IMPLEMENTING THEORY OF CONSTRAINTS IN A JOB SHOP ENVIRONMENT

By
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And
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Abstract

The Boeing Company is under performance pressures due to internal process performance and external cost pressures. The response has been a focus on manufacturing fundamentals to meet market demands on schedule and cost. Boeing has utilized Lean Manufacturing as the methodology for improving manufacturing.

This thesis describes an implementation of Theory of Constraints in a job shop environment in a Boeing component manufacturing shop. Lean Manufacturing and Theory of Constraints are described and compared as methodologies for improving manufacturing systems. This thesis demonstrates that the two methodologies can be integrated in one manufacturing system.

The TOC five-step continuous improvement methodology was utilized in the implementation as a framework for analysis. A process for identifying bottleneck operations in a job shop is detailed. The steps are to identify the process flows, determine constraints within the process flows and release material into the flowpath at the constraint production rate. It is probable that the actual constraint in the system will not be identifiable through data analysis, and methods for determining constraint operations through constraint engineering are described.

An implementation of the drum-buffer-rope material control process is described in this thesis. To enable the implementation, a data management system was developed. The system utilizes the concept of critical ratio scheduling priority, a time buffer to protect bottlenecks from starvation and process flow to provide the necessary information for operating in a drum-buffer-rope pull environment. The drum-buffer-rope material control policy provides a method for controlling the WIP and cycle time in a factory within a MRP framework.

The issues encountered in the implementation are detailed. These are related to information systems, organizational history, metrics, organizational culture and incumbent policies. These all provide challenges to implementation a TOC system and need to be managed properly for a successful implementation. The thesis provides several suggestions to overcoming these issues.

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1 INTRODUCTION

1.1 PROBLEM STATEMENT

"The production troubles contributed to a $178 million 1997 loss, Boeing's first in half a century and tarnished Boeing's reputation as one of the top manufacturing companies in the world."(Holmes, 1998)

The Boeing Company's merger with McDonnell Douglas in 1997 set the stage for the industry giant to take advantage of tremendous economies of scale. However, Boeing is producing more airplanes annually than ever before but is still not able to produce a profit. Several reasons for this have been cited, including:

- Production holdups due to poor communication of increased production rates to suppliers,
- An early retirement program that was run in the early 1990's that reduced the manufacturing knowledge and competency,
- Increased price pressure from Boeing's top competitor, Airbus Industries.

In addition, the Aircraft and Missiles division (A&M), a component of Boeing's Military Group, continues to be scrutinized for profitability due to reduced Defense Department spending. Although the division is recognized as a leader in developing advanced technology for military aircraft, a focus on program cost must be recognized to ensure future government contract awards.

Pressures to reduce manufacturing cost in the Boeing Company are greater than ever before. A key thrust used in the Boeing Company to improve the manufacturing processes has been Lean Manufacturing. While Lean Manufacturing has been proven to yield excellent results for certain manufacturing settings, it also has been shown that it is not applicable in every situation. In settings subject to high levels of variation, the Theory of Constraints is more suitable as a manufacturing methodology. This thesis explores the Theory of Constraints and its implementation in a Boeing manufacturing plant.

1.2 Approach Overview

This thesis describes a methodology for implementing Theory of Constraints concepts in a manufacturing setting with a focus on multistage disconnected flow processes. The purpose of this thesis is not to describe the benefits of implementing TOC. This has been documented in the form of case studies (Noreen, 1995), (Kendall, 1998) and (Koziol, 1988) for various types of manufacturing settings. In addition, simulations have been documented showing the benefits of Drum-Buffer-Rope material control versus MRP material control (Duclos, 1995). Instead, this thesis highlights a specific implementation, the methodology used and the key aspects of the implementation that are applicable to job shop environments. The research for this thesis was completed at Boeing's A&M Strategic Machining Center in Kent, Washington. The strategic goal of the project was to improve the manufacturing operations by focusing on inventory and cycle time reduction.

Chapter 2 of this thesis describes the background of the Strategic Machining Center and the specific nature of the factory that lends itself to an implementation of TOC. Chapter 3 provides background theory on TOC and lean manufacturing and provides a framework for utilizing both in a job shop manufacturing setting.

Chapter 4 of this thesis describes a methodology for implementing Constraints Management in a job shop environment. The framework utilized is a modified version of the 5-step TOC continuous improvement process developed by Eliyahu Goldratt (Goldratt, 1984). The aspects of TOC that are utilized in this implementation are continuous improvement and Drum-Buffer-Rope, a material control policy. While the TOC thinking process was used in identifying root causes of some problems in the factory, it will not be discussed in this thesis.

Chapter 5 describes some of the barriers to implementing Constraints Management in a traditional manufacturing environment, including technical and organizational issues. The specific issues confronted in this implementation are detailed and suggestions on dealing with these issues are presented. Chapter 6 evaluates the process and summarizes the thesis.

Several acronyms are used in this thesis. These are described in detail in the text, and are also included in a glossary at the end of the thesis.

1.3 Key Findings

This implementation did not progress to completion during the project. The infrastructure for implementing TOC was developed, including the information systems, the organizational design, management structure and the roles and responsibilities. However, data could not be collected to display the financial benefits of implementing TOC. Instead, the process used for implementation and the implications of using TOC in a job shop are detailed for application in similar environments.

Implementing TOC in a traditional job shop environment requires a complete analysis of the material control policies, factory operational policies and the manufacturing processes. The technical aspects of implementing TOC are complex if the setting is a job shop, but can be confronted if the TOC continuous improvement methodology is utilized as an implementation framework.

Efficient data management is crucial to the effectiveness of any TOC system. Understanding where the constraints are and understanding when to release material into the system requires data that is collected for that specific purpose. Data is typically collected for financial reporting purposes and may not provide the exact type of information that is necessary to identify constraints. Systems may need to be developed to enable the implementation of a drum-buffer-rope material control system.

The Theory of Constraints and Lean Manufacturing are improvement methodologies that have historically been considered to be incompatible in nature. We found that the implementation of Theory of Constraints does not preclude the implementation of Lean Manufacturing, and the two can be combined under job shop environments to gain the benefits of both.

The drum-buffer-rope material release system is an inventory control policy that is similar in nature to CONWIP and can be used in job-shop situations that exhibit high variability. The benefits of CONWIP material control are similar to that of drum-buffer-rope, namely fixed inventories, predictable delivery times, and controlled cycle times.

Most importantly, the organizational history and culture must be recognized and leveraged to successfully implement TOC in a factory. Widespread organizational understanding of the TOC concepts will greatly improve the implementation, as the effort requires involvement of several functional groups within the organization. Above all, implementation of a change of this magnitude requires diligence, organizational support and vision.

2 COMPANY BACKGROUND

2.1 *THE STRATEGIC MACHINING CENTER*

The Strategic Machining Center (SMC) in Kent, Washington is a key component of Boeing's Aircraft and Missiles (A&M) manufacturing operations. A&M in the Puget Sound area is organized as a set of manufacturing centers that specialize in a certain competency; Machining, Composites, Gear Manufacturing, Assembly and Chemical Processing. The A&M Puget Sound manufacturing organizations act as internal Boeing suppliers producing components for either the Information, Space and Defense Group (ISDS) or Boeing Commercial Airplane Group (BCAG), depending upon the capabilities and cost leverage. Historically the SMC has produced components as a main supplier to a military program such as the Minuteman Missile and the ALCM Missile program. As the programs continue to evolve through their lifecycle, the SMC targets Boeing programs that would best fit its capabilities to continue operations.

The SMC supports both Commercial and Military programs in component manufacturing. Although all components are for airplane structures, the two customers are entirely different in terms of the demands on resources and mode of operation.

2.1.1 Military Customers

The SMC supports the V-22, Joint Strike Fighter and F-22 Military programs. Boeing's military programs have a development life cycle of at least 3 years. Currently, all the military programs that the SMC supports are in the developmental phase of their lifecycles, which places an excessive strain on the SMC's resources. To optimally support a developmental program, the SMC must provide high responsiveness to engineering changes, exceptional quality, and low throughput times. In addition, extensive pre-manufacturing processes must be completed for developmental components and the system does not run in an optimized manner.

During program development, the contracting program provides the engineering requirements for components. The SMC then uses these requirements to develop manufacturing processes. Before a component is produced, the SMC develops NC machine programs, the key characteristics that need to be checked by the quality organization, the CMM programs, the manufacturing plan and the procurement plan. Once the pre-manufacturing processes are completed, a media try out (MTO), or test piece, is manufactured to ensure that the manufacturing procedures will result in an acceptable component. Because a majority of the military hardware is manufactured from titanium, which is very costly and difficult to obtain, the test components are typically manufactured using aluminum or steel. If the MTO is acceptable, the manufacturing process is certified as acceptable by the manufacturing engineering, factory management, and process engineering organizations and approved for manufacturing. If a quality discrepancy is found in the MTO, the process is repeated until a reliable manufacturing procedure is developed. If an engineering change on a component is introduced by the engineering organization, the up-front processes must be revisited. The development process tends to be iterative in nature and taxing on resources because the manufacturing organization is not experienced with producing the new components. In addition, engineering changes are abundant. When the manufacturing process is approved and a program enter the production stage of the product lifecycle, the SMC may be contracted to continue production if the business analyses show competitive cost structures.

2.1.2 Commercial Customers

Roughly 50% of the SMC's production is support for Commercial Airplane Programs. These programs typically exhibit lower volatility in demand, quantity, and product requirement changes. The stability in commercial components' demand allows the SMC to achieve improved cost performance because of the learning curve effect. As an internal supplier to Boeing programs, the SMC must compete for commercial production with other Boeing machining centers on the basis of cost, capacity and quality.

2.2 SMC Operations

The Strategic Machining Center is a milling focused factory with finishing and quality capabilities. The layout of the manufacturing center is functional, with machines grouped and managed primarily by capability. Each group of machines that have equivalent capabilities is assigned a factory work code (FWC) which is a classification nomenclature for machine types. Using the FWC simplifies the manufacturing plan because tasks can be assigned to FWC's instead of individual machines. This increases the flexibility of the SMC operations by allowing components to be programmed and processed on any machine within a FWC.

The center has an aluminum machining cell that acts as a factory within a factory, producing near-complete parts at exit from the cell. The cell was developed in conjunction with a previous LFM project (Alvarez, 1997) in an attempt to streamline manufacturing operations. The aluminum cell is the only deviation from a completely functional shop layout. A layout of the machining center is shown in Figure 1.

The factory is managed as a job shop, with all components made to order. The flexibility of the machines and number of different types of machines allows the SMC to market a broad range of capabilities to produce almost any machined component, from small 6 inch brackets to wing spars over 30 feet in length. Component manufacturing hours can range from 10 to 500 labor hours. Although there is a high variety of process flows, a typical component process flow is shown in Figure 2.

Components are introduced into the process as block material or forged casting (titanium parts). The majority of the value that is added to the components manufactured in the SMC is achieved on 3-5 axis milling machines. The NC machine type varies depending on the size, material and volume of components that are expected to be manufactured. The SMC currently runs on a 5-day / 3-shift manufacturing operation, with a full first shift, 75% second shift, and 25% staffing on third shift, totaling approximately 300 direct laborers. The operations are managed with area lead men, supervisors, and a general supervisor who reports to the center leader. Support to the manufacturing operations is managed functionally with inventory management, materiel, NC programming, manufacturing, industrial and process engineering. These functions report through independent functional organizations that support all the manufacturing centers of excellence in the Puget Sound area. The center leader manages operations directly through the general supervisor and has matrix responsibility through the functional organizations.

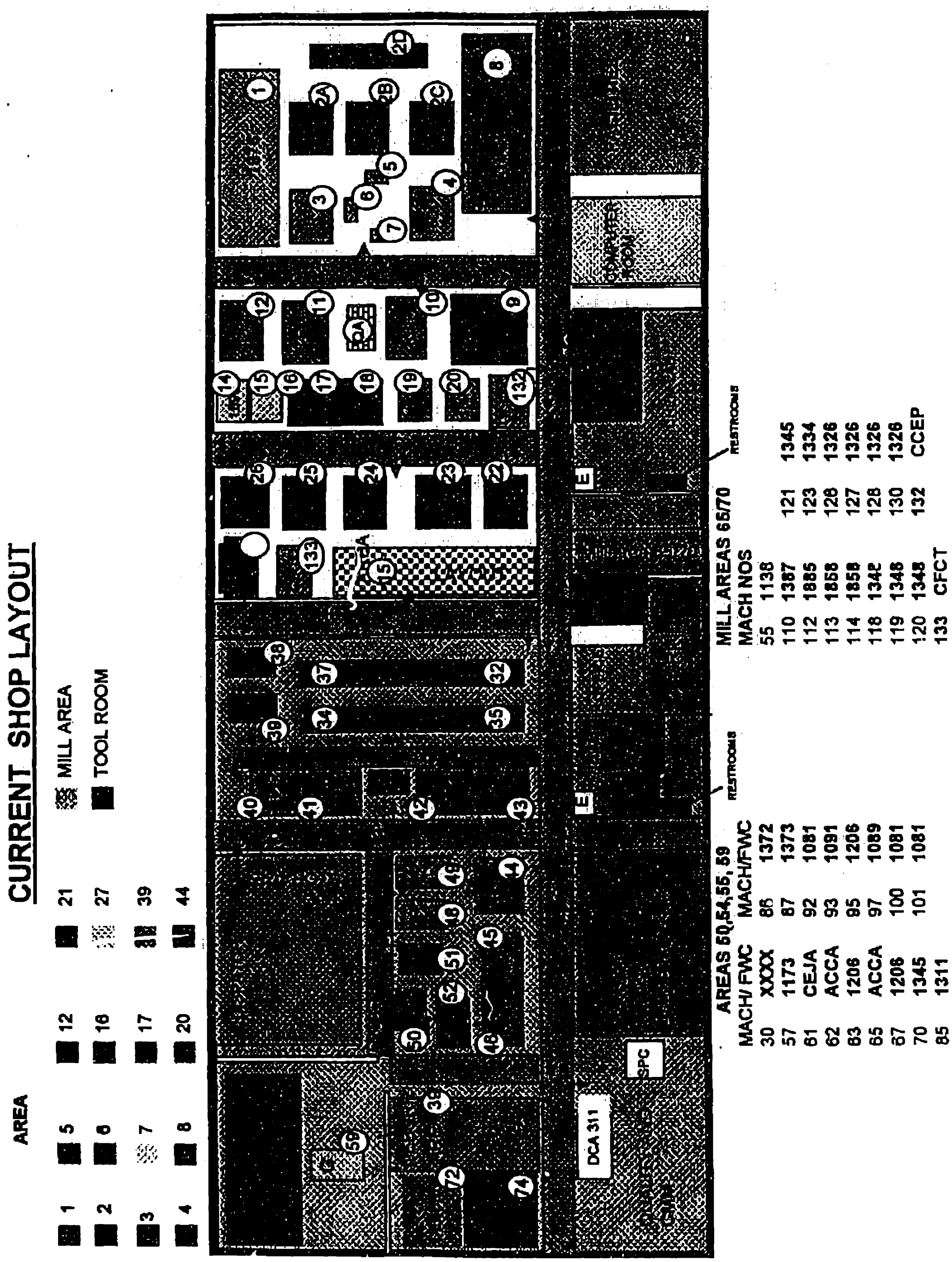


Figure 1: Factory Layout

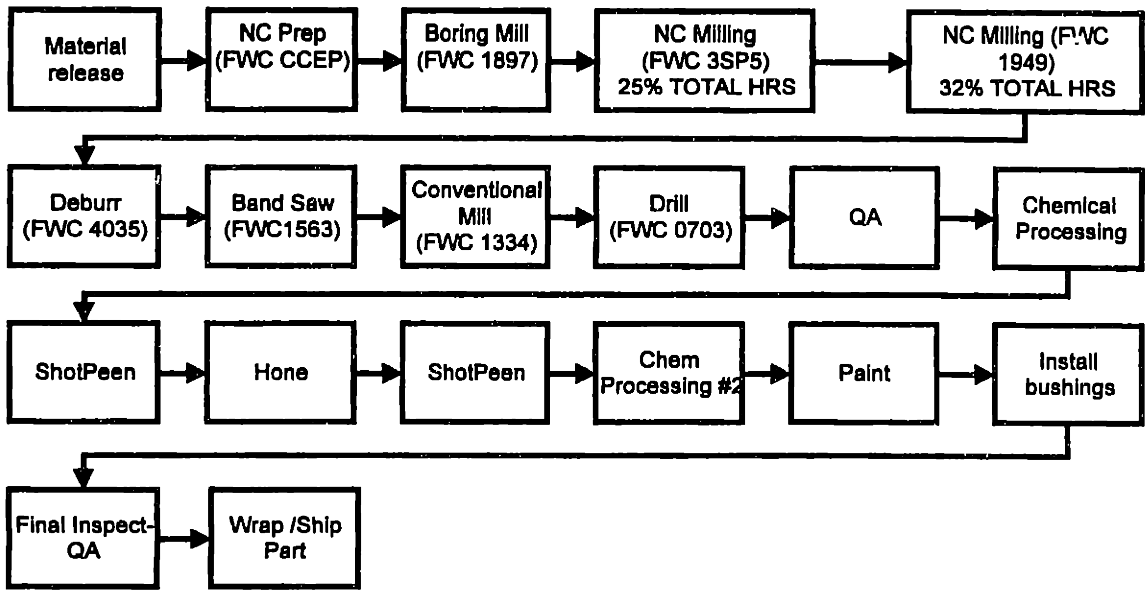


Figure 2: Sample Part Routing

2.3 THE SMC AS A JOB SHOP?

In the Product/Process matrix (Hayes and Wheelright, 1979) shown in Figure 3, a job shop is defined as having jumbled flows, low volumes, and low standardization. In general, the SMC exhibits this type of material flow. One exception is the set of products that are produced in the aluminum cell, which has a standardized flow with higher volumes. The aluminum cell is a disconnected line flow with no controls on inter-process inventory levels but with product routings that are common. The SMC can then be characterized as two distinct manufacturing shops which happen to exist in one building, a job shop and a disconnected flow line.

Job shops are inherently inefficient for high volume manufacturing. The lack of machine specialization increases direct labor costs because fixture changeovers are common and maximum utilization of machinery is difficult to achieve without significant inter-process inventory. A connected flow line or a continuous flow line will exhibit higher levels of automation and higher initial costs, but will have reduced recurring costs.

The advantage that job shops have over connected flow lines or continuous processes is the flexibility in the processes. The machinery is designed to handle product changes quickly and more easily than dedicated automated machinery. In addition, job shops are better equipped to handle inter-process variation because the stages are not connected. For this reason, job shops are a preferred structure for development manufacturing.

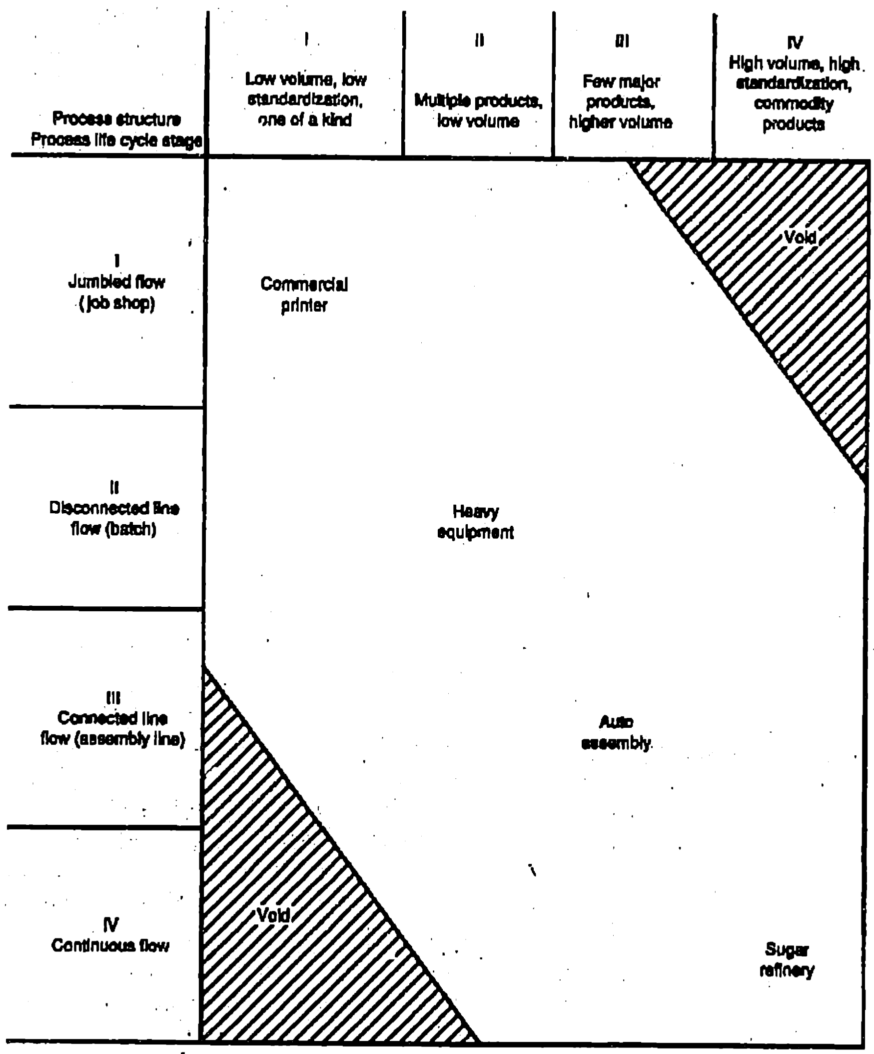


Figure 3: Product/Process Matrix

As a job shop, the competitive advantage of the SMC lies in its ability to produce low-volume products early in the project life cycle. The machinery in the SMC is not dedicated to a certain product type and is designed to be able to handle various types of fixturing. In addition, the SMC has no policy limiting inter-process inventory levels. This allows maximization of average machine utilization, and eliminates blocking effects. However, because the SMC is inefficient for high volume manufacturing, the product costs are higher than flow line production structures.

Having a higher recurring production cost increases the difficulty in obtaining program contracts that transition from the developmental phase to the production phase of the life cycle. The Boeing Company is left with two unattractive alternatives:

- Move production out of the SMC to a factory better suited for higher rate manufacturing. This would reduce the recurring product costs, but increase the ramp up non-recurring costs due to the loss of knowledge assets gained during development.
- Leave production in the SMC, capitalizing on the development knowledge but increasing relative ongoing production costs.

A third alternative would be to transition the factory layout and policies as the products transition to the production phase. When a program moves to the production phase, creating a dedicated product line to produce a small set of components would allow for specialization and reduced per part cost. Because this would entail purchasing capital equipment that is specialized and connects process stages, or moving the existing machinery into manufacturing cells, the initial investment in the transition period becomes prohibitive. By implementing a material control policy such as Drum-Buffer-Rope, the SMC can transition to a connected flow line in concept without the capital investment. This will be discussed in detail in the next chapter.

2.4 Variability in the SMC Production Schedules

The SMC production schedules exhibit high levels of variability. These are caused by:

- High deviations from planned start date of orders. A histogram of the deviation from planned start date for orders in a week is shown in Figure 4.
  The data show there is a high level of variation with an average start of 17 days late and a standard deviation of 35 days. The specific reasons for the deviation from planned start dates could not be determined from the collected data, but qualitative data provide the following reasons:

  1. To begin manufacturing an order, the material, operation plan, cutting tools, and NC machine program need to arrive simultaneously at the factory. The extreme outliers of the histogram can be explained by long lead-time material that was improperly scheduled.
  2. The engineering designs for a component could be delayed causing the factory metrics to show a late start.

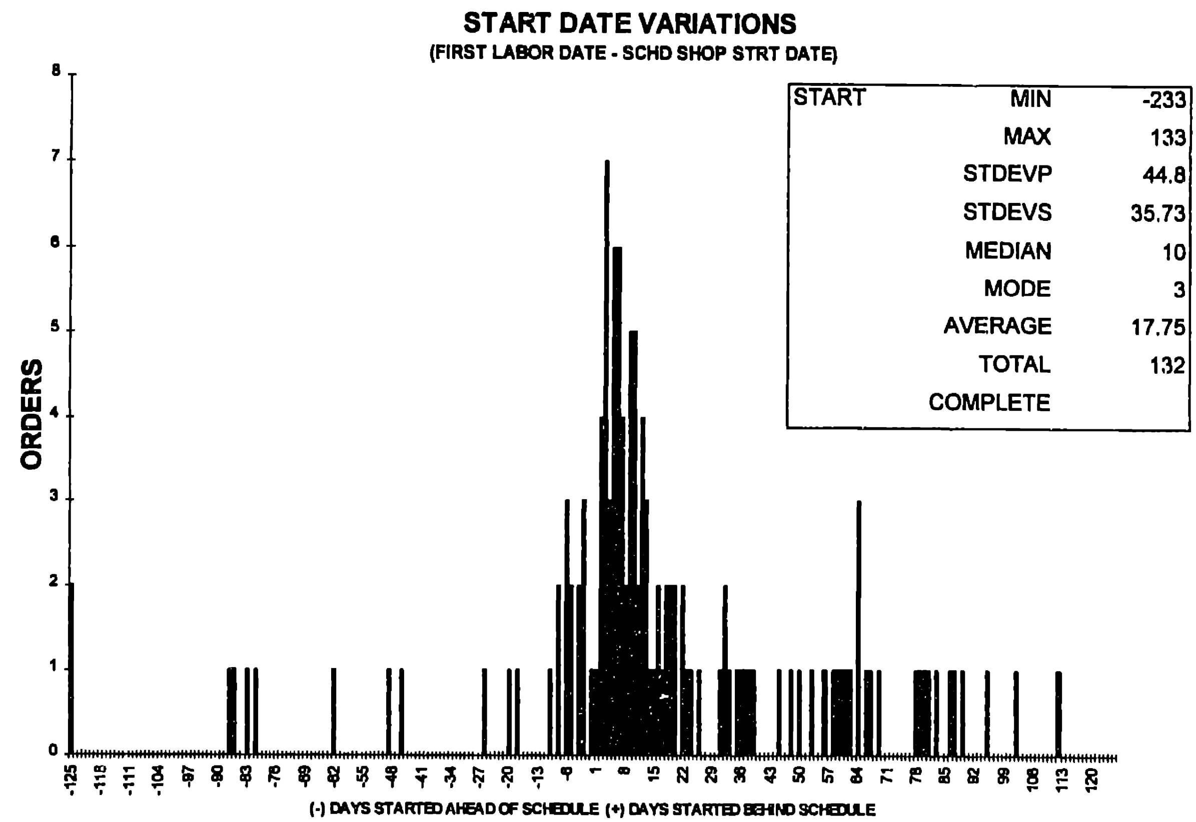


Figure 4: Start Date Variations From Scheduled Dates

3. A high number of iterations on an MTO could cause a delayed start on a production component.
4. The MRP system has no capacity constraints placed on the scheduling of orders. Therefore, an order could be ready to begin manufacturing but the factory could be temporarily overloaded, causing a late start.

Variation in start dates propagates throughout the system causing late orders.

- Variation in production times. Because roughly 50% of the manufacturing is developmental, a high variation in the expected manufacturing processing times can occur.

- Variation in machine uptime. For example, a sample machine (5-Axis Bedmill #8) had a mean time to repair of 11 hours.[1] However, the standard deviation in mean time to repair is 30 hours. The maintenance department has suggested that a majority of the repairs can be easily fixed, but because the machinery is outdated, finding certain machine components can often be difficult and time consuming. Therefore, most repairs can be done quickly but a small minority of machine repairs can take excessively long periods of time. The high variation in machine repair times contributes significantly to the production schedule variation.
- The factory is required to expedite certain orders by contract to the military to support grounded aircraft (DO/DX orders). In addition, the factory is expected to expedite components to support grounded commercial aircraft (AOG orders). This required expediting disrupts the production schedule and contributes to the production variability.
- The SMC has similar FWC's to those Boeing factories that produce components for commercial aircraft. In times of unexpectedly high demand, those factories may need assistance in producing their scheduled workload. The SMC has a policy of assisting other factories to maintain schedule performance if extra capacity is perceived to exist. These orders that are introduced to the factory are called emergent orders. This policy introduces additional variation to the production schedule of the SMC as the support is generally unplanned and needs to be expedited.
- Some military components have long processing times reaching over 500 hours. A scrap or rework to these components causes a large disruption in the production schedule as unplanned machine time will need to be consumed. While this may not occur often, the impact is significant when it does occur.

The high level of variability contributes significantly to the current operational methods. To absorb this variability, the factory overestimates the lead times for components and uses high levels of inventory to maintain high machine utilization rates.

[1] As measured from 1/98-8/98

3 BACKGROUND THEORY

Increased competition between manufacturing companies in the last 10 years has brought about several manufacturing concepts including Just-in-time, Theory of Constraints, Lean Manufacturing, and Quick Response Manufacturing. The overall goal of these production systems is to increase organizational competitiveness through increased profits. Although these systems differ on the approach to achieving higher profits, the underlying concept remains the same: Produce the necessary product when customers need it without unnecessary investments in capital, people or inventory. In addition, these concepts are all based on fundamental operations management science concepts.

3.1 Factory Physics

Managers in any factory must make decisions that affect overall performance that deal strictly with the management of resources, namely people, capital equipment and inventory. It has been shown that there is a fundamental relationship between WIP, cycle time, and throughput (Hopp & Spearman, 1996) which holds under very general conditions. This is described by Little's Law, which states:

$$Throughput = WIP / Cycle\ time \tag{3.1}$$

Where:

Cycle time = Average total time required to manufacture a component, including inter-process waiting time.

Throughput = Rate at which products are produced.

WIP = Average number of products in process.

Holding other variables constant, Little's law states that inventory is directly related to cycle time, and both have an effect on throughput. Put another way, a reduction in cycle time requires a reduction in inventory or increases in the production rates, with no other changes in production processes. This relationship between operating parameters is introduced here because it is the underlying concept behind Lean Manufacturing and the Theory of Constraints. An explanation is given in the next section.

3.2 Theory of Constraints

The Theory of Constraints, or Constraints Management, is a process improvement framework that was developed by Dr. Eliyahu Goldratt. The theory states that every system has at least one constraint that prevents additional product to be produced. Efforts should be focused on optimizing the output of the constraint to optimize the system as a whole.

An Example:

The TOC solution begins with the premise that different resources have different capacities and that statistical fluctuations and disruptions cannot realistically be eliminated (Noreen, 1995). Goldratt uses the example of a boy scout troop on a hike to communicate the effects of variability (Goldratt, 1984). Imagine a group of boy scouts on a hike in the woods. The troop as a whole can only move at the rate at which the slowest boy moves. Because some boys walk faster than others, the line spreads out, and a queue builds behind the slowest boy (Herbie). Goldratt proposes that Herbie is the troop's marching constraint and because the troop cannot go any faster than Herbie, he sets the pace for everyone.

If you consider that the hiking troop is similar to a linear manufacturing system, Herbie is the process in the system that produces at the slowest rate. On average, the troop can only move at Herbie's pace, or the manufacturing system can only produce at the rate of the constraint. Goldratt refers to Herbie as the system drum, as he sets the pace for the entire troop. The boys move at varying rates depending upon how they feel, which can be described as process variation in each manufacturing process step. Those boys in front of Herbie that can move faster are processes that outpace the system constraint. The distance between the boys can be considered to be work-in-process inventory, and greater distances (WIP levels) between Herbie (the constraint) and the faster boys (manufacturing processes) develop. If left uncontrolled, the faster boys in front of Herbie will be infinitely far from the rest of the troop, which equates to infinite queues within a manufacturing system.

Under the above situation, Herbie walks at a constant pace throughout the hike. In a manufacturing setting, it is possible to have a person that slows down as the hike continues, or a process that changes rates. By looking at the process at different times, a different process step may be identified as the constraint (or drum). This effect is described in detail in chapter 4.

3.2.1 Using Theory of Constraints for Continuous Improvement

A five-step method of continuous improvement has been proposed by Goldratt to maximize the returns on investment for any factory:

1. *Identify the constraint.* The first step is to identify the drum of the system.
2. *Exploit the constraint.* Without investing in capital to increase the capacity of the system constraint, optimize the constraint to maximize the throughput. This can be done through process improvements conducted on the constraint or scheduling to prevent starvation.
3. *Subordinate every step in the system to the constraint.* Every step must work to ensure maximum utilization of the constraint machine.
4. *Elevate the constraint.* If additional capacity is necessary from the system, increase it in the constraint.
5. *If a constraint is broken, go back to step 1. Avoid system inertia that creates additional constraints.* This means if a constraint is improved relative to other process steps, it will no longer be a constraint and the organization should focus on the new constraint.

This methodology was modified and used in the SMC to implement TOC. TOC instructors claim that the implementation of TOC generally does not require step 4 because capacity is generated through the application of steps 1-3. The details of the implementation are described in chapter 4.

3.2.2 Using Theory of Constraints for Material Control

A material release methodology called drum-buffer-rope (DBR) was developed by Goldratt to counter the infinite WIP syndrome. Returning to the boy scout example, a **rope** can be tied between the boy scout in the front of the line (the material release process) and Herbie (the **drum**). This keeps the distance (or the WIP) between Herbie and the front of the process constant. The length of the rope is likened to a **buffer** in the system between the material release and the constraint. Notice several key assumptions, which are:

- The boy scouts in front of Herbie slow down because they are tied by the rope,
- The boy scouts in back of Herbie, on average, can go faster than Herbie and therefore keep up in the hike.

A material control system that is similar to DBR is CONWIP (CONstant Work In Process). In a CONWIP loop, material is introduced into the system only when a component exits the system.

The total amount of inventory in the system is held constant. The DBR system is a modified CONWIP system. In Figure 5, both systems are represented (Hopp and Spearman, 1996).

In a Drum-Buffer-Rope system, the material is introduced into the system only when a component exits the constraint operation. The amount of inventory is held constant between the process start and the constraint. The DBR buffer is considered to be the amount of inventory from the start of the DBR loop to the constraint, not including the orders that are in process at the constraint. This buffer is measured in terms of hours of *constraint processing time*. Therefore, if no new orders were released into the system, the buffer size would indicate the time it would take to starve the bottleneck operation. The buffer, as referred to in TOC terms, is equivalent to the CONWIP level, or inventory level of the CONWIP loop.

Both DBR and CONWIP are examples of manufacturing pull systems because material is pulled into the factory only when necessary. The advantage of this system is that the total inventory is controlled. By controlling the in-process inventory, the cycle times can be controlled and predicted. This is a TOC concept based on Little's Law.

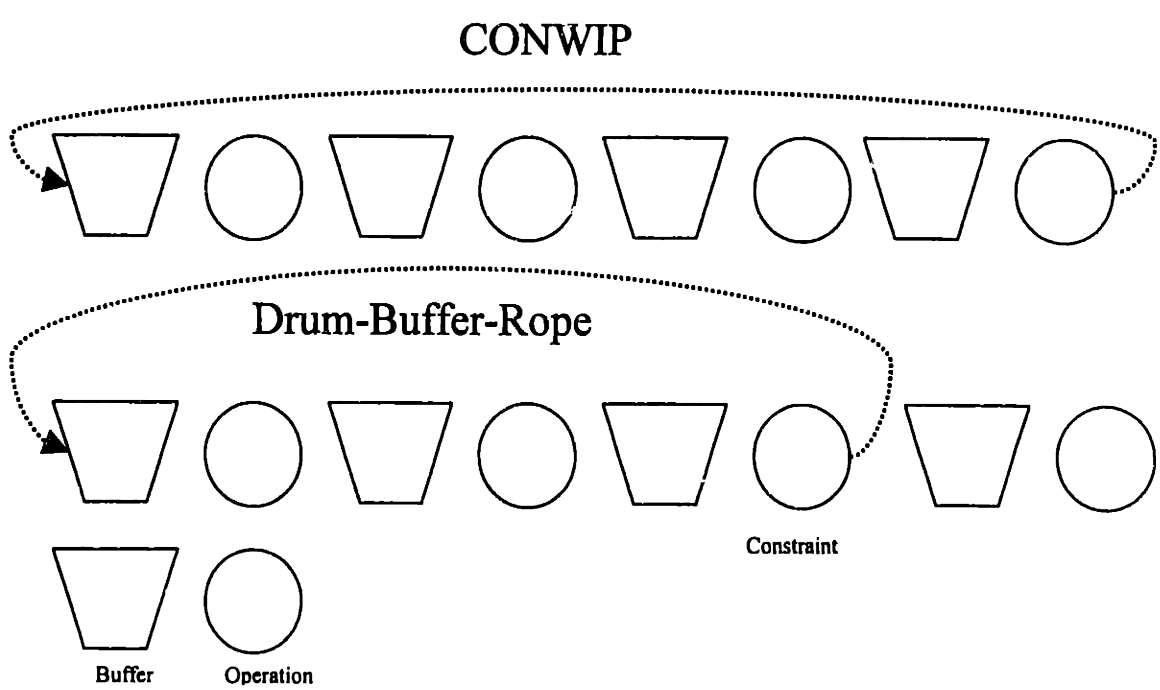


Figure 5: CONWIP & DBR Information Flow

For the remainder of this thesis, the terms bottleneck and constraint will be used interchangeably.

3.3 LEAN MANUFACTURING

The Lean Manufacturing system that was developed by Taiichi Ono at Toyota has become to be understood as a combination of production methods that improve competitiveness through reduced manufacturing costs. "The main purpose of the system is to eliminate through improvement activities various kinds of waste lying concealed within a company" (Monden, 1997). Eliminating waste in the manufacturing arena translates into reduced costs, thereby increasing profits. Several techniques have been used to manage the elimination of waste, which are:

- Just in Time Production – The theory behind just in time production is to produce only what is needed when it is needed in the quantities needed. The Toyota Production System (TPS) achieves just in time production through eliminating excessive production resources, overproduction, excessive inventory and unnecessary capital investment.(Monden, 1997)
- Heijunka (Production Leveling) – If the production demands are smoothed by eliminating inter-process arrival variability, the amount of inventory and excess capacity necessary to sustain the desired service levels will be reduced. In addition, the concept of smoothed production requires that each type of product be produced at the average demand rate. Therefore, if a company produced 5 different types of products, smoothing production requires that each product be produced every day at the average demand for that day. To achieve this, flexible types of machinery with optimized setup times must be in place. This will result in the ability to shift to changes in the market demands, a balance between processes and increased ability to introduce new products.
- Kaizen, or improvement activities – By continuously examining the current production methods and eliminating waste, "the levels of quality, lead time and cost reduction can be improved" (Monden, 1997). A continuous cleanup activity within an organization with strong management support can be an extremely powerful tool both for improving operations and increasing the effectiveness of the employees. By capturing every employee's creativity and knowledge, an organization can target waste in the business processes and eliminate them on a continuous basis.

3.4 LEAN MANUFACTURING VS. CONSTRAINTS MANAGEMENT

One of the basic tenets of lean manufacturing is the elimination of excess productive capacity. In a high volume production environment, it is possible to balance the production tasks of line employees to minimize the idle time. Each task is timed and matched to the cycle time of the process to enable a level production schedule. To enable this balanced flow process, the elimination of inter-process variability is critical to ensure constant production rates. Safety stock or excess capacity is located within production systems to ensure high production levels with small processing time variation, but large fluctuations in processing times create excessive disturbances in the production schedules.

TOC and Lean Manufacturing differ in the approach to managing the production capabilities of each process. Lean manufacturing suggests that variability must be eliminated from the process and the process steps must be balanced. TOC suggests that some variability cannot be removed, and thus the process steps in certain situations cannot be perfectly balanced. This is a key differentiation between the two methodologies.

Because the SMC produces components for programs in the development stage of the lifecycle, processing times exhibit high levels of variability. In addition, the flow path of the components through the factory changes as the mix of orders changes. This provides for a difficult environment to implement a balanced flow line. To achieve a balanced flow line without protective capacity would require increased inventory levels or reduced variability in the production schedules. The TOC approach to systemic improvement provides a mechanism for controlling inventory, cycle time, and delivery rates without the prerequisite for reducing system variability. Although variability reduction is preferable, chapter 2.4 showed that there are many causes of variability in the production schedules in the SMC and these causes are endemic to the system. Once the factory reduces the variability significantly, a lean manufacturing based approach to managing operations can be utilized. Balanced flow lines and single order flow can then be implemented. Until the variability is reduced, the TOC based approach to managing operations is preferable.

The Boeing Company has taken an initiative to integrate Lean Manufacturing techniques into its production system primarily through Kaizen events, which Boeing calls Accelerated Improvement Workshops (AIW's). The SMC has run several AIW's in the traditional Lean Manufacturing approach; A high number of AIW's results in many small incremental improvements in the organization that eventually result in an extremely efficient production system. However, after the first several AIW events, the return on investment was questioned and determined to not have a significant impact on efficiency or profitability versus the investment of time and money. One of the criticisms of the AIW approach at the SMC is that the factory is continually under significant schedule pressures and is not willing to let perceived bottleneck operations shut down production for an entire week to gain long-term improvements. Thus, improvement efforts have been focused on areas of the factory that are not critical to near term production. Therefore, even if the AIW is a success and improves the efficiency of the FWC or area, it may not have a significant impact on the organization as a whole.

Because of the difficulty in obtaining tangible results, the management team that is chartered to introduce and implement AIW's in Boeing A&M has developed a highly structured program. This team has attributed AIW failures to non-compliance with the documented process. The result is a strict dedication to the AIW process and a reluctance to explore other manufacturing methodologies, such as TOC. Although a dedication to any process is important in introducing change, it is possible to become so devoted to the Lean Manufacturing tools and overlook the benefits of TOC under such a regimented program.

While I agree that the Lean Manufacturing goals of eliminating waste, reducing cycle time and reducing cost are congruent to improvement efforts, it is possible to take advantage of Constraints Management in a Lean Manufacturing environment. For example, because the SMC is a job shop, an unbalanced flow line is preferable to the Lean Manufacturing model of balancing tasks. In addition, the TOC five-step framework for continuous improvement can be easily applied in a Lean Manufacturing environment. The key concepts from each methodology that can be combined in a job shop environment are shown in Table 1.

Table 1: Lean Manufacturing and Constraints Management

Lean Manufacturing	Constraints Management
Kaizen Events	Continuous Improvement Framework
5S – Workplace Organization	Drum-Buffer-Rope Material Control
Continuous Waste Elimination	Variation Buffering

Because the Boeing Company currently utilizes these Lean Manufacturing tools in its approach to achieving manufacturing excellence, the organization is relatively comfortable with the processes and concepts. None of the tools in Table 1 conflict with each other and all can be applied in one manufacturing environment. After all, both Lean Manufacturing and Constraints Management are brand names for applications of fundamental operations management science and not science in and of themselves.

The next chapter will outline the methodology used to integrate the two management systems in the SMC.

4 THEORY OF CONSTRAINTS PROCESS DEVELOPMENT

4.1 METHODOLOGY

As stated in chapter 3.2, Goldratt has designed a five-step method of continuous improvement focusing on Constraints Management. This methodology was modified and used in improving the manufacturing operations at the SMC as follows.

1. Identify the constraints.
2. Utilize DBR to control inventory within the manufacturing system.
3. Subordinate every step in the system to the constraint.
4. Exploit the constraint. Utilize AIW's to achieve necessary capacity.
5. Elevate the constraint. Utilize AIW's to achieve necessary capacity.
6. If the constraint is no longer the system constraint, go back to step one. Avoid system inertia that creates additional constraints.

In addition to the underlying Theory of Constraints concepts, the drum-buffer-rope material control process was utilized in the implementation to achieve the goals of reducing cycle time, inventory and increasing overall competitiveness. To enable the drum-buffer-rope process, a special data management system was developed to provide the correct information to the decision makers in the process.

The difference between the Goldratt model and our implementation model is we have added step 2. Although this step may be implicit in Goldratt's model in the subordination step, our environment required significant effort to enable DBR and thus warranted a separate implementation step.

The remainder of this chapter will describe each step in detail as it pertains to a job shop environment, and our implementation of this methodology.

4.2 SYSTEM BOUNDARIES

Before any numerical analysis is conducted, the boundaries to the target system must be identified. Although Constraints Management suggests that an entire system can be analyzed and managed by DBR, only certain systems lend themselves to successful application of DBR. As discussed in chapter 3.4, manufacturing systems which resemble job shops or disconnected flow lines with high levels of variability are difficult to manage as a balanced flow line. These types of systems are preferable to manage as a DBR system. Because the SMC is managed as a discrete step in the process of producing aircraft and is a system that absorbs production variability from the downstream processes (sub-component assembly and final assembly), an isolated internal DBR system was utilized.

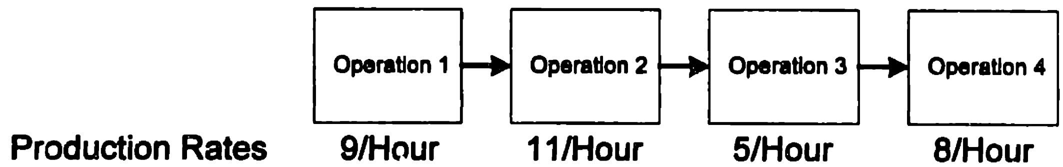
After analyzing the SMC's operations, the team agreed to begin our DBR loop at the warehouse that stores the raw material for the factory. At Boeing, these warehouses are called stores. The SMC has two stores that hold raw material for production, MMA10 and MMA9. These stores are designated as separate entities because one holds block metal (MMA9) while the other holds items such as castings and subassemblies (MMA10), but the two organizations are in the same building and are managed by the same supervisor. Several factors contributed to this decision, including:

1. The stores organization has recently undergone significant headcount reduction. Therefore, it has become increasingly difficult to supply all the material by the appropriate due dates, which are all controlled by the MRP system. By integrating the stores organization in the pull system, we are able to eliminate waste by having the stores personnel only work on orders that are *currently* necessary for the factory operations. Previously, the stores would cut material and send it to the factory regardless of the amount of WIP already in the system.
2. Once the DBR system has been implemented and the process reaches a steady state, the excess time buffer in the MRP system flow times will be recognized as waiting time in the stores. In other words, the material will wait in the stores area until it is needed by the factory. We can therefore reduce the standard flow times in the MP&R system and postpone the purchase of the raw material by the amount of average waiting time, reducing the material holding cost and component cost accordingly.

4.3 Step 1. Identify the System Constraints

4.3.1 Constraint Analysis – Continuous & Connected Flow Lines

When a manufacturing system is engineered as a continuous or connected flow line, identifying constraints is relatively straightforward. The process step that has the lowest production rate relative to the demand is considered the constraint. This can be determined by measuring the production rates of each step and the associated unavailable times due to blocking, machine downtimes, and starvation. Consider the following example:



For the above connected flow line, it is clear that operation 3 is the system constraint, limiting overall production to 5 units per hour. There will be an inventory buildup between operations 2 and 3 should this system continue with order starts at a rate greater than 5/hour. Conversely, it is possible to identify bottlenecks by finding the location with the greatest buildup of inventory. For a complex factory, identifying constraints by finding high inventory levels is often the only method because the data of production rates and machine unavailable times may not be collected in a format that can be used for numerical analysis. However, intricacies in the material flow through the factory may make it inaccurate to utilize queue analysis to identify bottlenecks.

4.3.2 Constraint Analysis – Disconnected Flow Lines & Job Shops

Goldratt suggests looking within the factory for queues that result to identify the constraints within the system. This bottleneck identification method may not be applicable in all cases. In a disconnected flow line the fluctuations in the way material is released into the system creates constraint "illusions". The following example shows how constraint illusions can arise.

4.3.2.1 Constraint Illusion Example

Consider the 2-stage manufacturing operation in Figure 6. The rate-limiting step is operation 2 but because the introduction of material into the system is at a rate greater than the first operation, the largest queue occurs in front of operation 1. After 2 days, operation 1 has a queue of 50 orders while operation 2 only has a queue of 12 orders. Analyzing the queues within the system will result in an incorrect assumption of constraint location within the process.

If, on average, the system is stable, the introduction rate of new orders will eventually become lower than the system production rate of 9 orders per day. If not, the internal queues will tend towards infinity. This reduction of order starts will result in the queue moving from operation 1 to operation 2. The person analyzing constraints in the system through queues will overestimate the chaos of their manufacturing system by thinking that the bottleneck moves around more than it actually does. Therefore, it is possible for the bottlenecks in a process flow to remain constant, but because of the variation in material release rates, the location of the internal queues may move around.

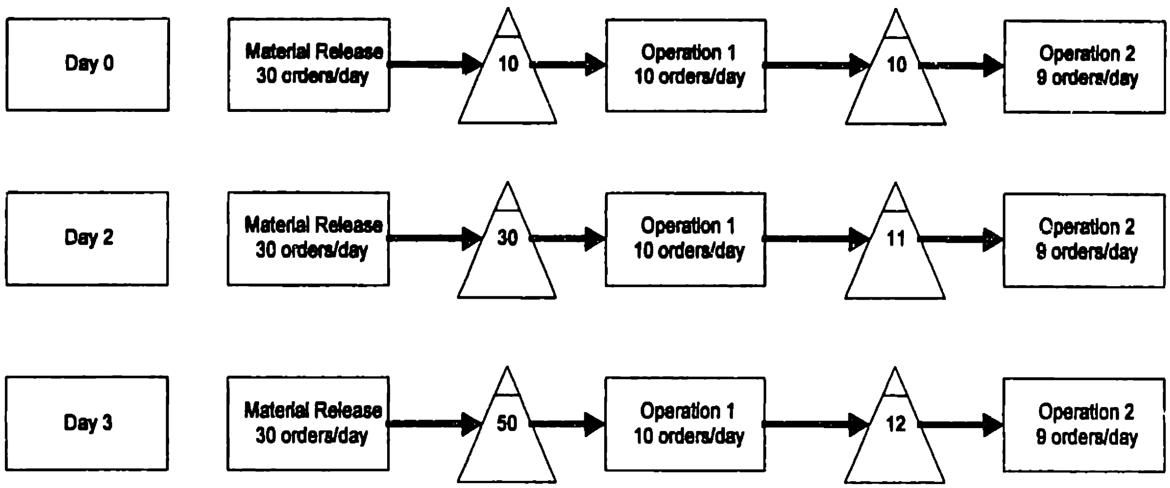


Figure 6: 2-Stage Manufacturing Process

This system cannot exist under a steady state condition because the amount of material within the system tends towards infinity. However, any make-to-order system that does not match the release of new orders to the rate of production will have fluctuations in the rate of material release into the system and possibly have temporary demand that is greater than the production rate of the system. The SMC had this type of demand fluctuation and exhibited the "constraint illusion" syndrome.

Without managing the rate of incoming work, it is difficult to determine the location of the bottleneck operation strictly on the location of work queues.

4.3.2.2 Constraint Analysis Dilemma in the SMC - Flexible Capacity

In the example shown in Figure 6, the capacity of each operation was known. In reality, capacity in a job shop or disconnected flow line is not a fixed number. The capacity of a manufacturing operation can change based on the queue in front of the operation, the operational policies of the factory and the mix of work being performed.

The amount of work present at an operation will affect the capacity of the resource beyond blocking and starvation effects. The accounting practices of the Boeing D&SG provide the foundation for this effect. When the business development group in the SMC produces proposals for new statements of work, the estimation of component costs is calculated by:

Component cost = *Estimated Base Labor Hours* * *Estimated Variance* * *Factory Wrap Rate* (4.1)

Where:

Estimated Base Labor Hours are calculated from historical data about component complexity and the required manufacturing processes.

Estimated Variance is an hour multiplier based on the complexity of the component and manufacturability. This is not variance in the traditional statistical sense but is the expected deviation from estimated base labor hours that the component is expected to have, based on historical knowledge.

Factory Wrap Rate is a $/hr value that allocates direct and indirect (overhead) factory costs based on estimated direct labor hours for a budget period. (Appendix A describes wrap rate calculation)[2].

From discussions with factory line management, it was clear that the factory wrap rate is a critical metric that is used to measure factory performance. This stems from assumptions about the component cost equation. To reduce the component cost, the estimated base labor hours, the estimated variance, or the factory wrap rate can be reduced. The estimated labor hours and the estimated variance are perceived to be based on the component complexity and cannot be greatly reduced. The wrap rate is perceived to be controllable through improved efficiency and effectiveness of capital allocation. Therefore, the leverage that the factory has to reduce component cost lies in reducing the wrap rate. The SMC currently has a stated goal of reducing the wrap rate by 15% by the end of 1999.

The levers that the factory has to affect the wrap rate are either reduced overhead costs or increased direct labor hours to absorb more overhead costs. Because the factory operations have responsibility for the direct labor, the metric has translated into "Maximize base factory labor hours (BFL)".

[2] Appendix A displays the methodology for calculating the wrap rate with fictional percentages and amounts, but the calculations remain accurate.

In the SMC, the mechanics charge their hours directly to the order that is being worked on. This allows for proper accounting of costs and allocation of overhead rates. When a mechanic is not working on a component, s/he is required to charge hours to an overhead account to account for the labor costs. Because this drives overhead costs up and simultaneously reduces BFL, it is an unwritten management policy to minimize the number of mechanics charging time to overhead. Several managers have expressed the following dynamic of cost allocation that occurs in the SMC (Figure 7).

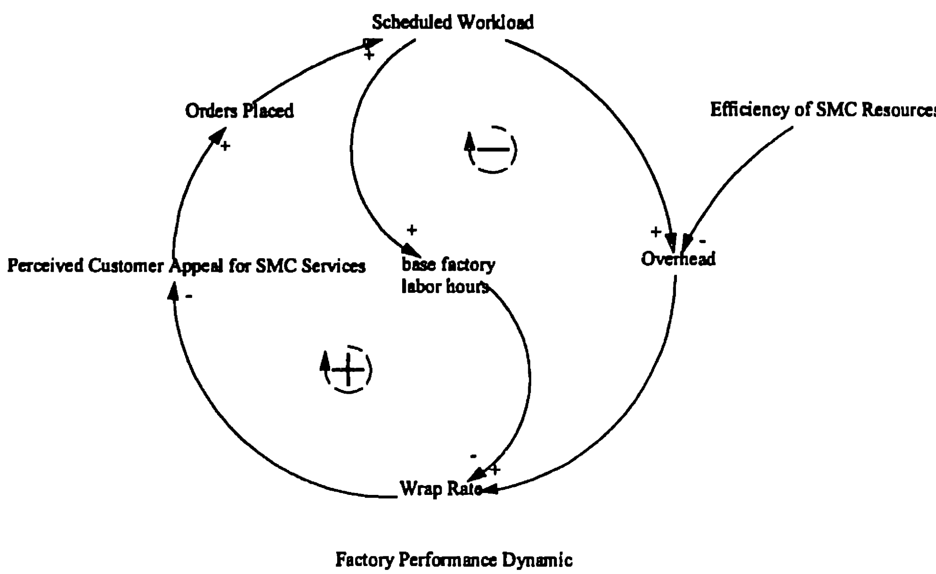


Figure 7: Perceived SMC Cost Dynamics

The current perception in the factory is that as BFL reduces, the relative amount of overhead increases in the short term because employees cannot be immediately eliminated from the cost structure. This drives up the wrap rate, which reduces the perceived customer appeal for the SMC services. This in turn drives down the scheduled workload, which in turn reduces the BFL. If this dynamic is real, the factory should try and maximize the direct labor hours to prevent an uncontrollable downhill spiral.

In response to this dynamic, there is a strong effort to have mechanics always clocked into an order. When this filters down to the mechanic, the message becomes, "If there is a low queue in front of your operation, either expedite orders to reach your station or slow down the pace of operation to maintain charging practices."[3] Either of these responses create a disturbance in the production schedule and make capacity analysis difficult.

The layoff factor contributes to the above dynamic, creating flexible capacity effects that are dependent upon the amount of WIP in factory queues. When the volume of work is reduced, the tendency of the organization is to reduce the workforce to control costs. While this is a perfectly natural response to an industry downturn, it eliminates any sense of trust between the company and the employees. It is in the mechanic's best interest to remain busy, and create the perception that the company in fact does need him around.[4] This provides an incentive to reduce productivity in times of low WIP. This effect was documented by Gomersall as "The Backlog Syndrome", in which he states there are four laws of inventory buildup (Gomersall, 1964):

First Law: Once a backlog had been built, it will tend to remain at a fixed level until one of the following occurs:

- The model is discontinued.
- Significant Changes in personnel and equipment are made.
- Business becomes depressed, or the enterprise fails.

Second Law: The work pace will tend to decrease as the backlog of work decreases.
Third Law: The work pace will tend to increase as the backlog exceeds the "security level," which is that backlog level above which the employees feel secure in reducing its size
Fourth Law: The size of the backlog maintained tends to be inversely proportional to the cycle time of the station having the work-in-process.

These laws suggest that the queue in front of each station has a direct effect on the productivity of the mechanics. These dynamics, coupled with a low understanding of the cost of holding inventory, contribute to the difficulties in understanding capacity and conducting constraint analyses in a job shop.

[3] Discussions with general supervisor
[4] Discussions with factory supervisors and lead men

A more sensible factory dynamic is shown in Figure 8. The customers' perception of SMC performance is based on total unit cost and not the wrap rate. By communicating this effect to factory personnel, the misperception of the importance of wrap rate could be eliminated and the focus on productivity rather than cost allocation could reduce the effect of flexible capacity in light of changing WIP.

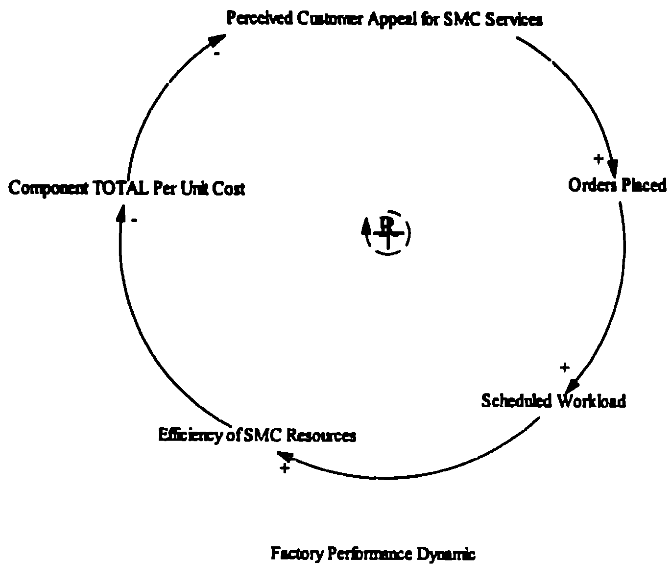


Figure 8: Improved Factory Perception Model

4.3.2.3 Constraint Analysis Dilemma in the SMC - Flexible Processing Times

In a job shop or disconnected line flow, the bottleneck analysis requires that accurate processing times *for the given production schedule* be known. In the SMC this data was difficult to obtain because of changes in the mix of orders, difficulties in the flow path definition, and the lack of an integrated ERP system.

Work Mix Changes - Due to the flexibility of job shops, it is typical that products are developmental, low volume runs. The mix of products at any given time may change, and the resource requirements change accordingly. For example, if the work mix for a given month requires many fixture setups, the available capacity for that resource will be reduced. Therefore, a constraint may change due to changing mixes of product orders. Predicting the constraint location within the factory requires not only an understanding of the available resource capacity, but accurate resource requirements for *each* planned product. Because of the developmental focus of job shop products, accurately predicting resource production times is difficult.

Flow Line definition - The SMC has a large number of flow paths through the factory. Each product routing was planned through the factory by a planning department, which is staffed by personnel who have significant manufacturing knowledge of process capabilities. Products are assigned to planning personnel based on department capacity. Therefore, products are not assigned to planners based on product type, product family or customer type. Because each planner has a different understanding of the manufacturing processes, this method of work assignment can lead to different plans for almost identical components.

Additionally, the product routing through the factory was developed with process capability, planned factory capacity, and cost considerations. Ideally, grouping parts into families prior to planning the routing through the factory would enable a single person to develop product family expertise, enabling consistency in product plans. Because the planning department balances process capability, factory capacity and cost considerations in determining product routings, similar products exhibit different flows through the factory. The long-term result of this mode of operation is an unnecessarily large number of product flows. To correct this problem would require an audit of every product routing through the factory and re-planning the routing so similar parts take the same path through the factory. This can be difficult to justify on a cost basis because of the non-recurring cost of reprogramming an NC machine, re-planning the product and re-training the employees that have gained experience in producing a given product.

The large number of product flows makes it difficult to identify constraints because of the accuracy needed in predicting resource demands for each order.

Data Collection - The manner in which the SMC information systems collect and store data increases the difficulty in determining the factory constraints. For example, orders planned for the factory are classified with a control code between 1-9. This is a nomenclature that is used for financial rather than factory management purposes. Certain products that are planned for the factory that are early in the product lifecycle are classified as control code 5. The estimated processing times for each FWC for control code 5 products are not available through the MRP system. Because the MRP system data is used in capacity planning, the resource demands for control code 5 products do not show up in the summary report and the estimate for the scheduled workload is lower than the actual workload. The factory estimates the control code 5 resource demands and adds those to the MRP data, but the process is manual and laborious. The data is not available real time and creates significant delays in the capacity planning process, increasing the potential for overload / underload conditions.

The inaccuracy, inapplicability and lack of timeliness of the data necessary for constraint analysis creates difficulties in conventionally determining constraint location. A solution to this problem is to choose a likely constraint and release material into the process at the rate of the suspected constraint's production. With managed material release, the internal queues will then highlight the system bottlenecks.

4.3.3 Constraint Analysis Dilemma in the SMC – Solution

Although the above sections highlight potential barriers that need to be overcome in the determination of constraints in a job shop environment, there is an efficient process that can be used. These steps, as applicable to a job shop, are:

1. Identify the process family flowpaths through the factory.
2. Identify a potential constraint within each flowpath.
3. Release material into the flowpath at the constraint production rate.

4.3.3.1 Process Flow Identification

Although the SMC can be characterized as a job shop, it is possible to break the products into process families that have a common process flow. Within each process family there might exist variations of the machines that are used to manufacture a component, but the higher level process steps are similar. For example, the process flows for three different products are shown in Table 2. While the specific routing of the products varies slightly, there exists a high level of similarity allowing these products to be grouped into a process family.

Table 2. PRODUCT ROUTING 1949 FAMILY

Operation	Machines for Part 114N1010-2	Machines for Part 114N1018-6	Machines for Part 114N3010-1	Machine Type
1	18K3	18K3	18K3	4-AXIS OM1 SUNDSTRAND (FMS)
2	18K3	18K3	18K3	4-AXIS OM1 SUNDSTRAND (FMS)
3			1563	SAW, BAND
4			1081	DRILL, PRESS, RADIAL
5	***1949***	***1949***	***1949***	***5-AXIS SERIES 80***
6	1563	1563		Band Saw
7	1334	1334		VERCI-POWER, MILL
8	4035	4035	4035	BURR. HAND
9	4035	4035	4035	BURR. HAND
10	0701	0701	0701	PROTECTIVE WRAP & IDENTIFY
11	403A	403A	403A	SHOTPEEN, PEENMATIC
12			1173	SUNNEN POWER STROKE HONS
13			0701	PROTECTIVE WRAP & IDENTIFY
14			3646	ASSEMBLE, MACHANICAL
15			4060	CLEAN
16	0701	0701	0701	PROTECTIVE WRAP & IDENTIFY

Certain routings within a process flow may include additional operations but the underlying plan is similar. Several tools were used to identify the process families, including group technology and process mapping.

4.3.3.2 Engineering the System Constraints

Once a job shop is simplified into process flows, the constraints within each process flow must be determined. Because of the nature of job shops, it may be difficult to identify a specific constraint in each process flow. A solution is to choose a machine to treat as the constraint in the process flow and begin a DBR system based on this machine. This is referred to as engineering a constraint.

Which operation do we choose to identify as the constraint of the process flow? Because of the difficulty in answering this question, we chose specific NC machines to use *as* constraints in the system. For each process flow in the SMC, there exists a single primary NC machine that does most of the value add to the components. These NC machines (Table 3) were chosen to be the analysis points of the system. The reasons for this were:

1. In the SMC, the NC machines are capital intensive equipment that would require significant resources to increase capacity. By implementing DBR with the NC machine as the drum of the system, the goal of the operation would be to maximize the efficiency of these resources. This ensures that the factory is obtaining the maximum throughput possible through these machines.
2. In the process flows that were identified in the SMC, the NC machines were the only resources that were not shared. Figure 9 shows that the flow of products through the factory diverges primarily at the NC machines. If another resource were chosen to be the constraint of the system, it would be difficult to ensure that the NC machines were not left idle unnecessarily. For example, if the quality assurance operation were chosen as the drum of the system, material would be brought into the factory at the rate at which QA completed orders. Because the order introduced into the factory could potentially go to any NC machine, variation in the types of orders could cause a local bottleneck in one NC machine while other NC machines were left idle. Using the NC machines prevents the occurrence of two flowpaths having the same engineered constraint.
3. The support operations (Non-NC machines) were primarily manual operations or would require low capital investment to increase capacity to support the NC machines.
4. The NC machines were running on 3 shifts while the support operations were not fully staffed 24 hours a day.
5. Because the majority of the value-add was conducted on NC machines, the components can be valued at near complete costs immediately after the NC operation. Therefore, to minimize the overall cost of operation, it is preferable to design a system that minimizes the inventory downstream of the NC machines. This will ensure that components that have a majority of the value do not queue in the system, minimizing inventory costs for the factory.

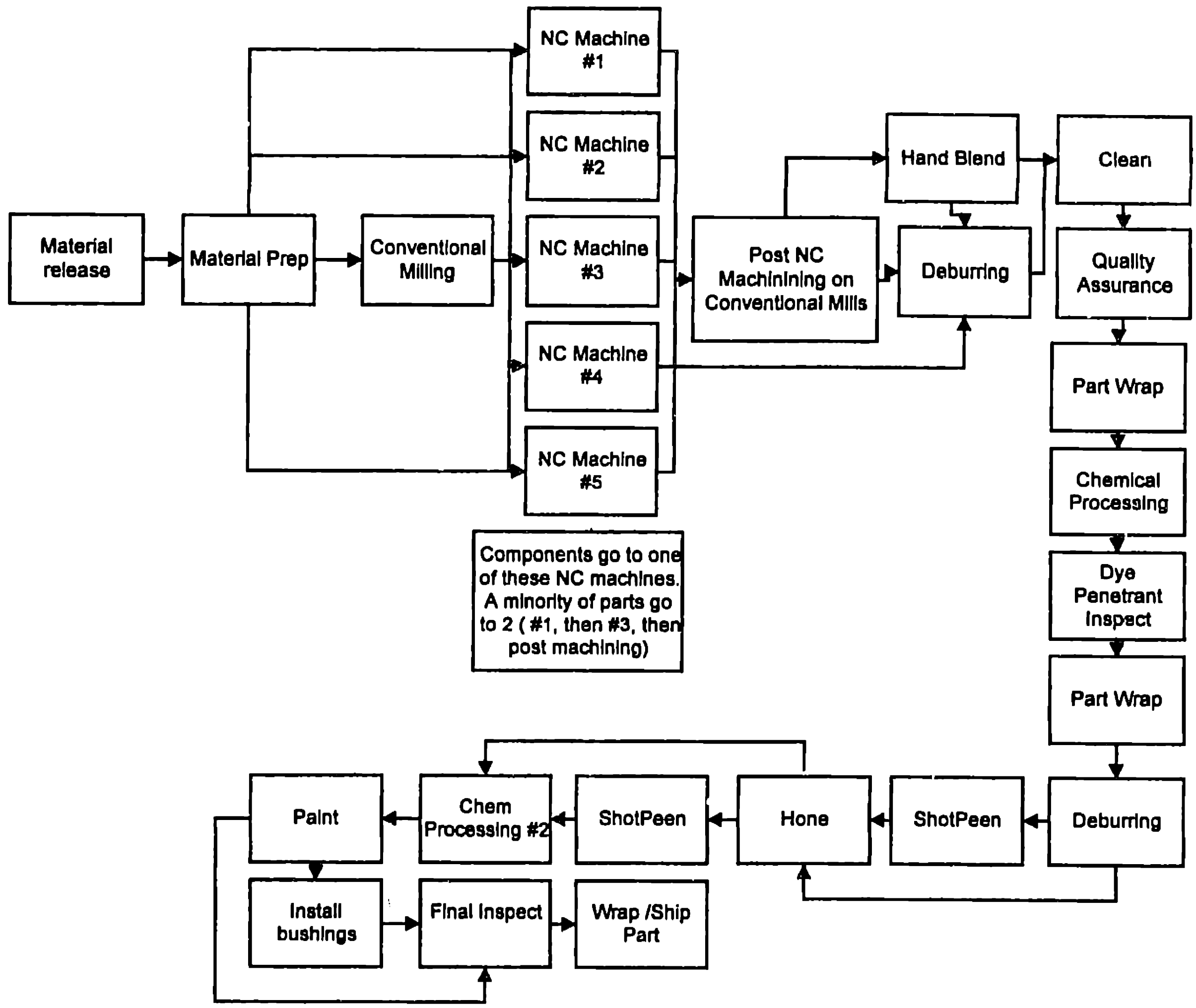


Figure 9: Generic Process Flow

Once a DBR system is operational, the incoming material to the factory will be controlled and predictable. If the operation that was treated as the constraint is not the actual constraint, queues will build in front of the real constraints. Because the non-NC machine operations are easily scalable, the capacity of those operations can be increased to drive the actual constraint to the engineered constraint.

Using the NC machines to differentiate the process flows, several process families were identified for the SMC (Table 3)

Table 3 Constraint Machines

Flowpath	EWC	Machine Type
1	CCGW	5-AXIS 3 SP. VERT. GANTRY
2	1949	5-AXIS 1 SP. HORIZ. MILL
3	1966	5-AXIS 3 SP. VERT. GANTRY
4	18K3	4-AXIS OM1 SUNDSTRAND (FMS)
5	1898	4-AXIS OM1 SUNDSTRAND (950 CONTR.)
6	1967	5-AXIS, 3 SP.VERT. GANTRY (CELL)
7	CCEP	3-AXIS, 3 SP. VERT. GANTRY
8	1966	5-AXIS, 3 SP.VERT. GANTRY (CELL)

Engineering a constraint is not the same as finding the constraint. This caused considerable confusion with the implementation team. We continued to refer to constraints when we actually meant the process we would treat *as* the constraint. Because the TOC courses that were taught to the implementation team did not describe the benefits of engineering a constraint, conveying our intentions to the implementation team was difficult. It is important to clearly define this distinction during the implementation process so those involved do not become confused.

4.4 Step 2. Utilize DBR to Control Inventory

For each flowpath, the process steps are now identified and a constraint is engineered. A DBR system can now be implemented in a job shop environment.

The policy rules for our DBR system are the following:

- All machines work any order that comes to it in a sequence governed by critical ratio.
- The amount of inventory is kept constant between the first operation and the constraint operation. More orders are introduced to the factory when the inventory level (buffer) drops below a target level.
- Orders introduced to fill the target level that are ahead of schedule will be analyzed to determine the benefit of the early start.
- Orders introduced into the system that require expediting *by customer contract* get a higher priority in the critical ratio ranking.
- Operations before the constraint work at a rate to ensure that the constraint is never starved.

In the SMC, it was determined that the best method for introduction of a DBR system was to do it on only one process flow as a pilot line. This would allow the factory to become accustomed to the DBR process without disrupting the entire factory. In addition, several managers were skeptical of the benefits of the process and wanted a test area run to observe the results. To implement this process, we chose the aluminum cell as a pilot line. This was chosen because the cell is almost a self-enclosed factory with near-complete components leaving the cell. Therefore, shared resources would not become an issue in creating local bottlenecks. In addition, it was thought that the cell could be improved through an inventory control policy. Prior to the pilot DBR line, the cell didn't have any internal inventory control policies.

To enable a DBR system, the following must be implemented:

- A buffer manager must be identified to manage the material flow process.
- The buffer manager must have a mechanism to know when to pull orders, how many orders to request, and which orders to request.
- The buffer manager must have a mechanism to inform the warehouse what to introduce to the factory.
- Buffer limits must be identified
- Mechanisms to track buffer sizes must be implemented

4.4.1 The Buffer Manager

An individual must be identified to manage the DBR process. Depending upon the mechanisms of the DBR process, this person may play an active role, (checking on a regular basis if orders need to be introduced into the factory), or a passive role (monitoring the process and making adjustments as necessary). The buffer managers in the SMC were identified as the industrial engineers who had the responsibility of managing the active factory orders. Because the IE understood inventory management concepts, the transition to buffer management would be easiest with this group.

The IE group was not penalized for having excessive amounts of inventory in the factory, so they had an incentive to ensure maximum utilization of every factory resource through additional WIP. To ease the transition from a utilization mode of thinking to a Constraint Management mode of thinking, it was necessary to introduce the IE's to Constraints Management through a formal class. A course called "TOC: The Production Way" was given by an instructor that was certified by the Goldratt Institute. This course introduces people to Constraints Management concepts through an interactive computer simulation environment. The course proved to be very effective in introducing counter-intuitive concepts to factory managers that had not previously thought about the drawbacks of high inventory levels.

4.4.2 *DBR Information Flows*

The DBR process is shown in Figure 10. The buffer manager must have the proper information to know when to request additional orders, how many to request and what types of orders to request.

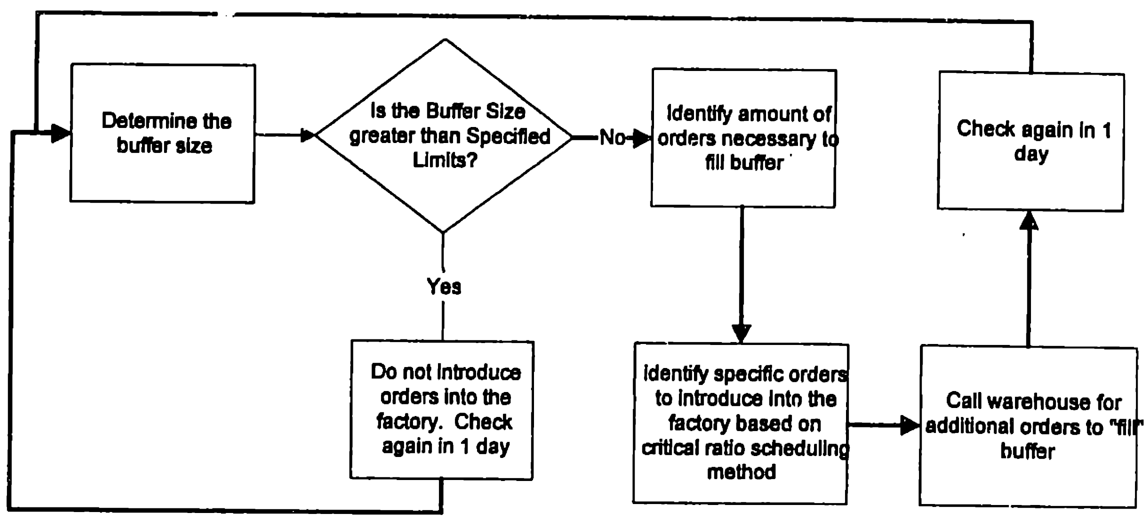


Figure 10: Buffer Management Decision Process

When to Request Orders

To reiterate, the buffer is the total inventory in the CONWIP loop that spans the first process to the bottleneck operation. The buffer manager must understand how much inventory is in the buffer in terms of constraint processing hours. S/he can then compare that value to the target buffer size and determine how many hours of constraint time must be introduced into the system, and how many orders are required to do so.

What to Request

For a given process flow, there may be a number of orders waiting to be pulled into the factory. The buffer manager must have a process for deciding which orders to pull into the factory. Depending upon the metrics of performance, the sequencing decision can be based on a number of approaches, including FCFS (First come first served), SPT(Shortest processing time), EDD(Earliest due date), or CR (Critical Ratio). The sequencing rule used in the SMC was CR.

4.4.2.1 Priority Rules – Critical Ratio Vs. SPT.

In the SMC, each operation currently has a queue because there are no material controls within the system. This tends to allow increased WIP and long lead times. Because the MP&R system has no capacity constraints, it is typical to have many late orders. For example, a random check showed that the number of late orders in the shop was 19% of the total number of orders. To minimize the number of late deliveries, the shop has been using the critical ratio method of priority scheduling. Critical Ratio is defined as the time remaining until an order is due divided by the processing time remaining on an order. Orders are ranked by increasing critical ratio, accounting for the time and work remaining in each order. At each station, the critical ratio of each order is calculated, and the orders are worked in the according rank. It has been noted in literature (Nahmias, 1996) that a efficient method of prioritization is the shortest processing time (SPT) rule, where each operation completes the orders that have the shortest processing time. However, under certain circumstances using SPT may create a system that allows significantly late orders.

In a job shop with prototype work, it is common to have a high variety of processing times for a given machine. If SPT is used, it is possible to have a large processing time order sit forever because shorter jobs arrive on a daily basis. To counter this effect, an SPT scheduling rule with expediting late orders could provide the expected results. However, to design a system that requires expediting orders would be introducing non-value added costs into the system. Therefore, it was decided to use CR as the sequencing rule throughout the factory. When the number of late orders in the factory is reduced or eliminated, an SPT sequencing rule could be utilized to elicit better systemic performance.

How Much to Request

In the SMC, it is typical that orders vary greatly in processing times. For example, a random audit of a machine queue showed a mean processing time of 35 hours with a standard deviation of 21 hours, or a coefficient of variance of .60. Therefore, when a constraint completes an order, it is likely that the next order that is waiting to be pulled from the warehouse does not require the same amount of constraint processing time. The buffer manager must understand the CR of each order in the queue of orders waiting in the stores, and how much of the constraint time each order will utilize. This includes the set up and run time for the constraint machine. Therefore, when an order is completed at a constraint, the buffer manager may have to pull 3 orders into the factory to fill the buffer.

4.4.2.2 The Buffer Management Table

A tool was developed to provide the buffer manager with the appropriate information to manage the buffer. The tool, the buffer management table (BMT), incorporated information from the factory floor control system, the MP&R system and the factory order planning system. An example of the BMT is shown in Figure 11.

Figure 11: BMT for FWC 1949

Rank	SHOP	AR	PART_NUMBER	ORDERID	QTY	STAT	LOC	FWC	CR	TR	LATE?	HOURS	CUM_HRS	FLG_CD	PRTY	ORDST
1	93205	17	5HW82352-103	0074222	1	I/W	MC-42	1949	-19.00	-19	YES	0.00	0.00			11995
2	93205	17	5HW84314-104	685370V	2	RFW	MC41	1949	-1.67	-8	YES	51.31	51.31			11956
3	93205	17	5HW84314-104	685370V	2	RFW	MC41	1949	-1.67	-8	YES	82.08	133.39			11956
4	93205	17	720M2348050-101	584629K	1	RFW	MC41	1949	-0.77	-2	YES	0.00	133.39			11995
5	93205	17	720M2347660-103	546355K	1	TBSU	B21A	1949	8.97	35	NO	0.00	133.39			12004
6	93205	17	115W5222-2	517188E	7	TBSU	D32A	1949	9.38	60	NO	33.52	166.91			11997
7	93205	17	115W5222-2	517188E	7	TBSU	D32A	1949	9.38	60	NO	66.35	233.26			11997
8	93205	17	115W5222-1	517189E	7	TBSU	D22A	1949	9.38	60	NO	36.44	269.70			11997
9	93205	17	115W5222-1	517189E	7	TBSU	D22A	1949	9.38	60	NO	66.74	336.44			11997
[redacted]																
25	93205		5HW82352-103	571461Q	1	R			-2.15	-20	YES	5.16	924.71			11911
26	93205		5HW82352-103	571461Q	1	R			-2.15	-20	YES	47.40	972.11			11911
27	93205		5HW82352-103	571461Q	1	R			-2.15	-20	YES	180.71	1152.82			11911
28	93205		114N4011-24	676205T	6	R			-1.49	-15	YES	8.10	1160.92			11908
29	93205		5HW82352-104	553767B	1	R			-1.29	-12	YES	5.71	1166.63			11919
30	93205		5HW82352-104	553767B	1	R			-1.29	-12	YES	47.81	1214.44			11919

With this single source of information, the buffer manager can make all decisions necessary to manage DBR. The columns provide the following information:

Column	Information
Rank	Provides the sequencing for the orders in the buffer for a given FWC. Orders will be worked in the sequence given on the BMT.
SHOP	The factory where the order currently exists.
AR	The area within the factory that the order is currently in.
PART_NUMBER	The Part number. There may be more than one order in the queue with the same part number.
ORDERID	The order tracking number. The ORDERID is distinct to an order.
QTY	The number of components to be manufactured in the given order.
STAT	The status of the order. I/W is in work, RFW is ready for work, TBSU is to be set up.
LOC	The machine number that the component is being worked on. Each machine has a specific identification number, but there may be more than one machine for a FWC group.
FWC	The Factory work code that the order is at. There could be more than one machine in a FWC, more than one FWC in an area, and there is more than one area to a shop.
CR	The critical ratio value for the order. The Critical Ratio is calculated for sequencing purposes only.
TR	Time remaining until the order is scheduled to be complete measured in days. A negative value represents a late order.
LATE?	If this value is yes, then the order is estimated to be late at completion. If it is no, then the order should get out of the factory on time.
HOURS	The estimated hours that the order will take on the constraint machine. This number accounts for machine variance, quantity, setup and run time.
CUM_HRS	The cumulative number of hours in the buffer.
FLG_CD	A Flag code identifying high priority orders.
PRTY	A flag code identifying special orders.
ORDST	The start date of the order.

For this sample BMT, orders 1 to 9 are orders that are waiting at the constraint and have completed all operations up to the constraint operation. The Flow path constraint is the FWC 1949, and there are four machines in this FWC group. Orders 10-16 are open orders that have begun the manufacturing process but have not yet reached the constraint operation. This can be confirmed because the FWC column shows that these orders are not yet at FWC 1949. The total hours in the buffer for this example is 673.37 hours. Orders 17-24 are orders that are waiting in the stores area waiting to be pulled into the factory. If the DBR system didn't exist, these orders would be in the factory. Orders 25 to 30 are planned orders in the MP&R system that are scheduled for the factory. This section gives the buffer manager a glimpse into what is coming in the near future.

The buffer manager for the 1949 FWC would look at the BMT table once a day and identify the current buffer size. For the given BMT, the buffer size is 673.37 hours. That is, there are orders in the factory that would keep the constraint busy for 637.37 hours. If the target buffer size is 725 hours, the buffer manager would notify the stores area to send orders 17-19 to the factory, filling the buffer up to the target number. If the target buffer size were 600 hours, the buffer manager would do nothing and wait for the next day. This process keeps the in process inventory near a target value. In addition, if the 1949 machines go down for a week, this process ensures that the organization would not waste resources by adding value to the orders when they would get to the constraint and sit.

4.4.2.3 Benefits Obtained From the BMT

With the due date information and the late estimation information, the buffer manager can determine how accepting emergent orders will affect his current capacity. Conversely, the buffer manager can estimate how much work s/he will need to offload in times of excessive load.

The buffer manager can now tell which orders in the factory are planned for his constraint machine. If the constraint machine has no orders queued and ready to work, the buffer manager knows where in the factory the next order is and can go and expedite that order. This helps in planning overtime and work for off-shifts. In addition, the buffer manager can accurately predict when an order will be completed with the constraint operation. For example, using Figure 11, a good estimate for order # 11 is that it will complete the constraint operation 457 hours from now, assuming a 24 hours day operation schedule. Once the DBR system is implemented and the non-constraint operations are subordinated to the constraints, the completion date of the order will be easily predicted. This will help the SMC customers plan around late orders and reduce the perceived variability of the factory. This will also help in expediting DO/DX or AOG orders through the factory.

The BMT will also provide information on the future orders in the same form as currently open orders. This will help the factory plan orders and make tradeoff decisions about batching orders. Lean Manufacturing concepts suggest that batching orders in operations should be minimized, but this assumes that the set-up costs for those operations are minimized. Because of the job shop nature of the factory, many set-ups are labor intensive and can take up to an entire shift to complete. For this reason, it is preferable to batch orders if doing so does not cause other orders to be late. By having information on future orders, the supervisors can better decide when to batch orders and when not to. Additionally, the BMT uniformly ranks orders according to the Critical Ratio policy. A factory wide policy improves the due date performance.

The BMT enables the factory to manage a DBR system based on the flow lines identified in chapter 4.2. The purpose of the BMT is to give the buffer manager the proper information about managing the inventory, and was achieved in an electronic format in the SMC. It is possible to manage a DBR system with Kanban cards, moving cards from the constraint to the warehouse to signal a pull for more material. An electronic Kanban was used because the warehouse is in another location than the factory. Additionally, the electronic format gave the buffer manager information about orders that are not active yet, allowing for proactive rather than reactive offloading under excess demand situations. In addition, the variation in processing times from order to order would make it difficult to utilize Kanban cards in the SMC.

4.4.2.4 Strategic Implications

Because the factory can now be managed as flow lines, it is feasible to plan in advance the manufacturing flow of a component to optimize the costs throughout the product lifecycle. During the initial stages, a component is planned on a specific flowpath depending upon the machining requirements. Once the component has undergone the MTO and is completing the developmental stage of manufacturing, a virtual cell can be created in the factory[5]. This virtual cell can manage inventory through DBR, but utilize a specific team of employees to manufacture the component. Capitalizing on the organizational learning benefits from traditional work cells, this team will coordinate troubleshooting and process improvement efforts. Intra-process communication will increase and the overall understanding of the manufacturing requirements for the component will increase.

Following a virtual cell implementation, if the volume of a component is high enough, the support functions can be brought near the NC machine to create an actual cell. This would decrease the waste of material travel, implicitly reduce the WIP, and reduce the overall cost of production. In this manner, the SMC can change its processes to match the stage in the product lifecycle that components are in. This will improve the demand for its resources because it will become more cost competitive as products move from development to production.

4.5 Step 3. Subordinate Everything in the System to the Constraints

Once the processes are in place to begin an engineered DBR process, it is important that the entire manufacturing system that is affected by the material flow be subordinated to the constraint operation. At this stage in the SMC, a potential constraint was identified, an information system was developed to manage the WIP and control the inventory levels, and processes were implemented to trigger the release of materials. Several issues remain, including:

- What if the constraints that we are releasing material to are not the actual constraints?
- How do we manage the non-constraint operations that are actually non-constraints?
- How do we know if the system is helping us? How much inventory is too much?

These questions all relate to the subordination process, and must be answered to complete the implementation process.

4.5.1 Managing Engineered Constraints

If the DBR process is implemented and operating properly, the actual system constraints will be apparent through the internal system queues that build. Because the non-constraints are easily scalable, the capacity can be increased to drive the actual constraint to the engineered constraint. This step begs the question of, "Why didn't we locate the constraint in the first place?" The answer is because it is difficult to locate in a job shop. Secondly, by identifying the ideal location for the constraint beforehand, the factory can design the process to fit in the operating environment. The factory management begins to get into the habit of managing constraints and maximizing the efficiency of constraint machines.

4.5.2 Managing Non-Constraint Operations

If a factory station is actually a non-constraint, it is underutilized by definition. This implies that the resource will be idle during the day. In most manufacturing organizations, idle resources are considered waste and a result of mismanagement. What results is a desire to maximize the

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[5] The term Virtual Cell was introduced to me by the Process Engineering group at the SMC.

utilization of non-constraint resources by processing orders that will keep the resource busy. The effect will then be wasted time by that resource from working on something that would sit in a queue somewhere else in the system. In the SMC, this was the mode of operation prior to the implementation of DBR. Without a system to measure the cost of inventory, there was no incentive to reduce the waste of resources from keeping machines busy. Management tried to keep all the resources busy regardless if it was a constraint resource or not. This would not be a problem in a balanced flow line, but job shops are typically not perfectly balanced.

The organizational impact of idle resources is significant. Even after completing the TOC course, factory supervisors had difficulty understanding that it could be more cost effective to *not* work on orders in non-constraint operations. Even if the supervisors understood the concept and wanted to support it, the metrics that the factory used didn't provide them with incentives to allow idle time in non-constraint operations.

Although a non-constraint, by definition, requires idle resources it does not necessarily imply that people must be idle. In fact, it is preferable to not have idle mechanics in the factory. Those mechanics that are primarily responsible for manning a non-constraint operation can be applied to assist the constraint operation mechanics when they run out of work. Several suggestions were made in the SMC such as using non-constraint operators to help with NC set-ups, help out with temporary bottlenecks that appear due to demand fluctuation or utilize the time to cross train on constraint operations. All these options allow the mechanics to remain productive while eliminating the excess production that occurs under the previous production policy.

In the SMC, all the factory mechanics were unionized and each had specific job descriptions. This presented several issues with cross-training operators and moving operators during idle time. Specifically, the NC operators were required to have a job grade that was higher than some of the non-constraint operators. Moving an operator from a non-constraint to a constraint operation would require a temporary upgrade for the lower grade employee, primarily resulting in a higher pay for the time of transfer. If the organization is used to such temporary upgrades, implementing a TOC mode of thinking will be easier.

4.5.3 *Buffer Sizing*

Goldratt suggests simply guessing an initial buffer size, and incrementally reducing the buffer size as confidence in the system increases and variation in arrivals to each machine is reduced. If TOC is used a continuous improvement process, this is an acceptable approach.

In the SMC, it was clear that an immediate reduction of inventory would create several organizational strains. First, the factory was uncomfortable with low amounts of WIP because the employees were responsible for maintaining maximum utilization of each machine. In addition, the variation in arrivals of orders to each machine had been significant enough that firefighting to control the inventory was the normal mode of operation. Our approach to setting the buffer sizes was the following:

1. Identify a buffer size that the factory would be "comfortable" with.
2. Identify the target buffer sizes that would provide optimal bottleneck utilization.
3. Chart the actual and target buffer size on a control chart
4. Reduce actual buffer size over time to meet target buffer size.

The DBR system was implemented in the factory with a target buffer size that was agreed upon by the stakeholders in the process. This included the buffer manager, the supervisor, and the factory managers. The initial buffer size was at a level that was much higher than the estimated optimal level to introduce the DBR process to the factory and gain confidence in the process. Although it would have been preferred to begin the implementation with a buffer level at the target level, it was important to obtain buy-in from the stakeholders. It was agreed that once the DBR system was running without incident, the buffer level would be slowly reduced to a level that more closely matched the target values.

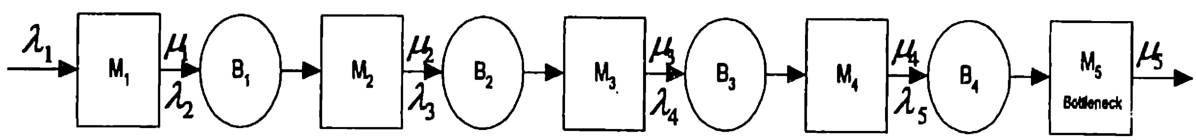
4.5.3.1 *Target Buffer Sizing*

The purpose of a buffer is to absorb variabilities within the system to ensure throughput levels. These variabilities can be caused by uncertain material arrivals, machine breakdowns, uncertain tool arrivals, uncertain processing times, and variable quality levels.
The goal of the factory should be to minimize the number of orders in the buffer, but keep enough to sustain the desired throughput levels. Because the throughput level is dependent upon the availability of machining time of the constraint machines, the metric of concern is:

P_o: The probability of the inventory buffer directly in front of the constraint machine being less than one and the machine being empty. To maximize throughput would be to minimize P_o.

The DBR policy is used to control the amount of inventory in the CONWIP loop from the start of the process to the constraint machine, and *not* to control the level of inventory in the buffer directly in front of the constraint machine. The purpose is to maintain the throughput of the constraint machine. Intuitively, the larger the CONWIP level, the less likely the constraint buffer is to drop to zero.

Assume that the flow through a flow line is as follows:



Where:

M_i = Machine i.

Bi = Queue i.

μ_i = Service rate of machine i.

λ_i = Arrival rate to machine i.

$\rho = \lambda/\mu$

$\mu_i = \lambda_{(i+1)}$

Machine 5 is the bottleneck machine in the process, and the process steps following the bottleneck are omitted from the model. The internal queues are not directly limited in size and follow the same process distribution. The orders in the system are identical in processing time at each step, and the cost and revenue generated for each order is identical in this model.

If we assume Poisson distribution of arrivals into the system, Exponential distribution of service times for each operation, FCFS service disciplines, and single servers at each workstation, Markovian queueing models can be utilized to analyze the individual queue responses (Nahmias, 1997).

The DBR buffer (measured in units of time vs. #'s of orders) can then be determined from the orders in the system as follows:

$$\text{DBR Buffer } (B_{DBR}) = (L_1 + L_2 + L_3 + L_4 + N_1 + N_2 + N_3 + N_4) * T_B \qquad (4.2)$$

Where:

B_{DBR} = The target buffer size used in daily management

T_B = The bottleneck processing time of each order.

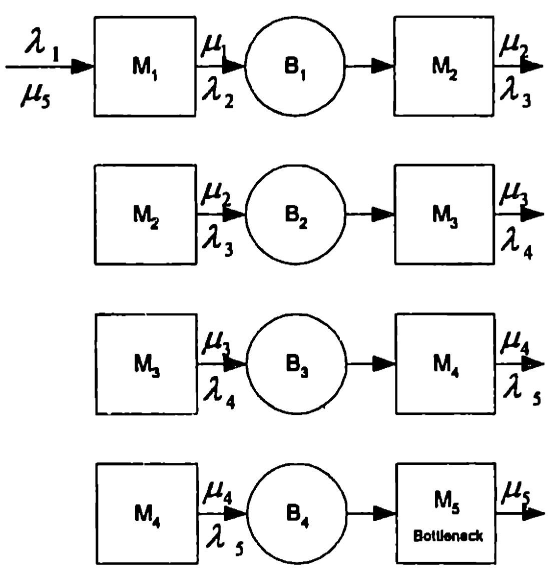
N_1, N_2, N_3, N_4 = Number of orders in machines 1-4

L_1, L_2, L_3, L_4 = Number of orders in queues 1-4

Assume that each order utilizes the same constraint processing time. Under a worst case scenario, it can be assumed that each machine always has one order. Also, if operation 5 is the bottleneck, Equation 4.2 becomes:

$$\text{DBR Buffer } (B_{DBR}) = (L_1 + L_2 + L_3 + L_4 + 4) * 1/\mu_5 \qquad (4.2a)$$

To understand how much inventory will be kept in the individual queues B_1 through B_4, the line can be simplified into 4 2-machine lines:



The arrival rate of work into the system equals the processing rate of work leaving the bottleneck because of the DBR loop. Every time an order is completed through the bottleneck step, another order is started.

This concept of decomposition of the flow line is based upon work detailed by Stan Gershwin (Gershwin, 1994). Although Gershwin utilizes a state-space/conservation-of-flow analysis to determine transfer line inventories, I will use traditional queueing theory analysis to determine queues and buffer sizes internal to the system. The advantage to the queueing theory analysis vs. the Gershwin analysis is that the problem becomes very easy to solve with the data available to the factory. The drawback is that the accuracy of the results is compromised. This is discussed in more detail at the end of this chapter.

Because of the nature of the data collection in the SMC, the arrival patterns and the production patterns of each machine are available. These data can be used to determine what each queue, on average, will contain. The analysis will contain two portions: an analysis of the desired queue size if the second machine is a bottleneck (B_4), and an analysis to determine what the queue size will be of non-bottleneck queues (B_1-B_3).

Non-Bottleneck Machine Pairs

For any non-bottleneck machine pair, the utilization will be less than 1. A queueing theory approach utilizing the M/M/1 model is used to determine the average number of orders waiting in queue. Because these are uncontrolled queues, we are not concerned with limiting the size of these queues. The relevant equations are (Nahmias, 1997):

$$P_o = (1-\rho), \qquad if\ (\rho \leq 1) \tag{4.3}$$

$$L_i = \frac{\rho_{i+1}}{1-\rho_{i+1}}, \qquad for\ i \geq 1 \tag{4.4}$$

Where:

P_o = Probability of the queue being empty

L_i = Number of orders in the queue, on average

ρ = Utilization

The utilization of each non-constraint is known from actual data, and can be used to determine L_I for use in Equation 4.2a.

Bottleneck 2-Machine Pair

To determine the buffer size of a bottleneck 2-machine pair is slightly more complicated. A M/M/1/K queueing model can be used to determine the buffer variables where (Nahmias, 1997):

$$P_o = \frac{1-\rho}{1-\rho^{K+1}}(\rho \neq 1) \tag{4.5}$$

$$Ls = \frac{\rho}{1-\rho} - \frac{(K+1)\rho^{K+1}}{1-\rho^{K+1}} \tag{4.6}$$

$$Po(K) \leq \alpha \tag{4.7}$$

Where:

Ls = Average number of orders in the queue

α = Maximum limit for the probability of an empty buffer. This is a designated value. If we want the DBR buffer to be empty only 1% of the time, α will be .01.

K = Buffer Size

In our model, $Ls=L_4$ because the 2-machine pair with the bottleneck contains B_4. Equation 4.7 states that the probability of the buffer before the bottleneck becoming zero is less than a predetermined constant, α. Solving 4.7 for K yields (Radovilsky, 1997):

$$K \geq \frac{\ln\left(\frac{(\rho+\alpha-1)}{\alpha}\right)}{\ln(\rho)} - 1 \tag{4.8}$$

Using 4.8, the minimum buffer size required to provide a specific α for a specific ρ can be determined and charted (Figure 12).

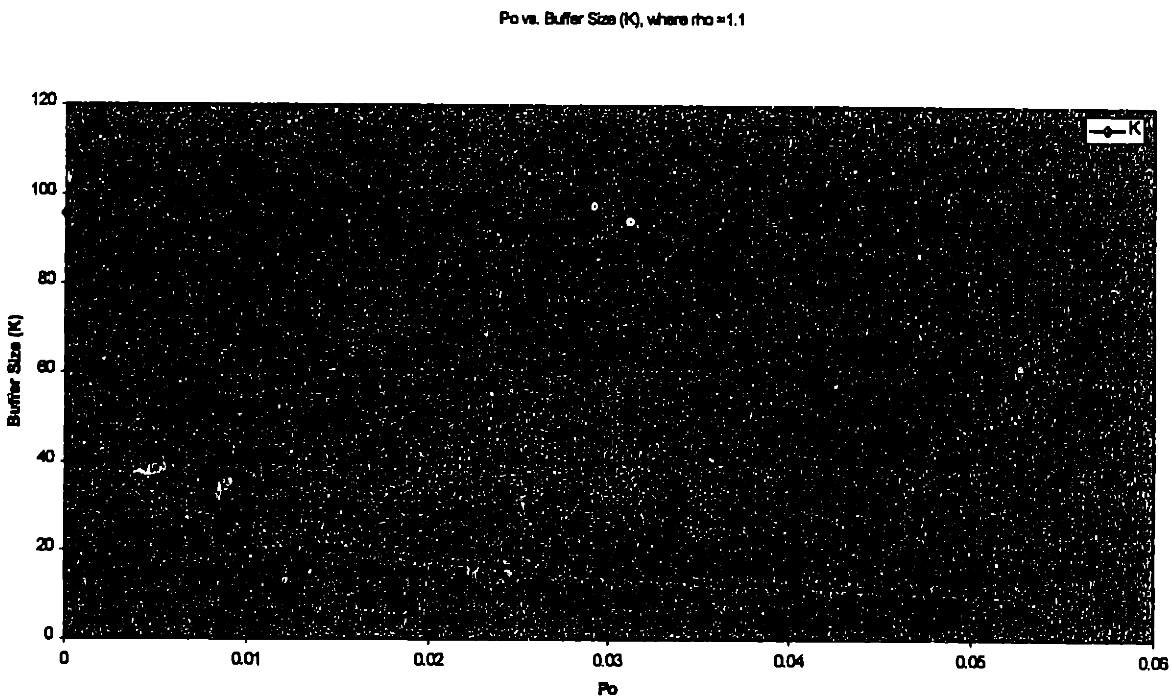


Figure 12: K Vs. P_0 For $\rho = 1.1$

Figure 12 shows that if the bottleneck has a utilization of 1.1, the required buffer size grows exponentially to support increased throughput. Also, as the buffer before a constraint increases, the amount of increased throughput available from having the additional buffer has diminishing returns. Using this chart, it is possible to determine the probability of starving the bottleneck for a given buffer size. However, it is possible to better optimize the inventory levels than guessing with Figure 12.

There exists a tradeoff of holding inventory. Holding more inventory increases the throughput, but also increases the total cost of the operation. Using Radovilsky's approach for analyzing time buffers, the K can be analyzed to optimize the return to the company, balancing the cost of holding inventory vs. the increased throughput available from a higher buffer level. Using the following equations for net profit:

Net Profit = NP = Throughput – Operating Expenses (4.9)

Throughput = TH = Revenue – material cost = μ(1-Po)*C_{TH} (4.10)

Operating Expenses = OE = Ls*C_{OE} (4.11)

Where:

C_{OE} = Cost of holding inventory

C_{TH} = Throughput per unit sale = Unit Price – Materials Cost

Ls = Average number of units in the system

Throughput is considered to be the revenue less material costs per component. If each component is considered identical, the throughput generated by each component will be the same. Combining 4.6, and 4.9-4.11, the following equation results:

$$NP = \mu(1\text{-Po})C_{TH} - Ls * C_{OE} \tag{4.12}$$

Combining 4.12 and 4.6 yields:

$$NP = \mu\left(1-\frac{1-\rho}{1-\rho^{K+1}}\right) * C_{TH} - C_{OE} * \left(\frac{\rho}{1-\rho}\right) + \frac{C_{OE}(K+1)\rho^{K+1}}{1-\rho^{K+1}} \tag{4.13}$$

Equation 4.13 describes the net profit that is achieved with holding K units in the buffer before the bottleneck given the system cost constants. To maximize the profit, the differential of equation 4.13 with respect to K must be determined. Equation 4.13 is non linear with respect to K and thus it is difficult to solve explicitly for NP(K). However, this NP equation can be optimized using numerical techniques (We used Microsoft Excel solver) for a given C_{TP}. C_{OE}, and utilization to result in an optimal buffer size. This will yield the buffer size that optimizes the return to the factory without having to arbitrarily set a target α. The inputs into the Excel Solver were:

Objective function (Maximize): NP (Equation 4.13)

Decision Variable: K

Constraints: K>0

Once K is determined from optimizing equation 4.13 and the individual queues are determined using equation 4.4, the B_{DBR} can be determined:

$$\text{DBR Buffer } (B_{DBR}) = (L_1 + L_2 + L_3 + L_4 + 4) * 1/\mu_5 \tag{4.2a}$$

The following example shows how these equations can be applied. Assume the 5-machine process line with the following characteristics:

Table 4. Example Buffer Size Problem

	Machine 1	Machine 2	Machine 3	Machine 4	Machine 5
λ (orders/day)	20	20	20	20	20
μ (orders/day)	25	40	26.666	50	18.18
ρ	.8	.5	.75	.4	1.1
L_i	4	1	3	.667	8.57

The individual queues L_1-L_4 are calculated using Equation 4.4. L_5 is determined by using Microsoft Excel Solver with the following cost constants:

$C_{OE} = 3$

$C_{TH} = 10$

$\rho = 1.1$

In this example, the arrival rates at each machine before the constraint is the arrival rate at the first machine because of the conservation of material in the system.

$B_{DBR} = (4+1+3+.667+8.57)*.055$ days = .948 days, or 19.91 hours assuming a 21 hour production day. This means that the entire DBR loop should have a target of orders that utilize 19.91 hours of the constraint time. Under this example, the P_0 for the bottleneck is 12.9%. Although this may seem high, it represents the optimal tradeoff between holding inventory and increased throughput.

Running the same example with $C_{OE} = 1$, the results are:

$P_0 = 3\%$

$B_{DBR} = (4+1+3+.667+13.95)*.055$ days = 1.25 days, or 26.12 hours

The optimal solution results have a higher buffer level because the cost of holding inventory is reduced as compared to the increased throughput that the additional inventory would provide.

This numerical analysis can be used for any job shop environment to determine the B_{DBR} given inherent system variabilities.

4.5.3.1.1 Theoretical Buffer Sizing: Assumptions Vs. Reality

The simplification of the transfer line to individual 2-machine transfer lines may create inaccuracies in the model because the assumption that μ is exponentially distributed may not hold due to the inter-process variation. To confirm the extent of the inaccuracy, further studies will need to be conducted comparing these theoretical results to a simulation. It is conducted in this forum as a rough approximation of the possible buffer size. Because TOC is a continuous improvement process, the accuracy of the target buffer size is not as critical as an understanding of the proximity to the possible buffer size or the velocity of change of the DBR buffer.

In addition, using an exponential distribution assumes a standard deviation of service times that is equal to the mean service time. If the actual system deviates significantly from this, additional inaccuracies are introduced into the model. Also, the exponential distribution introduces a memoryless property of execution, or the remaining service time for a component being machined at any given time is independent of the time that the component has been in work. This assumption clearly deviates from reality, but is necessary to complete the model. Further work should be conducted to develop a model with general statistical distributions.

4.5.3.2 Buffer Size Control Charts

Figure 13 shows a control chart that can be produced to manage the DBR system. The UCL and LCL were plotted using 3 sigma limits on the buffer sizes. The daily buffer sizes are plotted and the target buffer size as calculated from chapter 4.5.3 is plotted. If the buffer size remains in control, but is always above the target value, the control chart will be evidence to the managers that the B_{DBR} should be reduced. If the buffer size exhibits extreme variability (Coefficient of Variance >1) the operations managers can conduct root cause analysis to determine the cause of variation and have data to show what the cost of variation reduction vs. benefits would be. The control chart serves several purposes:

- It can be used to manage the amount of inventory in the factory.
- It can be used to measure the variation in the material arrivals
- It can be used to enhance buy-in of the material reduction plan to achieve near-theoretical values.

As the organization gains confidence in the material pull system, steps 1-3 in determining the DBR buffer sizes can be eliminated. However, it is important to maintain higher than necessary inventory levels initially to prevent stockouts. This will prevent disbelief in the system in initial introductions of the system.

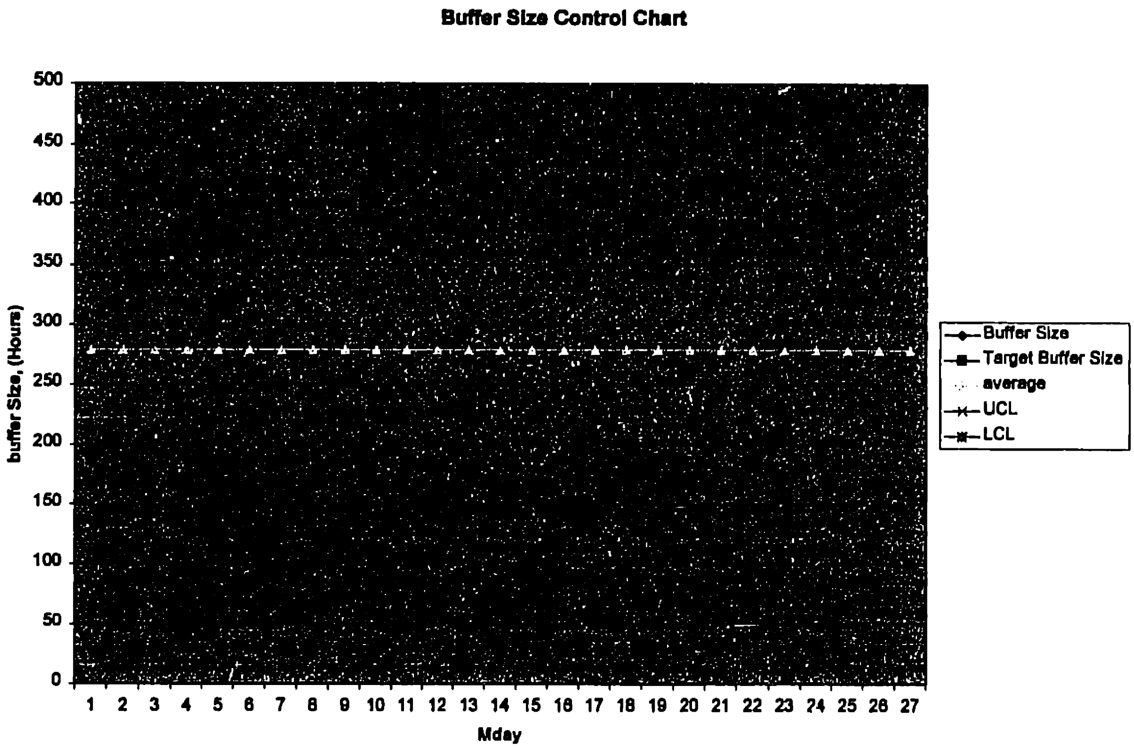


Figure 13: Buffer Control Chart

4.6 STEP 4. EXPLOIT THE CONSTRAINTS

Once the DBR system is in place and the factory (vs. the MP&R system) controls the material release, the constraints can be exploited to maximize throughput. Many techniques can be used for this step, including:

- 24 hours a day staffing of constraint operations. This includes processing during lunch, breaks and shift changes. In the SMC, this was achieved by staggering lunches with operators from non-constraint operations.
- Off-line machine setups. On a constraint machine, a parallel setup process was instituted that increased the production rate by 70%. Because the NC machines are computer controlled, the operator can be setting up the fixtures and material for the next order while the previous order was running.

- Ensure order availability. To maximize the efficiency of the NC machines, the factory had a policy of preparing the next order for operation, including checking the availability of cutters, material, NC documents and fixtures. This would ensure that when an order was complete, the next order would have the necessary components to begin the operation.

Once the factory reaches this stage in the implementation process, AIW's can be utilized to exploit the constraint operations. Although an AIW that is completed in a non-constraint may result in cost reductions, it may not improve the strategic ability of the factory to respond quickly to customers' needs or maximize throughput. AIW events that are conducted on constraint operations will increase the capacity of the factory and ensure that improvement efforts result in throughput increases. This will increase the confidence that the organization has in both TOC and Lean Manufacturing.

4.7 Step 5 & 6. Elevate the Constraint

These steps are included in this framework because this methodology could be used in a continuous improvement process. The SMC didn't reach these steps during the study period. The first 4 steps must be implemented and run until the system reaches equilibrium before step 5 is attempted. This is because it is possible that more capacity may not be necessary.

The constraints in the system were designed to maximize the returns on investment of the high-capital factory resources. If there exists demand for the factory resources after step 4 is completed, a thorough analysis of the new investment must be conducted and justified on long term factory contracts. If the constraint is broken, the systemic constraint has moved to another location in the value stream. Because of the design of the system, a broken constraint will mean that the constraint has moved to the market. The response by the factory will then be to provide the new business development group in the SMC with the appropriate gaps in the production schedule and search for Boeing production that will match the capabilities and timing of the factory excess capacity. It is possible that the SMC will have occasional market constraints due to the job shop nature of order placement. It is therefore important that the SMC utilize the BMT to prevent gaps in the production schedule and maintain the constraint in the factory.

It should be noted that the Theory of Constraints frameworks were utilized in the design of the DBR system, but the exact process of implementation differs from that suggested by Goldratt. The intricacies of the SMC required that a modified process for implementation be used. In addition, the complication of implementation can vary greatly from one company to another. Noreen states, "The companies we visited that were using DBR scheduling reported that very little time or effort was required to set up and run the system" (Noreen, 1995). Conversely, to implement DBR in the SMC took significant resources and development time. The difficulty in implementation is a direct function of the extent of bureaucracy, the capabilities of the information systems, and the type of processes conducted in the factory. The complication of implementation in the SMC will be described in detail in the next chapter.

5 TOC IMPLEMENTATION ISSUES

Implementing Theory of Constraints in any environment has far reaching implications because of the systemic nature of the improvement process. To effectively implement a DBR system, several business functions will be affected and the organizational interactions must be managed effectively. A successful implementation will encounter issues reaching across functions, management levels and technologies. This chapter intends to illustrate several of the issues encountered in implementing TOC in the SMC. The issues covered in this chapter are:

- Information Systems
- Organizational History
- Metrics
- Culture
- Policies

5.1 *INFORMATION SYSTEMS*

5.1.1 *Current MRP System*

The SMC production schedule was driven by an MRP system developed within Boeing called MP&R. The Material, Planning and Release System (MP&R) controlled requirements generation, product structure, make and buy order release, inventory accountability, and historical records. In the SMC, each FWC is assigned a flow day number called *Puget Sound Flow Days* that is used in the MRP system to calculate the lead times on a sub-component. Once the plan is developed and the routing exists for the component, the flow day number for each FWC that the order will go to is added up to obtain the estimated time that the order will spend in the factory. If no plan is developed, a "plug" value is assigned to the plan, which is an estimate of the flow days at each FWC. The MP&R system compares the need date for the order to the flow days required and determines the start date of the order. Several issues arise from this system:

1. The system has no capacity constraints for each factory. Therefore, if the customer requests an order for 100 parts to be due on the same day, the system will start all 100 parts on the same day, regardless of the capacity in the factory to actually begin that many parts. The SMC has developed a reactive system called IESS. The IESS system sums the estimated run times for all components scheduled for a given month at each FWC. The capacity planner can then analyze the load estimate for a FWC in a given month and see if the estimate for the

month exceeds the available capacity and staff accordingly. This system is not effective because it only gives information on the order of months and is not useful for detailed capacity planning. In addition, the IESS system does not include the estimated times for work that is other than control code 1 or 2.

2. The system uses the FWC flow days to estimate the lead-time for an order. However, the flow days used are independent of order size, complexity or machining difficulty. For example, an order of 1 part and an order of 10 parts will receive the same number of flow days if the orders visit the same FWC's in the factory. This will create disruptions in the scheduling process.
3. The MP&R system does not integrate variability in the BOM explosion. The estimated flow time for a component is a function of the operations that the order uses. However, for a given operation, the actual processing time may vary tremendously. For example, the coefficient of variance of processing times for the 3-Axis, 1 Spindle Horizontal Mill (FWC 1949) was 2.5. To account for this variability, the users of the system have assumed extremely long Puget Sound Flow Days to ensure completion of the product. Components are then started much earlier than necessary.

These all create a distrust for the system due dates, and the "Late to Order Due Date" metric is therefore not well understood. However, without an accurate method for relating the MP&R production plan to factory capacity, the organization has a tendency to have a large number of late orders.

5.1.2 Disparate Information Systems

The SMC has several legacy systems that house and store data necessary for factory operations. A layout of the systems and their functions is shown in Figure 14. The systems transfer data when necessary for proper functioning, but obtaining data from different systems in a relational format proved to be difficult. The most relevant systems to the factory are:

The On-line Planning (OLP) system holds factory floor routing information including run times for each operation, Puget Sound Flow days for each operation, and manufacturing details for each FWC.

The Factory Floor Control System (FFC) takes information from the Order Location System (OLS) and the MP&R to develop internal factory WIP reports to facilitate day to day operational management.

The MP&R system holds order specific information including due dates, BOM explosions, and inventory information. This system obtains information from several external systems and releases orders as the due dates arise.

A problem that was encountered with planning work for the bottleneck operations was that the FFC system didn't connect with the planning system, so the FFC queues didn't contain information concerning run times and estimated order cycle times. Therefore, the supervisors knew what was in the queue for each FWC but didn't know how long each order would take. The more standard items' run times were obvious to the supervisors because of past experience, but the developmental orders caused scheduling problems. Also, because the FFC system didn't connect to the planning system, the supervisors on the factory floor didn't know what orders in the factory were coming to their area. This made it impossible to determine the actual DBR buffer size for a given flow line.

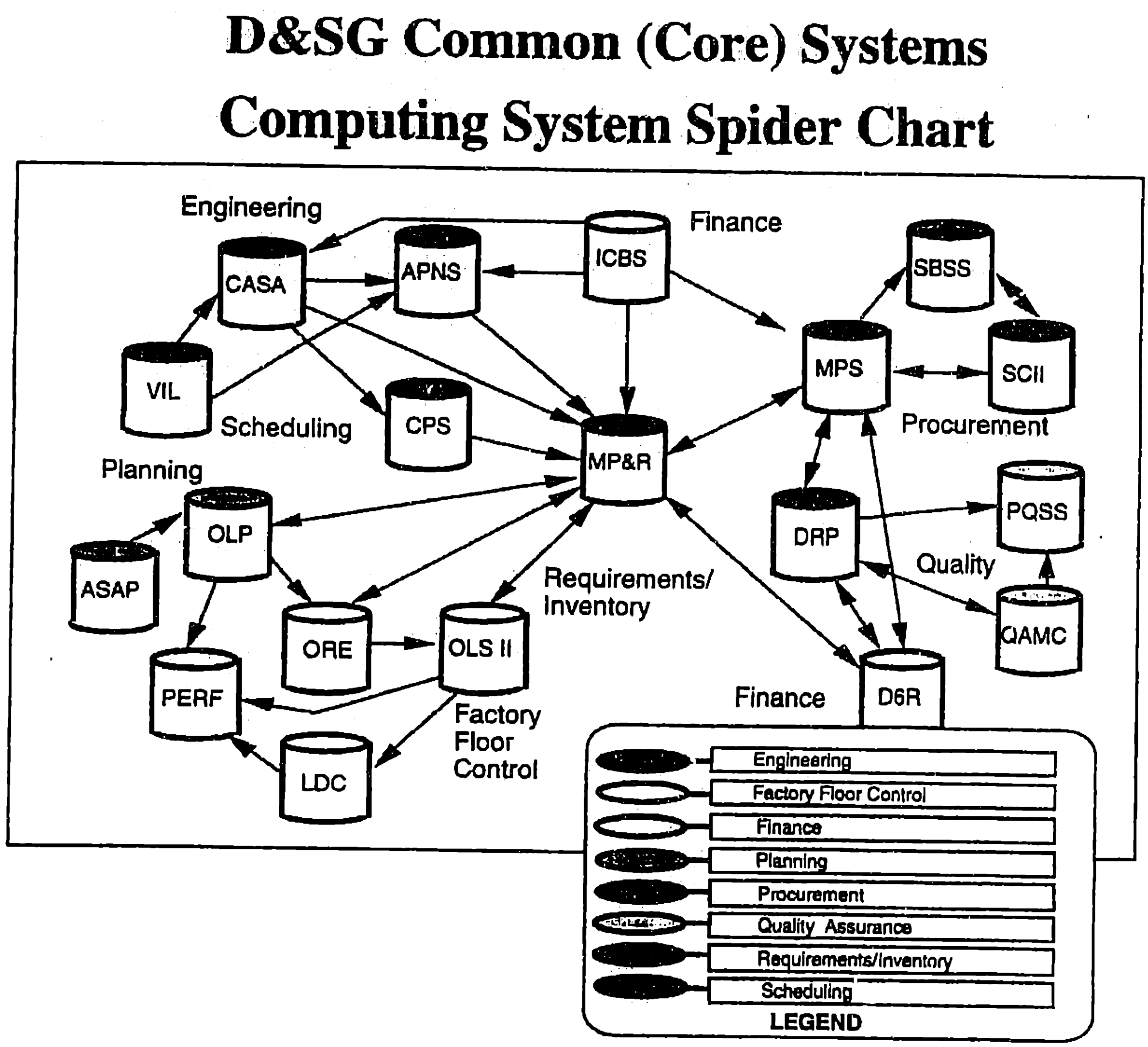


Figure 14: Information System Web

The solution I developed was to create a tool that extracted the necessary data from the disparate information systems and create an alternate factory floor control system, called the buffer management table (Chapter 4.3.2.2). This provided information concerning the buffer size (in hours of run time for each FWC that was treated as a constraint), the priority of each order, and the locations of each order on the factory floor. It also ranked each order in a global priority scheme. This system was relatively easy to implement and provided the data visibility to manage the factory. It was initially thought to be impossible to gather the proper data and calculate the information necessary to implement DBR because of the disparity in the information systems. With the proper interface software, the information solution was developed using Microsoft Office products and programmed in Visual Basic. Disparity in the information systems should not be a significant barrier to a DBR implementation.

5.1.3 Desired Scheduling System

Goldratt suggests that a simple method of scheduling would be to schedule the bottleneck operation and not each and every discrete operation in the factory. Every order is allocated the actual amount of processing time on the constraint FWC. Every process other than the constraint prioritizes based on a FCFS basis. The production variability is dealt with by scheduling the bottleneck only for a certain percentage of the actual available machine capacity. The advantage to this scheduling policy is that the scheduling costs are reduced, predictability to order schedule is increased and the inventory levels are controlled. To achieve this finite capacity planning system, several commercial information systems are available that can be used in addition to conventional MRP systems. Adding a finite capacity scheduling system is the next step in the TOC implementation in the SMC. This would integrate the internal DBR system with the external demands for the factory resources and produce production schedules that are realistic and predictable.

5.1.4 Information Systems Issues Review

In implementing a drum-buffer-rope system in a traditional factory controlled by an MRP system, information systems issues will arise concerning data availability, data integrity and timeliness. Ideally, a finite capacity scheduling system will utilize data from each of the different IS systems and create a production schedule that is independent of the MRP system. This will allow the factory to create a pull system within the scope of the implementation that separates the factory from the push of the MRP system. This is absolutely necessary in any TOC implementation and it is possible that a solution similar to the one developed for Boeing will be inexpensive, accurate and sufficient for TOC implementation.

5.2 ORGANIZATIONAL HISTORY

The SMC has attempted to implement several different manufacturing methodologies in the past 5 years. These include SPC, AIW events, and cellular manufacturing. During discussions with factory employees, a negative attitude towards improvement efforts was discovered. "We go through this every year, and every year it's something different. The management introduces these great ideas then pulls the budget before we can get the full benefits," says one factory supervisor. This has resulted in an organization that resists any type of new initiative in the factory. The management then sees the factory personnel unwilling to embrace changes that are expected to improve the operations. This deepens the rift between the management and the non-management employees.

The most effective method for alleviating the effect of the "flavor of the month" title that our project had was sending the key stakeholders to TOC courses taught by Boeing employees that understood the intricacies of the SMC. These courses allowed the factory personnel to learn about TOC in an interactive manner and decide for themselves that this methodology would be applicable to our factory.

Another strategy to overcome the history impacts is to include key personnel early in the implementation process. This includes not only top management but factory leadmen. An implementation team must be developed with representatives from every function that is to be affected by the DBR process, which generally means everyone. In our project DBR implementation meetings were held bi-weekly that included representatives from:

Pilot Area Supervisor	Pilot Area Lead person- 1st shift
Pilot Area Industrial Engineer	Industrial Engineering Manager
Inventory Management Manager	Inventory Management Analyst
3 Lean Team Analysts	Machining Center Manager
SMC Business Management	New Business Development Manager
Process Engineering Manager	Process Engineer
Manufacturing R&D Manager	Stores Supervisor
Stores Manager	Manufacturing Engineering Manager

These meetings were spent as working meetings to detail the roles and responsibilities of the people under a DBR process. The effectiveness of the meetings lay in the collective process that was used in coming up with solutions to potential barriers to implementation. This increased the buy-in that the organization had in the process and the visibility of the project in the SMC.
We initially didn't include all the stakeholders shown above in our discussions detailing our implementation. As a result, we found that those people that would be affected by the process changes but did not participate in designing the new system didn't fully support the suggestions that we presented. Only after having a direct involvement did those individuals begin to buy in to our ideas. The conclusion that was generated was that change cannot be forced on a group, and must be accepted to be self-sustaining.

In addition, creating a cross-functional group to implement a systemic improvement cleared up misunderstandings between functions about the current business policies. Because a significant portion of the training is conducted on the job, the knowledge that is passed throughout the organization becomes tribal and word-of-mouth. The result is the organization may have written policies in place but follows unwritten policies to effectively conduct the daily tasks. This creates a possible situation where one group does not fully understand what another group's actual policies are.

5.3 METRICS

The metrics that the center explicitly uses to monitor performance are Quality, Cost, Delivery, Safety, Morale. Of these, the most important metric that is followed by the SMC is delivery, or adherence to schedule. A component that is late to schedule can create shortages at the assembly line and potential line stoppages. Because of the high costs involved with a line stoppage, the SMC focuses heavily on the delivery metric. Delivery schedule adherence was measured several ways:

1. Proactively, the adherence to order start date was measured. This gave a measure of how "on-time" orders were started and would give a mechanism for continuous improvement of the up-front operations.
2. The total number of late orders in the factory were watched in a weekly report produced by the IE group. This provided the managers a method for determining the overall performance of the factory.
3. The number of orders that were late to the customer need date were closely watched and reported on a weekly basis in the Thursday Counter report. This was a count of all the military orders that were 15 M-days[6] and all commercial orders that were 10 M-days away from customer load date. This is the date that the customer plans to load the component in the next assembly.

Although these metrics to track schedule performance were watched, there was a general confusion about the exact date that the components are due to the customer. This stemmed from the inflated Puget Sound Flow days in the MP&R system. It was assumed by some factory personnel that although the system flagged orders as past due, there was a buffer in between the

[6] An M-Day is Boeing's notation for regular scheduled production days, not including weekends and holidays.

actual due date and the real due date. While some reports used the factory due date (the factory's promised delivery date), some reports used the customer due date (the customer's desired date of receipt) and some used the customer load date (the absolute last day that the customer can have the part). This caused mistrust for what was actually late in the factory and a misunderstanding of the performance of the factory.

Base Labor Hours

As stated in chapter 4.3.2.2, the amount of BFL is a closely watched metric for factory performance. Because it is the major driver underlying the wrap rate, it is perceived to improve factory performance if the BFL can be maximized. However, using this as a performance metric can result in business decisions that sub-optimize the performance of the factory. For example, watching the BFL value as a performance indicator provides incentives for higher levels of WIP. To maximize the BFL, the factory must ensure that all employees are allocating their time to a specific order at all possible times. To absorb the large amount of production variability in the SMC, a large WIP value is kept to ensure that everyone is kept busy during the day. Because the costs associated with holding WIP are not tracked in the DS&G group, employees are incented to maintain BFL through higher WIP levels than necessary. In addition, there exists the potential for overproduction to occur to increase the BFL value.

Also, with a strong emphasis on BFL comes a counterincentive to continuous improvement. Several factory supervisors expressed their discontent with the BFL metric as it would make sense to "go and make parts with files instead of machines." It is clear that there is a balance between maximizing the BFL and improving efficiency but the fact remains that there is a conflicting incentive structure that causes confusion for the managers.

Inventory Levels

The SMC has not tracked the cost of holding inventory that is WIP. Several reasons exist for this, including information system deficiencies and progress payments. A typical military contract requires that the government purchase the raw material that is to be used in manufacturing. The SMC also gets progress payments, which are incremental payments based on the amount of progress that is made on manufacturing a component. These contracts are written to protect Boeing from the holding cost of the material during the long production lead times. However, because the company gets paid for partial production of components, it is perceived that there is no real cost relating to the time value of money involved with holding inventory. In reality, there are intangible costs to holding inventory other than the time value of the money invested in the material. These additional costs are:

- Higher WIP levels increases the opportunity for obsolescence of material. If design changes occur during the process, more inventory must be scrapped or reworked.
- Production problems that go unnoticed for any period of time cause greater rework or scrap costs.
- Inventory increases the cycle time of the entire process by creating internal queues.
- Additional handling costs exist for moving, storing and tracking material in the factory.

Managing a manufacturing operation requires visibility into four critical variables: throughput, capacity, inventory, and cycle time. These four variables are tightly coupled, and changing one has a direct impact on the other three.

By increasing capacity, a potential exists for increasing throughput or decreasing cycle time, or achieving some combination of the two. The exact amount of change of each variable depends on the associated costs, but the exact benefit of the two is a strategic decision.
By decreasing inventory, the cycle time can be reduced because components no longer wait in queues in the factory and can be processed closer to a single part flow system. Conversely, the capacity can be reduced to achieve the same levels of cycle time.

These levers are tightly intertwined and must be appreciated to achieve the corporate goals of customer satisfaction before decisions are made on which benefit to pursue when changing a variable. Understanding the inventory levels is critical to making these tradeoffs.

5.3.1 Managerial Metrics - Daily

To elicit the proper organizational behavior, it is important that the correct measures be placed and followed in the factory. Because entirely different modes of behavior are necessary at constraint operations vs. non-constraint operations, different performance measures need to be used.

5.3.1.1 Constraint Metrics

The goal of the factory should be to maximize the throughput of a constraint operation. This will result in the highest output for the organization as a whole. Therefore, the throughput of the constraint machines should be measured. Conversely, the organization can strive to maximize the utilization of the constraint operations. Although both metrics achieve the same goal, intricacies in the system need to be understood before either can be utilized in the factory.

- *Throughput Metrics*. An *Orders produced/day* measure is a throughput measure. The SMC has struggled with determining a throughput metric because the high variation in the time resources of a constraint that each order takes. Orders/day would be a rough estimate of the throughput and not precise because throughput for one day could range from 1 to 5 orders depending upon the type of work being performed. A *Dollars generated/day* throughput metric would be difficult because the SMC is an internal Boeing supplier and does not have a set transfer price for components. The SMC transfers the actual cost of products based upon Equation 4.1, which does not reward the factory for exceptional performance.

  A transfer price for components can be determined that rewards the factory for exceptional performance. Orders are received into the SMC as work packages, such as 757 stub beam components. The expected return on investment for a given program can be aggregated down to the component level and used to estimate the maximum cost per part that the Boeing Company can afford to reach overall corporate profitability goals. By setting these transfer prices, a daily throughput metric can be calculated. This would provide an unbiased measure for throughput at each constraint operation. This would provide the factory with a real performance metric. Implementing this process will require further work in the SMC, but may be easily implemented in other situations.

- *Maximum Utilization Metric.* The goal of the organization should be to maximize the throughput for the constraint machines, or conversely to maximize the utilization of the constraint machines. If the constraint operations are NC machines, spindle meters are available that measure the utilization of each machine and can be connected to PC's to generate reports. This would provide the factory with a constraint utilization metric. This is not the preferred metric because installing these meters was thought to have negative organizational impacts.

5.3.1.2 Non-Constraints Metrics

Typical manufacturing operations are thought to be running smoothly if there is a consistent work pace. To be properly subordinated, a non-constraint should *not* operate under a constant work pace. A relevant analogy is a non-constraint should be managed as a firestation[7]. Firemen are measured by the speed at which fires are extinguished, not in the volume of fires that are extinguished in a given month. When a fire occurs, the firemen should work at maximum speed to put it out, then remain idle until the next fire. Accordingly, a non-constraint operation should be measured in the speed at which orders are processed and not in the volume of orders processed in a given day. This will prevent overproduction in areas that have capacity to outpace the constraint machines. The ideal metric for the non-constraint operations would be a measure of wait time for orders, or average queue time. The goal of the factory should be to minimize this average queue time. This is currently measured in the factory for each FWC, but should be only measured for the non-constraint operations because we expect a queue time at constraint operations due to our preset time buffer.

These metrics are to be used daily and published to assist management decisions and provide performance evaluation.

5.3.2 Managerial Metrics - Monthly

Goldratt has proposed a method of managerial accounting called throughput accounting that better measures the performance of the manufacturing system (Goldratt, 1984). Throughput accounting measures three key metrics:

Throughput (T) = Revenue, or the rate at which the system is generating money.
Inventory (I) = WIP + capital assets, or all the money that is tied up in the system.
Operating expenses (OE) = All costs not incurred in developing throughput, including direct labor.
These key metrics can be converted into other business metrics by the following:

Income before taxes:	T - OE
Return on Investment:	[T-OE] / I
Inventory Turns:	T / I
Productivity:	T / Headcount

The benefit of using Throughput Accounting versus standard cost variance reporting for managing operations is gained primarily because it does not create incentives to create WIP. In

[7] Thanks to Stan Gershwin for this excellent analogy.

addition, it gives all the managers a simple method for understanding how their decisions impact the bottom line of the business unit. In essence, Throughput Accounting is a method of cash flow accounting and is not a new concept. Noreen notes that TOC companies use it in addition to the GAAP Financial accounting practices to assist management in pricing and investment decisions (Noreen, 1995).

By utilizing a Throughput Accounting method of reporting, the SMC can focus on maximizing the output of the constraint FWC's and not optimizing the efficiency of each and every operation. In addition, the total cost of operation will be included in the performance of the factory, including inventory holding costs. These metrics should be published on a monthly basis to provide feedback to upper management on the performance of the factory. The type of data required for this report is not required for daily operations nor is it feasible to calculate these reports daily. For factories with a less complicated information systems infrastructure, it may be simpler to implement a Finite Capacity planning system that will generate these reports on a more frequent basis.

In summary, to effectively implement a DBR system it is important to correctly measure the performance in a manner consistent with the behavior that is desired. Traditional metrics do not account for inventory holding costs, and these methods for daily and monthly metric publication provide visibility into inventory.

5.4 CULTURE

Ed Schein defines culture as, "A pattern of shared basic assumptions that the group learned as it solved problems of external adaptation and internal integration, that has worked well enough to be considered valid and, therefore, to be taught to new members as the correct way to perceive, think, and feel in relation to those problems." (Schein, 1992) The culture of the SMC is a double-edged sword: it allows it to perform what needs to be done today but prevents it from quickly adapting to new manufacturing methods. This section is intended to highlight some examples of organizational culture that can make implementation of TOC difficult, and to propose some tactics used to overcome these issues.

Step 3 of the TOC implementation is "Subordinate the system to the bottleneck". This is possibly the most difficult step in the implementation because the systemic nature of the process step.

By definition, a DBR system should not have equal utilization or output rates of each process step. Due to variations in material arrival patterns, FWC utilizations close to 100% will yield queues that tend towards infinity in steady state conditions. In the SMC, there was an unwritten policy to maximize utilization of every FWC. "If I don't keep all the machines running all the time, (the general manager) will come down and have a fit." said a factory industrial engineer. This "maximum utilization" metric, although not explicitly measured in the SMC, has created a culture that believes if a machine is not running, the company is losing money. This pervades the culture from top management through to the factory mechanics. "If I paid 2 million dollars for a machine in my own shop, you'd better believe I would have it running all day!" said one of the factory supervisors. This directly opposes the structure of the DBR process.

In addition, the "firehouse" mode of operation that is described in chapter 5.3 for non-constraints is necessary to obtain the full benefits from DBR. Because this is a different mental model of efficient operation than the one held by the current culture, the concept was resisted. There were countless times during the implementation that we answered the question, "What's wrong with the way we do things now?" This is an example of cultural stagnation that prevents an efficient change of operational modes. While this is important to ensuring consistency in daily operations, it makes for a difficult implementation of a new process.

Ed Schein details turnaround change management as having two critical components.

1. The first condition for change is that the organization must be unfrozen (Schein, 1992). This means that there must be some impetus for change, typically a crisis situation or a new directive from management. The unfreezing of the organization is the understanding that prior operating methods are now obsolete and must be changed.
2. The second condition of turnaround change management is there must be "a turnaround manager or team with a clear sense of where the organization needs to go, a model of how to change, and the power to implement the model" (Schein, 1992).

The SMC was undergoing feasibility studies that would show if it was cost effective to keep the factory operational. The SMC was in a crisis situation and we used this to unfreeze the organization and encourage the understanding that the operating methods must be changed. Unfreezing by this method resulted in either a desire to find a change to keep the SMC alive, or an apathy about the entire situation in general. This apathy can be attributed to the numerous layoff cycles that the Boeing Company has had, strengthening a culture that feels the cycles are inevitable which no amount of change can affect.

Because implementing TOC in a traditionally managed manufacturing environment is such a change to the culture, it is important that there explicitly be support from management surrounding the project. If the employees do not feel as if they can implement TOC without retribution due to falling traditional metrics (such as 100% utilization of all operations), the organization will not follow whole-heartedly. This implies strong support from top management is necessary in a TOC implementation. We had several people in the organization resist change because they were not sure if the upper management would appreciate their support. This supports Schein's second condition for turnaround change management.

Schein implies that change can occur only if the two requirements for turnaround change are met sequentially. Therefore, the organization must first be unfrozen before a team is instituted, or a model of change is developed. We found it more effective to implement change by simultaneously fulfilling the two requirements for change. For example, the unfreezing mechanism didn't have a strong effect on everyone in the organization. Once several key personnel were unfrozen, a team was set up with the goals of implementing TOC. Once the team was initiated, more people became unfrozen. This cycle continued and more people continued to join the team. Eventually top management was included and explicit support was granted, but only once this iterative process had occurred. This "bandwagon" effect can be used to gain buy-in from opposition to implementation if the team presents the process as inevitable.

The SMC was undergoing significant internal and external strains during the implementation. Boeing announced a plan to layoff a large portion of its Puget Sound workforce, adding to the apathy towards the project. The factory had metrics that were not clearly understood and felt that the performance was satisfactory, and the division was consolidating several manufacturing facilities into the SMC to save overhead costs. While the situation was challenging, a crisis was critical in unfreezing the organization. Can it be done without a crisis? Possibly, but an extremely strong management push and a dedication to completion must exist. Culture is possibly the biggest barrier to implementation and must be dealt with accordingly.

5.5 Policies

TOC literature states that a business policy may be a systemic constraint, and those must be dealt with as physical constraints. In the SMC this was true, and the implementation team dealt with policies that prevented implementation using a root cause approach. Whenever a policy was presented that conflicted with the implementation, the reason for the policy was questioned and that reason was questioned. The following is an example of the analysis:

Policy barrier: We can't pull orders from the bottleneck to the stores area because they don't know what we need.
Why? Because we currently do not tell them what we need.
Why? Because they send orders based on the MRP schedule. There is currently no need for us to tell them.
Why? Because that is their policy.
Why is that their policy? Because it ensures on-time performance.

The result of the deep understanding of the policy is that the MRP system was used to ensure on-time performance, but was based on unrealistic assumptions. We decided to tell the stores what we need instead of waiting for them to send us the orders. A following policy barrier was exposed:

Policy barrier: We can't tell them what we need because we don't know what we need.
Why? Because we don't know what they have that is coming to our FWC.
Why? Because the information systems do not give us that information.
Why? Because that functionality doesn't exist.

Our response was to build the BMT, which gave the factory the information necessary to run a DBR system. This analysis was not conducted on paper but in real time discussions. While these discussions tended to be lengthy, the results were a clear understanding of the policies that the SMC used and the reasons for those policies. It is important to note that these discussions should occur with those in the organization that are responsible for executing the policy in question. This will result in tribal knowledge that cannot be found elsewhere.

In addition, the policies of the organization are synonymous with the culture. Those people who execute the policy will be the ones to support a change, so the process of root cause analysis alone can increase the buy-in on the policy change.

6 EVALUATION

6.1 System Design

The methodology for implementing TOC in the factory provided a simple to understand framework for TOC. This ease-of-use allowed for analysis of a complex manufacturing system by people of many different backgrounds. Because TOC is based on the fundamentals of operations management science, applying it in a manufacturing setting allowed for the implementation of theory in a real setting in an easy to understand framework.

The job shop nature of the factory increases the complexity of the implementation, but it was found that most orders can be grouped into process families. This was powerful in simplifying the task of identifying the bottlenecks in the factory. The bottlenecks were not identified through traditional capacity analysis because of the job shop complexities. Instead, the bottlenecks were engineered and process steps were treated as bottlenecks as a way to initiate the DBR process and pull orders into the factory. This provided the ability to control the system as desired and maximize the returns on capital investments. A drawback to engineering constraints is it caused considerable confusion in the implementation.

Implementing the Buffer Management Table was critical to enabling the drum-buffer-rope system. The tool provided the necessary information to the people responsible for making the inventory management decisions. One drawback to the system was that it added to the large number of applications that the factory relies on for operation. Preferably, a single ERP system can be used with a finite capacity scheduling module. The importance of data availability for analysis alone presents a strong case for an ERP implementation. Without the correct data, decision making is done blindly and without cause.

6.2 Implementation

Our project reached stage 4 in the implementation methodology. The success of each step is detailed below.

1. *Identify the Constraints* - We identified the constraints and flow paths in the system concurrently.

2. *Utilize DBR to control the inventory within the manufacturing system* - A DBR system was enabled with the Buffer Management Table and the policies of DBR were defined and detailed by the end of the project. Although the DBR material release process was designed, it had only begun to be operational by the time of this writing. Our plan was to run a pilot DBR system on the aluminum cell in the factory and utilize the results there to improve and change the system as necessary. We would then expand the DBR process to other flowpaths in the factory.
3. *Subordinate every step in the system to the constraint* - We concentrated our subordination steps on the process steps that were in the aluminum cell flowpath. To subordinate downstream processes that didn't have the capacity to outpace the designated process that we were treating as the constraint, an AIW improvement workshop was conducted.
4. *Exploit the constraint* - Efforts to exploit the constraint began once step one was completed. Off-line set-ups were initiated to maximize the available run time of the constraint machine.

At present, the process has not continued through conclusion to gather results quantifying the benefits of this implementation.

During the implementation, we attempted to include as many functions in the process as we could. The most significant impact of including these functions in the implementation team was to increase the visibility of the project and increase the buy-in of implementation. Without including all the functions in the process, we would not have had the knowledge nor the support to complete the project. In retrospect, a clearly defined team from the start with strong management support would have improved the speed at which the project progressed. Our team evolved over time culminating in a large cross-functional implementation group. Also, if we had included more personnel in the project the velocity of acceptance would have been greater. There were still difficulties in encouraging acceptance of the implementation even at the conclusion of my time at Boeing.

A prerequisite to any implementation of TOC should be to send everyone involved to a formal TOC course presented by a Goldratt certified instructor. Certification is a simple process and we had two such people in our organization. This course helped introduce the concepts to the factory and smoothed the introduction of our plans into practice.

6.3 Application to Other Job Shop Systems

This implementation methodology can be utilized in any factory that has enough variability to warrant an unbalanced flow line. The process is generic enough to be tailored to any situation. Also, the issues that were confronted in this implementation are probably common enough to be seen in many different factories.

In summary, the TOC methodology used was an effective framework for implementing TOC and could be applied to any job shop environment. Implementing a DBR system in an MRP framework and an underlying Lean Manufacturing environment can be done provided the right data can be collected and presented in a TOC format.

7 GLOSSARY

AIW – Accelerated Improvement Workshop, Boeing's version of Kaizen events. These are utilized to reorganize work to achieve cost reductions.

AOG – Code that Boeing uses to identify orders that need to be expedited because the component is necessary to get an aircraft operational. The acronym stands for "Aircraft on Ground".

BFL – Base Factory Labor hours. The total direct labor hours that the factory is credited for in a given time period.

BMT – Buffer Management Table. The output of an information system that collects and manipulates data and presents it in a TOC framework.

DO/DX – Codes applied to orders that the Factory is required to expedite under contract with the US military.

DBR – Drum-Buffer-Rope. A material control policy developed by Goldratt. DBR is a modified CONWIP process.

FWC – Factory Work Code. A nomenclature given to a group of machines that are identical in capability, size and programming methods.

IESS – An internal information system developed to facilitate the planning of work schedules and capacity factors.

MP&R – The Material, Planning and Release System is the factory MRP system, developed in house.

MTO – Media Try Out. A component that is developed as a test part to qualify a manufacturing process.

SMC – Strategic Machining Center. The acronym used to identify the factory by the Puget Sound employees.

TOC – Theory of Constraints

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APPENDIX A: WRAP RATE CALCULATION

The following analysis is shown to describe the methodology that the Boeing Aircraft and Missiles Division uses to allocate direct labor and overhead costs to product transfer prices. The implications on factory performance measurement are also described. The actual numbers and percentages used in the example are fictional and only for academic purposes.

The SMC costs are applied to products based on a direct labor allocation. The wrap rate is an estimation of the cost of operating the factory for one hour of direct labor. Table A-1 shows the spreadsheet used to calculate the factory wrap rate. The entire table describes the allocation of direct and indirect labor costs for one hour of direct labor. The table is relatively self-explanatory. Each line is calculated by (Example):

Line 4 QA FDS Production = 1.01 * .185 = .1869
The 1.01 value is a sum of lines 1 and 2, as described in the base line input column. 0.185 is the multiplying factor found in the rate column. Therefore, for every 1.01 hours of base labor, the factory uses 0.185 hours of QA and factory direct support labor.

Lines 1-6 are used to estimate the different types of direct labor that correspond to one hour of direct touch labor. These are calculated from multiplication factors in the rate column. The types of direct labor are quality assurance, factory direct support, and product rework. These are not directly allocated to the components but are considered a type of direct labor.

Lines 7-11 convert the hours in lines 1-6 to dollars using the $/hr factors in the rate column.

Lines 12-13 estimate additional costs that correspond to direct labor and direct product support, which includes expediting and product management. Line 14 identifies the total direct labor dollars, which is a sum of all the direct labor dollars from lines 11-13. This is the cost of direct labor functions for each hour of direct labor.

Line 16 estimates the fringe benefits that can be attributed to the direct laborers. This is a percentage of the total labor dollars.

The overhead is estimated in lines 19-22, and is calculated by using a multiplication factor on different direct labor dollars. The exact labor dollars that the multiplier is used on is shown in the base line input column, and varies for the different types of overhead. It should be noted that the overhead is applied as a function of direct labor hours.

Lines 25-31 allocate various factory costs such as travel, computing and factory computing support to the direct labor dollar. Once again, these costs are allocated as percentages of each hour of direct labor.

Line 34 allocates the cost of procuring material in the factory.
The total at the bottom represents the cost of operating the factory for one hour of direct labor.

In summary, the wrap rate is a rate that the organization uses to estimate the hourly cost of running the factory. All costs are spread over some value of labor hours, either direct or factory indirect support. Therefore, the major drivers of the wrap rate are the direct labor, total overhead, and other direct costs.

Because the wrap rate is an allocation of costs based on direct labor, it is best used to estimate the costs for products that are highly labor dependent. Because the majority of the value add on the components produced in the factory is done on NC machines, the wrap rate is not a highly accurate allocation of factory costs. The general movement for US industry has been to shift towards activity based costing to quantify specific product costs. However, even with activity based accounting, the rule of thumb is to use it to make pricing decisions rather than as a metric to measure factory performance.

Table A-1: Wrap Rate Calculations

The following analysis is shown to describe the methodology that the Boeing Aircraft and Missiles Division uses to allocate direct labor and overhead costs to product transfer prices. The implications on factory performance measurement are also described. The actual numbers and percentages used in the example are fictional and only for academic purposes.

Wrap Rate Example

Line #	Hours	Base Line Input	Rate	Factor base Hours	Dollars
1	Basic Factory Labor	1	-	-	1.0000
2	Rework	1,2	0.01	1	0.0100
3	Mfg Factory Direct Support	1,2	0.172	1.01	0.1737
4	QA FDS Production	1,2	0.185	1.01	0.1869
5	Product Direct Support	1,2	0.099	1.01	0.1000
6	Total Hours	1,2,3,4,5			1.4706
	Labor Dollars				
7	Basic factory labor+Rework	1,2	$ 15.00	1.01	$ 15.15
8	Mfg Factory Direct Support	3	$ 15.00	0.17372	$ 2.61
9	QA FDS Production	4	$ 15.00	0.18685	$ 2.80
10	Product Direct Support	5	$ 15.00	0.09999	$ 1.50
11	Total direct labor hours	7,8,9,10			$ 22.06
	Lump Sums				
12	Manufacturing	1,2,3,4	$ 0.11	1.37057	$ 0.15
13	Product Direct Support	6		1.47056	
14	Total Labor dollars with Lump sums	12,13,14			$ 22.21
15					
16	Fringe	14	10%	$ 22.21	$ 2.22
17					
18	**Overhead**				
19	Product Pool	14	5.00%	$ 22.21	$ 1.11
20	Manuacturing	7,8,9,12	110.00%	$ 20.71	$ 22.78
21	Material	27	10.00%	$ 1.01	$ 0.10
22	Total Overhead	16,17,18			23.9917
23					
24	**Other Direct Costs**				
25	Travel Direct		0%	0	0.00
26	Travel PDS	1,2	2%	1.01	0.02
27	Travel Mfg FDS	1,2	1%	1.01	0.01
28	Travel QA FDS	1,2	1%	1.01	0.01
29	Mfg computing costs	1,2,3,4	$ 2.00	1.37057	2.74
30	Product computing costs	6	$ 0.04	1.47056	0.06
31	total other direct costs	20-25			2.84

32						
33	**Procurement**					
34	Material Usage	1,2	$ 1.00	1.01	$ 1.01
	Other cost				
28	Freight	27	0.06	$ 1.01	$ 0.06
29	Q&A	14,15,19,26	0	$ 51.26	$ -
30	COM	14,15,19,26	0	$ 51.26	$ -
31	**Total Cost**	14,16,19,26-30			$ 52.33