Lehigh University
Lehigh Preserve

Theses and Dissertations

1990

Evolving towards theory of constraint-based manufacturing planning and control systems

James W. Wagner
Lehigh University

Follow this and additional works at: https://preserve.lehigh.edu/etd

Part of the Manufacturing Commons

Recommended Citation
Wagner, James W., "Evolving towards theory of constraint-based manufacturing planning and control systems" (1990). *Theses and Dissertations*. 5362.
https://preserve.lehigh.edu/etd/5362

This Thesis is brought to you for free and open access by Lehigh Preserve. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of Lehigh Preserve. For more information, please contact preserve@lehigh.edu.

Evolving towards Theory of Constraint-Based Manufacturing Planning and Control Systems

by

James W. Wagner

A Thesis

Presented to the Graduate Committee

of Lehigh University

in Candidacy for the Degree of

Master of Science

in

Manufacturing Systems Engineering

Lehigh University

1990

This thesis is accepted in partial fulfillment of the requirements for the degree of Master of Science.

Dr. Roger N. Nagel,
Advisor

3/6/90
Date

Dr. Keith M. Gardiner,
Director,
Manufacturing Systems Engineering

3/6/90
Date

Dr. Marlin U. Thomas,
Chairperson,
Industrial Engineering

3/7/90
Date

Acknowledgements

I would like to express my thanks to Dr. Roger N. Nagel, who guided my research and writing efforts. His socratic approach to instruction helped make this learning experience full, rewarding, and complete.

I would also like to acknowledge Lehigh University's Center for Manufacturing Systems Engineering for the financial support which made my graduate studies possible.

Most importantly, I am thankful for my family and their unwavering support in all my endeavors.

Table of Contents

Abstract	1
1. Introduction	3
American Manufacturing: Facing Global Competition	3
The Role of Manufacturing Planning and Control Systems	7
Introduction to Theory of Constraint Manufacturing	10
Organization of this Paper	11
2. Theory of Constraint Manufacturing	13
History	16
Global Measurements	17
Control Measurements	19
Rules of Constraint Management	23
The Myth of Balanced Capacity	29
Utilization Issues	30
Buffer Management	32
Implementation Issues	36
A Simple Plant Example	39
3. Manufacturing Resource Planning	47
The MRP Approach	48
What's Wrong With MRP?	52
The Role of MRP in Manufacturing Planning and Control	57
A Model Production System: Educational Tool	61
4. Just-In-Time Manufacturing	70
Characteristics of Just-In-Time Manufacturing	71
JIT and TOC: A Similar Approach to Continuous Improvement?	76
5. Conclusion	81
References	85
VITA	88

List of Figures

Figure 1: Projected World Productivity Leader 5

Figure 2: Projected Productivity Levels 6

Figure 3: Pipeline Analogy for Machine Capacity 24

Figure 4: Protective Capacity 30

Figure 5: Buffer Management 34

Figure 6: Model Production System 40

Figure 7: Identifying the Constraint 42

Figure 8: TOC Approach to Product Mix 44

Figure 9: Model Production System Resources 61

Figure 10: Model Production System 62

Figure 11: Identifying the Constraint 64

Figure 12: TOC Approach to Product Mix 65

Figure 13: Production Schedule for Resource B 66

Figure 14: Model Production System Buffer Regions 67

Figure 14: Simulation Results 68

Abstract

Increased competition in the global marketplace has forced American manufacturers to look for more effective ways to manage their operations. The firm's manufacturing planning and control system is the focal point of managerial efforts and policies.

Manufacturing Resource Planning started as a methodology to generate component requirements and schedule resources on the shop floor. It grew into a philosophy which includes aggregate planning, purchasing, cost systems, accounting and performance measurement functions.

Just-In-Time manufacturing began as a methodology to minimize inventory and increase the velocity of orders flowing through production facilities. It evolved into a philosophy based upon the whole person concept, continuous improvement, world class quality standards, and the systematic elimination of organizational slack.

The Theory of Constraints originated as a methodology for increasing system performance by focusing improvement on the portion of the system with the greatest potential for improvement. It has evolved into a philosophy based upon systematic and controlled continuous improvement, the relationships between system throughput and inventory

levels, and global performance measures. The application of the Theory of Constraints can provide a highly focused approach for improvement in production systems and measures.

The Theory of Constraints, Manufacturing Resource Planning, and Just-In-Time Manufacturing all originated as methodologies geared toward improving the effectiveness of shop floor management practices. All three have evolved into management philosophies. This paper shows how they can be combined into an overall management philosophy.

Manufacturers can use such a philosophy to improve the effectiveness of their manufacturing planning and control system. Such a system can provide a significant competitive advantage. A manufacturer will be better able to respond quickly to customer demands with a quality product, on time, and in the right quantity. The end results are satisfied customers, insured survival of the firm, increased profits, reduced operating expenses, and less difficulty in managing the business.

Chapter 1

Introduction

American Manufacturing: Facing Global Competition

The decade of the eighties brought an unprecedented sense of need for reform among U.S. manufacturing companies. Many domestic firms have witnessed reductions in market share due to tougher domestic competition as well as the "invasion" of foreign firms. In some cases, entire industries have become dominated by such firms.

As reported by the M.I.T. Commission on Industrial Productivity, American industry watched in disbelief as the balance of trade shifted drastically in six of the eight key manufacturing industries studied since 1972 [2]. Staggering negative trade balances are currently reflected in automobile, consumer electronics, machine tool, semiconductor and computer, steel, and textile industries. The commercial aircraft and chemical industries still enjoy a positive trade balance, but in 1988 the overall trade deficit grew to approximately $120 billion.

In recent years, many publications have documented the onslaught of foreign competition along with the resulting imbalance in world trade [2] [12] [30]. These reports leave the American manufacturing community wondering just how long

this trend can continue before the entire U.S manufacturing base is relegated to second class status.

Table 1 illustrates one important fact that many reports which attempt to explain the outlook for American manufacturers seldom include: the United States is still the world leader in productivity, in terms of real output per worker [19]. Which explains why the standard of living in the U.S. has not eroded along with the balance of trade.

PRODUCTIVITY LEADERS (real output per worker)

Rank 1988	Rank 1950		1988	1950	Ave Annual Increase
1.	1.	United States	$41,362	$23,979	1.4%
2.	2.	Canada	$39,125	$18,415	2.0%
3.	7.	France	$35,388	$ 9,132	3.6%
4.	9.	Italy	$35,206	$ 7,024	4.3%
5.	8.	West Germany	$33,489	$ 8,270	3.7%
6.	5.	Belgium	$33,067	$11,054	2.9%
7.	6.	Norway	$31,919	$10,530	3.0%
8.	4.	Netherlands	$31,776	$12,541	2.5%
9.	3.	Britain	$29,614	$12,887	2.2%
10.	10.	Japan	$29,575	$ 3,640	5.7%

Note: Figures are adjusted for inflation in 1988 dollars. Comparisons of real gross domestic product per employee are based on "purchasing power parity" exchange rates.

Table 1

This dispels the popular myth that there is something fundamentally wrong with the American manufacturing culture. Hour for hour, American factories produce more goods than any in the world. What is needed to become more competitive in the global marketplace are better measurements to improve the way American manufacturing facilities are managed.

PROJECTED PRODUCTIVITY

(Based on average growth, 1950 to 1988)

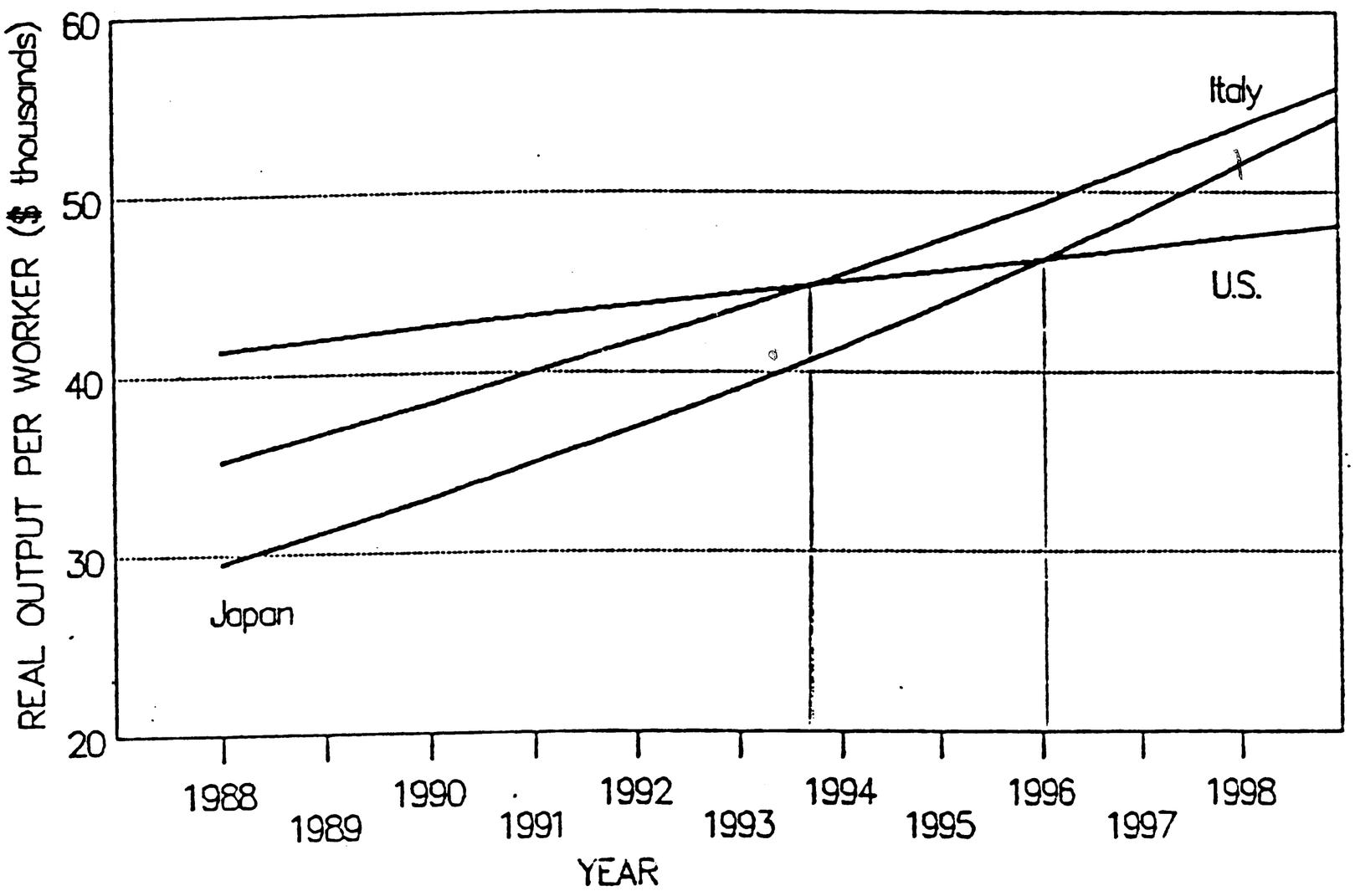

Figure 1: Projected World Productivity Leader

This data also shows that the U.S. would lose the top spot by 1994, if this historical trend continues (See Figure 1). Overall U.S. productivity has been growing more slowly

PROJECTED PRODUCTIVITY

(Based on average growth, 1950 to 1988)

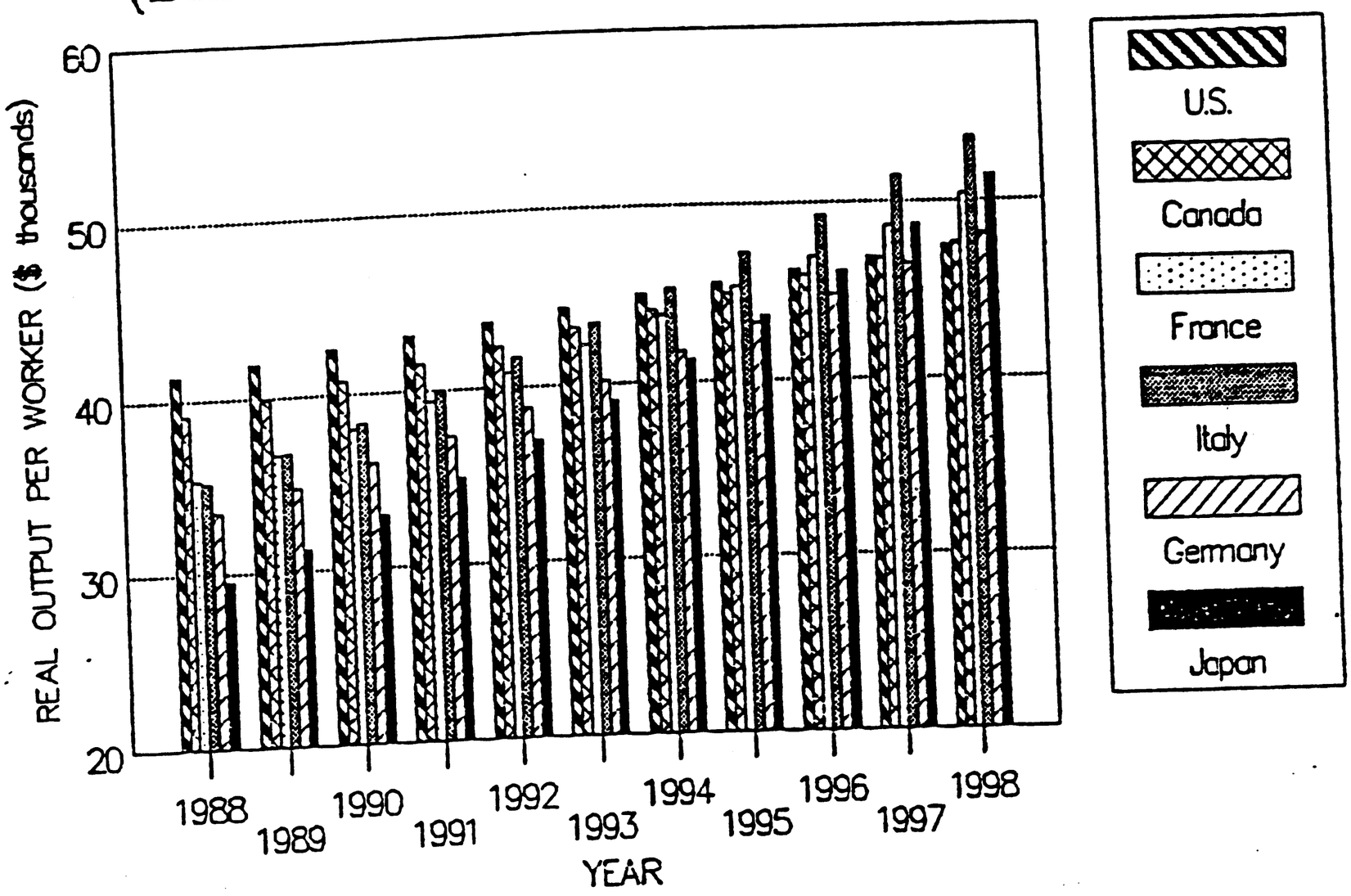

Figure 2: Projected Productivity Levels

than that if its trading partners for at least 50 years. Indeed, if America's productivity keeps growing at this rate, Canada, France, Italy, Germany and Japan would surpass it before the year 2000 (See Figure 2). The solution: increased innovation and efficiency in the way Western manufacturing plants are managed.

Numerous books and articles have also demonstrated that the installation of computers and technically advanced machinery in our factories will not be sufficient, by

itself, to restore our competitive edge. The more pressure we apply for increases in productivity, the more elusive becomes the objective of recovering competitive strength. The savings available are marginal, yet they require much effort and ingenuity to accomplish. The problems that we face are *structural* and *competitive* and require fundamental changes in strategy as well as the way we operate our factories.

The Manufacturing Studies Board of the National Research Council concluded that the most important factor in improving responsiveness, flexibility, costs, and quality in U.S. manufacturing firms will be the effectiveness of management practices, organizational design, and decision-making criteria [16]. The rapidly changing, highly competitive, global manufacturing environment requires the development of an aggressive operations-based competitive strategy.

The Role of Manufacturing Planning and Control Systems

The firm's manufacturing planning and control (MPC) system is the vehicle of communication that is increasingly being used to coordinate the execution of the overall manufacturing strategy. The MPC system is identified as the central focus for computer integrated manufacturing (CIM) [32]. The MPC system provides the link between financial, engineering, sales/marketing, and quality assurance en-

tities. The effective application of CIM philosophies, and therefore MPC systems, is essential for improving competitiveness in the years to come.

Global competition is the result of recent advances in communication and transportation technologies. It has brought with it increased customer expectations for product quality, customization, delivery performance and value. This has intensified the demand for effective MPC systems.

The importance of sound, innovative manufacturing management practices cannot be underemphasized. If American manufacturing firms are to maintain their position as the world's most productive, they must embrace management philosophies that will be unsurpassed by any other.

The time has come to re-evaluate the way we measure the performance of MPC systems. "Show me how you are going to measure my performance, and I'll show you how I will behave". [18] This brief synopsis of human behavior says a lot about the manner in which performance measurements impact overall system performance. It is important to measure and reward performance appropriately. This paper will emphasize simple measures which help firms to adopt a long-term perspective and focus on overall system performance. Performance measures should be developed to encourage behavior which supports the overall goals of the enterprise.

The most effective MPC systems are those that achieve the highest throughput, with a given level of resources, while remaining responsive to customer demands. The MPC system should be based on policies that are simple and consistent, so that the planning and execution functions can be performed within the system in a routine manner. These systems should be supported by an integrated data base that is consistent, accurate and appropriate. The data base should be accessible to all functional divisions within the firm, so that information can be shared and the global objectives of the firm are readily communicated.

It is important to note that the so-called "ideal" MPC system is not a static target. There is always room for improvement. Furthermore, it is necessary for the system to be tailored to the specific needs of the firm, which will change over time.

To summarize, the preceding discussion has shown that there is clearly a need for improvement in American manufacturing companies. Furthermore, it would be very difficult to obtain significant improvement via marginal changes in manufacturing productivity. Rather, such change should be directed at employing better measurements to improve the way we *manage* our companies. Since MPC systems are the backbone of manufacturing management, it is *there* that we should direct our efforts.

Introduction to Theory of Constraint Manufacturing

Theory of Constraint (TOC) manufacturing is based on the concept of making a firm competitive by focusing managerial attention on total system performance. The manufacturing organization adopts one goal: to make money now and in the future, thus ensuring prosperity. Three financial measures, profit, return-on-investment, and cash flow, are used to determine how well the firm is doing.

The day-to-day control mechanism in TOC manufacturing is the evaluation of progress in terms of three key operating measures: throughput, inventory, and operating expense. These measures correlate to the financial indicators, mentioned above. The manufacturing organization focuses effort on increases in throughput and reductions in inventory and operating expense to provide a favorable impact on the financial measures.

These global measures are used to evaluate the efficiency of MPC systems and develop methodologies for their operation that work within the limitations which exist within the manufacturing organization. This section is merely a brief introduction, meant to set the stage for the remainder of the paper. For more detailed information, please refer to Chapter 2.

Organization of this Paper

The greatest opportunity for improvement in American manufacturing firms lies in changing the way the enterprise is managed, to support the goals of the organization. Significant changes in the way we think will be required to accomplish this task.

This paper draws upon several contemporary manufacturing philosophies to show how American firms can progress from MPC systems based on traditional practices (ie: manufacturing resource planning (MRP)) to systems that will facilitate low-inventory manufacturing. This evolution has already begun in many firms that are making commitments to increase flexibility and responsiveness to customer demands by reducing inventories and production lead times.

The objective of the paper is to show how American firms can adopt these practices to develop more effective MPC systems. This will provide a significant competitive advantage, which is urgently needed in today's competitive environment. The emphasis is on MPC systems that are based on MRP II methodology, although the principles discussed are also applicable in the general case. The primary source of improvements are based on "Theory of Constraint" philosophies. Some concepts are also included from the domain of "Just In Time" (JIT) manufacturing.

The development of MPC systems for competitive manufacturing is presented in five chapters. The first chapter has established the need for and importance of improvements in MPC systems of American manufacturing companies. Chapter 2 presents an in-depth discussion of TOC philosophies, measurements, and examples. Chapter 3 is devoted to MRP. The major sections cover it's historical development, strengths, weaknesses, and reforms required in evolving to TOC. Chapter 4 explains how JIT concepts can be integrated with MRP and TOC to produce a highly responsive, efficient and flexible MPC system. Conclusions and a summary are presented in Chapter 5.

Chapter 2

Theory of Constraint Manufacturing

The first chapter has shown that American manufacturing firms should seek better measurements, instead of marginal improvements in productivity, to restore competitiveness. More appropriate performance measures would lead directly to improvements in the way manufacturing facilities are managed. It is my belief that the successful application of Theory of Constraint philosophies will provide such improvements, helping us to meet the competitive challenges of the future.

A secondary research intent of this paper is to provide the reader with a comprehensive overview of TOC concepts. This paper provides an objective summary and review of TOC philosophies. TOC appears to many to be a simple extension of common sense management. The typical reader wonders why it is considered new, and feels its the way they have been managing all along. Experience with TOC, however, shows that it is at odds with many standard management measures. Thus the application of TOC is found to be subtle, and not as straight-forward as thought at first.

The reader will develop a foundation for further study of the Theory of Constraints. Since the successful application of TOC concepts involves a fundamental change in the way people think about managing a factory, it is difficult to achieve through reading and study alone. It can be assimilated much more completely in an active role. Participants learn while analyzing their own production systems and, occasionally, from their own errors.

Many of the previously published articles involve comparisons which seldom differentiate between methodology and philosophy [1] [15]. MRP, for example, is a methodology which is commercially packaged as software. TOC (and JIT) are philosophies. TOC is not implemented like a software package. MPC systems based on commercial software packages typically rely on rigid discipline and the direction of experts (often from outside the firm). In TOC manufacturing, management is primarily concerned with developing the ability to manage in terms of the "throughput world" instead of the "cost world". In the throughput world the organization will focus on the flow of profit through the constraint, rather than on some conventional objective, such as maximizing the efficiency of all resources. This change is a product of learning experiences geared to induce employees to invent their own solutions and become experts in their own right. It leads to the development of a

process of ongoing improvement within the organization, which is essential to avoid stagnation.

This chapter begins with an introduction to basic issues about manufacturing organizations in the context of TOC manufacturing. Next, the fundamental rules and ideas of constraint management are presented along with some comparisons to traditional management practices. Implementation issues and the management of change is addressed. Finally, an example is presented to illustrate the contrast between TOC and conventional practices.

History

About 1980, Dr. Eliyahu Goldratt began asking fundamental questions about how American factories are managed. Not satisfied with conventional methods, he developed new ideas based on scheduling jobs in production facilities while considering limitations in the capacity of machines, personnel, tools, and other resources. The schedules produced were feasible and accurate. Since that time, Goldratt and Robert Fox have gone on to expand the original concept by developing a logical approach to managing the entire enterprise. This approach to manufacturing is based on focusing attention on the entities within the system that limit overall performance, hence the name: "Theory of Constraints". TOC continues to evolve beyond shop floor scheduling, emphasizing total system performance and the process of continuous improvement.

Global Measurements

As mentioned in Chapter 1, the goal of the firm is to make money now and in the future, thus ensuring prosperity. The three financial measures, profit, return-on-investment, and cash flow, are used to evaluate performance. Profit is an absolute measure which simply reveals how much money the firm has made. **Return-on-investment**, a relative measure, provides a measurement which gauges performance based on the investment in the firm. **Cash flow** is the term which is used to address the perpetual question of whether or not the firm is generating cash at the rate required to support operations.

Three formal operating measures used in TOC manufacturing are throughput, inventory, and operating expense. **Throughput** is defined as the rate at which the factory (system) generates money through sales. An important distinction in this definition of throughput is the reference to *sales*. When something is produced it doesn't become throughput until it is sold. (Before it is sold, its simply inventory.)

Inventory consists of the money invested by the system in acquiring things which are intended for conversion and resale. This includes raw materials, work-in-process, finished goods, supplies, and machinery. Supplies and

machinery are converted to operating expense as they are consumed. External reporting, for tax purposes and the investment community, mandates the use of "value added" inventory valuation procedures. This falsely inflates profit levels, since finished goods inventory is equated to profit in the conventional technique. Most professionals agree that separate financial statements should be prepared for external reporting and internal managerial purposes [9]. Inventory valuation for internal purposes should not include value added due to direct labor. Expenditures for labor are included in operating expense. These practices yield earnings statements which provide a much better indicator of performance in light of overall objectives.

Operating expense is the money that is spent turning inventory into throughput. This includes all expenditures that actually contribute to converting inventory into sales. Examples include wages, salaries, depreciation of buildings and equipment, effective sales promotions and scrapped material.

Throughput, inventory and operating expense can be readily correlated to traditional financial measures, as shown in Table 2.

Management's main objective can be expressed as "simultaneously increasing throughput while reducing inventory and

Net Profit = Throughput - Operating Expense
Return-On-Investment = Net Profit / Investment
Productivity = Throughput / Operating Expense

Table 2: Correlation of Performance Measures

operating expense", although all three variables need not change simultaneously in order to affect a positive change.

Control Measurements

Control measurements can be used to monitor subsystems as well as complete systems. The three control measurements prescribed in TOC are throughput-dollar-days, inventory-dollar-days, and local-operating-expense.

Throughput-dollar-days are a measure of due date performance. This is a method of quantifying the deviation of the firm from its promised commitments to clients. Throughput-dollar-days measures the due date performance of a plant or a division by assigning to every missed order a value equal to its selling price multiplied by the number of days the shipment is already late. In the past, due date performance was typically evaluated using a more myopic measure, such as the percentage of orders that were shipped on time. Throughput-dollar-days give management a much

better indication of due date performance. It can also be extended to measure the performance of subsystems such as production departments and functional areas, like engineering and accounting.

Inventory-dollar-days is a measurement which gives management a better way to evaluate the impact of carrying inventory. In recent years, manufacturing professionals have universally accepted the fact that carrying inventory which cannot be sold is undesirable. In conventional practice, inventory levels are typically computed simply by summing the value of all inventory on hand. Inventory-dollar-days improves upon this measure by including the time that the goods are held prior to sale. To calculate inventory-dollar-days, multiply the value of the inventory by the length of time it will be on hand. The inventory-dollar-days for an entire plant is the sum of the individual inventory-dollar-days for each item. Upon examination it becomes apparent that, generally speaking, the items that make the largest contribution to inventory-dollar-days are those that are expected to be held for an extended period. The reduction of these inventories will not have an adverse effect on customer service. In fact, these inventories usually are the result of producing goods the plant cannot sell, as in attempts to boost local efficiencies, reduce

variances, or to cover up for a drop in sales in some previous period.

Local-operating-expense is defined as the operating expense over which the local area has full control. When dealing with control measurements, one should only assign to a subsystem those expenses which are controlled solely by that subsystem. This allows the personnel in the subsystem to concentrate on (and be rewarded for) reductions in those expenses which they are responsible for. In assigning local-operating-expense, a production department would not be assigned some percentage of the plant's administrative staff, for example, since those people have no control over it.

Performance measures should focus on overall capabilities, not on one set of costs. Simplicity is another important aspect of sound performance measurement practices. This view is epitomized by the ideas put forth in TOC literature which emphasize a disregard for local performance measures, in favor of global measures. TOC proponents advocate the abandonment of individual work center or departmental efficiencies in favor of aggregate plant measures such as inventory-dollar-days.

It is my belief that TOC provides a means for firms to establish measures that will translate the impact of local actions into overall organizational performance. Firms that

are engaged in the application of TOC will be involved in a process of fundamental change. Changes which involve detailed analyses of the way they operate, frequently challenging operational procedures and reward systems. What better time to develop concise, meaningful, performance measures that really reflect the impact of actions on the bottom line of the firm?

Rules of Constraint Management

The rules and corollaries that are explained in the following five subsections are a mixture of common sense and non-traditional thinking. They are deceptively simple and frequently contradict methodologies that are widely used in manufacturing companies. In many ways TOC challenges us to question and evaluate the way we operate our factories.

The examples used in this chapter apply to a manufacturing firm which has an internal constraint, meaning the firm has one or more processes which have a level of demand greater than 100% of available capacity. This prevents the firm from manufacturing all the goods it is able to sell. The concept of a constraint is not limited to machines within production systems. It can be used to analyze the relationship between functional departments within the organization or external to the firm. The principles discussed can readily be extended to firms with external constraints or constraints which exist in some functional department such as engineering, marketing, etc.

1. Identify the constraints of the system.

In finding constraints in a manufacturing area, talk to those who have direct line responsibility for daily production. Where do they go first when looking for late

orders? Which work centers consistently seem to have the most work-in-process (WIP) queued up?

Another method, of course, is to calculate the daily requirements of all suspect work centers and compare the results with the daily capacity available. While this appears to be the most logical approach, bear in mind that the data used for time standards are at best unreliable and quite possibly, totally wrong.

2. Develop methods to exploit the constraint(s).

The throughput of the constraint determines the throughput for the entire system. Think of a production line in terms of a pipeline (see Figure 3). The production rate of each station on the line corresponds to the diameter

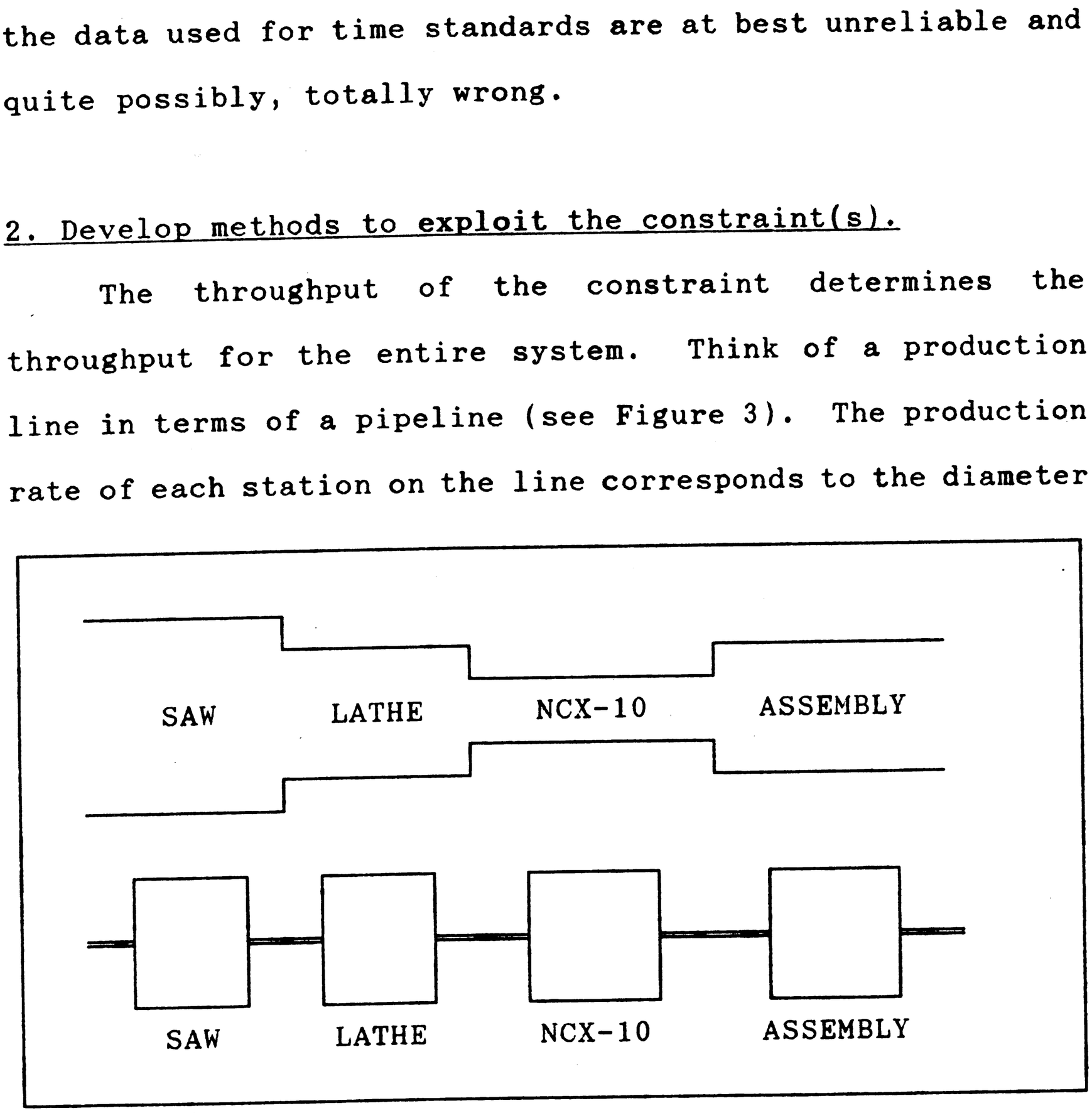

Figure 3: Pipeline Analogy for Machine Capacity

of the pipe at that stage. This analogy shows how a constraint in a manufacturing area will determine the throughput of the entire system. Thus, it is imperative that the constraint be managed in such a way that its throughput is maximized.

The following methods illustrate the concept of exploiting the constraint:

- Establish a buffer of work-in-process before the constraint to insure that throughput is not lost while the constraint sits idle, waiting for work.

- Employ quality control techniques before material is processed by the constraint. This will prevent wasting time at the constraint by processing defective material.

- Take added precautions to prevent material which has already been processed by the constraint from being scrapped during subsequent operations.

- Challenge operational policies that permit unnecessary idle time at constraints. For example, when a machine operator goes to lunch, does the machine sit idle or does another operator keep it running?

The key point is, lost production time at a constraint is equivalent to lost throughput for the system.

3. Subordinate everything else to support the decision.

To fully embrace this rule, it may be necessary to think in "unconventional" terms. For instance, it could happen that the throughput of a manufacturing plant might

be improved by *increasing* the direct labor content of operations. This could occur in a case where an additional 30 minutes spent by a non-constraint operation would save 15 minutes of processing time at a constraint. At first glance this sounds like a step in the wrong direction. However when the increase in throughput for the system is compared to the change (if any) in operating expense, it becomes apparent that this would be the proper thing to do. The level of utilization of non-constraint resources is not determined by their own potential, but by the constraints in the system.

Obtain a commitment from management (on all levels) to change performance measures and cost accounting practices so that they provide an appropriate indication of performance. Policies that mandate an overall level of machine utilization, for example, would be in direct conflict with TOC rules. It is important to examine policies and procedures in light of the overall operational objectives of throughput, inventory, and operating expense.

4. Elevate the system constraint(s).

The constraints should "set the pace" for the rest of the system. Release material into the system only as fast as the constraints can process it. A sufficient length of time should be allowed for some deviation from the optimal

schedule during the journey to the constraint resource. Experience will be the guide as to what is needed.

If material is released to maintain some arbitrary level of efficiency (as in traditional practice) the result will be high levels of work-in-process inventory. Excess WIP has the following effects: increases difficulty in controlling quality and minimizing rework, complicates scheduling, and makes the system less responsive to market demands and engineering change orders.

The master production schedule must be based on the throughput of the constraint resource(s). Once this has been achieved, scheduling the non-constraint resources is easy because of their excess capacity. The resulting schedule is realistic, since it is free of safety factors such as queue time estimates commonly used in MRP systems.

The throughput of the system is protected by a WIP buffer that queues work to prior to processing by the constraint. This buffer is referred to as a "time buffer" since its function is to protect the throughput of the constraint for some predetermined length of time. The duration is equivalent to the amount of time required by the constraint to process the work in the buffer. The time buffer prevents the constraint from being starved for work in the event upstream processes are interrupted. The key aspects of strategically placed inventory buffers are

presented later in this chapter, in the section titled "Buffer Management".

5. Do not allow inertia to become the system constraint.

TOC manufacturing requires a commitment to the process of ongoing improvement. As changes are implemented that eliminate constraints (by exploiting their potential) don't manage the system as if the old constraint were still present. Re-examine the situation to find the new constraints.

If a firm has one or more internal constraints, it is able to sell everything it is currently able to produce. As policy changes occur, manning levels are adjusted, or additional equipment is acquired the constraint may shift within the factory or even outside the factory. If throughput is improved to the point that the factory is able to produce more than it can sell, an external constraint exists. In this case the external constraint is the market. If new markets are found, new products are introduced, or staff levels are reduced the constraint may move back into the factory once again. This is the beginning of a cycle which continues as internal constraints are solved, throughput is increased to the point that the market becomes the constraint. The external constraint serves as a catalyst

for growth by providing opportunities to expand markets, enter new markets, or introduce new products.

Any time the constraint is internal the marketing staff should prioritize the products they are trying to sell. Simply stated, they should focus on the sale of items which are produced using the least amount of available constraint time. The entire product line can be prioritized to identify those items that generate the most revenue per hour of constraint time consumed. This will maximize profit.

Constraints come in many forms. Other types of constraint include policy, technology, vendors, and government regulations. An example of a policy constraint would be a requirement calling for the use of the traditional formula for economic order quantity to determine all lot sizes.

The Myth of Balanced Capacity

Traditionally, manufacturers have tried to design production systems in which capacity was balanced across a sequence of processes. A simple mathematical analysis of this situation, including ordinary variations in processing times, shows how difficult it is to operate such a system at the theoretical output rate. The effect of the statistical variation is cumulative. The only way to compensate for this phenomenon is to provide WIP between every operation, which is undesirable.

Instead of balancing capacity, TOC suggests focusing efforts to balance the flow of products through the system. Rather than adding WIP to a balanced system to buffer the effects of statistical variations, it is preferable to manage the unbalanced system according to the Theory of Constraints.

Utilization Issues

An internal constraint is defined as a resource that has demands which are greater than 100% of the capacity available. Thus, in order to maintain throughput, a constraint resource should always be in prcduction or being set up for its next operation, with special consideration taken to minimize the number of setups.

Non-constraints on the other hand, have an additional time element called *protective capacity* (See Figure 4).

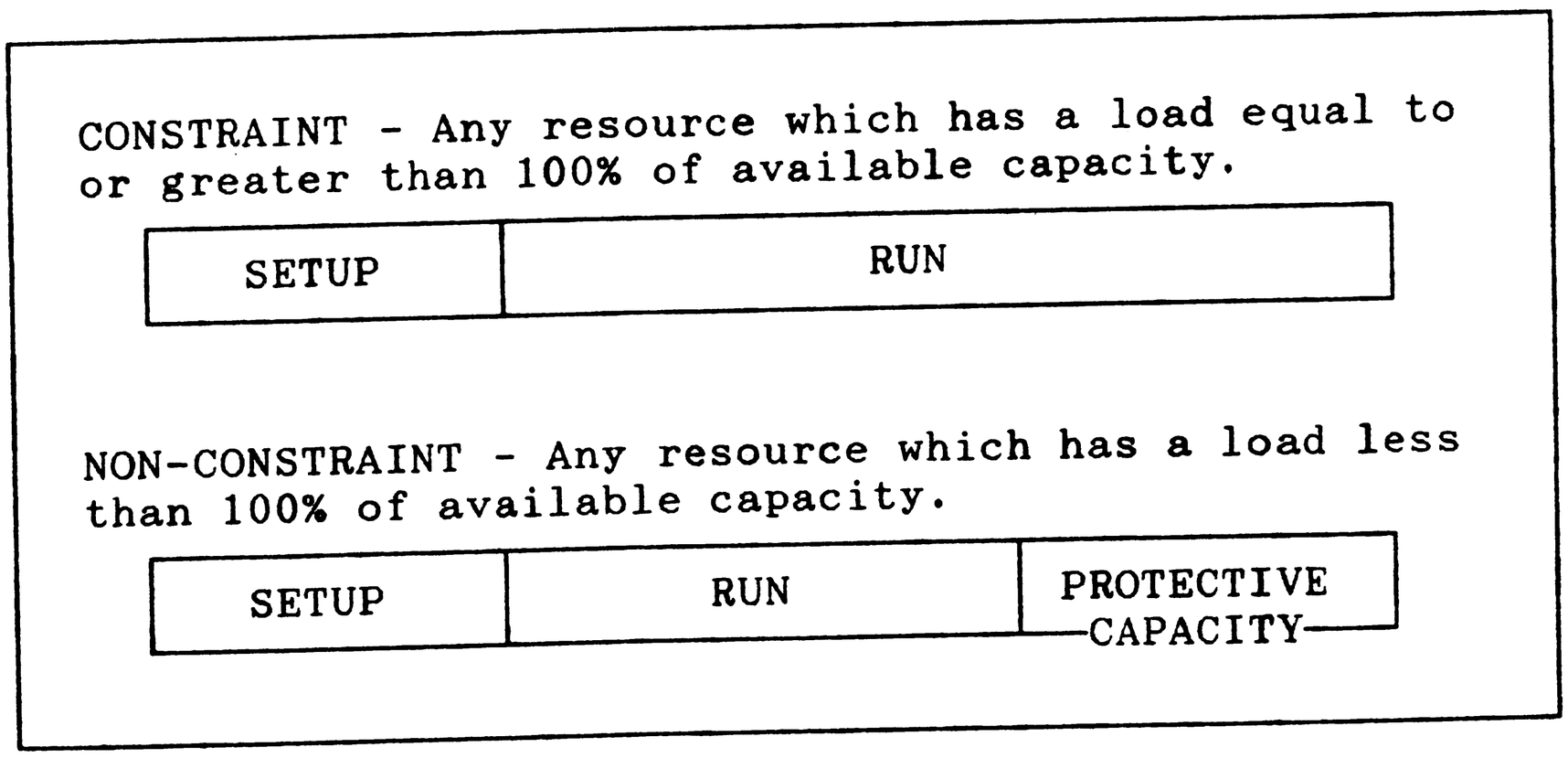

Figure 4: Protective Capacity

This idle time occurs because non-constraints are loaded to less than 100% of capacity, by definition. Excess time could be used to produce additional inventory, but that would be counter-productive since we are producing all we can sell. Protective capacity will manifest itself as idle time or it can be used in some way without effecting throughput. The protective capacity of non-constraints provides the following competitive advantages (which are not available in a manufacturing system with balanced capacity):

- The ability to absorb statistical variations or respond to fluctuations in product demand without carrying WIP inventory. Only the throughput of constraints must be protected in this manner.

- Extra setups can be performed at non-constraint resources. This allows the firm to use smaller process batch sizes to reduce WIP inventory without sacrificing throughput.

- Increased system responsiveness to react to unforeseen business opportunities, quality issues, and demands for product customization.

Since non-constraints have excess capacity, there is little incentive to employ setup reduction programs there. Rather, setup reduction programs should be applied to the constraints. In addition, since downtime equates to lost sales, maintenance personnel should be instructed to give the constraints top priority. If a constraint resource breaks down, drop everything else and fix it.

A non-constraint resource could be made into a constraint if it became unable to meet all the demands placed on it for recovering from statistical fluctuations, making extra setups, or other such occurrences. This does not occur, as long as proper scheduling techniques are employed.

The reduction in WIP which can be obtained by implementing low-inventory manufacturing has some important benefits. The velocity of orders moving through the factory increases as WIP is reduced. The lead time reduction minimizes dependence on marketing forecasts. This makes the firm more profitable, since the ability to manufacture only goods which can be sold is improved. The costs of carrying inventory, scheduling, quality, and engineering change orders are all reduced as the level of WIP diminishes.

Buffer Management

The strategic placement of inventory buffers is an important TOC concept. Buffers should be placed at critical locations, defined below, to insure that system throughput and due date performance are maintained. The three critical locations for buffers are:

(1) before the constraint process

(2) in front of the market

(3) at the point where non-constraint throughput is assembled to constraint throughput.

Buffers protect against the effects of routine disturbances and variations. The illustration in this section describes a constraint buffer. An example which illustrates the use of buffers for assembly operations and marketing concerns is featured later in the paper. Due date performance is protected by the buffers at assembly areas. Assembly buffers allow for variations in time of arrival between components which have dissimilar process routings. Shipping buffers protect the system from fluctuations in market demand.

The purpose of the buffer is to insure that the constraint is never starved. The size of the buffer is measured in units of time. The amount of inventory in the buffer provides time which is used to protect against disturbances. If an order expected in the buffer from upstream operations is delayed, a "hole" in the buffer results. According to buffer management principles, buffers are divided into three regions, as illustrated in Figure 5. Orders progress from Region III to Region I over time as the constraint, assembly area, or shipping area consumes inventory. A general guideline used in managing the buffers is that all items in Region I should be physically present in the buffer. If not, expediting should be used to get that order back on schedule. In Region II a small percentage of holes are permissible. Exceptions should be

noted for orders that have been delayed. In Region III, more holes are tolerated.

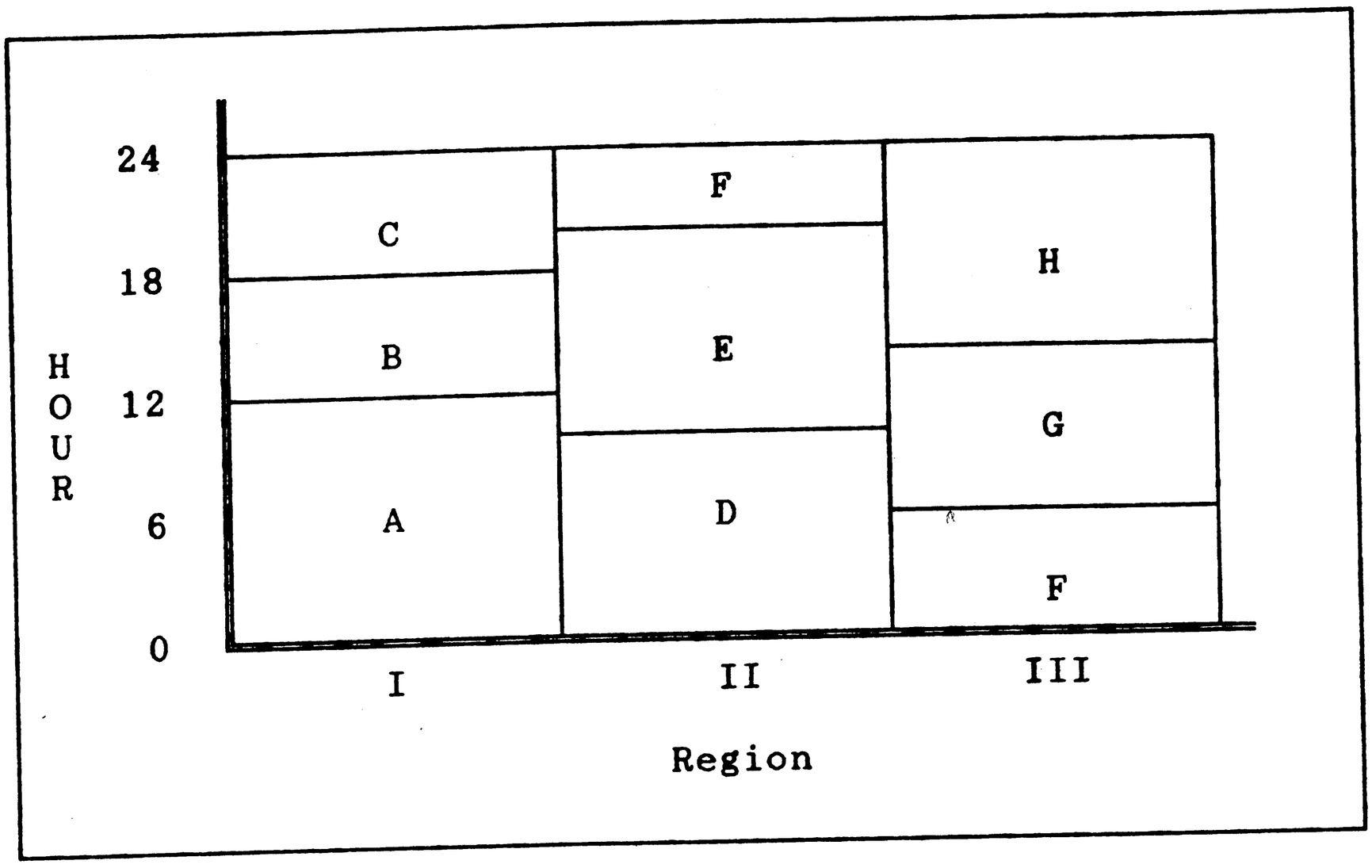

Figure 5: Buffer Management

The size of a buffer is determined by trial and error. The time buffer should stage enough work to cover the majority of disturbances. Begin with some arbitrary amount and gradually reduce this level until the buffer level occasionally comes close to empty. Experience in operation is the best guide.

By analyzing the buffers according to buffer management principles, managers can identify orders that may jeopardize system throughput or due date performance. More importantly, they can determine *why* the material is late, and take

steps to eliminate such disturbances with help from engineering, maintenance, purchasing, etc. Buffer management provides an impetus for improving the reliability for upstream operations.

It is possible to control an entire plant using buffer management. As the resource being protected consumes an order, one should be released into the system. This allows the firm to maintain a level amount of WIP inventory in their production system. This results in predictable manufacturing lead times, a competitive advantage for the firm.

Implementation Issues

Managing resistance to change is the greatest challenge facing the implementation of TOC philosophies. Organ and Bateman explain the root cause of resistance to change:

> Early perspectives on resistance to change construed it either as an unhealthy trait of the particular persons demonstrating it or as a deep-rooted frailty of human nature in general. Not infrequently, those proposing change and confronting resistance viewed it as "defensive," "irrational," or "pathological."
>
> We now realize that to view resistance to change as a form of sickness or irrationality is at best simplistic, if not self-serving on the part of those advocating change. The inescapable reality of organizational change is that it never redounds to the equal benefit of all parties affected, and ... it is usually the case that some parties lose when change occurs. It is therefore instructive to regard most forms of resistance to change as eminently rational behavior acted out for self-interest. [21, p.656]

Perceptions vary as to what people expect as a consequence of change. Change is commonly believed to result in a loss of security or autonomy. Those in managerial roles may project reductions in power and status. People lose their "investments in the status quo" if long years of learning and mastering a set of operations have to be discarded as a result of change.

It is clearly important to allay these concerns if the organization is going to adopt the sweeping changes necessary to incorporate TOC manufacturing. The key elements in

an implementation plan designed to elicit cooperation from the entire organization are involvement, participation, education, and communication.

An invitation to participate in planning and execution of change is frequently used to enlist support. Involvement promotes a sense of identification with the proposed change, thus leading to commitment to see the change effectively implemented. Education of all personnel, from top management to the factory floor, is paramount to the success of any large-scale change. Another critical factor is the enlistment of top management's support. None of these efforts would be possible without communication.

One theme that should be emphasized in the application of TOC manufacturing is learning process. The responsible parties should feel some ownership of the new ideas in order to affect long-term changes in attitudes and behavior. This process is exemplified by the "socratic approach" to teaching TOC principles. This is a technique which involves providing thought-provoking discussion and questions, rather than pre-formulated answers, to the implementation team so that they come up with their own solutions. This type of problem solving approach is described below:

1. Use scientific reasoning to identify core problems.

2. Use consensus-type problem solving to provide simple solutions.

3. Induce the "owners" to invent and implement these solutions.

The implementation of TOC manufacturing requires dramatic changes in the rules used to manage the company. Birk [3] recommends a three-tiered approach to education:

> **Management Education** - This is designed to promote the involvement and support of top management. Top management must understand the impact of the changes and the necessity for departure from conventional methods currently in use.
>
> **Production Management Education** - This includes materials management, purchasing, scheduling, factory supervision, and support functions. It must provide a full understanding of the concepts, with particular emphasis on scheduling and managing constraints.
>
> **General Education** - All other employees should be exposed to the basic concepts. The finance department must be exposed to the ramifications on cost accounting.

The implementation of Theory of Constraint manufacturing is an iterative process that requires change in three main areas: focus of productivity improvements, scheduling methods, and the cultural environment.

A Simple Plant Example

At this point in the paper, the following things have been accomplished: We have established a need for improvements in the way American manufacturing firms are managed. It has been suggested that the application of the Theory of Constraints can help make management more efficient via changes in MPC systems. Such improvements should make manufacturing firms more competitive. The fundamental measurements, rules, and concepts of TOC manufacturing have been introduced. Some of the difficulties encountered during the process of organizational change were explained.

Experience has shown that although one may agree with the simple logic of TOC philosophies, it is nonetheless very difficult to change the way we think about managing a manufacturing system. To illustrate this phenomenon, consider a model of a simple production system, shown in Figure 6.

In this model system the student is charged with the operation of a simple plant [18]. The plant produces a product called Product P, which sells for $90 per unit, and the market will take 100 units per week. Product P is assembled by Resource D, who does all the assembly work in the plant. The assembly operation takes 10 minutes, and involves combining a purchased part costing $5 and two

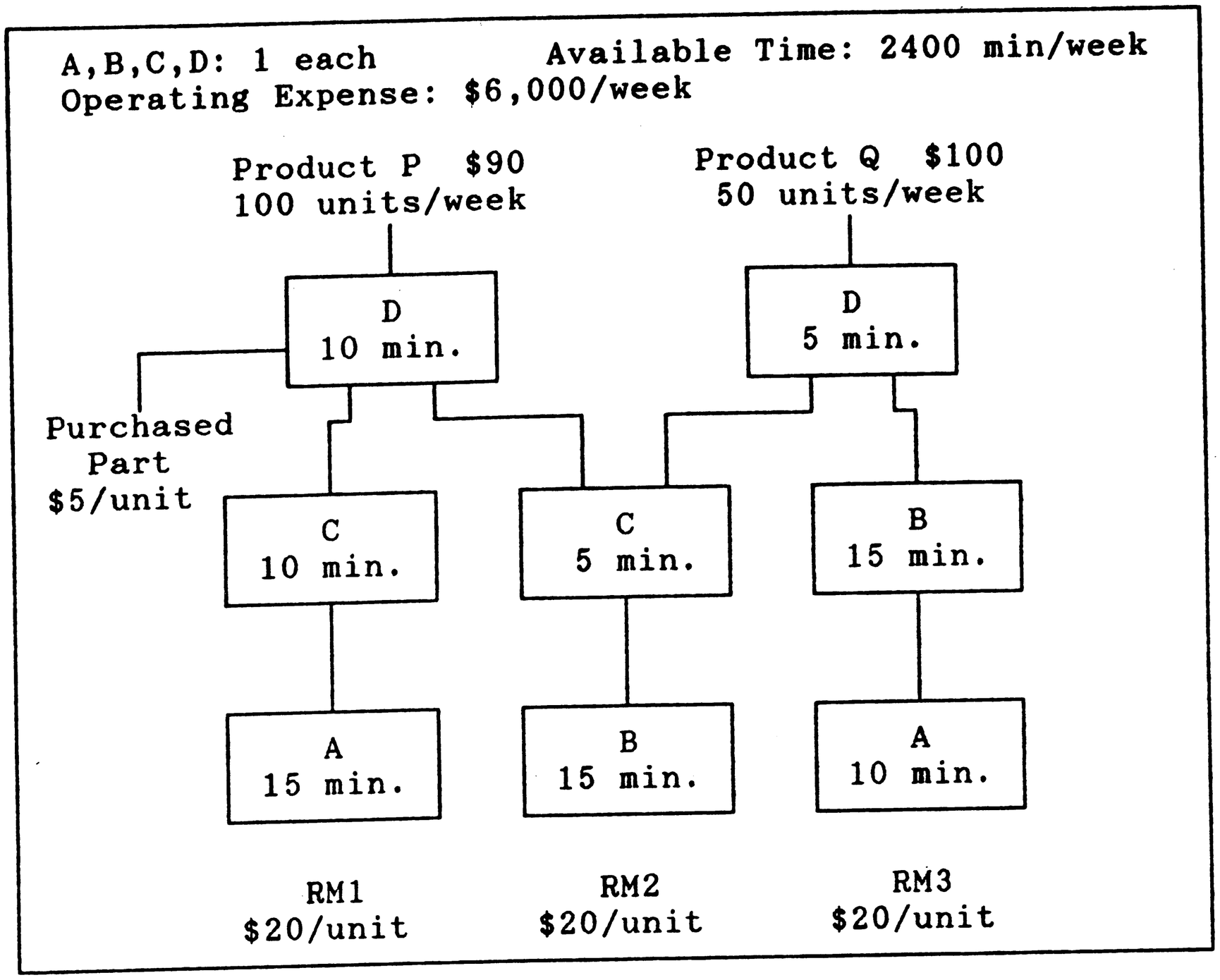

Figure 6: Model Production System

manufactured parts. Those manufactured parts are made from two different raw materials. Raw Material 1 starts out with Resource A, which takes 15 minutes to work on it, and then it goes on to Resource C, where 10 minutes are spent. Raw Material 2 starts with 15 minutes at Resource B, followed by five minutes at Resource C. When all three of these components are assembled by Resource D, the plant has produced finished Product P.

The plant manufactures a second product, Product Q, which sells for $100, at a rate of 50 per week. It is also assembled by Resource D, but requires only five minutes for assembly. It uses two parts, one made from Raw Material 3 costing $20, which goes through Resource A and then B, and the other part used is the same component used in Product P. The plant has only one of each Resource A, B, C, and D. The plant operates for 2,400 minutes (40 hours) per week at a cost of $6,000 per week for operating expenses. The first question for the student: how much money can this plant make in one week?

Starting with Product P, selling price of $90 less raw materials which cost $45, results in a contribution margin of $45 per unit. At 100 units per week, Product P generates $4,500 each week. With Product Q selling at $100, raw materials at $40 and 50 units per week comes out to $3,000 per week. So total sales are $7,500 and operating expenses are $6,000, suggesting net profit is $1,500 per week. This methodology assumes that the plant can make everything. Did we stop and think about identifying the plant's constraint? Surprisingly, even when this type of problem follows an introduction to TOC rules, most people proceed directly to some sort of profit calculation without considering even the first TOC rule -- identify the constraint.

To answer this question adequately, one must compare the work load required for each resource with the capacity of each resource available. To evaluate Resource A, note

Resource	Process Load/Week	Available Time/Week	Percent Load/Week
A	15 X 100 = 1,500 10 X 50 = 500 2,000	2,400	83%
B	15 X 100 = 1,500 15 X 50 = 750 15 X 50 = 750 3,000	2,400	125%
C	10 X 100 = 1,000 5 X 100 = 500 5 X 50 = 250 1,750	2,400	73%
D	10 X 100 = 1,000 5 X 50 = 250 1,250	2,400	52%

Figure 7: Identifying the Constraint

that 15 minutes are required for each Product P made and 10 minutes for each Product Q. Therefore, making all 100 pieces of Product P would take 1,500 minutes and 50 pieces of Product Q is another 500 minutes. The total work load on Resource A is 2,000 minutes, or 83% of available capacity. The remaining work centers are evaluated in the same manner, the results are shown in Figure 7. This calculation shows that there is an internal constraint present, Resource

B, so the profit calculation made earlier must be invalid (because it isn't possible to make everything).

Now the task is to determine the "best" product mix. Earlier in the discussion it was shown that the contribution margin of Product P is $45 per unit and $60 per unit for Product Q. Furthermore, upon considering direct labor content, it takes 55 minutes to make each unit of Product P and 50 minutes for Product Q. So it seems logical to make all 50 units of Product Q and then use the rest of the capacity on Product P.

To allocate the capacity of Resource B, the constraint, 30 minutes are required for each of 50 units of Product Q made. This accounts for 1,500 minutes of Resource B, leaving 900 minutes for Product P. At 15 minutes per piece, 60 units of Product P can be produced.

Now the expected profit using the product mix of 60 units Product P and 50 units Product Q can be computed. Product P generates $45 per unit, for a contribution of $2,700. Product Q generates $60 per unit, or $3,000, for a total contribution of $5,700. The operating expense is $6,000, so the plant would lose money!

Let's review the logic behind the product mix decision. When it was decided that the most profitable product mix must be determined, it was because Resource B had been identified as a constraint or key resource. However, when

the cost was calculated, all resources were treated as if they were equal, all labor was handled the same. Since Resource B is the critical one, the product mix decision should have been based on it because the constraint dictates how much can be produced. How many units of the constraint does it take to get one unit of Product P? Which product generates more profit for the system? Figure 8 illustrates a TOC approach to determining the product mix.

Product	P	Q
Selling Price	$90.00	$100.00
Raw Material Costs	$45.00	$ 40.00
Unit Contribution	$45.00	$ 60.00
Constraint Time (Resource B/Unit)	15 min.	30 min.
Contribution per Constraint Minute	$ 3.00	$ 2.00

Therefore, Product P is preferable.

Figure 8: TOC Approach to Product Mix

So every time the constraint is used to make Product P, $3 per constraint unit-time is generated. Product P allows us to utilize the constraint better.

To confirm this, calculate the profit generated by the system if 100 units of Product P are produced, followed by as many units of Product Q as time allows. 100 units of

Product P will require 1,500 minutes of Resource B, leaving 900 minutes in which to make components for Product Q. At 30 minutes per unit, 30 units of Product Q can be produced. With this product mix, the contribution of Product P would be $4,500 and the contribution of Product Q would be $1,800. The profit margin using this approach would be $6,300 less operating expenses, or $300.

The TOC approach has many advantages in this example, aside from the fact that it allows the system to show a profit. The TOC approach to product costing requires less time, effort, and money than the conventional approach. With this method it isn't necessary to know the amount of time required at each and every operation. Operating this production system would also be easier using TOC practices. Instead of releasing raw materials in an effort to maximize the utilization of all four resources, focus attention on keeping the constraint busy. By releasing material only at the rate it would be processed by the constraint inventory costs, the cost of quality, and the level of management effort would all be minimized. Throughput, and therefore profit, would be maximized.

In conventional management practices it is very common to strive for the highest possible efficiencies on all resources in the plant. The performance of workers and production supervisors are commonly measured this way.

Consider the utilization of Resource A which would result if the product mix is 100 units of Product P and 30 units of Product Q. To make each Product P, 15 minutes of Resource A are required, or 1,500 minutes of work for Resource A. To make 30 units of Product Q, another 300 minutes of work are required at Resource A. So, the total work load on Resource A is 1,800 minutes per week out of 2,400 minutes of available capacity per week. If Resource A is used to make only what is needed, it's efficiency would be 75%. This would not be tolerated in a plant operated under conventional practices. If Resource A were operated at 100% efficiency, the plant would not be able to sell any more product. Since Resource B is already operating at 100% of capacity, the extra material processed by Resource A would pile up as excess work-in-process inventory.

The focus of the next chapter is Manufacturing Resource Planning. The strengths and weaknesses of MRP are examined in light of the fact that MRP is presently the most widely used manufacturing planning and control methodology in American firms. Ideas are presented which suggest how firms can begin a transition from MPC systems based solely on MRP methodology to systems which use MRP combined with TOC. The chapter concludes with an example which illustrates the TOC approach.

Chapter 3

Manufacturing Resource Planning

This chapter deals with the role of MRP in a TOC-based manufacturing planning and control system. It begins with a brief overview of Manufacturing Resource Planning. A detailed discussion of MRP methodology can be found in Vollman, Berry and Whybark [32]. The term MRP refers, in this paper, to the fundamental technique that began with material requirements planning and has been extended to closed-loop MRP, MRP II, and beyond, using other techniques such as finite scheduling.

The limitations of MRP are presented in the second section of the chapter to emphasize the need to develop a more streamlined approach to manufacturing planning and control. The contributions that MRP can make in a TOC-based MPC system is the topic of the third major section.

The chapter concludes with an example which provides a comparison between traditional operational policies and the same policies modified to include the TOC approach.

The MRP Approach

MRP began in the 1960s as an alternative to order point systems, which were based on average demand plus safety stocks (to protect against fluctuations in demand). The introduction of business computing systems made MRP a workable technique on a wide scale. MRP offered the ability to order based on scheduled requirements for the items that use the material. As people learned the importance of properly managing the master schedule, MRP evolved into a priority planning system. Subsequently the term "closed-loop MRP", was coined to signify the addition of iterative procedures which improved scheduling. More recently, MRP II added interfaces to the financial system.

Central to the approach is an MRP component inventory planning system surrounded by other logistics modules such as the master schedule, capacity planning, order release, and shop floor control. Typically, the MRP system takes a combination of actual and forecasted customer orders and develops a master schedule of production. The master scheduling task is normally aided by a "rough-cut" capacity planning module. MRP explodes independent demand for a product, by using a backward scheduling technique which traces through the bill of materials, into dependent demand for its components. The resulting requirements are aggre-

gated and time-phased using established lead times and lot sizes to orchestrate the release of production orders. Planned order releases are used to conduct capacity analyses which test the overall validity of the production plan. Feedback on the actual status of production and purchase orders is compared to MRP due dates to establish priorities which are used to manage production facilities. The order priority system is used to help resolve the sequencing difficulties which arise from the competition for limited resources.

The MRP database, which includes the routing file, bills of material, and inventory status data, has proven to be a vital element in the implementation of CIM strategies. Firms have successfully used integrated databases and systems to meet the challenges imposed by shrinking product development and life cycles since the late seventies. A central database serves to coordinate the activities of independent functional areas. Since many firms have already spent a great deal of time and labor to put such databases and support systems in place, it would be highly attractive to continue using the MRP database, albeit in a slightly different manner.

Some notable add-ons to MRP II have recently been developed. Finite-scheduling software is being used to cope with schedules that are unrealistic, a common problem among

MRP users. Unworkable schedules are generally the result of the way MRP assumes infinite capacity when developing detailed production schedules. Finite-scheduling software produces meaningful schedules that plant personnel can believe in. It has also proven useful in making last minute changes to the production schedule such as determining quickly whether a hot new customer order can be accommodated without jeopardizing completion of other orders already in progress.

Another type of add-on product which is gaining popularity is a simulation package which allow users to perform "what-if" analyses without disturbing the database. Schedule simulation is useful in predicting bottlenecks and other problems while there is still time to correct them.

Despite such enhancements, many experts feel that the basic flaws inherent in MRP methodology will prove fatal to the technique. Two passages from Kanet typify the view of MRP which has become increasingly popular in recent years:

> MRP is *big business* in the field of production and inventory management, yet there is a rising tide of disappointment with the MRP-based methods and growing evidence that MRP may well *not* be "the" way to go in manufacturing.
>
> U.S. manufacturing has embraced MRP because it held the promise for reducing inventory and improving customer service, yet I see little evidence of any widespread major improvement along these lines. [13, p.57]

Aggarwal reports that while MRP offers no challenge to employees, it requires such extreme discipline and commitment at all levels that 90% of MRP users are unhappy with the results obtained [1].

Sheridan points out that only about 10% of companies with MRP II systems have achieved what the experts consider "Class A" status, meaning that they have realized 95% (or better) inventory accuracy and 95% on-time delivery to customers [29].

The following section will explore some of the more renowned criticisms of the MRP methodology. The third major section of this chapter will explain how MRP can continue to play a key role in low-inventory MPC systems which are founded on the application of TOC principles.

What's Wrong With MRP?

Throughout the decade of the eighties it seemed that production and inventory management experts were consistently faulting MRP users for inaccurate computer records, unrealistic master schedules, lack of top management commitment, and inadequate employee education. While it appears that these were common problems, it is still unclear if companies who successfully solved them have been able to realize enough improvement in their operations to put them ahead of their competitors.

The implementation problems described above would reduce the effectiveness of *any* type of MPC system. Any MPC system which is implemented without some basic level of sound data management practices, realistic aggregate production planning, top management commitment, and adequate user training will perform poorly.

Many publications suggest that implementation and operational issues are only part of the problem. The problems inherent to the MRP methodology, detailed below, seem to indicate that MRP is not a panacea, as has been frequently claimed since it gained widespread popularity.

Critics argue that MRP is too transaction oriented, meaning employees spend a disproportionate amount of time keying in data to update the computer on the status of shop-

floor activity, inventory, and other dynamic variables. MRP fosters the "hidden factory" syndrome, which simpler, less cumbersome MPC systems seek to eliminate. The hidden factory processes transactions on paper and in computer systems to support the operation of the real factory. The relative portion of operating expenses attributed to hidden factory costs have continued to rise as MRP-based systems have evolved. Low-inventory MPC systems, based on TOC and JIT principles, offer a reduction in the number of transactions required for routine operations.

Among the most common complaints levied against MRP are those regarding detailed production scheduling. The difficulties encountered in producing such schedules can be overcome using tools like finite-scheduling, as mentioned in the previous section. However, these enhancements are not free; they add to the initial cost of the system as well as the ongoing operating expenses.

MRP's sequential, independent processing of information has also been criticized as a fundamental weakness. The systematic MRP approach plans material at one level and then utilization of labor and machines at another level. Lot sizing, for example, is done prior to and independent of capacity planning and order sequencing/scheduling. To account for this, buffers of inventory and planned lead time are embedded everywhere within the system. Without the

addition of extra time and effort for a technique similar to schedule simulation, it is difficult to say with confidence whether or not a given master schedule can really be accomplished.

Detractors contend that MRP systems lack well-designed formal feedback procedures. When a problem occurs on the shop floor, or raw material is delayed, there is no well-defined methodology for the system to recover. This promotes the creation of personal safety buffers by material planning personnel. MRP appears to be inadequate in handling last-minute changes to accommodate rush orders or unclog plant bottlenecks. Typically, critics point out, people must intervene to make changes that the MRP system can't handle. Informal manual procedures are commonly developed to cope.

The planned lead times that are included in every order often show up as excess work-in-process inventory. Since lead times are provided *a priori*, they cannot take into account the sequence in which jobs will be processed or the number of jobs that will be competing for limited production resources. The build-up of safety lead time, queue time, transaction time, and other forms of organizational slack has been referred to as the "cascaded contingencies" of MRP.

A norm of traditional manufacturing management which has crept into the majority of MRP-based MPC systems is the

tenet that the majority of production resources should be utilized as much as possible. This results in the release of excess work-in-process inventory to the floor in order to boost resource utilization. As mentioned in Chapter 2, excess WIP results in additional expense in quality control, scheduling, engineering change orders, etc.

Shop floor control modules in MRP-based systems seldom allow for variations in batch sizes. The Theory of Constraints differentiates between process and transfer batches to improve overall system performance. A **process** batch is defined as the number of pieces a work center processes before switching to another job. A **transfer** batch is the designation for the number of pieces transported between work centers by material handling equipment. Transfer batches are used in TOC manufacturing to take advantage of the protective capacity available at non-constraint resources. Protective capacity is used to increase the material velocity of orders going through the system. This is achieved by performing more frequent setups at non-constraint resources in order to reduce batch sizes. Conversely, process batch sizes are increased for constraint resources to boost system throughput by reducing the number of setups performed as much as practical.

To summarize, while I do agree that MRP has continued to evolve and become more effective, my conclusion is that

the flaws are so basic that the MRP approach, by itself, cannot provide the improved MPC system effectiveness that is needed to develop world class manufacturing capabilities. Incremental improvements to MRP, no matter how rapid, will not be enough to provide the performance improvements needed to restore our competitive edge. What is needed is a new approach to manufacturing planning and control which is built on sound, logical principles, capable of providing real improvements in the effectiveness of management practices.

There is no need to consider abandoning the MRP approach. I advocate the use of MRP practices in two key areas: (1) in long-range, aggregate planning functions and (2) to use MRP systems to provide a central, commonly accessible, integrated database. These issues will be addressed in the next section, which will expand on this approach and identify some of the important contributions that MRP can make in low-inventory MPC systems.

The Role of MRP in Manufacturing Planning and Control

One of the important tasks that MRP is well suited for in a low-inventory MPC system is long-range planning. In an aggregate sense, it is very capable of coordinating production capacity with anticipated market demand. The "rough-cut" capacity planning exercise linked to the creation of a master schedule *does* take into account a plant's overall capacity constraints. This facet of MRP is unencumbered by assumptions which treat production resources as though they have infinite capacity.

Master production schedules which approximate the output of products on a time-phased basis can be used to identify the demands placed on production and purchasing resources a year or more in advance. MRP is useful in timing the release of purchase orders for components and materials, and in providing advance notice of likely future requirements which can be communicated to vendors.

Perhaps the most important aspect of MRP is the database. It can serve as a focal point in integrating the exchange of information between functional departments. This ability is particularly attractive to the thousands of U.S. manufacturers that have already established such databases as well as procedures to ensure that they remain accurate as conditions change. It would be difficult to

overestimate the magnitude of the competitive advantage that is afforded by the information available to a firm which has access to a top-notch integrated database. Well-formulated MPC systems do not stand alone. They must be driven by data that are appropriate, consistent, and accurate. The payoffs achieved with good MPC systems derive largely from a substitution of information for inventory and other forms of organizational slack.

My opinion is that firms who recognize the need for the sweeping changes in management practices professed by TOC and JIT philosophies should adopt a two-tiered approach. First, recognize that MRP is useful as both an aggregate planning tool and as a focus for an integrated database. Secondly, TOC philosophies can provide workable schedules which can be executed in a low-inventory production environment. Appropriately applied, TOC principles will result in measurement systems and management practices which can help optimize the performance of the enterprise as a whole. A genuine commitment to the process of continuous improvement will enable firms to progress to world class producers.

MRP systems produce management reports which are used to assess the performance of manufacturing operations and to interface with other functional areas, such as marketing, finance, and engineering. Performance measures and reward

systems play a very important role in the effectiveness of management systems.

Firms implementing TOC or JIT methodologies should carefully evaluate their concept of labor efficiency. These philosophies require operators to produce only what is scheduled and no more. Operators are expected to use excess capacity to perform additional setups or other tasks which traditionally were classified as indirect labor functions. Correspondingly, machine efficiency takes on a different meaning in a low-inventory environment.

Traditional cost accounting measures have occasionally resulted in local optimization at the expense of the total performance of the system. One example of this phenomenon is a policy which triggers the release of work orders to maintain high utilization of production resources, without regard to the potential sale of the finished products. Such policies may have a negative impact on long-term system performance by rewarding production workers for creating finished goods inventory which cannot be sold.

A comparison of past and present performance is commonly used to gauge progress. This technique is only appropriate for measures that are truly relevant to the overall effectiveness of the system. It is counter-productive, for example, to compare direct labor hours from one period to another without regard for other factors which may

be present. Suppose a firm adds a gee-whiz robotic assembly system. Those who justified the system may be pleased to report the reduction in direct labor, but they also may tend to neglect the corresponding increase in indirect labor or overhead support staff. Effective performance assessment requires the development of an evaluation system that identifies the contribution of each factor, and then tracks and combines them.

These are some of the more compelling issues regarding effective performance measurements. As mentioned in the introductory chapter, this topic will recur throughout the paper.

To supplement the ideas presented thus far in this paper, the following section is included to illustrate the type of changes that are involved in applying the TOC approach.

A Model Production System: Educational Tool

To illustrate the application of TOC scheduling logic and operating policies a model of a production system will be presented and discussed [18]. The model is essentially a simplified version of the manufacturing simulation packages commonly employed in the design and analysis of production facilities. It is a computer-based, stochastic representation of a simple production facility. The intent of this exercise is to demonstrate the difference in system performance that results when traditional MRP-based management practices are changed to accommodate TOC rules for scheduling and managing a production facility. It also allows one to analyze how we think about managing a factory without being distracted by the simple problems which typically require managerial attention, such as absenteeism.

The model plant consists of five different types of resources engaged in the conversion of four types of raw

Resource	Quantity	Setup Time (minutes)
B	1	15
C	2	60
G	2	120
M	2	30
W	1	0

Figure 9: Model Production System Resources

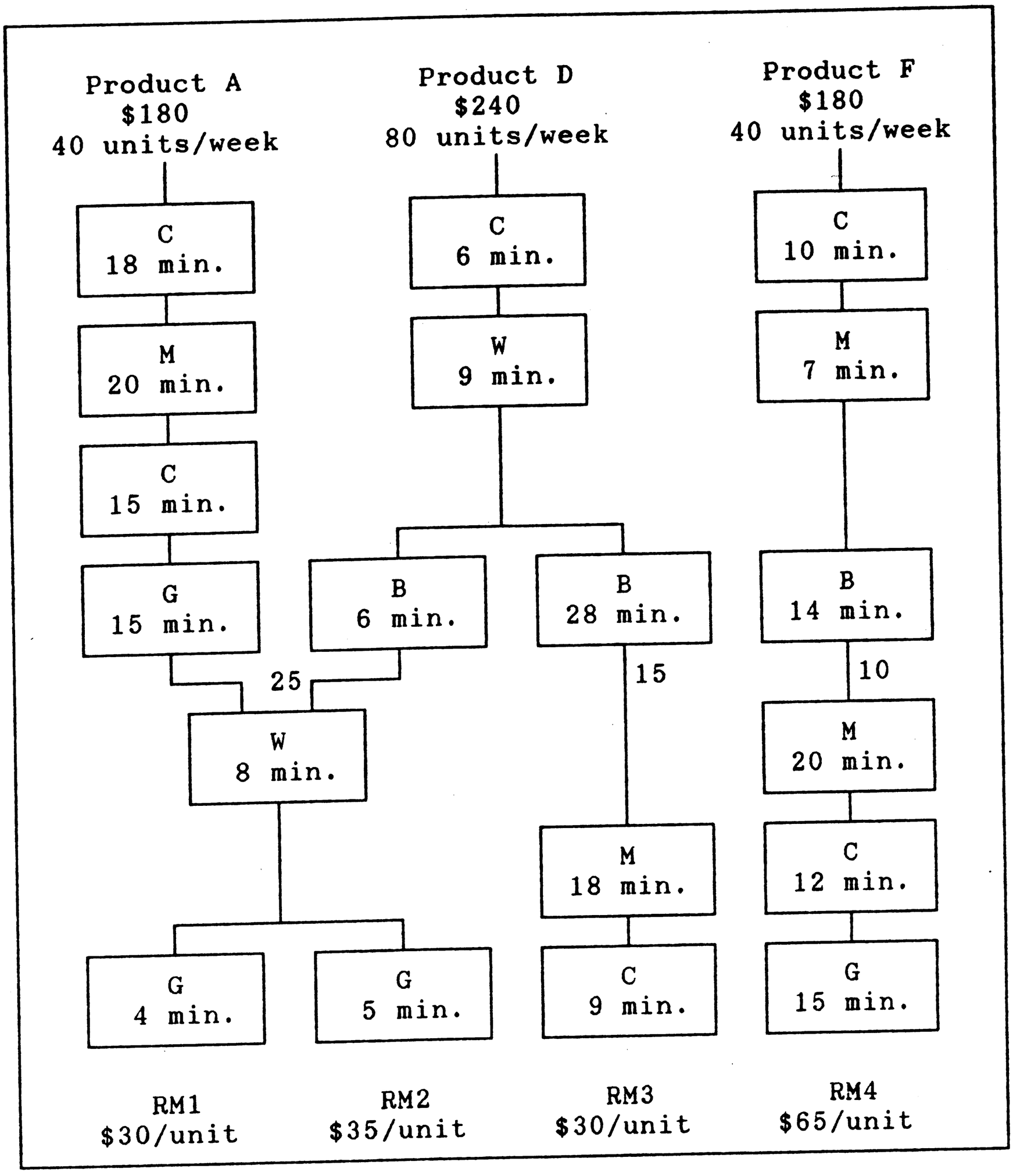

Figure 10: Model Production System

materials into three different finished products. (Refer to Figures 9 and 10.) Note that the plant consists of a total of eight production resources. All resources except

Resource W require an average amount of setup time each time they begin working on a different order. The plant begins each run with 50 pieces of work-in-process inventory as indicated in the diagram.

The weekly demand rate and selling price for each product is included in Figure 10. The operating period for each simulation run is one week. The plant starts with $2,500 in cash with which raw materials are purchased. Additional funds are generated by the sale of finished goods, which are assumed to be instantly sold as they are completed. At the end of the simulation run $11,000 is subtracted from the cash-on-hand for operating expenses. Figure 10 reveals the bill of materials and routing data for the three products, in addition to serving as a representation of the fictitious plant.

The operating rules used by plant management for the first simulation run are based on the traditional MRP approach. The objective is to produce 40 units of Product A, 80 units of Product D, and 40 units of Product F. The general operating principles of *"Keep everyone busy!"* and "Minimize setups" are the mottos on the shop floor. Cash is spent to purchase raw materials in accordance with these objectives. The results, shown in Figure 14, are discussed later in this chapter.

In the second simulation run the plant is operated according to TOC principles. The first task is to identify the constraint. According to the data in Figure 11, the

Resource	Process Load/Week	Available Time/Week	Percent Load/Week
B	3,325	2,400	138%
C	3,505	4,800	73%
G	2,385	4,800	50%
M	2,940	4,800	61%
W	1,480	2,400	62%

Figure 11: Identifying the Constraint

constraint is Resource B. Therefore, the first operating rule for the plant is *"Keep Resource B busy!"* In accordance with TOC logic, a corollary to the first rule is (for the other resources in the system) *"Perform a setup and begin work at any station which has material to work on; don't worry about idle time."* We have found that there is an internal constraint in the plant, so it is not possible to produce all of the products that the market will buy. The next step is to determine which products require the least amount of constraint time per dollar of contribution margin. This data is used to select the most profitable product mix, given the plant's limited resources. The results shown in

Figure 12 reveal that the most profitable strategy is to produce 40 units of Product A and 40 units of Product F, then devote the remaining constraint time to Product D.

Product	A	D	F
Selling Price	$ 180	$ 240	$ 180
Raw Material Costs	$ 65	$ 95	$ 65
Unit Contribution	$ 115	$ 135	$ 115
Constraint Time (Resource B/Unit)	0 min.	34 min.	14 min.
Contribution per Constraint Minute	*	$ 3.97	$ 8.21

Therefore, Product D is least preferable.

* denotes *market constraint* exists for this product

Figure 12: TOC Approach to Product Mix

Note that the market is the constraint in the case of Product A; the plant can produce all that the market will absorb without consuming any of Resource B's capacity. To compute the amount of constraint time that can be devoted to Product D, subtract the requirements for Product A and Product F from the total capacity available during the week. This leaves over 30 hours of capacity for Product D, time for approximately 50 units, assuming Resource B would incur two setups during the week in the production of each of the three different components required.

Given the most desireable product mix, 40 units of Product A, 50 units of Product D, and 40 units of Product F, the requirements for each type of component can be tabulated, thereby developing a production schedule for Resource B.

The key operating strategy for scheduling production for a constraint resource is the use of a time buffer of work-in-process inventory to protect throughput. This is accomplished by releasing material into the system at the rate it is processed by the constraint. The time buffer provides protection against unanticipated disturbances. The schedule developed for Resource B is shown in Figure 13.

Task	Time Required	Starting Time
Process 10 units RM4	155	0
Process 15 units RM2	105	156
Process 15 units RM3	435	261
Process 30 units RM4	435	696
Process 35 units RM2	225	1,131
Process 35 units RM3	995	1,356

Note: All figures are mean values, in minutes.

Figure 13: Production Schedule for Resource B

This production schedule is used to plan the purchase and release of raw materials by timing their release so that they will arrive slightly before they are scheduled to be processed by the constraint.

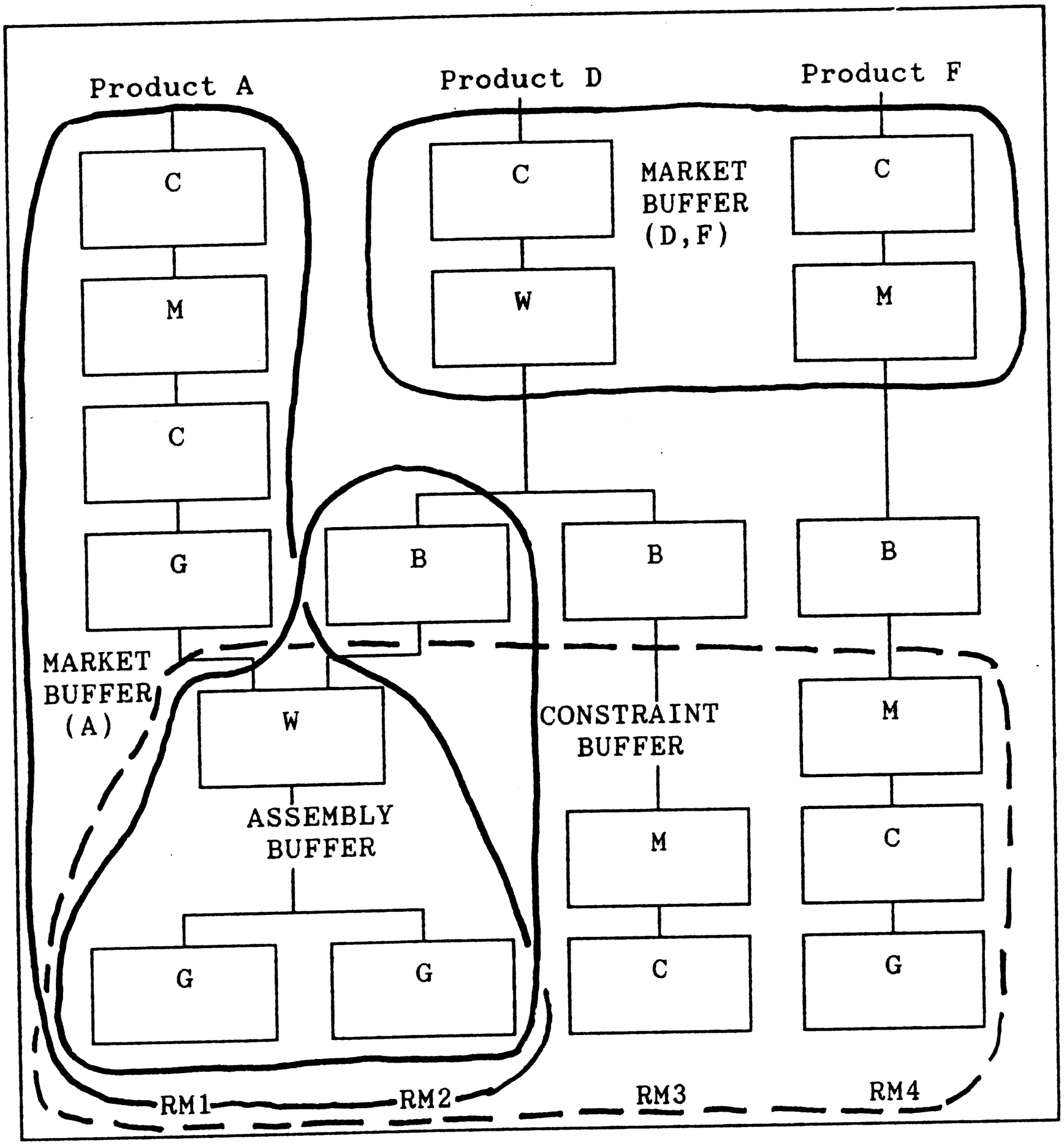

Figure 14: Model Production System Buffer Regions

Figure 14 illustrates how the resources in the production system affect the plant's constraint, market and assembly buffers. Note how every non-constraint resource within the production system can be monitored using buffer management techniques.

The weekly performances obtained during simulation runs using these two different approaches are shown in Figure 15.

Management Approach	Type 1 (MRP)	Type 2 (MRP/TOC)
Net Profit	$ 4,640	$ 5,305
Return On Investment	8.4%	9.6%
Sales	$25,080	$26,160
Inventory-Dollar-Days	15,440	2,820
Percent Utilization:	(Run + Setup = Total Util.)	
Resource B	95 + 5 = 100	97 + 3 = 100
Resource C	68 + 18 = 86	57 + 29 = 86
Resource G	63 + 27 = 90	35 + 41 = 76
Resource M	70 + 8 = 78	48 + 6 = 54
Resource W	53 + 0 = 53	41 + 0 = 41

Figure 15: Simulation Results

Several noteworthy trends are evident in the results. The methodology used to define operational policies for the first run produced "better" resource utilization as defined by the percentage of available time that was used for

production. However, the performance of the system as a whole is improved in the second run, as reflected by increases in profit, return on investment, and throughput as well as a reduction in work-in-process inventory. The inventory reduction results from the difference in material release strategies. In the first case, material is purchased and released in order to keep everyone busy.

Simulation exercises of this type are useful learning aids in the process of changing the cultural environment to encourage the application of TOC philosophies. These exercises do more than simply illustrate fundamental concepts. When presented as challenging phenomena for cooperative group analysis, rather than as dogmatic stand-alone solutions to the world's problems, such learning tools embody the type of changes that are occurring in many diverse companies that have taken steps to begin a process of ongoing improvement.

Chapter 4 will introduce concepts that are commonly attributed to Just-In-Time manufacturing which I believe can be effectively combined with TOC concepts to further improve an MRP-based MPC system.

Chapter 4

Just-In-Time Manufacturing

This paper would be incomplete without exploring Just-In-Time manufacturing, an approach to manufacturing management which has been steadily growing in popularity among Western manufacturers during the past ten years. JIT manufacturing involves the application of the Japanese approach to manufacturing management, adapted to account for the cultural and socio-economic differences between Japanese and American companies.

Like MRP and TOC, JIT originated as a shop floor methodology but was eventually developed into a complete management philosophy. Firms advocating JIT practices are seeking competitive advantages via manufacturing operations, as explained in Chapter 1. These goals are essentially shared by most every firm that has chartered a course to improve its agility and responsiveness, not just those embracing JIT. To provide a complete analysis of JIT philosophy is beyond the scope of this paper. This chapter begins with an overview of JIT methodologies, then examines the similarities in the JIT and TOC approaches, and closes with a discussion of JIT performance measures.

Characteristics of Just-In-Time Manufacturing

The goals of JIT manufacturing are generally acknowledged as the pursuit of zero inventories, zero transactions, and zero disturbances (a.k.a. routine, reliable execution of the production schedule). O'Grady [20] identifies a fourfold explanation of JIT objectives:

- o attack fundamental problems
- o eliminate waste
- o strive for simplicity
- o devise systems to identify problems.

In other words, a process of continuous improvement which employs a fundamental problem-solving approach to drive organizational slack to zero.

In terms of aggregate planning functions, JIT drives toward more stable production schedules which are met by eliminating interruptions caused by quality problems and disturbances. Disturbances are handled first by encouraging workers to take the time to solve unexpected problems as they happen, and secondly by providing sufficient capacity to absorb the sort of statistical variations that are expected to occur in any production environment. Reduced lead times and work-in-process inventories result in less uncertainty between the master schedule and actual demand,

which allows firms to shift from make-to-stock operations to a make-to-order mode.

JIT methodologies include the reduction of the number of levels in the bill of materials and the number of part numbers that require planning resources. This emphasis is closely coupled to the importance placed on the development of manufacturing process cells that are capable of producing complete products, or at least major sub-assemblies. These cells are operated with a drive toward setup time reduction, diminishing lot sizes, the pursuit of improved quality via process improvement, and velocity of product through the system. They promote continual improvement as a goal and as a rule for routine operations, as well as worker involvement; using the worker's knowledge to reduce overhead staff support. JIT proponents claim that increased material velocity results in orders that move through the factory so quickly that it is unnecessary to use a complex shop-floor control system to track their progress. More importantly, JIT production facilities are highly responsive to customer demands due to WIP inventory reductions.

Many of the JIT objectives are time related; the idea is to reduce the time required to:

- receive and inspect materials arriving from suppliers
- move product between work centers
- set up equipment

- o run product (including time between batches)
- o move product between factories, warehouses and distribution centers.

As the time spent performing these activities is reduced, material velocity is increased, less inventory is required, and the firm becomes more responsive to changes in demand rate or product mix. If quality problems, equipment malfunctions, absenteeism and other factors that slow down these activities can be minimized, then time and inventories can be further reduced.

Firms implementing JIT purchasing techniques are seeking better working relationships with an increasingly smaller number of vendors. The promise of JIT purchasing techniques is that both the supplier and customer will benefit from a new level of cooperation, coordination, and integration of purchasing functions. This relationship is geared toward cost reductions for both parties, which stem from inventory reductions, increased quality, and stable schedules that lead to long-term blanket orders. JIT purchasing is a good example of a "new" technique that has primarily been associated with JIT yet could be readily applied in an MPC system which is based on virtually any management philosophy.

The "whole person concept" is described as the keystone of continual learning and improvement [32]. It is based on

the premise that firms have much to gain if they can think in terms of hiring people's minds as well as their muscles. Workers are cross trained among traditional direct labor tasks to provide added capacity to handle workload surges and solve quality/production problems. They are also trained in areas typically associated with indirect labor: maintenance, data entry, scheduling, and problem solving. The added autonomy also provides some intangible benefits to the firm in terms of employee satisfaction, motivation, and the development of personnel who may emerge as candidates to fill future leadership positions.

Continual improvement and worker involvement are considered maxims for day-to-day JIT operations. The idea is that each day one should get better in some dimension, such as improved process yield, more output, or fewer breakdowns. JIT formalizes the process of eliciting ideas from production workers for productivity improvements and task simplification. In the past, worker participation was an informal process in most Western firms, and political or interpersonal barriers to worker input were commonplace. JIT serves as a focal point which tends to reduce the gap between traditional white collar/blue collar roles by sharing both the responsibility and the rewards for productivity improvements.

The grouping of equipment into manufacturing cells is another strategy which is often associated with JIT, yet appears to be effective (when properly utilized) regardless of the underlying MPC system philosophy. The equipment needed to manufacture a family of similar products or subassemblies is selected and configured in a cellular arrangement. Workers are cross trained so that they can operate several different pieces of equipment or perform various functions. The layout of equipment serves to minimize WIP inventories and material handling requirements, while enhancing worker interaction and autonomy. The most significant advantage that manufacturing cells offer is flexible capacity. Production capacity or product mix changes can be handled readily, simply by increasing or decreasing staff levels.

JIT and TOC: A Similar Approach to Continuous Improvement?

TOC manufacturing began with a shop floor methodology which was based on the elimination of production bottlenecks. The strategy was simple: to find and exploit the portions within the manufacturing system which had the greatest potential for improvement. TOC manufacturing evolved into problem-solving techniques which helped "separate the important few from the trivial many." Like JIT, TOC focuses on continuous improvement and the elimination of organizational slack, in the form of excess inventories and unnecessary transaction processing. Both methods advocate only producing that which can be sold, never releasing orders simply to utilize people or equipment. Excess capacity is viewed as a competitive weapon, which can be used to absorb variations in demand or in the manufacturing processes. Excess capacity translates into flexible capacity, which allows the firm to be responsive to variations in market demand or to take advantage of unanticipated business opportunities.

Both JIT and TOC recognize the overall performance improvements that occur when the velocity of products travelling through the system is increased. TOC manufacturing utilizes a technique, outlined in Chapter 3, which

differentiates between process and transfer batches to improve material velocity and system throughput.

In JIT manufacturing, this competitive advantage results from the utilization of a kanban or "pull" type system to control the day-to-day material flow and scheduling tasks. Instead of releasing individual work orders to meet production requirements, scheduling is accomplished by planning a level output of product according to a predetermined hourly, daily, or weekly product mix. Rao and Scheraga explain the change encountered while progressing from a traditional Western manufacturing environment to JIT:

> Most companies using MRP II are discrete batch manufacturers, where production planning and control is done by job lot or work order. However, when a company implements JIT ... it progressively takes on more and more of a repetitive character, with production planning and control done by flow rates. [24, p.44]

Under the pull system, no work center is allowed to produce parts just to keep people or machines busy. A work center is only authorized to produce when it has been signaled that there is a need for more parts in a downstream department. The net results of a level production schedule and the pull system are lot size reductions, quality improvements, limited WIP inventories, and faster throughput.

Shop floor control in TOC manufacturing is described using an analogy referred to as Drum-Buffer-Rope. The Drum

corresponds to the capacity of the bottleneck resource which is used to determine the production rate which the remainder of the production line "marches to". The only places within the system where work-in-process inventory is allowed to accumulate are the Buffers, which are strategically located to protect system throughput and due date performance. The Rope refers to a signal which is used to coordinate the introduction of orders into the system with the production rate of the constraint. Chapter 2 contains a detailed explanation of buffer management practices.

In TOC, system constraints determine how setup time reduction efforts should be applied. TOC recognizes that setup time reduction is only crucial for resources that are constraints, or could become constraints depending upon order mix or statistical variations in process times. JIT methods call for reductions in setup time throughout the production system. This subtle difference is representative of the relationship between JIT and TOC. The JIT approach involves the elimination of waste throughout the system. TOC, on the other hand, approaches the process of improvement with a narrower focus: concentrate on the system constraints. In JIT systems, WIP inventory is distributed throughout the system. When a plant employs the buffer management techniques proposed by TOC, inventory is concentrated at key places in the system. Both techniques

provide a system which is highly responsive to customer demands, but the TOC approach is better in terms of protecting system throughput.

An important point to consider regarding JIT philosophies is that a majority of the ideas which are commonly associated with JIT manufacturing are not the strict intellectual property of Just-In-Time proponents. The JIT concepts described in this chapter can be applied to complement the flexibility, responsiveness, and production capacity of most any MPC system. Firms should not feel a need to choose between MRP, JIT, TOC, or any other approach. Instead, they should proceed in a logical fashion to tailor the appropriate ideas in order to improve the overall effectiveness of their MPC system.

An important facet of both JIT and TOC philosophies is the need for departure from performance measures based upon traditional cost accounting techniques. It is essential to measure the effectiveness of an MPC system appropriately. Performance measures should focus on overall capabilities, not on one set of costs. Simplicity is another important aspect of sound performance measurement practices. Firms should be prepared to change performance measurement and reward systems as they incorporate TOC and JIT philosophies into their operations. Some of the least effective measurement systems are those that involve the use of reports or

data that aren't understood by the people using them to evaluate or modify behavior. If a performance measure is not understood on a fundamental level, it probably won't be used to benefit the firm in terms of long-term performance. Education at all levels and top management commitment will be important in this transition.

Chapter 5

Conclusion

This paper has shown how increased competition in the global marketplace has forced manufacturers to look for more effective ways to operate. The firm's manufacturing planning and control system is the focal point of managerial efforts and policies.

Mass production efforts developed to manufacture equipment during World War II led to the beginning of the modern manufacturing era. Economies of scale provided the world with low cost, mass produced goods. During the past three decades, economies of scale gave way to economies of scope. Advances in technology, world-wide sourcing, and other factors as explained in Chapter 1 have resulted in higher customer expectations. Highly competitive markets demand small production runs, stringent quality standards, and a high degree of product customization. These requirements translate into a demand for management philosophies which incorporate flexible and responsive production systems capable of delivering world class products.

Manufacturing Resource Planning started as a methodology to generate component requirements and schedule resour-

ces on the shop floor. It grew into a philosophy which includes aggregate planning, purchasing, cost systems, accounting and performance measurement functions.

Some people would have you believe that if you optimize all of your processes and functions, you are guaranteed optimum system performance. In manufacturing management just the opposite is true. In order to optimize the throughput of every process in a factory, you would have to buffer each process with work-in-process inventory. High levels of inventory result in manufacturing systems which hide quality problems and are unresponsive to changes in product demand.

Just-In-Time manufacturing began as a methodology to minimize inventory and increase the velocity of orders flowing through production facilities. It evolved into a philosophy based upon the whole person concept, continuous improvement, world class quality standards, and the systematic elimination of organizational slack.

The Theory of Constraints originated as a methodology for increasing system performance by focusing improvement on the portion of the system with the greatest potential for improvement. It has evolved into a philosophy based upon systematic and controlled continuous improvement, the relationships between system throughput and inventory levels, and global performance measures.

Some people consider JIT and TOC to be very different. We have seen how methodologies can be extended to develop management philosophies for the entire organization. The more you view JIT and TOC as philosophies, the easier it is to view them as compatible.

I believe they are very compatible and really quite the same. Systems based purely on JIT spread inventory around; the TOC approach uses inventory strategically to protect throughput or to determine where system constraints are. JIT becomes less effective when the product mix changes; TOC can tolerate product mix changes. (If product mix changes cause the constraint to change, you have to recognize the new constraint and manage accordingly.) In essence, TOC combines a more focused approach to continuous improvement with the most important benefits of JIT: high product velocity, high quality, worker autonomy, etc.

Firms should develop and use simple, easy to understand performance measures to encourage behavior that supports the overall goals of the firm. Given the demands imposed by customers in our increasingly competitive global marketplace, the most important measure appears to be manufacturing lead time performance. Simple measures, such as throughput-dollar-days, can help manufacturing companies to use due date performance for a competitive advantage.

Additional market pressure for responsive manufacturing systems and high quality standards are indicative of increased managerial complexity. In this competitive environment we need to manage the flow of information as well as the flow of material.

Developing more effective management tools provides a manufacturing company with a powerful competitive weapon. A manufacturer will be better able to respond quickly to customer demands with a quality product, on time, and in the right quantity. The end results are satisfied customers, insured survival of the firm, increased profits, reduced operating expenses, and less difficulty in managing the business.

The application of the Theory of Constraints can serve as a focal point for such improvements. To be successful, firms must make a commitment to analyze their business in a fundamental sense and customize their MPC system to their unique situation. This paper has shown how MRP, TOC, and JIT can contribute to more effective MPC systems. Firms that maintain or develop a position as a world class manufacturer in the years ahead will devote significant energies to improving their MPC systems and, thus, the way they manage their business.

References

1. Aggarwal, Sumar C., "MRP, JIT, OPT, FMS? Making sense of Production Operations Systems" *Harvard Business Review* (September-October 1985), pp. 8-12,16.

2. Berger, S., Dertouzos, M.L., Lester, R.K., Solow, R.M., and Thurow, L.C., "Toward a New Industrial America" *Scientific American* (June 1989), pp. 39-47.

3. Birk, Donald M., "Increase Your Profits By Managing Your Constraints" *1986 APICS Conference Proceedings.* American Production and Inventory Control Society, Falls Church, Virginia, 1986.

4. Chew, W. Bruce, "No-Nonsense Guide to Measuring Productivity." *Harvard Business Review* (January-February 1988), pp.110-118.

5. Cross, Kelvin F., *Manufacturing Planning: Key to Improving Industrial Productivity.* Marcel Dekker, New York, 1986.

6. Civerolo, John J., and Rice, Don, "MRP II and JIT Make a Tough, Competitive Combination" *American Production and Inventory Control Society 1986 Conference Proceedings* pp. 120-124.

7. Federico, Pat-Anthony, *Management Information Systems and Organizational Behavior.* Praeger, New York, 1935.

8. Goldratt, Eliyahu M., and Cox, Jeff, *The Goal.* North River Press, Croton-on-Hudson, New York, 1986.

9. Goldratt, Eliyahu M., and Fox, Robert E., "The Fundamental Measures" *The Theory of Constraints Journal* (August-September 1988), pp. 1-21.

10. Goldratt, Eliyahu M., and Fox, Robert E., *The Race.* North River Press, Croton-on-Hudson, New York, 1986.

11. Groover, Mikell P., *Automation, Production Systems, and Computer Integrated Manufacturing.* Prentice-Hall, Englewood Cliffs, New Jersey, 1987.

12. Gunn, Thomas G., *Manufacturing for Competitive Advantage*. Ballinger Publishing, Cambridge, Massachusetts, 1987.

13. Kanet, John J., "MRP 96: Time to Rethink Manufacturing Logistics" *Production and Inventory Management Journal* (Second Quarter 1988), pp. 57-61.

14. Krenz, Keith A., "Theory of Constraint Seminar" Lecture Notes, Lehigh University, Bethlehem, Pennsylvania, September 15, 1989.

15. Lundrigan, Robert, "What is this thing called OPT?" *Production and Inventory Management* (Second Quarter 1986), pp. 2-12.

16. Manufacturing Studies Board, National Research Council, *Toward a New Era in U.S. Manufacturing*. National Academy Press, Washington, D.C., 1986.

17. Miller, Stanley S., *Competitive Manufacturing*. Van Nostrand Reinhold, New York, 1988.

18. Nagel, Roger N. "Executive Decision Making Workshop" Seminar Notes and Materials, Lehigh University, Bethlehem, Pennsylvania, June 22-23, 1989.

19. Nasar, Sylvia, "Taking the Long View of America's 'Decline'". *U.S. News and World Report* (January 8, 1990), p. 58.

20. O'Grady, Peter J., *Putting the Just-In-Time Philosophy into Practice*. Nichols Publishing, New York, 1988.

21. Organ, Dennis W., Bateman, Thomas, *Organizational Behavior*. Business Publications, Plano, Texas, 1986.

22. Plenert, Gerhard and Best, Thomas E., "MRP, JIT, and OPT: What's 'Best'?" *Production and Inventory Management* (Second Quarter 1986), pp. 22-29.

23. Plossl, G.W., and Wight, O.W., *Production and Inventory Control Principles and Techniques*. Prentice-Hall, Englewood Cliffs, New Jersey, 1967.

24. Rao, Ashok, and Scheraga, David, "Moving from Manufacturing Resource Planning to Just-In-Time Manufacturing." *Production and Inventory Management* (First Quarter 1988) pp. 44-48.

25. Reinfeld, Nyles V., *Handbook of Production and Inventory Control.* Prentice-Hall, Englewood Cliffs, New Jersey, 1987.

26. Safizadeh, M. Hossein, and Raafat, Feraidoon, "Formal/ Informal Systems and MRP Implementation" *Production and Inventory Management* (First Quarter 1986) pp. 115-120.

27. Schonberger, Richard J., *Japanese Manufacturing Techniques: Nine Hidden Lessons in Simplicity.* Free Press, New York, 1982.

28. Schonberger, Richard J., *World Class Manufacturing: The Lessons of Simplicity Applied.* Free Press, New York, 1986.

29. Sheridan, John H., "MRP II: Still a Sound Control Strategy?" *Industry Week* (July 3, 1989), pp. 39-45.

30. Skinner, Wickham, *Manufacturing, The Formidable Competitive Weapon.* Wiley, New York, 1985.

31. Teresko, John, Goldstein, Mark, and Patterson, William Pat, "MRP II: Managing a Manufacturing Company" *Industry Week* (March 23, 1987) pp. 44-46.

32. Vollman, Thomas E., Berry, William L., Whybark, D. Clay, *Manufacturing Planning and Control Systems.* Irwin, Homewood, Illinois, 1988.

33. Wagner, James W., "Evolving Towards Theory of Constraint-Based Manufacturing Planning and Control Systems" Unpublished Report, Lehigh University, Bethlehem, Pennsylvania, 1989.

34. White, Richard W., "Is it Time for a Physical Exam of your Materials Requirement Planning System?" *Production and Inventory Management* (Third Quarter 1986) pp. 24-29.

35. Wight, Oliver W., *Manufacturing Resource Planning: MRP II Unlocking America's Productivity Potential.* Van Nostrand Reinhold, New York, 1984.

VITA

James Walter Wagner was born in Detroit, Michigan to James Sexton and Julia Elizabeth Wagner in 1961. He received a Bachelor of Science degree in Mechanical Engineering, with an emphasis in manufacturing, from Michigan Technological University in February, 1984. Upon graduation he was employed by Cone Drive Operations, Textron, in Traverse City, Michigan with responsibilities for manufacturing engineering projects. In January, 1989 he accepted a fellowship at Lehigh University to pursue a Master of Science degree in Manufacturing Systems Engineering. In March, 1990 he will resume his career, having accepted the position of CIM engineer with General Electric Aircraft Engines in Evendale, Ohio.