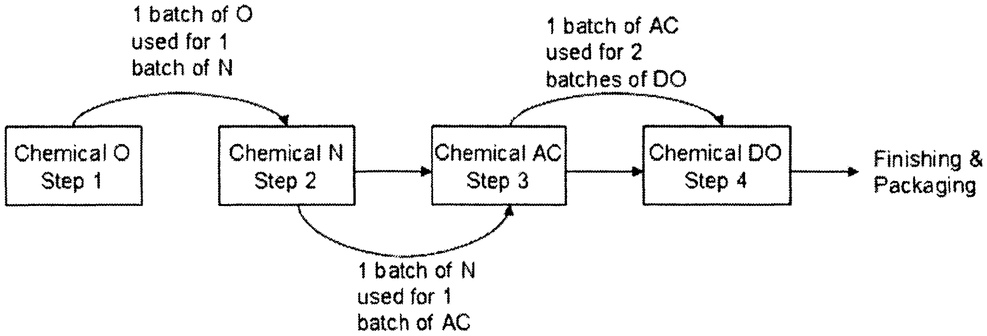
Figure 38 – Manufacturing Steps for DO Chain



After completing Step 2, the intermediate N must be shipped to an external manufacturer for further processing. SynChem does not have the processing capability required to prepare the intermediate chemical N for the third step. The supplier delivers the material to SynChem, which is then processed in Step 3.

The stoichiometric relationships in the recipes dictate the quantities that are used of a material in the next step. Figure 39 shows the batching relationships for the chemicals in the chain. The actual quantities in kilograms made per batch were treated as given parameters.

Figure 39 – Material Requirements for DO Chain



5.4.2 Approach to Scheduling Before Kaizen Event

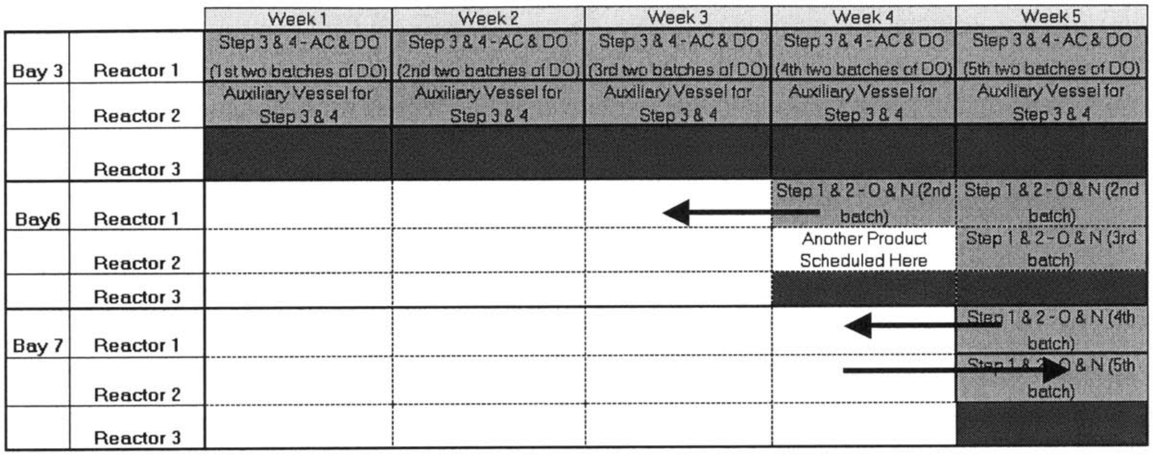
Figure 40 shows the approach to scheduling of production of the chemical chain prior to the kaizen event. The table shows on each cell, which steps of the chain (e.g., Step 1, Step 2, etc.) and thus which intermediate chemicals, are made in a given reactor and in a given week. For example, in week 3, in reactor No. 2 located in bay 3, the Steps 3 and 4 of the DO chain are scheduled for the complete week. The intermediate AC (Step 3) is manufactured first in reactor 1 of bay 3 at the beginning of the week and two batches of the final chemical DO (Step 4) are made during the rest of week 3.

Only the scheduling of events for five weeks into the future in three bays of a facility is shown for the purposes of the example.

The empty white cells in the schedule represent weeks on which reactors are available to make any other product other than the DO chain.

There are cells which are identified as "Auxiliary Vessel for Step 3 & 4". Steps 3 and 4 require two reactors, respectively, to be able to manufacture chemicals AC and DO. Sometimes, a process might require two, even three or four reactors. Such cases arise because there is a crystallization or separation involved. The chemical reaction takes place in one reactor and then the product is transferred to a second reactor for the crystallization stage or right after filtration. During this time of transfer and subsequent cleaning, both reactors are unavailable for any other purpose. In some other cases, the transfer line of a second reactor is connected to the main reactor and serves as a pre-scrubber where the vapors from chemical reactions released in the main reactor are treated, before these vapors are released to a final scrubber and then into the atmosphere.

Figure 40 – Approach to Scheduling for DO Chain Before Kaizen Event



		Week 1	Week 2	Week 3	Week 4	Week 5
Bay 3	Reactor 1	Step 3 & 4 - AC & DO (1st two batches of DO)	Step 3 & 4 - AC & DO (2nd two batches of DO)	Step 3 & 4 - AC & DO (3rd two batches of DO)	Step 3 & 4 - AC & DO (4th two batches of DO)	Step 3 & 4 - AC & DO (5th two batches of DO)
	Reactor 2	Auxiliary Vessel for Step 3 & 4	Auxiliary Vessel for Step 3 & 4	Auxiliary Vessel for Step 3 & 4	Auxiliary Vessel for Step 3 & 4	Auxiliary Vessel for Step 3 & 4
	Reactor 3	■	■	■	■	■
Bay6	Reactor 1				Step 1 & 2 - O & N (2nd batch)	Step 1 & 2 - O & N (2nd batch)
	Reactor 2				Another Product Scheduled Here	Step 1 & 2 - O & N (3rd batch)
	Reactor 3				■	■
Bay 7	Reactor 1					Step 1 & 2 - O & N (4th batch)
	Reactor 2					Step 1 & 2 - O & N (5th batch)
	Reactor 3					■

The cells in dark grey represent the instances in which a given reactor is empty and idle. Most of the time, a reactor would be idle in a bay, if there are two jobs (two batches of two chemicals; the chemicals may be the same, or may be different) running in parallel in the other two reactors. It is very difficult for operators to run three batches in one single bay, mostly because the tasks or the processing steps of the three jobs being processed are not designed to be run in parallel by one single person. In other cases, there are equipment constraints (piping, pumps, and pre-scrubbers) that will not allow for three jobs to be run at the same time in a bay.

SynChem reached an agreement with the manufacturer to whom chemical N is shipped after completion of Step 2, to ship a large batch of chemicals every five weeks. These two first intermediates (O & N) would be manufactured on the same week or the week prior to shipment utilizing several reactors. Figure 40 shows that Steps 1 and 2 (chemicals O and N) are scheduled in weeks four and five in four different reactors that are located in two different bays (which might not necessarily be close to each other).

AC and DO would be manufactured continuously in one same bay. Eventually, if a processing step gets behind, or if there is a problem with a reactor in bay 3, where AC and DO, is being made, production would be shifted to another bay, for example, bay 7. Of course, production that was scheduled for bay 7 now is delayed.

If processing of any other chemical scheduled in the same reactor but one week before Steps 1 and 2 gets delayed, the scheduling of Steps 1 and 2 would be delayed as well, or would be moved to another bay, moving production of lower priority chemicals to other bays or simply delaying their production. These changes are shown in Figure 40 with arrows. These changes ultimately affect productivity and service levels of other materials.

5.4.3 Changing Scheduling for the DO Chain

A one-week kaizen event was organized to find new ways to make products "flow" from raw materials to final product by avoiding wasteful movement of material, idle resources, and wasteful inventory. To make a product flow, under the KOS jargon, means to eliminate all interruptions to the value-adding activities in the production process and eliminate most, if not all, of the idle time that a product spends in inventory, queuing, and handling. At the time this thesis was written, the production trials for the proposed process were still to be executed. Personnel familiar with the production process felt confident on the success of the project. Future success will depend on the organization's capability to implement the chemist's and engineer's vision.

5.4.3.1 Methodology

The team involved came up with a way to schedule the production of the DO chain that allows for a pull-based strategy and a leveled production load for the work center and its operators. The steps that the team went through were the following:

1. Determining the rate at which the chemical had to be made (Takt time).
2. Go through the production steps and equipment requirements to manufacture the product.
3. Arrange the starting and ending points of the processes and schedule the production runs, accordingly, to be able to make the product at the desired rate.
4. Verify labor requirements and establish any need for material buffers between steps.

The team consisted of a process chemist, a development chemist, an operator that had considerable expertise in the processes that were evaluated, an internal consultant with experience in operations and industrial engineering, and an equipment reliability engineer.

5.4.3.2 New Approaches

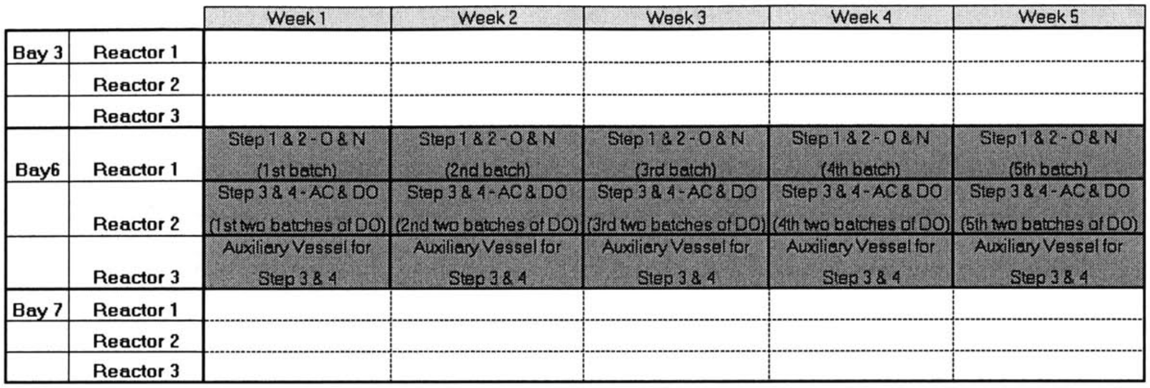
The team avoided "old" assumptions as to the way production is scheduled and used new approaches. The team allowed reactors, distillers, centrifuges, and filters to stand idle when it would improve overall throughput and productivity. A process running in one reactor (or centrifuge) would be on hold, if necessary, for the length of time that another batch in parallel was being processed in another reactor in the same bay. Holding one of two processes running in parallel would be required in some cases in order to utilize only one operator or to avoid a conflict later on, when the materials leaving the reactors converged at the same time in a subsequent step, such as centrifuging.

The processes for all four chemicals were to be scheduled in one same bay. Currently, for several chemical chains, intermediates and final chemicals are manufactured in different bays and, in some cases, even in different facilities. After a new chemical is introduced into the product portfolio, and its manufacturing process is validated on a given facility or reactor, production personnel are very reluctant to relocate the process to another work center. Scheduling production of all intermediates and the final chemical in one single bay would avoid significant material movement.

5.4.4 Proposed Schedule for DO Chain

Figure 41 shows, at a higher level, how scheduling for the DO chain would look. The four chemicals in the chain can be made using three reactors that are dedicated 100% to this product at all times. Steps 1 & 2 (chemicals O & N) are now made in the reactor that was idle in the scheduling approach prior to the kaizen event. Instead of manufacturing Steps 1 and 2 very close to the shipping date, as is done with a lot of other products, the load is spread evenly across the five weeks between shipments. By doing so, capacity is freed up in other reactors and bays at the plant. For example, Figure 41, shows how for bays 3 and 7, the equivalent of three weeks of capacity is now available in weeks four and five to schedule the production of other chemicals (compare with Figure 40).

Figure 41 - Proposed Scheduling for DO Chain After Kaizen Event



		Week 1	Week 2	Week 3	Week 4	Week 5
Bay 3	Reactor 1					
	Reactor 2					
	Reactor 3					
Bay6	Reactor 1	Step 1 & 2 - O & N (1st batch)	Step 1 & 2 - O & N (2nd batch)	Step 1 & 2 - O & N (3rd batch)	Step 1 & 2 - O & N (4th batch)	Step 1 & 2 - O & N (5th batch)
	Reactor 2	Step 3 & 4 - AC & DO (1st two batches of DO)	Step 3 & 4 - AC & DO (2nd two batches of DO)	Step 3 & 4 - AC & DO (3rd two batches of DO)	Step 3 & 4 - AC & DO (4th two batches of DO)	Step 3 & 4 - AC & DO (5th two batches of DO)
	Reactor 3	Auxiliary Vessel for Step 3 & 4	Auxiliary Vessel for Step 3 & 4	Auxiliary Vessel for Step 3 & 4	Auxiliary Vessel for Step 3 & 4	Auxiliary Vessel for Step 3 & 4
Bay 7	Reactor 1					
	Reactor 2					
	Reactor 3					

Steps 1 and 2 only need one reactor, and both steps can be carried out in one week. Steps 3 and 4 require two reactors and can also be made in one week. The five batches of chemical N that are accumulated at the end of five weeks are shipped in one large batch to the outside manufacturer. The outside manufacturer sends back, at the same frequency, a large batch of material that can now be used to make five batches of chemical AC (Step 3) during the next five weeks.

5.4.4.1 Detailed Gantt Chart for One Week

A detailed Gantt chart showing the scheduling of the four manufacturing steps in one week is shown in Appendix 2 to Appendix 4. This Gantt chart was developed by the team during the kaizen event. The cells in the spreadsheet that have an asterisk and no fill color (see Appendices 2-4) are the times when a process or equipment is idle. Equipment was allowed to be idle in order to wait for the other processes that are running in parallel to be staffed at appropriate times and to avoid equipment constraints, such as two processes requiring the same transfer pump or the same pre-scrubber.

There is a seventh day, every week, on which the equipment would be idle (see Appendix 2). This time, initially, could be used to buffer the variability in processing times. It is important to note that, because there are already idle times within the first six working days, some buffers have already been built into the schedule.

The seventh day could also be used to perform equipment maintenance, to assure that in the other six days of the working week the equipment will perform as desired. Still, another option is to use the day to make other products that can be produced within 24 hours, which in reality, are very hard to find among SynChem's product portfolio. Finally, the cycle could be repeated every six days, instead of seven. After a certain number of cycles (and upon which inventory has been built up), say, four cycles (6 days x 4 x 2 = 48 batches of DO over a period of 24 days; 48 batches of DO are required over a period of 28 days), another one or two chemicals with a processing time of one to four days could be made in the same bay.

5.4.5 Advantages of Leveling Load from DO Chain in One Bay

There are clear advantages of leveling the load for this chemical and for its assigned bay:

1. Scheduling for bay 6 (used as an example in this case) becomes trivial, since it is now dedicated 100% for one item, and can accommodate, at most, one or two more items, which must be produced after several cycles of the DO chain have been manufactured. These one or two chemicals can be accommodated in the schedule based on three criteria: annual volume, total processing time, and equipment requirements (reactors in the bay must be capable of manufacturing the product selected).
2. Scheduling for the rest of the bays becomes also easier. The work centers, bay 3 and bay 7 in Figure 38, appear as a blank sheet of paper, where the planning staff can now schedule production of other chemicals. In Figure 37, the planning team is definitely more constrained in capacity and will have problems, for example, in weeks 4, 5, and perhaps in week 6, scheduling production. In the weeks immediately prior and after the batches of O and N have to be made, there might be delays of the previous processes that delay a shipment or cause distress in the manufacturing operations.
3. Problems in the manufacturing of the DO chain become now visible and must be resolved immediately. One of the things the KOS system is trying to achieve is the same sense of urgency that production staff has in an automobile final assembly line at a Toyota facility when production problems arise. SynChem management has been looking for ways to create a "moving line" in their production, which "flow" could be easily noticed and for which a

type of "andon" cord could be implemented. In the scheduling system proposed by the team for the DO chain, all of these objectives are met. Because these chemicals are to be made only in these three reactors, and because the delay or interruption of the manufacturing process of one of the intermediates of the chain would delay the manufacturing of the complete chain and ultimately the final product, a sense of urgency is generated whenever a problem arises. In addition to this, because a problem in this work center would be very visible and catastrophic to the performance of the plant, maintenance staff and manufacturing support staff would have an incentive to keep the work center without flaws and well maintained.

4. Because, according to the operators working at SynChem and from direct observations, it is extremely difficult to work in the manufacturing process of three chemicals in parallel in the same bay, whenever the plant is producing the last two chemicals of the chain, there will be an idle (and empty) reactor in that bay. In the same fashion, in week 5, whenever there is the need to manufacture the first two steps of the chain before shipping, there will an empty reactor in each of the bays that is manufacturing the first two intermediates. The urgency of the shipment, plus the fact that two chemicals are being made in that week in the bay, make it extremely difficult for the operator to be able to make a third chemical in parallel. Labor is not the one single issue with parallel processing of three chemicals. There are also times, in which, as was mentioned before, a process requires the availability of two or more reactors. Because, in the process redesign, the team took into account the processing steps in which two reactors were needed for one single chemical, and scheduled the steps accordingly, three chemicals (which are all compatible and all of the same nature with some similar raw materials) could be made in parallel in one single bay. In most cases, one single operator will be able to operate a bay, but there are instances in which a second operator is needed. These times are to be coordinated with team leaders, supervisors, and other plant operators to assure that there will be somebody available when it is required.

5.4.6 Extending Production Load Leveling to High-Volume Chemicals

The same type of analysis carried out for the DO chain could be applied to the other five chemical chains that account for half of the total value that flows through the plant. All intermediate chemicals of these chains (as was the case for the DO chain) could be manufactured in one to three bays in one single plant, all close to each other, in order to minimize material movement.

Green[15] discussed in his thesis the process of assigning certain products and product families to different work centers in a discrete manufacturing environment. In this case, which happened to be at a manufacturing unit at Eastman Kodak Company, the work centers were filling lines and the product was discrete. In this project, the objective of optimizing production and reducing inventory at hand required the staff to dedicate lines to certain products, categorized as A, B, or C (the type of prioritization is not really as relevant, as the fact that there is one).

Assigning product families to equipment and dedicating the equipment to manufacture such families might be in the best interest of SynChem.

Along with the DO chain, the team involved in the re-engineering of the process observed that there was opportunity to work on two other high-volume chemical chains (of the six mentioned that account for 50% of the value). One of the six chemicals is already being manufactured in equipment dedicated to it. The difference with this one particular chemical is that there are two subsequent steps that are being made in different facilities. If the complete chain were integrated into one facility, the material movement would be avoided, and there would be more coordination in the manufacturing steps of the chain.

Many papers have been written on scheduling chemical batch processes in multi product environments. Others have been written on chemical batch processes with shared work centers and with constrained capacity. Chi-Wai Hui and Avaneesh Gupta described an MILP formulation for short-term scheduling of multistage multi-product batch plants.[16] Carlos A. Mendez and Jaime Cerda worked on, quoting its title, "optimal scheduling of a resource-constrained multi product batch plant supplying intermediates to nearby end-product facilities."[17]

Although all these are noble attempts to provide tools to the chemical process industry for scheduling production runs, it is very hard for manufacturing units, such as SynChem, to actually apply such tools. First of all, the number of products and work centers that SynChem manages goes well beyond the number of decision variables and constraints with which these papers deal with. SynChem lacks the software and trained staff that can continuously update such algorithms and apply them to day-to-day operations. Third, variability in the processes and the issues that arise in production from equipment breakdowns, lack of manpower, upsets in the processes, defects in raw materials, lack of materials, etc., usually make the plans generated by these scheduling optimization tools obsolete within a couple of days, unless variability is accounted for in the mathematical model.

The suggestion to separate the chains into families, as was done already with the two high-volume chemical chains in SynChem, in terms of volume and value, and dedicate the highest value chemical chains to two-three bays, the medium-value chemical chains to four to five bays, and the lower volume (and thus lower *relative* value) items to the rest of the bays and reactors available has several advantages. This grouping of items and work centers simplifies the scheduling problem: Once the high-value items have been assigned to the equipment and the production load level established, planners need not worry about the scheduling of this items. The visual planning tool described in this section would allow operators, support staff, and management to determine if the production is getting ahead or behind of demand, and contingency plans can be adopted on time. By assigning the B items to a fixed set of work-centers, the number of options is constrained and the number of combinations of possible schedules is reduced. The group made up of C items would be the hardest to schedule, but so are the items of even less relative value, compared to the total product bill. These items would be made to order or would be held in inventory, if needed, in order to keep the production load level relatively constant at a pre-established utilization rate. To avoid overproduction, planners must have clear rules, as to which items to put on the queue for a work center. If a product's inventory is relatively high, then the product should be moved back in the queue to allow for another product to be made in the work center.

Production load leveling for high-volume items means that the production rate for these items will be held constant. In order to do this, it is necessary to assign it to dedicated work centers and re-engineer the process to make it "fit" with other products that can or should also be made in such work centers. A visual planning tool such as the heijunka box mentioned in an earlier section allows operators and supervisors to know whether the rate of production is higher than the rate of pulls, if inventory is building up or vice versa. Production rate should not be changed immediately, since the processing of products take several weeks. Instead, the production rate should remain constant. During this time, demand rate will spike after some time, but on average, will remain equal to the production rate. Only, if after several weeks (or months) the rates of production and the rates of pulls seem to differ considerably and the ahead or behind limits are met, then the rate should be revised and the scheduling of the batches changed. Given the state of the industry, SynChem should expect a declining rate of pulls.

5.5 Summary

This chapter introduced the concept of production load leveling and its importance for SynChem. Production load leveling allows for repetitiveness, consistency and incremental improvement of the manufacturing processes. SynChem should divide its product portfolios by volume and by chemical chains. The production of these families of chemicals can be dedicated to pre-selected bays or reactors. A production rate is established based on the average demand, which for high-volume chemicals tends to be relatively stable over time.

The case study on the DO chain provides an example of the benefits of dedicating the production of a chain to one production area (ideally a bay or a set of reactors close to each other). There are gains in capacity, asset utilization, and labor productivity, less movement of materials, and opportunity for continuous improvement and a higher sense of urgency.

In order to find an optimal way to manufacture a high-volume chemical chain in a given set of reactors, a team of experts (process chemists, industrial engineers, development chemists, and operators) must dive deep into the details of a process. Equipment must be allowed to remain idle and scheduling of processes should take changeovers, labor requirements, and equipment constraints into account in order to maximize throughput. Visual production scheduling can be utilized to compare rate of production against rate of demand and adjust the production rates, accordingly, by setting “ahead” and “behind” limits for inventory.

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CONCLUSION

In this thesis, we explored two main concepts that are commonly used by discrete manufacturers that attempt to implement lean manufacturing systems in the context of a chemical batch processing unit: continuous batch size reduction and production load leveling.

The Evaluation of Batch Size Reductions

The analysis on all the chemical chains analyzed in this thesis, and during the six month internship that led to this project, showed that the total variable manufacturing costs would increase if batch sizes were to be cut between 40 to 50%. The actual amount of this increase in variable cost depends largely on the annual production volume of the chemical chain. For low-volume chemical chains, the increase in annual variable manufacturing cost that results from reducing batch sizes by 40-50% is anywhere between $500 up to $4,000. For some low-volume chemicals, the negative impacts of reducing the batch size might be marginal, even negligible. For high-volume chemicals, the increase in annual variable manufacturing costs can be anywhere between $5,000 and $25,000. Because in all cases, it was assumed that there was enough equipment availability (capacity) to absorb the increase in required capacity that the batch size reduction of a chemical entails, costs associated with capacity are not included. Therefore, the impact on the plant of continuously reducing batch sizes could be further negatively impacted once the cost of equipment capacity is included in the equation.

Evaluating Future Batch Sizing Decisions

There are cases in which reducing the batch size might be a good decision, especially when demand for a product has fallen considerably. In other cases, such as is the case for products to be used in the thermal printing value chain, demand is increasing very rapidly, and increasing the batch sizes or the campaign sizes might lower annual variable manufacturing costs. In any case, each decision should be evaluated and analyzed considering the tradeoffs between higher setup and labor costs and lower inventory holding costs.

SynChem can use the models presented in this thesis to assist in the decision making process when evaluating the reduction of a batch size due to increase or decrease of demand for a final chemical. For chemical chains with four or higher number of intermediates, the models and the approaches presented in this thesis still apply and may be extended for even longer chains.

Monitoring and changing batching policies more frequently should only be done for strategic products or high-volume chemicals. The benefit of changing batching policies of low-volume chemicals whose demand is changing rapidly (in percent terms), is negligible and well below $1,000 per year. For higher volume chemicals (top 40% of SynChem's volume) there might be an annual savings of over $2,000 per year per chemical by revising the batch sizes.

Synchronizing Chemical Chains to Lower Inventory Levels

It is by synchronizing chemical chains in medium- to lower-volume chemicals, that SynChem can obtain the most leverage of reducing batch sizes. By reducing or increasing the batch size of an intermediate to make only what will be used in the next step, SynChem can avoid the buildup of inventory that does not add any value in the next two to three years (if not longer). SynChem should also modify the recipes of subsequent steps to use up the materials that they have already accumulated but will not use within the next three to five years. Following both strategies can lead to a one-time intermediate chemical inventory reduction anywhere between $500,000 and $700,000. Because the batch size reductions are not drastic, but in the 10 to 20% range, the effects on unit manufacturing costs are not as negative as they would be, if one were reducing the batch size of the chemical by as much as 40 to 60 %.

DO Chain as an Example of Production Load Leveling

The scheduling proposal for the manufacturing steps of the DO chain, serves as an example of the benefits of production load leveling for high- to medium- volume chemicals at a chemical batch manufacturer. This proposed schedule frees up about eight reactor weeks (one reactor for eight weeks) and simplifies the scheduling of other chemicals by completely freeing up two bays. One operator, with sporadic assistance from a team member, could be able to operate one bay. Labor requirements for the proposed schedule could drop by approximately 25 – 30 %. Movement of material is reduced, and constant work in process can be implemented. Repetitiveness and predictability allows for operators to engage in continuous improvements and to have more cycles of learning for the implementation of standard work in the area. Interruptions to the production become very visible and forces first-line management to address problems immediately.

Implementing Production Load Leveling at Synthetic Chemicals

Production load leveling requires dedicating families of products to work centers. This simplifies the scheduling problem for the planners by setting limits to the number of possible combinations that can arise in the process of scheduling a given manufacturing step to a given work center or bay.

Synthetic Chemicals should focus on the higher volume chemicals first (10 – 15 chemical chains that account for 60% - 80% of the value that flows through SynChem's facilities). By following the methodology followed for the DO chain when working with these high volume chemicals, dedicating them to work centers and determining the optimal way to schedule them according to an average rate of production, SynChem can obtain the most leverage from production load leveling. After implementation of production load leveling with high-volume chemicals, then the implementation on medium-volume chemicals (those 65% of chemicals that constitute 15% of the value for SynChem) can follow.

Without production load leveling, it will be very hard for SynChem to implement any type of pull-based system or other hybrid system such as CONWIP.

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APPENDIX 1

Discrete Manufacturing vs. Batch Chemical Processing: Other Considerations

Crama et al.[18] summarized in a table from Ashayeri et al.[19] the important general characteristics in discrete manufacturing operations and in the processing industry. The operating characteristics for the Synthetic Chemicals department at Eastman Kodak Company were added.

Appendix 1 - Chemical Process Industry vs. Discrete Manufacturing

Relationship With the Market	*Process Industries*	*Discrete Industries*	*Synthetic Chemicals (Kodak.)*
Product type	Commodity	Custom	Commodity & Custom
Product assortment	Narrow	Broad	Broad
Demand per product	High	Low	High (30%), Low (70%)
Cost per product	Low	High	Low & High
Order winners	Price & delivery guarantee	Speed of delivery & product features	Price, delivery guarantee, quality
Transporting costs	High	Low	High
New Products	Few	Many	Few

The Product Process	*Process Industries*	*Discrete Industries*	*Synthetic Chemicals (Kodak.)*
Routings	Fixed	Variable	Fixed
Facility's lay-out	By product	By function	By function, fixed
Flexibility	Low	High	Low
Production equipment	Specialized	Universal	Specialized
Labor intensity	Low	High	Low but some labor intensive activities.
Capital intensity	High	Low	High
Changeover times	High	Low	High
Work in process levels	Low	High	High

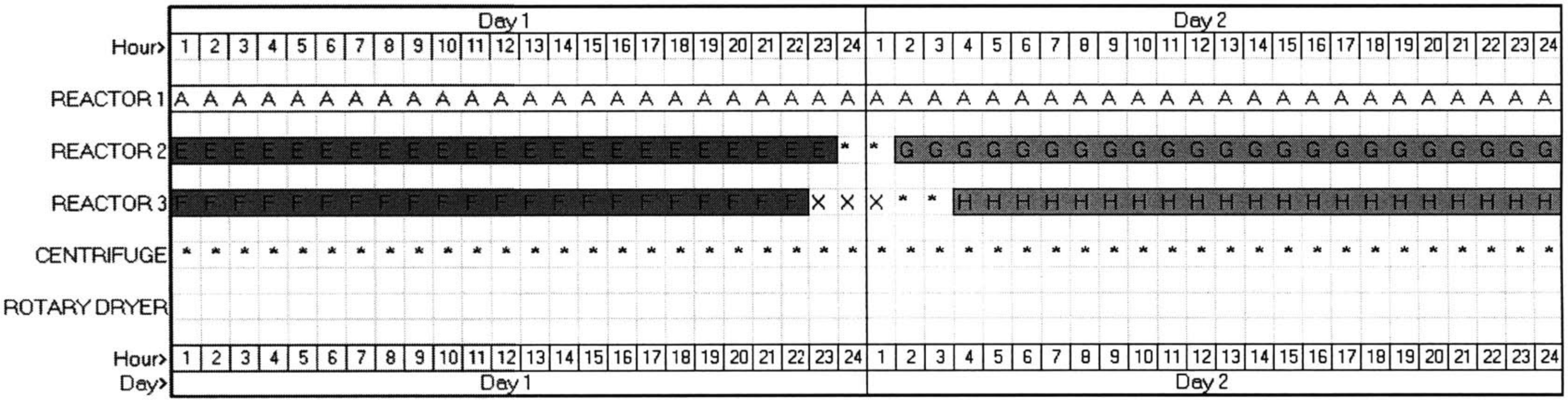
Volumes	High	Low	High (30%), Low(70%)

Quality	***Process Industries***	***Discrete Industries***	***Synthetic Chemicals (Kodak)***
Environmental demands	High	Low	High
Danger	Sometimes	Hardly	Sometimes
Quality measurement	Sometimes long	Short	Sometimes long

Planning & Control	***Process Industries***	***Discrete Industries***	***Synthetic Chemicals (Kodak)***
Production	To stock	To order	To stock
Long term planning	Capacity	Product design	Capacity
Short term planning	Utilization capacity	Utilization personnel	Utilization Capacity
Starting point planning	Availability of capacity	Availability of material	Availability of capacity
Material flow	Divergent and convergent	Convergent	Divergent and convergent
Yield variability	Sometimes high	Mostly low	High
"Explosion" via:	Recipes	Bill of materials	Recipes
By and Coproducts	Sometimes	Not	In most cases
Lot tracing	Mostly necessary	Mostly not necessary	Necessary

APPENDIX 2

Weekly Detailed Schedule for DO Chain – Days 1 and 2



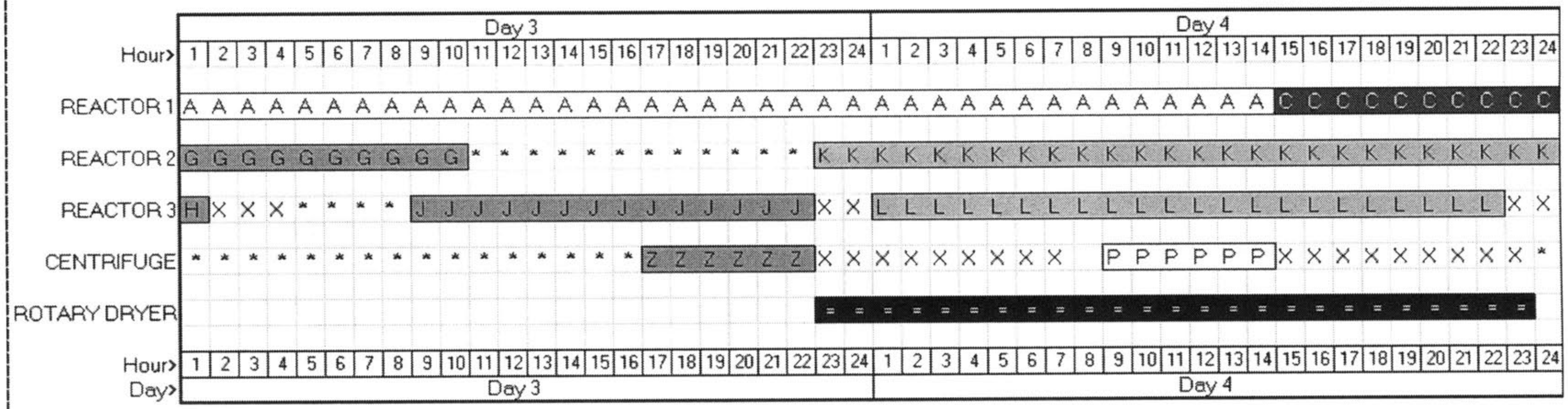
	Day 1																								Day 2																							
Hour>	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
REACTOR 1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
REACTOR 2	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	*	*	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
REACTOR 3	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	X	X	X	*	*	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
CENTRIFUGE	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
ROTARY DRYER																																																
Hour>	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Day>	Day 1																								Day 2																							

Legend

A.	Chemical O
E.	Chemical AC
F.	Chemical AC - Reactor 3 Required - Prescrubber
G.	Chemical DO - 1st part of process in Reactor 2
H.	Chemical DO - Reactor 3 Required - Pre-scrubber
X	Cleaning and Setup
*	Idle Time - Waiting Time

APPENDIX 3

Weekly Detailed Schedule for DO Chain – Days 3 and 4



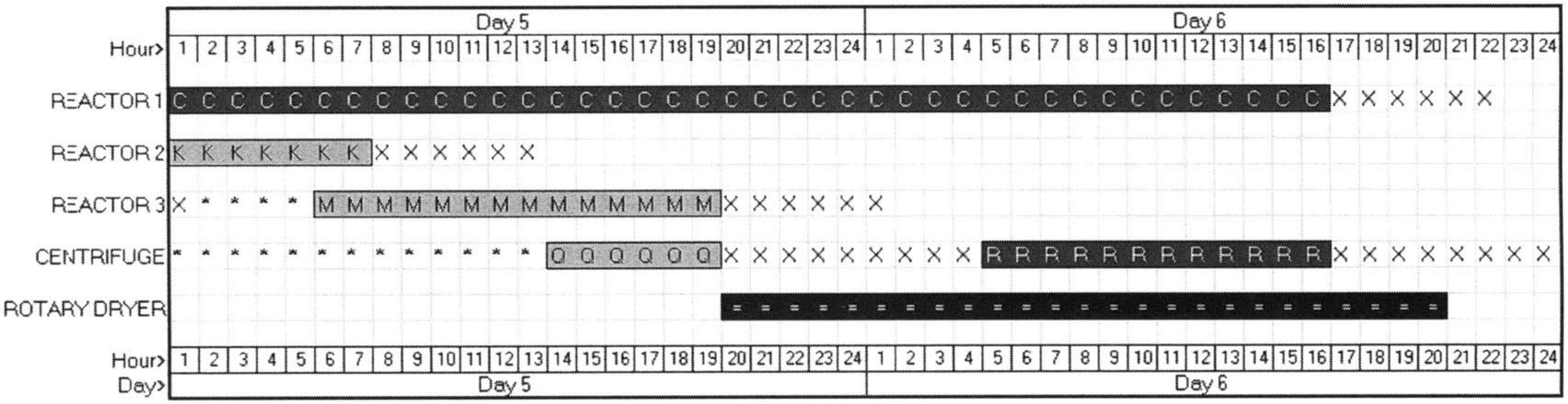
	Day 3																								Day 4																							
Hour>	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
REACTOR 1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	C	C	C	C	C	C	C	C	C	C
REACTOR 2	G	G	G	G	G	G	G	G	G	G	*	*	*	*	*	*	*	*	*	*	*	*	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	K
REACTOR 3	H	X	X	X	*	*	*	*	J	J	J	J	J	J	J	J	J	J	J	J	J	J	X	X	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	X	X
CENTRIFUGE	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Z	Z	Z	Z	Z	Z	X	X	X	X	X	X	X	X	X		P	P	P	P	P	P	X	X	X	X	X	X	X	X	X	*
ROTARY DRYER																							=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	
Hour>	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Day>	Day 3																								Day 4																							

Legend

A.	Chemical O - (continued from Day 2)
C.	**Chemical AC**
G.	Chemical DO - 1st part of process in Reactor 2 (cont.)
H.	Chemical DO - Reactor 3 Required - Pre-scrubber (cont.)
J.	Chemical DO - 2nd part of process in Reactor 3
K.	2nd Batch - Chemical DO - 1st part of process
L.	2nd Batch of DO - Reactor 3 Required - Pre-scrubber
P.	Chemical O - Centrifuging
Z.	1st Batch-Chemical DO - Centrifuging
=	**1st Batch - Chemical DO - Drying**
X	Cleaning and Setup
*	Idle Time - Waiting Time

APPENDIX 4

Weekly Detailed Schedule for DO Chain – Days 5 and 6



	Day 5																							
Hour>	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
REACTOR 1	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
REACTOR 2	K	K	K	K	K	K	K	X	X	X	X	X	X											
REACTOR 3	X	*	*	*	*	M	M	M	M	M	M	M	M	M	M	M	M	M	M	X	X	X	X	X
CENTRIFUGE	*	*	*	*	*	*	*	*	*	*	*	*	*	Q	Q	Q	Q	Q	Q	X	X	X	X	X
ROTARY DRYER																				=	=	=	=	=
Hour>	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Day>	Day 5																							

	Day 6																							
Hour>	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
REACTOR 1	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	X	X	X	X	X	X		
REACTOR 2																								
REACTOR 3	X																							
CENTRIFUGE	X	X	X	X	R	R	R	R	R	R	R	R	R	R	R	R	X	X	X	X	X	X	X	X
ROTARY DRYER	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=				
Hour>	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Day>	Day 6																							

Legend

C.	**Chemical AC - (cont.)**
K.	**2nd Batch - Chemical DO - 1st part of process - (cont.)**
M.	**2nd Batch of DO - 2nd part of process in Reactor 3**
Q.	**2nd Batch of Chemical DO - Centrifuging**
R.	**Chemical AC - Centrifuging**
=	**2nd Batch - Chemical DO - Drying**
X	Cleaning and Setup
*	Idle Time - Waiting Time