# SYNCHRONOUS MANUFACTURING: IMPLEMENTING "PULL" PRODUCTION IN A JOB SHOP ENVIRONMENT

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

Master of Business Administration
and
Master of Science in Naval Architecture

In Conjunction with the Leaders for Manufacturing Program at the
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## Abstract

In a recent contract, CVN 78, Northrop Grumman Corporation has been experiencing significant pressure from the Navy to reduce cost in the design and construction of the new nuclear aircraft carrier class. Furthermore, the joint venture project between General Dynamics Electric Boat and Northrop Grumman Newport News to build the next fleet of Virginia Class Submarines has budgetary incentives tied to the contract. In order to meet these expectations, Northrop Grumman Newport News shipyard has responded by focusing on ways to better synchronize manufacturing in order to meet schedule and reduce costs.

Migrating from the traditional push production to the concept of pull production, it is projected that inventory and operating expense will reduce significantly as pull will help to synchronize production efforts. There are different ways to approach the implementation of pull. Goldratt's Theory of Constraints was chosen as the most appropriate method in the job shop environment of the shipyard's Fabrication Shop.

This thesis focuses on the design of a Drum-Buffer-Rope implementation of the Theory of Constraints in a high variability, high volume steel fabrication shop. Additionally, it describes how this method was selected over alternative pull systems. Finally, a case study of implementation design will be described along with an evaluation of the system design.

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|---|---|
| Thesis Supervisor: | Donald Rosenfield |
| Title: | Senior Lecturer of Management |

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|---|---|
| Thesis Supervisor: | Henry Marcus |
| Title: | Professor of Marine Systems |

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My advisors, Hank Marcus and Don Rosenfield were instrumental in guiding me throughout the project. I appreciated their tough questions and direction throughout the project and thesis.

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To Mom and Dad, thank you for your support, advice and for always listening. You have given me the courage to persevere.

Finally, Mario, my soul mate, you have been a saint to support me through these past couple of years. I am blessed to have such a wonderful friend and husband.

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## Abbreviations

**CONWIP** – CONtinuous Work In Process
**CCR** – Capacity Constrained Resource
**CMMI** – Capability Maturity Model Integration
**CRP** – Capacity Resource Planning
**CVN** – Nimitz Class Attack Aircraft Carrier designation
**EOQ** – Economic Order Quantity
**JIT** – Just In Time
**MOF** – Modular outfitting facility
**MPL** – Manufacturing Process Leader
**MPO** – Manufacturing Process Owner
**MRP** – Material Requirements Planning
**MRP II** - Material Resource Planning
**NGNN** – Northrop Grumman Newport News
**PE** – Process Excellence
**SFA** – Structural Fabrication and Assembly
**TOC** – Theory of Constraints
**TPS** – Toyota Production System
**VCS** – Virginia Class Submarine
**WIP** – Work In Process

# 1 Introduction

## *1.1 Project Motivation*

This thesis describes an internship project completed by the author during the Summer and Fall of 2005. This project was sponsored by Process Excellence, a new division created by direction of Mike Petters, President of Northrop Grumman Newport News. With mounting pressure from Northrop Grumman's customer, the Navy, to bring costs under control, the Process Excellence division was formed in an effort to streamline process improvement efforts across the shipyard. This project was created to support the pilot implementation of a "pull" production system within the Operations division, assess the key enablers and barriers to implementation, and formulate suggestions for sustainability post implementation.

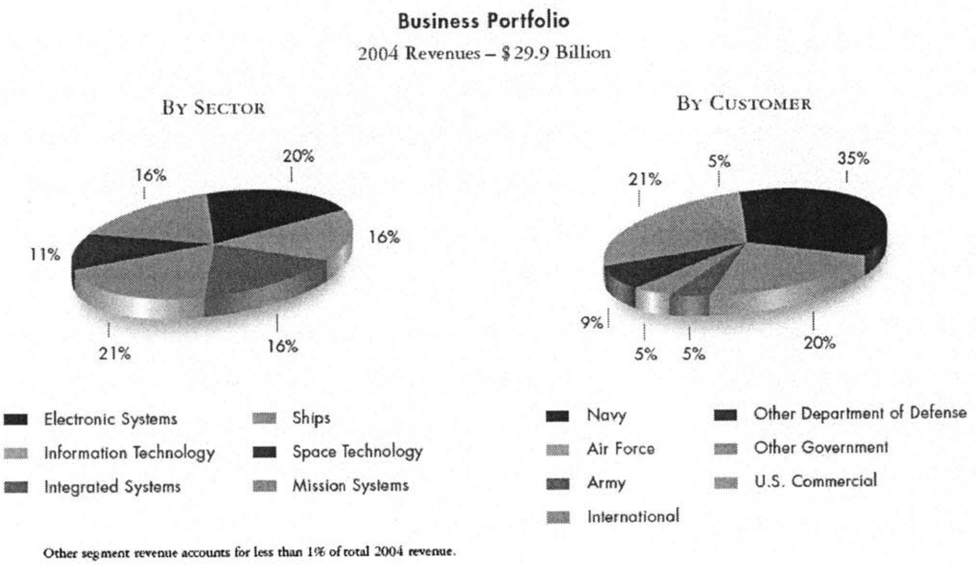
The Operations division was considering options for their approach to scheduling production in order to effect better management of shop floor execution and change management, reduce inventory, and reduce operating expenses. Currently, production is scheduled and managed using the traditional manner: material is released into the system based upon a Material Resource Planning (MRP) system that schedules production months and sometimes years before production. Changes made to the system are handled by the shop floor (i.e. work overtime to get the product out the door). However, the Lean community within Northrop Grumman concluded (with the help of an outside consultant) that the push system created excess inventory when raw material was released into production without a clear indication that the downstream customer would be ready to consume the finished product. This excess inventory added to the difficulty of managing production. There was motivation, therefore, to pilot a test to see how "pull" production would improve the system. The goal of the pilot was to reduce inventory and operating expenses.

The pilot was tested in the Structural Fabrication and Assembly division of Operations in 2004. Since then, cost reduction results have indicated that pull within the Structural Assembly shops could reap larger benefits if expanded into other manufacturing areas of the shipyard. This thesis focuses on the continued implementation of pull to Structural Fabrication and will describe a design of implementation case study. Furthermore, the original problem statement that brought the Northrop Grumman's leadership to the decision to implement pull will be explored. Finally, a justification for the method of pull selected will be discussed.

## 1.2 Northrop Grumman Corporation

Northrop Grumman employs 125,000 across 25 countries serving U.S. and international military, government and commercial customers. Northrop Grumman is headquartered in Los Angeles, California and is comprised of 8 sectors: Electronic Systems, Information Technology, Integrated Systems, Mission Systems, Newport News, Ship Systems, Space Technology, and Technical Services [24]. Northrop Grumman was ranked number 3 among the top 100 defense companies in 2004 with total revenue of $29.9 M [6]. Below is an illustration of Northrop Grumman's business portfolio from their 2004 Annual Report [23]. (The depiction shown in Figure 1-A combined Ship Systems and Newport News into one sector titled *Ships*. The Technical Services sector was added since this report and is not included in the following figure.)

**Figure 1-A: Northrop Grumman's Business Portfolio**



Other segment revenue accounts for less than 1% of total 2004 revenue.

Process improvement within each of these sectors is accomplished with a variety of methodologies including some that follow strictly Lean principles, some that follow Six Sigma principles, and some that apply Capability Maturity Model Integration (CMMI). Most Sectors are merging process improvements into combinations of Lean and Six Sigma. The Newport News Sector uses mostly Lean process improvement tools with an increasing number of Six Sigma tools. The Theory of Constraints does not enjoy widespread usage at Northrop Grumman.

## 1.3 Overview

The thesis proceeds as follows:

**Chapter 2, Northrop Grumman Newport News** provides background about the business of shipbuilding. It continues to explore the organizational structure at one of Northrop Grumman's eight sectors: Northrop Grumman Newport News.

**Chapter 3, Defining the Problem Statement** discusses the problem statement in more detail and analyzes possible solutions, such as the Theory of Constraints and the Toyota Production System.

**Chapter 4, Theory of Constraints** explains constraints management in more detail and describes conventional approaches and metrics used in a Theory of Constraints application.

**Chapter 5, Implementation Design – A Case Study** provides an example of how the Theory of Constraints was applied in a manufacturing setting at Northrop Grumman Newport News.

**Chapter 6, Managing Change** provides insight from the author on managing change.

**Chapter 7, Conclusions** provides advice for prospective Drum-Buffer-Rope applications and discusses the key enablers and barriers of a successful project.

# 2 Northrop Grumman Newport News

*"We shall build good ships here at a profit - if we can - at a loss - if we must - but always good ships." – Collis P. Huntington.*

In 1886 Collis Potter Huntington founded the Chesapeake Dry Dock and Construction Company in Newport News, Virginia. The Company later became known as Newport News Shipbuilding and Dry Dock Company. Newport News delivered its first ship, a tugboat named Dorothy, in 1891. Newport News Shipbuilding is the largest domestic yard and the only shipyard capable of building and refueling the U.S. Navy's Nimitz Class Aircraft Carriers. The shipyard has seen production boom and ebb as a result of government policy changes as well as changes in ownership. The shipyard was acquired by Tenneco in 1968 as a cash safety net to smooth hard times. Tenneco aided in collecting the hundreds of millions of dollars in change orders the Navy owed due to cost overruns. In 1991, however, Tenneco began bleeding money and embarked on a restructuring plan that involved shedding companies that were either losing money or not making it fast enough. As a result, in 1996, Newport News Shipbuilding became an independent shipyard once again [7]. In 2001, General Dynamics bid $2.1B for the shipyard and Northrop Grumman acquired the shipyard with a $2.6B counter bid.

## *2.1 Shipbuilding Industry in the United States*

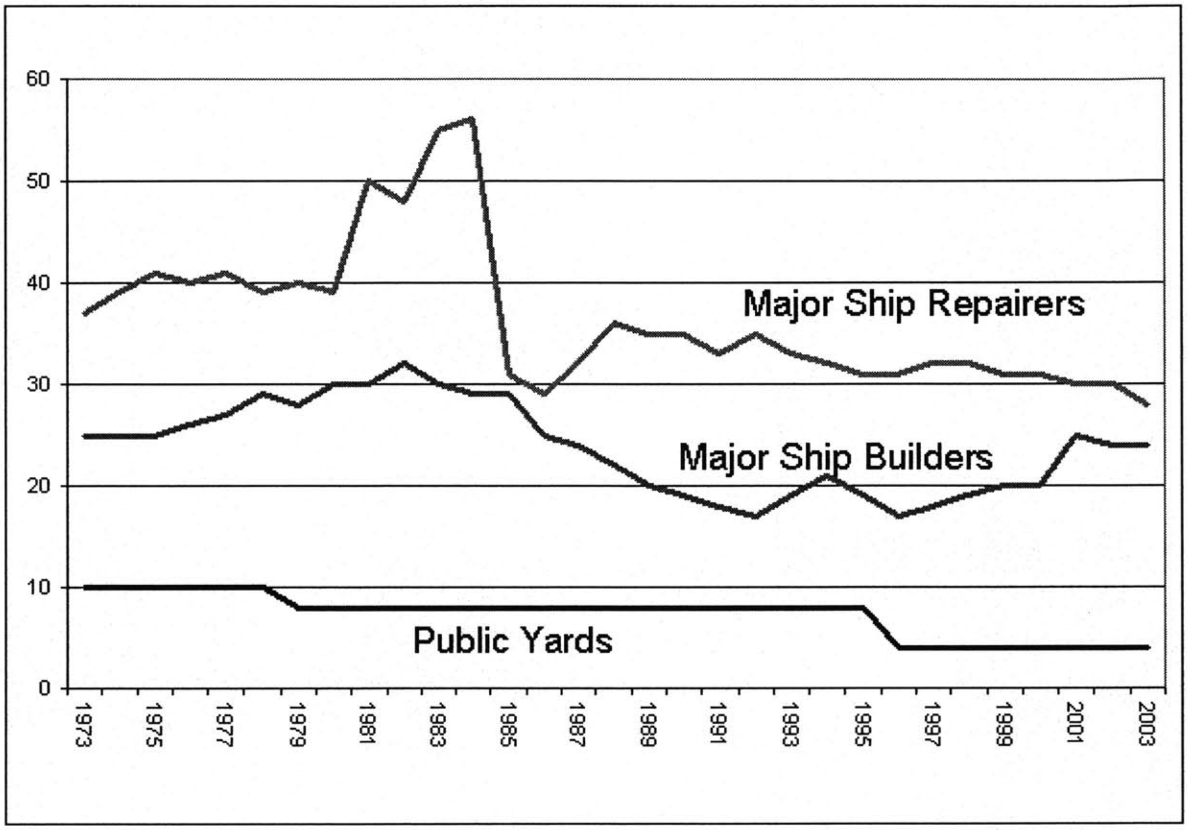
"The United States is and always has been a maritime nation" [14]. Shipbuilding in the United States began before the revolutionary war when Andrew Sprowle, a merchant and ship owner, established the Gosport Shipyard in November of 1767 [22]. This shipyard is now Norfolk Naval Shipyard located in Portsmouth, Virginia.

This industry has changed dramatically over nearly two-and-a-half centuries. Shipbuilding boomed through the end of World War II with the rise in demand of the U.S. maritime fleet. While there are over 250 shipyards remaining in the U.S., approximately 2/3 of the revenue are generated by six major shipyards (the "Big Six") that build and repair ships. Furthermore, 90% of these contracts are with the Navy [30]. The Big Six are currently controlled by two companies: Northrop Grumman Corporation and General Dynamics.

Figure 2-A shows the trend of the number in major shipbuilders over time. The trend includes 9 major shipbuilders (the "Big Six" - NASSCO, Newport News, Ingalls, Electric Boat, Bath, and Avondale plus Bender, VT Halter Pascagoula, and Kvaerner Philadelphia) and 15 major ship repairers (Tampa Bay Shipbuilding, Atlantic Dry Dock, Metro, Toledo, Marinette, Fraser, Bay, Todd, Gunderson, VT Halter Moss Point, United Marine Enterprise, Alabama, AMFELS, Austal USA, and Signal International Pascagoula.) The third line represents the

number of public yards in the United States over time [21]. This trend shows a striking decline in the number of U.S. shipyards from 229 in 1984 to 93 in 2003.

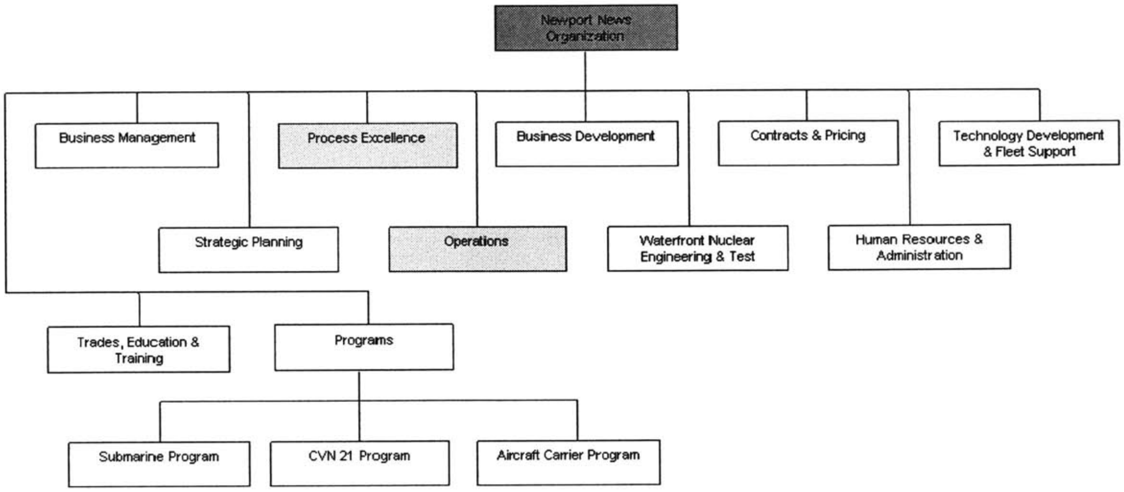
**Figure 2-A: Numbers of Major U.S. Shipyards**



## 2.2 *Organizational Structure*

Figure 2–B illustrates the organizational structure at Northrop Grumman Newport News. The project described in this thesis was sponsored by the Process Excellence division and modeled a process improvement in the Operations division.

**Figure 2-B: Organizational Structure at Northrop Grumman Newport News**



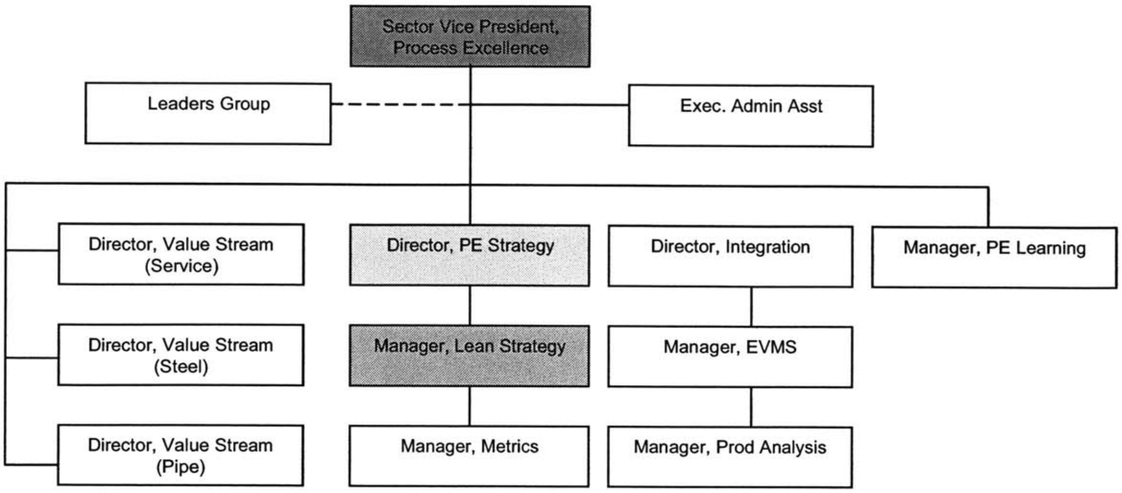
## 2.3 *Process Excellence*

At the time of this paper, the Process Excellence (PE) division was the sector's newest addition to the shipyard. It was established in late 2004 by the newly appointed Sector President, Mike Petters. The mission of the PE division was to "improve our performance in order to give our Navy customer more for their money." To expand, PE's vision was the following:

> *We will be proactive advocates of our shipbuilders. We will unleash the power of all our greatest assets, our people, to continuously identify and eliminate waste and improve total value stream performance. We will create and sustain positive momentum by recognizing and rewarding individual and team success.*

The head of Process Excellence, titled as a Sector Vice President, reports directly to the President of the shipyard. The organization of PE was still forming and evolving during the six-and-half month project described in this thesis. Below is a depiction of the organizational structure at the time of the project.

**Figure 2-C: Process Excellence Division**

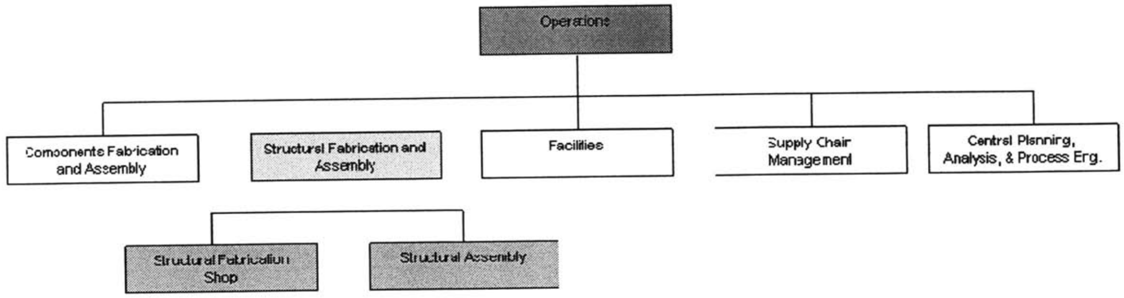


The direct sponsor of this thesis was the Manager assigned to Lean Strategy. PE's mission related to the process improvement described in this thesis in that they both were striving to reduce costs and add value to Northrop Grumman Newport News' (NGNN) customer. PE also supported this thesis because it provided additional insight into Structural Fabrication and Assembly's (SFA) process improvement evolution. This will help PE to better assess the best approach to pull production, cost reductions, and adding value. Improving synchronization, via a demand driven signal (pull), across the shipyard was projected to reduce operating expense and inventory. For example, the Structural Fabrication shop (a 400 member facility) projected a $2M per year savings in operating expense upon successful implementation.

## *2.4 Structural Fabrication and Assembly*

Structural Fabrication and Assembly (SFA) is one of the 5 divisions of the Operations department. This thesis describes a process improvement applied to the SFA Shops. In the Fall of 2004 a pilot of the process improvement had been implemented in Structural Assembly and evolved into full adoption in late 2005. The process improvement was planned to expand into Structural Fabrication in Spring 2006. This thesis describes the design phase of the implementation. See Figure 2-D below for an overview of the organizational structure in Operations at Northrop Grumman Newport News.

**Figure 2-D: Operations Division**



Similar to the Vice President of Process Excellence, the Senior Vice President of Operations reports directly to the President.

SFA has two separate production facilities, Structural Fabrication and Structural Assembly. Structural Fabrication supplies Structural Assembly along with 30 other customers across the shipyard. Ninety percent of their production is sold to Structural Assembly. Structural Fabrication produces structural plates and shapes that are required for assembly. Structural Fabrication production pulls raw plates and shapes into the shop and burns (cuts), bevels, drills, grinds, or forms them into the designed specifications required by their customer. Structural Fabrication sells or delivers kits, hull forms, and plates to their customers. Kits include all the parts needed by Structural Fabrication's downstream customer to build a structural hull assembly. At the peak of both aircraft carrier and submarine contracts Structural Fabrication employs approximately 400 people.

Structural Assembly builds sub-assemblies, pre-assemblies, Modules and Base A's[1]. Pre-assemblies are required to construct sub-assemblies. Sub-assemblies are required to build Modules or Base A's. Figure 2-E shows the hierarchy of final assembly structure. The term Module is used to describe an assembly used to construct the hull of a Submarine and Base A is used to describe an assembly used to build the hull of an Aircraft Carrier. Structural Assembly's downstream customers are the Dry Dock and the Modular Outfitting Facility (MOF) to build the final stages of Aircraft Carriers and Submarines respectively. Approximately 1350 Base A's comprise a Nimitz Class Aircraft Carrier and 7 Modules make up a Virginia Class Submarine (VCS). At the peak of both carrier and submarine contracts Structural Assembly employs approximately 200 welders and fitters.

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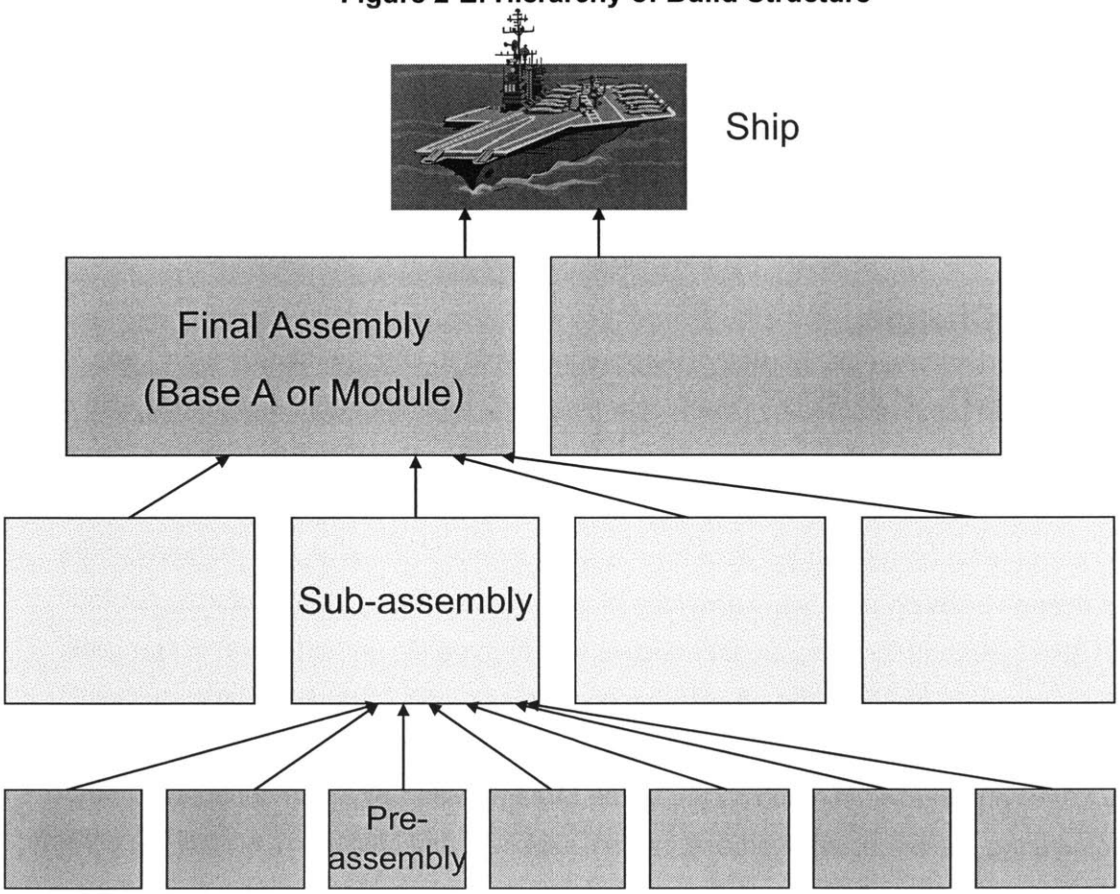
[1] "Base A" is a term that is applied to the constructed structural unit that is built in structural assembly and is erected on-board the ship. The term is a carryover from the legacy system that was used prior to the implementation of SAP.

**Figure 2-E: Hierarchy of Build Structure**



# 3 Defining the Problem Statement

In defining the problems and their solutions it is imperative that three questions are answered: what to change, what to change to, and how to accomplish the change. These questions are adapted from Dr. Goldratt's TOC Thinking Process [28]. In this next section these three questions will be answered and an analysis of alternative approaches to consider.

## *3.1 What to Change*

SFA embarked upon the journey of discovering "what to change" shortly after Lean Manufacturing[1] had been adopted by the shipyard in 2001. Lean Manufacturing along with cost reduction pressure from the Navy had posed many questions to the way business was done at the shipyard. The biggest question: how does a shipyard use these process improvements and innovative manufacturing techniques to efficiently build the most complex and technologically advanced ocean vessels? Like many divisions of the shipyard facing manufacturing related decisions, SFA searched for a more cost effective way to manufacture structural assemblies.

The leadership of SFA hired an external consultant to help them arrive at a succinct problem definition that would reap benefits felt by both ends of the division, fabrication and assembly. After an exercise in mapping the Value Stream[2] within SFA, the consultant noted that manufacturing synchronization among internal suppliers and customers across the division was a common problem.

To further expand on the problem an example will be described in SFA's environment. In Structural Assembly, front line supervisors claimed that if they could get the *right* material at the right time they could reduce the time it takes to build an assembly. The typical situation, however, looked like this: the trades would prepare an area for assembly as scheduled only to be waiting for material from their upstream supplier(s). Because they received the required material late, they would work hard to get the assembly delivered on time. Unfortunately, despite their efforts to work around the issue, there was not enough time to compensate for the late delivery of a few key components of the assembly and the unit would be delivered late to the customer. This lack of synchronization would consume cycle time (and capacity) to build

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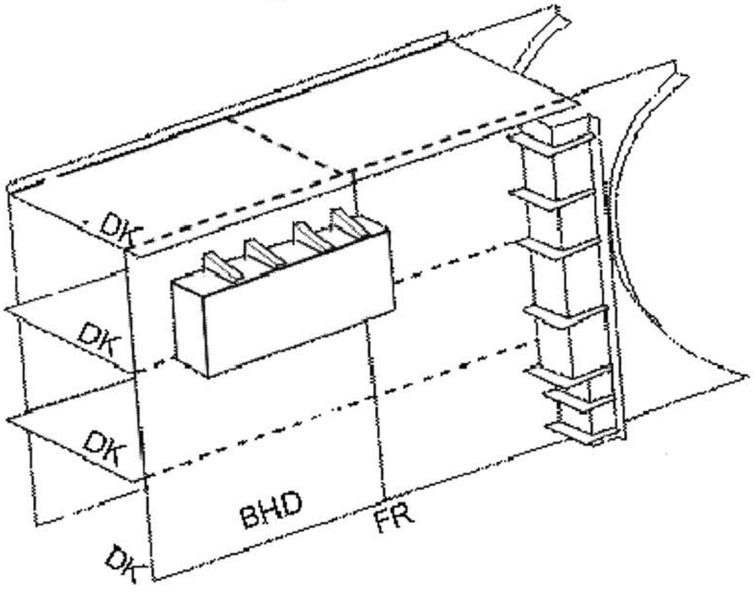
[1] "Lean Manufacturing is simply a group of strategies for the identification and elimination of the waste inside the value stream" [5].

[2] "The process of identifying and charting the flows of information, processes, and physical goods across the entire supply chain from the raw material supplier to the possession of the customer. Value Stream Mapping is a basic planning tool for identifying wastes, designing solutions, and communication Lean concepts" [5].

the assembly and the effect snowballed. Assemblies scheduled for that build area were delayed and so on.

To illustrate this problem, SFA's leadership used an example from a Base A built in 2003. A typical Base A (or Module) is a final assembly made up of various pre-assemblies. Pre-assemblies are structural pieces such as a bulkhead with stiffening attached. Figure 3-A is an illustration of the Base A[1] used in the example.

**Figure 3-A: Base A**



This particular Base A is made up of 17 pre-assemblies. A Material Requirements Planning (MRP) system schedules the start and completion date of each Base A. (The term used to define the space a final assembly consumes during assembly is "footprint".) A total of 1,350 Base A's are required in the construction of a Nimitz Class Nuclear Aircraft Carrier and there is a limit to the number of Base A's that can be built at one time due to space constraints – or footprint capacity. It is imperative, therefore, that each Base A is planned with care.

With all the effort put into making a perfect build plan for each Base A, there is little room for error. Should one Base A slip its schedule, subsequent units planned in that footprint are also rescheduled. This ripples to other footprints as well because Base A's are integrated into a

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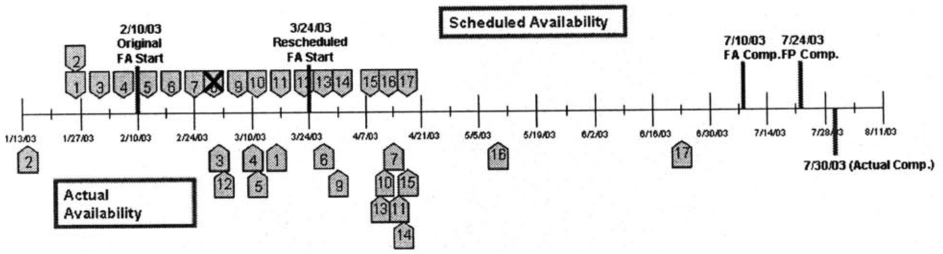
[1] Illustration courtesy of Northrop Grumman Newport News.

Superlift[1] and each adjacent Base A to the one that slipped will be required to “wait” for the missing link.

Figure 3-B[2] illustrates how imperative it is that each foot print receives the correct material in the correct order to complete the unit on time.

**Figure 3-B: Scheduled vs. Actual Pre-Assembly Availability**



The boxed numbers in figure 3-B represent each of the 17 pre-assemblies that make up the final Base A. At the top of the timeline, each pre-assembly is sequenced to be received at the footprint, on average, every two weeks. If one pre-assembly is out of sequence, however, the entire Base A assembly has to stop construction. The front line supervisor has to decide whether he/she should formulate a work around or move the crew to another job and bring in a new crew to continue the build once the material arrives. Both alternatives mentioned are costly to the division.

The numbers at the bottom of the timeline were the actual availability of each of the pre-assemblies at that point in time. From the picture, the actual Base A construction could not commence until mid-March when pre-assembly #1 arrived. The scheduled availability also reflects this with a “Rescheduled Final Assembly Start” of March 24. The completion date, however, held at July 10 as planned. Because of the rescheduled date, the remaining pre-assemblies not received were also pushed out. The issue of receiving the pre-assemblies in a sequenced manner persisted after the unit was rescheduled. (Note: pre-assembly #8 was canceled in this example). Despite all the issues production faced and a six week delay in starting, the target completion date slipped by a mere two weeks. This shows that there is some extra “padding” built into the planned schedule to protect the downstream customer from scenarios such as this. In this case, however, it was not enough. It can be concluded that

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[1] A Superlift is made up of multiple Base A’s for one lift in the dry dock during construction as opposed to multiple lifts required for single Base As.

[2] Illustration courtesy of S. Holcomb, Northrop Grumman Corporation.

should the synchronization improve and material arrive in the correct sequence as scheduled, this "padding" could be removed and the cycle time to build a Base A would reduce significantly.

The situation, however, was not optimal in terms of cost or employee potential. Figure 3-C[1] shows the man-hour matrix that indicates how the level of effort was low throughout most of the construction and peaked at the very end.

Figure 3-C: Man-Hours Spent to Build a Base A

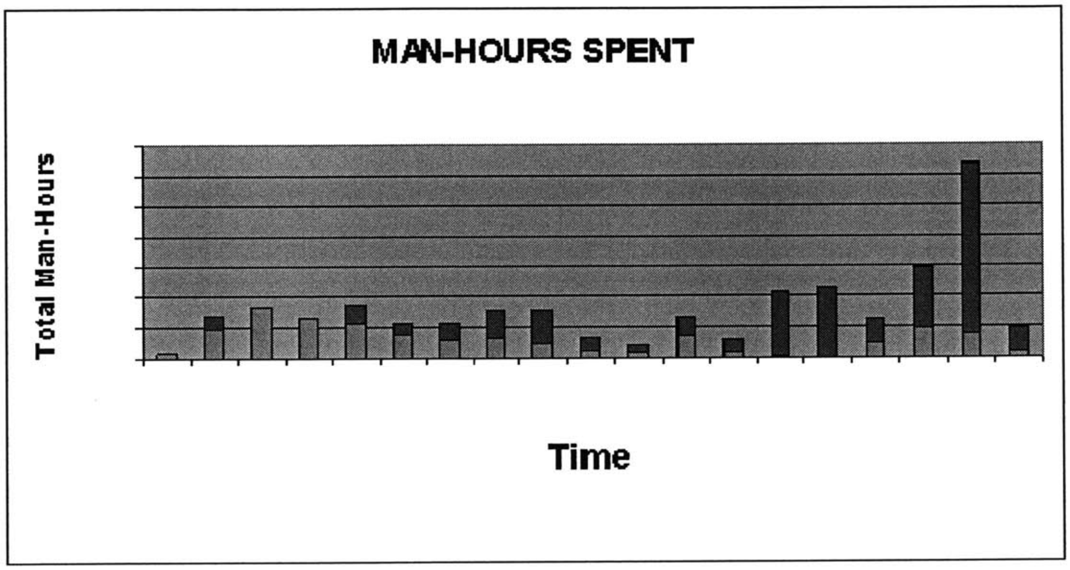

Figure 3-C identifies the total man-hours spent per period. Specifically, the dramatic increase in man-hours toward the end of the build period should be noted.

This scenario troubled the leadership of SFA and SFA's Lean Council took this information and set out to solve the problem of unsynchronized workflow. Once they understood what needed to be changed, they moved on to answering the question of "what to change to".

## *3.2 What to Change to*

The SFA Lean council, upon understanding the problem, created a variety of solutions that could improve synchronization across the division. The Lean Council, with the help of an external consultant, agreed that a method that incorporated demand driven "pull" would help to synchronize suppliers and customers to ensure they were only producing goods that their

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[1] Illustration courtesy of Northrop Grumman Newport News.

customer needed. *Pull* in this case meant no one upstream should produce a good or service until the customer downstream asks for it [32].

## 3.3 How to Accomplish the Change

A myriad of possible ways to implement pull were considered and consolidated into four options for SFA's Lean Council to consider. The first option was a "fixed level of work in process (WIP)" also known as the CONWIP (Constant Work In Process) approach. In other words, at the target level of inventory, additional material for an additional Base A could not be released until a Base A left the system and was sold to the customer. CONWIP's fundamental difference from MRP is that WIP, rather than throughput[1], becomes the control point. Spearman and Hopp determined that it is more difficult to manage production through MRP because the release rate in a push system is set with respect to capacity. If the release rate is set too high, the system will be choked with WIP. Too low, and revenue will be lost. However, estimating capacity, as compared with determining the level of WIP to hold, is not simple [16].

The second option was a variant of the Toyota Production System (TPS) which places kanbans[2] at each major production step to create a one piece flow rather than the traditional batch and queue type flow. This application is commonly used in high volume flow and balanced line manufacturing environments. Toyota owes much of its success in the automotive industry today to this system created by Taichi Ohno.

> *...Through trial and error, Taichi Ohno discovered that building cars and parts in a one-piece flow in a leveled and mixed production sequence beat large-batch and queue production. With very lean inventory, however, Toyota soon discovered that problems encountered by outside parts suppliers were shutting down production.*
>
> *Toyota responded by setting up an organization to train suppliers in the TPS. It took Toyota about a decade to develop TPS, and at least another decade to teach it to their suppliers. At Toyota, this manufacturing philosophy means that you build what the customer orders as soon as possible after receiving the order, and keep the total value added time as short as possible. Any time that a product spends sitting in a queue represents waste [20].*

A third was a Drum-Buffer-Rope application in which the system's capacity constraint controlled the material released into the system. This would limit the amount of inventory in the system and allow production to focus on the jobs that were needed by the downstream

---

[1] "Throughput is defined as the production per unit time that is sold" [16].

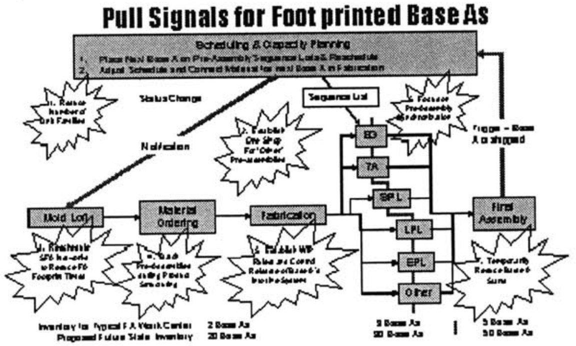
[2] "Kanban is Japanese for card. Pull Scheduling combined with traveling instructions conveyed by simple visual devices in the form of cards, balls, carts, containers, etc. and can be applied to both material flow in the factory, information or project flow in the office, and material flow between suppliers and customers" [5].

customer. This was an application of Dr. Goldratt's Theory of Constraints and will be described in more detail in section 4 of this thesis.

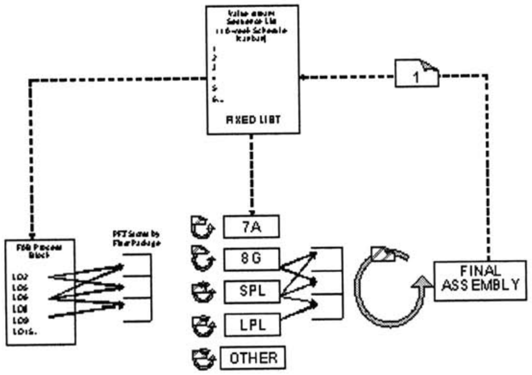
The fourth option was to continue operating as they have been. The Lean Council considered each option and made a decision to pilot the third option, Drum-Buffer-Rope. Figure 3-D illustrates each of these options.

## Current System
## MRP/Fixed Scheduling System

## Option 1 - High Level Base A Pull Process



## Option 2 – Low and High Level Pull Process with 10 Week Fixed Sequence List



## Option 3 – Drum, Buffer, Rope

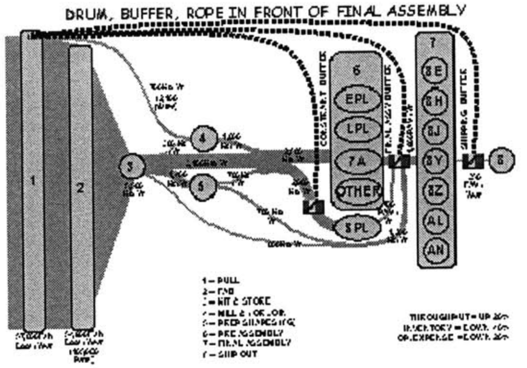


Figure 3-D: SFA Options for Pull Production[1]

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[1] Courtesy of S. Holcomb of Northrop Grumman Corporation.

The TOC option was ultimately selected as the best choice, because of SFA's unique mix of automated production lines and job shop work centers typical in shipbuilding. As compared with other approaches, the TOC was better for SFA's manufacturing environment: mixed job shop and flow, products that continue to undertake design changes throughout the manufacturing period, complex product mixes, and unbalanced lines. A more detailed comparison between the options will be described in section 3.5 of this thesis.

The Council decided to pilot the TOC approach in late 2004. The goals of this pilot were:

- Better synchronization of all work centers involved in assembly.
- Reduction in WIP in the SFA system
- Shorter lead times on Base A construction
- Identification of opportunities to reduce operating expenses
- Identification of excess capacity in SFA

It was important to understand that SFA's decision to implement TOC is not a movement away from NGNN's Lean implementation. The primary goal of Lean in SFA is to reduce production lead time by eliminating waste. This aligns with the TOC goals: increase throughput, decrease operating expense and decrease inventory. The TOC system is a technique for implementing "pull", which is especially effective in a facility that produces complex and diverse products with few opportunities for assembly line flow.

## *3.4 Traditional Production Management*

One of the options suggested was to maintain the traditional approach to managing production – via Materials Requirement Planning (MRP) or fixed schedule. MRP is a type of computer software that calculates requirements for materials using inventory data, bills of material, and the production schedule (Cox, 1998). MRP was revolutionary to manufacturing with the integration of computers into manufacturing in the late 1970's and provided a more robust solution as compared with the previous method of scheduling production. MRP determines the parts requirements for raw material and lower level assemblies, provides a signal to launch new orders, manages the timing of scheduled work orders, and drives the shop floor control and capacity requirements planning systems [28].

Although it is one of the most important processes in support of manufacturing, it makes some false assumptions. Stein [28] illustrates the impact of considering static versus dynamic data when scheduling production. In short, MRP assumes a standard lead time and lot size for all processes. Instead the lead time should be adjusted in regards to the type of capacity (productive, protective, or excess) it is signifying. Lead time should be driven by the impact of the load on the protective capacity, in other words if protective capacity is reduced, the material should be released sooner. Furthermore, lot sizing in most MRP applications is driven by the economic order quantity (EOQ) formula. This formula assumes that every setup activity will result in a cost, setup and carrying cost is constant, lot size is constant, and products have costs and those costs will remain constant.

$EOQ = \sqrt{(2US / IC)}$
Where,
$U$ = Annual usage
$S$ = Setup cost
$I$ = Inventory carrying cost
$C$ = Unit cost

Should any of the above assumptions break, however, this lot sizing technique is invalid. The lot sizing and lead time issues are addressed in the various applications of "pull" production.

Furthermore, MRP fails to address the capacity limitations of a plant. In other words, infinite capacity is assumed which can create problems when demand is at or near capacity. A solution, Material *Resource* Planning (MRP II), has added more capability to address these issues [16]. Capacity planning can now be achieved in conjunction with the master scheduling process, allowing planners to utilize a more forward looking approach. However, this method of capacity planning is based on assumptions that are difficult to model in dynamic environments. One assumption made by MRP II is that all time within a given availability is equally available to each order [28]. In other words, demand is distributed evenly over time. In effect, capacity resource planning assumes that time to go through a process center does not change when load exceeds capacity. In reality, however, we understand that it takes longer for a part to pass through a heavily loaded resource [16].

## 3.5 MRP vs. JIT vs. TOC

MRP is known as "push" production because product is manufactured regardless of the customer's needs. In other words the product is *pushed* onto the customer. A solution to break the assumption created in MRP's model is a system called *pull* production. Pull production, therefore, implies that product is only manufactured if there is a customer need *pulling* that product through production.

There are several ways of implementing pull production to resolve the static assumptions that MRP makes and to implement a more dynamic method for scheduling production. Just-in-time (JIT), also known as the Toyota Production System (TPS), is one method of implementing pull. The Theory of Constraints (TOC) is another variant of pull manufacturing. A third method termed CONtinuous Work In Process (CONWIP) is yet another approach of pull implementation. Studies have been done that describe the benefits to applying one method over the other based upon the application and its inherent manufacturing environment.

Most manufacturing environments fight the battle with too much inventory or not enough (overstocked vs. stock-outs). This is a delicate balance that is driven to tip towards "too much inventory" if production personnel do not trust the system. This lack of trust is a learned behavior. In one scenario; a foreman works the crew overtime to get a product out the door for a customer who will not stop hounding the supplier only to find the same part sitting idle on the customer's loading dock the next evening. Why did the customer trouble the foreman for a part not needed right away? The foreman did not trust the system because it had failed in the past. So the only way to ensure that production's performance was covered was to move up the due date.[1] But can the customer be blamed? Is there a more systemic approach that can be used to optimize the flow of material and synchronization?

Figure 3-E is a depiction of how the lack of demand driven pull adversely affected synchronization across the division.

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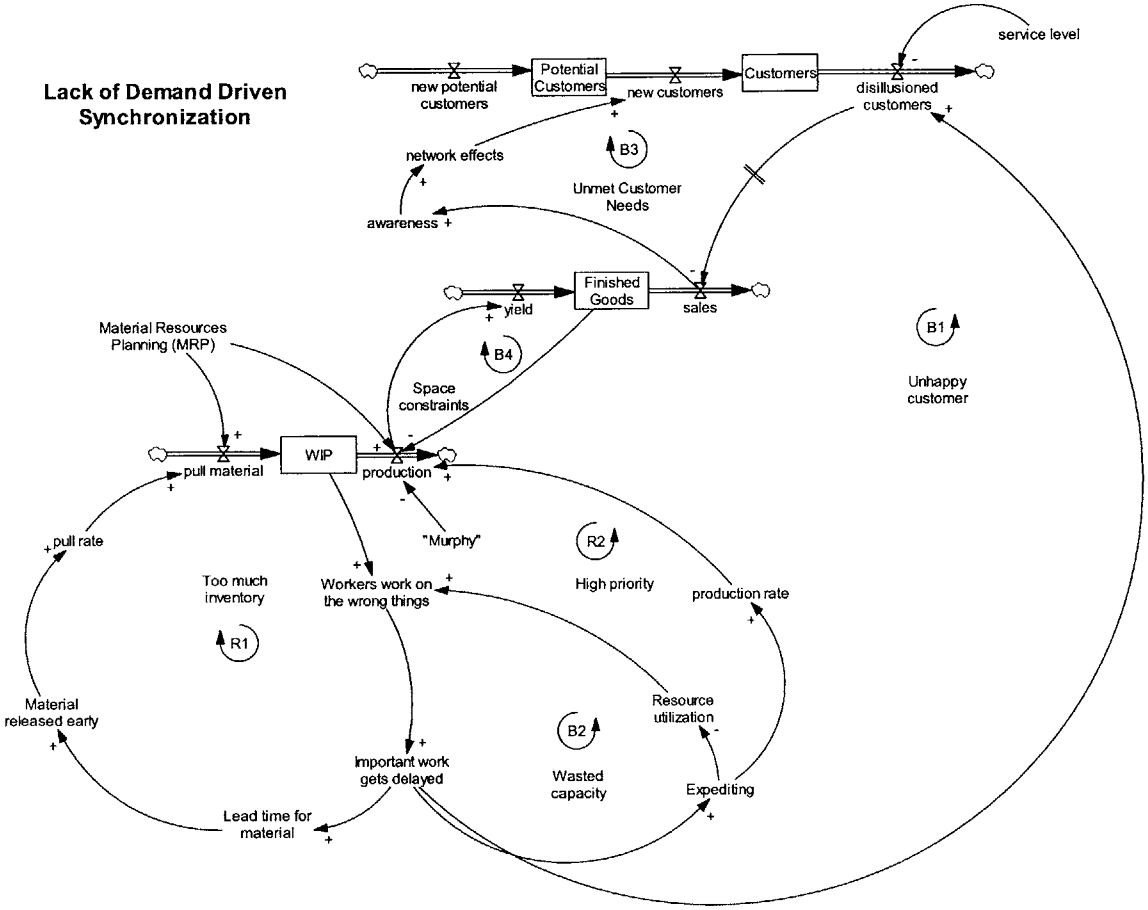
[1] Story adapted from S. Holcomb, Northrop Grumman Corporation.

Figure 3-E: Effects of a Push Production System



Reinforcing loop 1: The increase in work in process (WIP) inventory caused by push production creates too much inventory and there is a higher probability that workers will work on the wrong things. As important work gets delayed, the lead time for material increases, thus causing material to be released earlier and increasing the rate at which material is brought into the system. This goes full circle to create more WIP into the system.

JIT addresses this issue by placing buffers or "kanbans" in front of each process step. These kanbans create a signal for the upstream operation to produce a product. Again, the mantra behind pull production states that an operation is only executed if the downstream customer or operation demands output from the operation. TOC addresses the issue by focusing on the protective capacity placed in front of the capacity constraint. Lead times and lot sizes are adjusted to ensure that the capacity constraint is never starved.

Michael Pitcher discusses the benefit of TOC compared with JIT in job shop environments in his article published for the Society for Manufacturing Engineers.

> *Many companies have benefited greatly from the JIT approach; however, the method has failed dramatically in some environments. When a business is more of a job shop environment, then the kanban approach no longer makes sense. As product mix by form, fit, and function change, routings and process times become widely divergent. The prediction of kanban sizes becomes impractical and temporary--bottlenecks will appear everywhere. In this environment, the TOC model of drum-buffer-rope (DBR) excels and exposes the broader potential effectiveness of DBR [25].*

## 3.6 Why TOC

TOC was chosen as the appropriate application in SFA because of the mixed job-shop and flow environment of SFA. Due to the wide product mix and volume fluctuations, the TOC required less process discipline at each operation as compared to JIT. JIT is more widely used in high volume and line flow environments where product variation is relatively low. The automotive industry is an example of an environment where JIT has been successful.

Furthermore, the defense industry is one in which design changes are made frequently. The flexibility to adjust to these changes in design was inherently easier in the TOC application. The number of buffers impacted by a change in the TOC as compared to JIT was far fewer. Therefore, the TOC was a more practical approach when considering that manufacturing must remain flexible to potentials design changes.

JIT is a great fit for flow environments with balanced lines. However, unbalanced production lines create frequent changes that impact the numerous buffers and kanban cards placed between each resource. The TOC, however, is not impacted by unbalanced production lines because changes outside of constraint locations will not affect the system.

Finally, the TOC is a great tool in understanding where bottlenecks and constraints lie in the system. In the TOC's five focusing steps, constraints are identified. Neither JIT nor CONWIP give insight to the constraint of the system.

Figure 3-F[1] outlines a summary of the applications for TOC and JIT.

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[1] Table is adapted from S. Holcomb, Northrop Grumman Corporation.

**Figure 3-F: Drum-Buffer-Rope Compared with Just-In-Time**

| TOC DBR | JIT |
|---|---|
| "Better" for: | "Better" for: |
| • Mixed job shop & flow | • High volume flow |
| • Incomplete design | • Complete design |
| • Complex product mix | • Lower variability |
| • Unbalanced line | • Balanced line |

# 4 The Theory of Constraints

Dr. Eliyahu Goldratt introduced the Theory of Constraints in the 1970's in order to couple the goal of an organization (to make more money) with the policies and behaviors that a company puts in place. The goal can be reached in three ways: 1) reduce inventory, 2) reduce operating expense, and 3) increase throughput. Dr. Goldratt postulated that most companies create policies which drive behaviors that are not aligned with the goal. He described these gaps as conflicts and shares that in order to reach the goal, management must break the conflicts that hinder the system from reaching its potential.

This section will provide a brief overview about the theory behind the manufacturing application of the Theory of Constraints (TOC) called Drum-Buffer-Rope, five focusing steps to consider when approaching a process improvement such as a TOC implementation, and what metrics should be adopted to align with the TOC.

## *4.1 Drum-Buffer-Rope*

Drum-Buffer-Rope (DBR) is a term to describe one approach of the TOC when applied to a manufacturing environment. DBR was introduced in 1986 in Dr. Goldratt's best-selling novel *The Goal*. Dr. Goldratt determined that there are three motivations in any business:

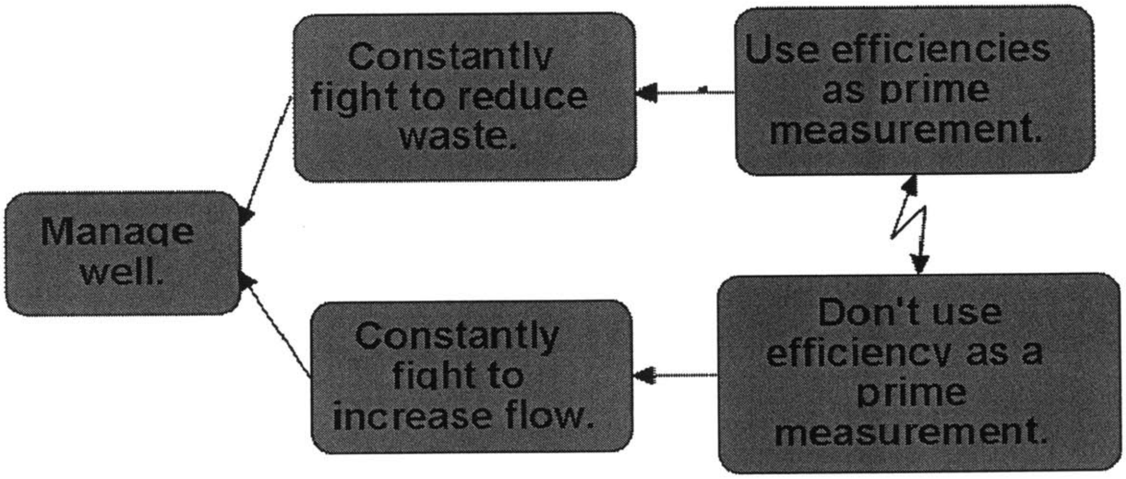
1. *The only reason that companies do anything is to make money.*
2. *Anything that a company does to speed up the processes that generate money is appropriate.*
3. *Each business operation is one big process with many sub processes.*

The motivations above are the core assumptions that the TOC are founded upon. Dr. Goldratt concluded that a company who keeps these motivations in mind will prosper.

In applying the TOC to Operations, Dr. Goldratt described the core conflict that production managers face. In order to manage well, production managers must constantly fight to reduce waste (Figure 4-A). A means to accomplish this is to use efficiencies as a prime unit of measurement. Production managers must also strive to increase flow and therefore, to accomplish this, managers should not use efficiencies as a prime unit of measurement. The two create a conflict that production managers must balance. The assumption that creates this conflict is the assumption that a resource standing idle is waste. Once these "false" assumptions are removed, there is no core conflict. It is analogous to asking a designer to design a fast and efficient car. The two are tradeoffs rather than complimentary parameters.

Another example of a conflict that production managers face is one between cost and schedule. Managers are told to keep cost low and at the same time meet the production schedule. This conflict is exacerbated if costs are reduced to a point where there is limited surge capacity in the work force to accommodate an unexpected increase in the production schedule.

**Figure 4-A: Production Management Conflict [9]**



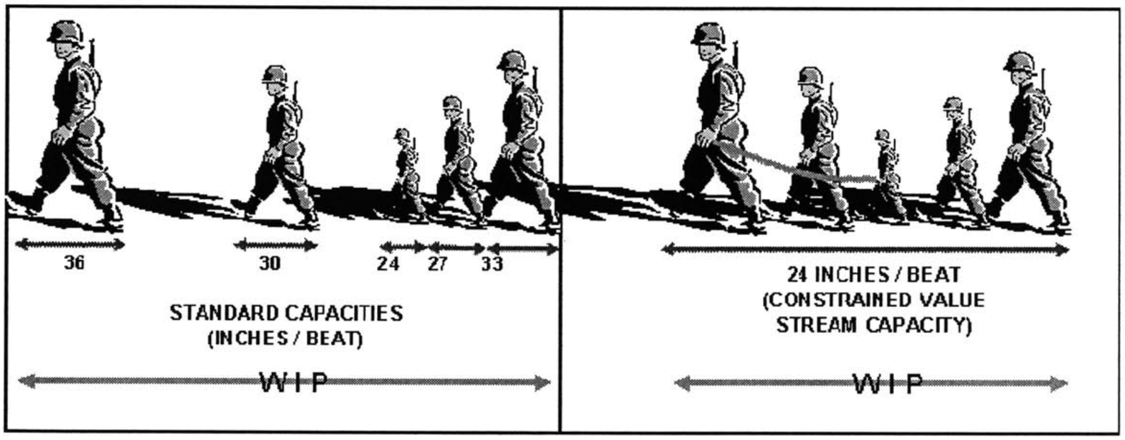
DBR is a method used to schedule operations. There are three main components that control the release of inventory: the constraint or drum, the buffer, and rope. The drum can be described as a resource that constrains the throughput of a system. In some organizations the system is constrained by a resource within the production facility and in most organizations the market constrains throughput. Throughput is defined as items that are *sold* to the customer (rather than material sitting in finished goods inventory ready for sale).

### 4.1.1 The Drum

An example that ties the drum, buffer, and rope together is the Boy Scout troop analogy used in Dr. Goldratt's novel *The Goal* [11]. The chaperone noticed that the troop started to march in a tight pack, but over time, the troop spread out. Every hour, the chaperone had to stop the troop so that he could keep an eye on the entire troop and ensure no one got lost. He realized that this was a waste of valuable time and they needed to make it to camp before dark. In short, the goal of the troop was to make it to the campsite together and as such they had to stick together. It took some time, but the "constraint" was identified and told to march at the front of the troop. His pack was lightened and shared among the other troopers so that he could march as quickly as possible. The troop stayed together and made it to the campsite before dark.

The slowest hiker was the drum since he constrained the hiking capacity of the troop. In manufacturing, it is impossible to move the constraint to the front and therefore a rope connecting the drum to the lead is necessary. The buffer is analogous to allowing space between the drum and the hiker just in front of the drum. That way if the resource in front of the drum stumbles, the drum can keep marching. A picture of the troop analogy and its application in manufacturing is shown below in Figure 4-B.

**Figure 4-B: The Boy Scout Troop Analogy**[1]



The space between each trooper is analogous to work in process inventory. Thus, another benefit of tying manufacturing together in this manner is the reduction in WIP.

The drum is so titled because the manufacturing system marches to its schedule in order to keep all work centers and resources synchronized and aligned with the constraint. Therefore, other functions within the system should not outrun the constraint. In the five focusing steps the drum is exploited to ensure that the constraint is achieving the greatest utilization possible.

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[1] Courtesy of S. Holcomb of Northrop Grumman Corporation.

### 4.1.2 The Buffer

The buffer is placed before the drum, shipping, and final assembly operations that are fed by the constraint and a non-constraint. The protection is to allow recovery for things that will go wrong. Furthermore, each buffer should be linked or synchronized so that material is only fed to a buffer that is required by a downstream buffer or operation. Synchronization prevents the system from producing excess or unnecessary inventory. For example, if work is slowed at a final assembly operation, all other buffers and operations should be slowed.

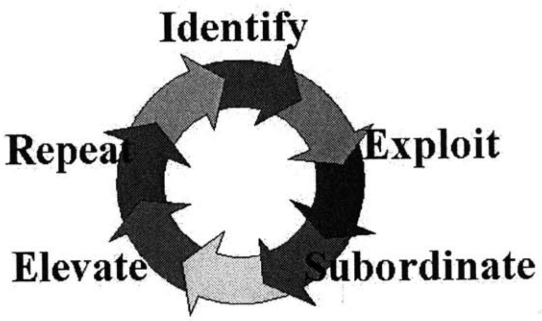
### 4.1.3 The Rope

The rope is a mechanism to schedule the gating process for non-constraint resources. This is to allow time for the non-constraint resources to process the material before it arrives in the constraint buffer.

## *4.2 Five Focusing Steps*

In any process improvement there are five focusing steps that should be applied. These steps are aligned with the TOC and the terminology is the same. Figure 4-C[1] shows these steps and how the process is iterative once step 5 is complete.

**Figure 4-C: The Five Focusing Steps**



*Step 1 - Identify*

The first step is to identify the constraint in a system. In a DBR approach this equates into a constraint that limits the throughput of the system. In manufacturing the constraint can typically be identified by finding the largest queue of work in process. This means that resources upstream of the queue can outrun this resource. In some manufacturing

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[1] Image taken from: < http://www.legsource.com/BooneRetreat/constraint_management.htm> [accessed October 26, 2005].

environments, there may be many piles of inventory and identifying the constraint may not be as clear. It is not important that the "correct" constraint be identified, but rather thar one is identified and the following steps are followed to create a schedule that synchronizes the constraint to all operations. If the "wrong" constraint is chosen, the "right" one will become apparent as it will be unable to keep up with the schedule and the process can be realigned.

*Step 2 – Exploit*

Step 2 requires that the constraint identified be exploited meaning that everything should be done to get the most out of its existing capacity. In Goldratt's novel *The Goal* [11], the facility did things such as overlap lunch hours and manage shift changes with the aim of ensuring that the capacity constraint did not sit idle.

*Step 3 – Subordinate*

The third step is to subordinate all other work centers and policies to the constraint. This requires that lead times be centered on the protective capacity required at the capacity constraint.

*Step 4 –Enhance*

Step 4 should only be done once improvements to steps 2 and 3 have been exhausted. This step is designed to increase the capacity of the system if the demand continues to exceed the capacity of the constraint. This typically requires significant capital expense and therefore, should be used as a last option to increase capacity.

*Step 5 – Go Back to Step 1*

The final step connects back to step 1 signifying the importance of continuing to evaluate the system and ensure that the assumptions made are still valid. In short, Dr. Goldratt included this step to ensure that inertia did not set in and the process of continuous improvement was adopted in the framework of the five focusing steps. To encourage continuous improvement, one most continuously identify and break constraints. By identifying and breaking constraints additional capacity can be realized at minimal cost. Do not allow inertia to become the constraint [31].

## *4.3 Buffer Management*

Buffer management is the focal point and represents the control mechanism of most TOC applications. It is used to identify orders which are experiencing issues and resolve those issues before they impact the constraint, and therefore, throughput of the system. It can also be a tool to track and identify operations which consistently create late orders so that a focus can be made to improve such operations.

At implementation, buffer management is a tool to validate the buffer sizes chosen during the design phase. As the appropriate buffer size is determined, buffer management aids in understanding the problem areas of the system. The buffer is so named because it buffers the constraint from variation in production. Furthermore, the buffer is referred to as a time buffer because jobs in the buffer are representative of available work for the capacity constraint [31].

## *4.4 Performance Measures*

In the language of the TOC, there are three metrics that companies should consider. These metrics relate to the general motivations of a business mentioned in section 4.1. The first metric is throughput, which is the speed at which a company makes money.

Throughput = Sales revenue – direct material cost

The second metric is inventory. Inventory represents the value of raw material that resides in WIP or finished goods. This metric should be kept as low as possible because this is cash that the company has spent on production but has not yet generated revenue. The third metric is operating expense. Operating expense includes all costs of operations other than direct material costs. The most important of these is throughput because this generates cash for the company [4].

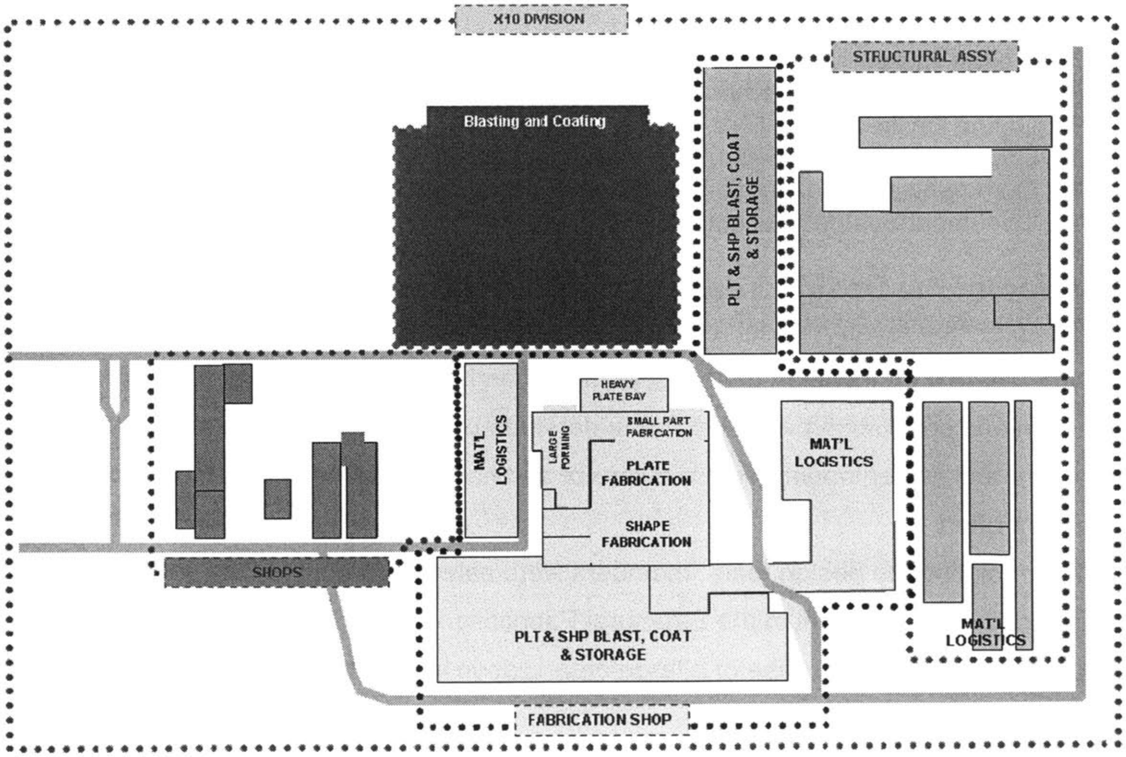
# 5 Implementation Design – A Case Study

The TOC had been recently implemented in NGNN's Structural Assembly in 2004. In late 2005 the change had been adopted in all areas of Structural Assembly. A signal from the Capacity Constrained Resource (CCR), final assembly, and final delivery was tied to the material release point. The material was released from the "post-fab zone" or finished goods from the Structural Fabrication Shop.

SFA Leadership had then decided to continue the implementation through the remainder of the division: upstream to the Structural Fabrication Shop. The following section will describe the scope of the project to implement the TOC in the Structural Fabrication Shop and steps used to design the implementation. This 12 step approach described was adopted from the Avarham Goldratt Institute (AGI).

Figure 5-A[1] shows an overview of Structural Fabrication and Assembly. The case study focuses on designing an implementation strategy for the Structural Fabrication Shop. Structural Assembly (the original TOC pilot) is also depicted in the following figure.

**Figure 5-A: Structural Fabrication and Assembly**



## *5.1 Scope*

This project is focused in the Operations Division, and specifically the Structural Fabrication Shop of the Structural Fabrication and Assembly (SFA) department, of Northrop Grumman Newport News (NGNN). This includes everything from the internal procurement of material, to the fabrication of shapes and plates, to the assembly of kits for delivery to the Structural Fabrication Shop's customers.

## *5.2 Approach*

This describes the approach used to design the implementation of a Drum-Buffer-Rope production system in Structural Fabrication. The approach used was based on recommendations from AGI, Dr. Goldratt's Five Focusing Steps, lessons learned from the team that piloted implementation in Structural Assembly, and recommendations from the design team tasked with Structural Fabrication's implementation. Below is an outline of the 12 steps of designing a DBR implementation that the team followed (courtesy of AGI).

**Implementation Plan:**

1. Appoint the Design Team
2. Educate the Design Team
3. Complete System Design Pre-Work
4. Decide on the Constraint / Drum
5. Decide on the Scheduling Rules for the Drum
6. Establish Buffer sizes
7. Tie the Rope
8. Define Buffer Management
9. Define Desired Behaviors
10. Create an Implementation Action Plan
11. Communicate and Reinforce Desired Behaviors
12. Document System Design

### 5.2.1 Appoint the Design Team

The first step recommended by AGI was to appoint the design team. Prior to this step, one should create a project plan to set expectations and objectives for the project. This enables the selection and solicitation process to be understood by all members. It is also assumed that management and senior leadership are aware of and have agreed to support the process improvement effort.

In appointing the design team, members were selected to enable the greatest wealth of knowledge of the environment in the Structural Fabrication Shop. Additional members were selected by discretion; in the case of a large organization like NGNN it is difficult to educate all divisions about new process improvements or changes. This was an opportune time to involve

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[1] Courtesy of Northrop Grumman Corporation.

other divisions in the team not only to educate but also to get an outsider's perspective. Once a short list of desired members was drafted, the next step was to contact their managers and determine if their time could be allotted to the implementation design effort. If permission was granted, the final step would be to contact the desired team member.

The design team consisted of 13 members. This was a manageable number of team members that added value from different facets of the organization. Members included a production foreman, a material control supervisor, a production control supervisor, a production control manager, a production control employee, three manufacturing engineers, three planners, a quality manager, a simulation engineer, and an intern (the author).

### 5.2.2 Educate the Design Team

The first step in educating the team was a 2-day training seminar given by AGI. This was a powerful tool to introduce novices to the TOC. Part of the training involved discussion of the difficulties behind managing production. Simulation was used to model some of the policy constraints companies use based on "false" assumptions and how they affect the goal of meeting customer demand.

Prior to the kickoff session with the design team, the team leaders furthered the education process by providing copies of Dr. Eliyahu Goldratt's book *The Goal* and articles that described the TOC application in settings similar to the Structural Fabrication Shop. At the first workshop with the team, we discussed the lessons learned and results from the implementation in Structural Assembly and watched a video based on *The Goal*. Following these, the team discussed the key themes, analogies, and lessons used in the video. The main themes that were passed along to the team members were:

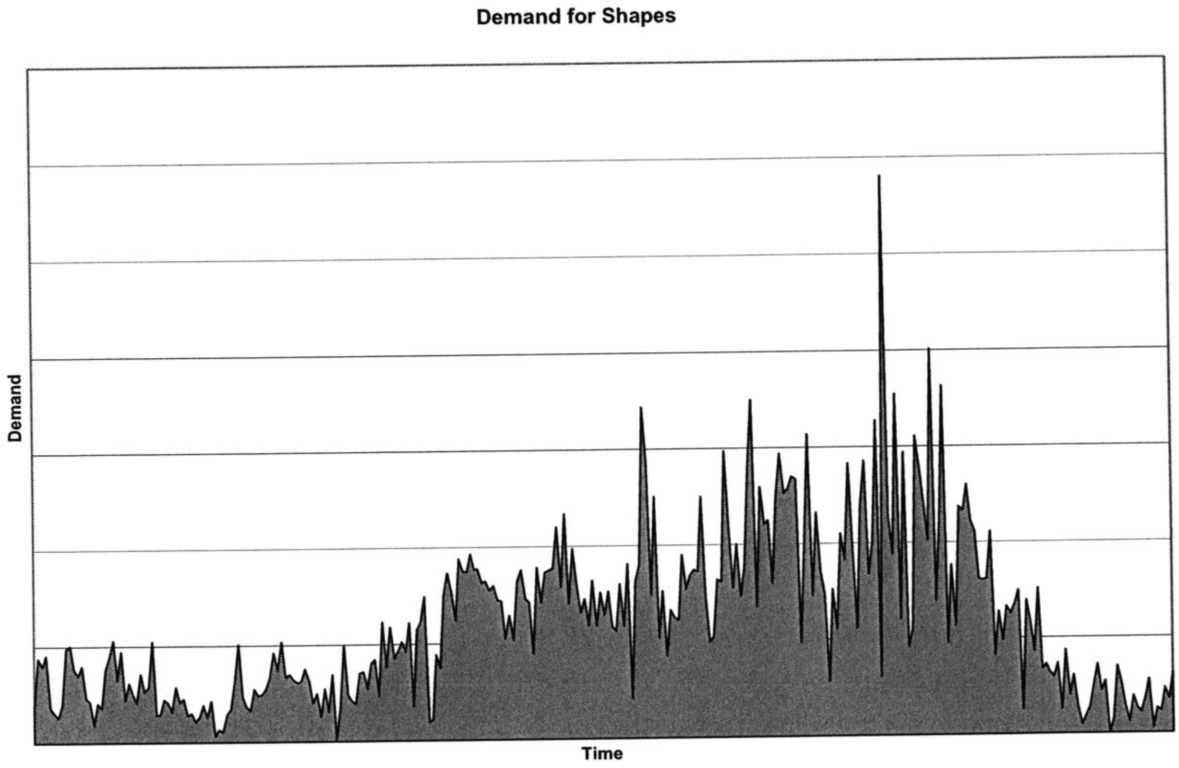
- The TOC measures: throughput, inventory, operating expense.
- Defining a constraint as the resource that limits output of production.
- The five focusing steps of continuous improvement.

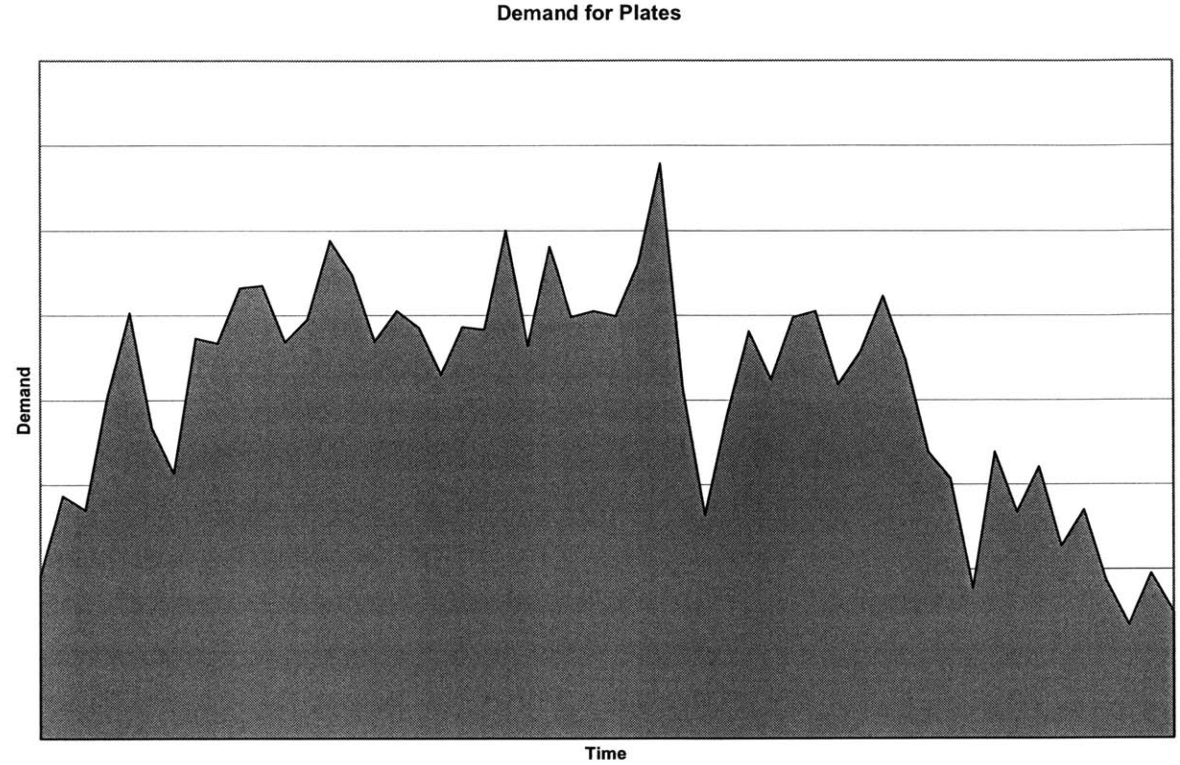
The education process is an important step to ensuring that all team members are on the same page. Invariably some team members will have had more exposure to the subject than others and it is imperative that the "playing field" be level in terms of understanding the theory before decisions are made that will impact the implementation.

### 5.2.3 System Design Pre-work

Before gathering the team to decide on a constraint, data regarding demand history and forecast, inventory levels, and work center loads were collected. Figure 5-B illustrates the cyclical demand for shapes and plates. (The actual numbers are masked for proprietary reasons.)

**Figure 5-B: Demand Data Collected**





These data was used to create a work flow diagram of Structural Fabrication. By averaging the demand of the period collected and understanding stage of contract (see Figure 5-D) we were able to analyze the rough break down of flow in the Fabrication Shop. The process flow was created with the help of team members who understood the process flow and could confirm the breakdowns that were calculated. It was difficult to accurately forecast the utilization of each bay because the next contract would be an entirely new design. Additionally, Structural Fabrication recently added capacity to their system in the form of new machines and capabilities. Therefore, predicting the demand of the new machines along with the uncertainty behind the new design was not an easy task. The process flow in most manufacturing environments is complex. The workflow was simplified to the extent that general flows and volumes were not lost.

With the understanding of demand, forecast, and approximate work center loads, the team created the work flow of Structural Fabrication shown in Figure 5-C:

**Figure 5-C: Fabrication Shop Workflow**

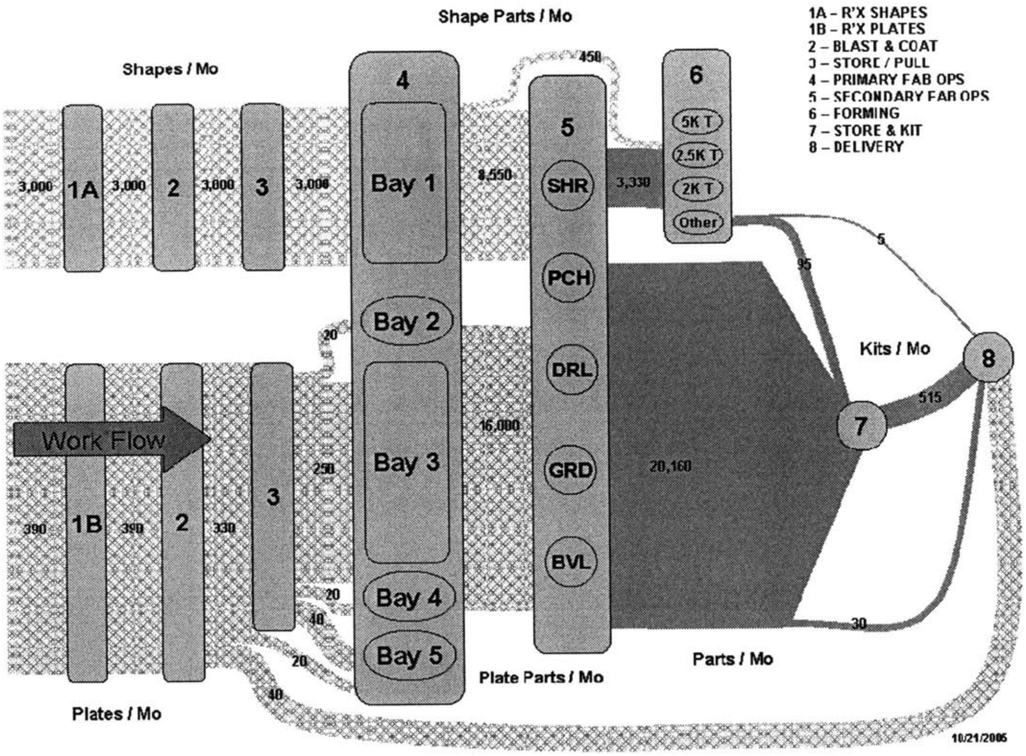
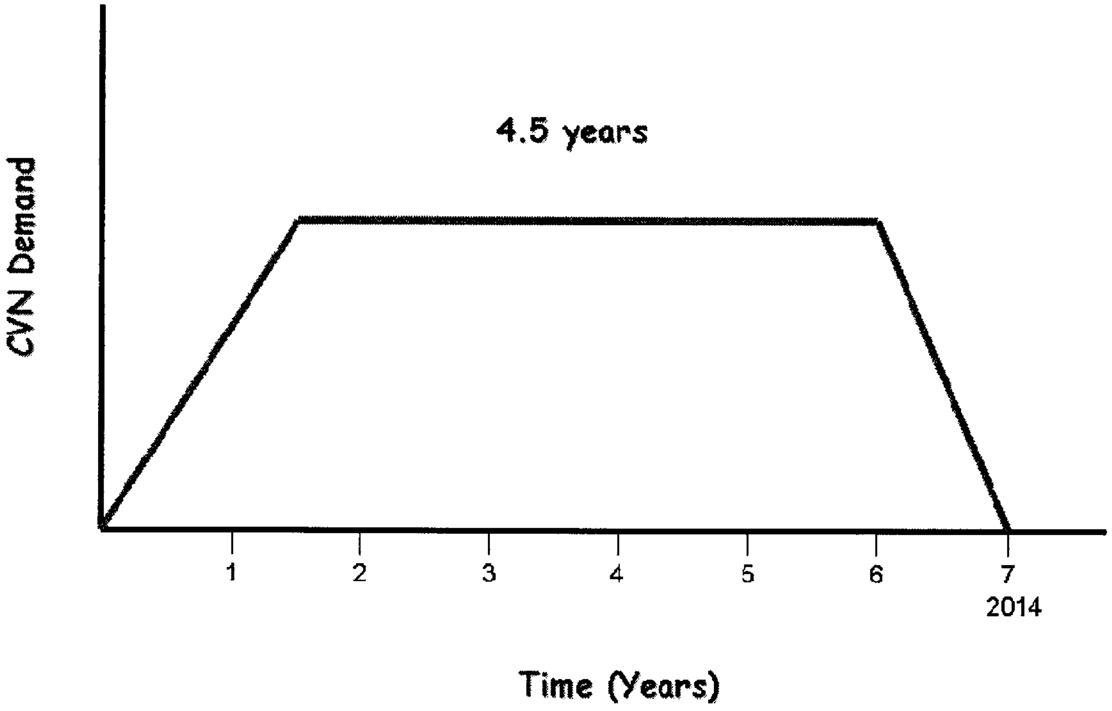


Figure 5-C enables the team to view the workflow on one screen and still gather the aggregate volume flowing through each work center. The thickness of the paths represents the volume of material flowing in the left to right direction from one resource to the next. The rectangles labeled 1A and 1B are processes in which the Fabrication Shop receives shapes and plates respectively. Once the shapes and plates are received, they are blasted and coated with a rust preventive coating (2). Depending on the schedule and demand the plate/shape is either: stored for later use (3), delivered to the customer (8), or pulled directly into the shop (3). Once the plates or shapes are pulled into the shop they undergo primary operations (4). Primary operations are burning operations such as cutting pieces out of plate using an automated burn machine. Once the primary operations are complete the work flows to secondary operations (5) or forming operations (6). Secondary operations include shearing, punching, drilling, grinding, and beveling. Forming operations include rolling, pressing, and forming plates. Most of the material is then stored and prepared as a kit for their downstream customer (7). All products are delivered to the customer (8).

We had to ensure that the data gathered represented the "peak" demand period. It was assumed that demand for Submarine (VCS) contracts in Structural Fabrication was relatively steady, whereas demand for Aircraft Carrier (CVN) contracts involved a ramp up and ramp down period during the production cycle. Data gathered and shown in Figure 5-B was taken from the 4.5 years that represent peak demand for CVN parts (see Figure 5-D).

**Figure 5-D: Typical Demand for Aircraft Carrier Assemblies**



### 5.2.4 Decide on the Constraint

The steps laid out in the project plan for team identification of the capacity constrained resource (CCR) were the following: 1) develop a short list of candidate constraints for further investigation, 2) identify necessary data required to determine the constraint selection, 3) collect and analyze work center data, 4) determine constraint(s) for DBR implementation, 5) devise a plan to exploit the CCR, 6) present exploitation plan to Lean Council (management) for approval.

In a team meeting following the creation of the workflow diagram shown in Figure 5-C, the team met to decide on a constraint. We discussed criteria (according to Dr. Goldratt) that a CCR should satisfy for optimal selection. These criteria were explained to the team before a short list of candidate constraints was constructed. The criteria were adapted from AGI's training manual and turned into questions that we could ask about each proposed candidate.

- Do a majority of the product lines flow through the proposed candidate?
- Is it a resource that is expensive to add capacity to?
- Is the resource easy to schedule?
- Is the resource heavily loaded or utilized?
- Is the resource proprietary or core technology?
- Does the resource generate a high yield?
- Is the resource easily buffered?
- Are downstream work centers frequently waiting for the proposed resource?

If "yes" was the answer to all or a majority of the above criteria, then it was understood that the resource was a good candidate for a CCR.

The team proposed a list of 11 candidate constraints that each member felt fit the mold of a constraint. After some debate, it was unclear which candidate was the best fit for Structural Fabrication. The next step was to request that each member assign a utilization percentage (out of a total 100%) to at least three candidates. For example, one might assign 45 points to one candidate, 30 points to another, and 25 points to a third. After totaling each of the utilizations, one resource came out as a clear "winner" in this exercise. The team then verified the criteria for the each of the candidates, and the candidate that received the most points also met each criterion mentioned above. The team was satisfied with the selection of the CCR and it was agreed that Step 1 of Dr. Goldratt's Five Focusing Steps had been accomplished.

The constraint chosen in this case was LO8B, a burning machine that had more capabilities than other burn machines. LO8B was able to bevel and perform circular cuts which significantly reduced lead time. If the material was routed to another burning machine, a manual beveling operation would be required to complete the operation. Because LO8B had extensive capabilities, it was heavily utilized. Therefore, it became a constraint in Fabrication due to its inherent features and not because the capacity of the shop was truly constrained by this machine. Figure 5-E shows how LO8B fared against the other candidates selected by the team.

Figure 5-E: Constraint Candidates in Structural Fabrication

| Rank Order Value | Work Center Name | Work Center Designation | Majority of product lines? | "Expensive" to add capacity? | Easy to schedule? | Heavily loaded? | Proprietary or core? | High yield? | Easily buffered? | Downstream workcenters idle? |
|---|---|---|---|---|---|---|---|---|---|---|
| 350 | NC Burn | LO8B - bay 3 beveling MG | x | x | x | x | x | x | x | occassionally |
| 95 | LG FORM | 2500 Ton Press |  | x | maybe | x | x | x | x | x |
| 70 | SS-L51 | PROFILE LINE BAY 1 |  | x | x | usually | x | x | x |  |
| 35 | LG FORM | 2000 Ton Roll |  | x | x | x | x | x | x | x |
| 35 | LG FORM | 1000 Ton Press Bay 4 |  | x | maybe | x | x | x | x |  |
| 35 | NC Burn | L08MG's - plasma square cut | x | x | x | x | x | x | x |  |
| 30 | NC Burn | L015 - old machine cutting TO's, hand orders |  | x | x | x | x | x | x | x |
| 20 | LG FORM | 5000 Ton Press |  | x | x |  | x | x | x | x |
| 5 | SS-M8A | B274 PLATE PREPARATION BUILDING | x | x |  | x |  | x | x | occassionally |
| 5 | SS-M9A | B275 SHAPE PREPARATION BLDG | x | x |  | x |  | x | x | occassionally |

Following the constraint selection the team moved on to Step 2; develop a plan to exploit the CCR. In understanding what it meant to exploit a constraint we used Dr. Goldratt's definition and drew the analogies from *The Goal.* In short, the exploit phase was a plan to get the most out of the CCR's existing capacity. This can be done by offloading work to other work centers and taking measures to ensure that no time is wasted at the CCR. An hour of production lost at the constraint is an hour lost forever.

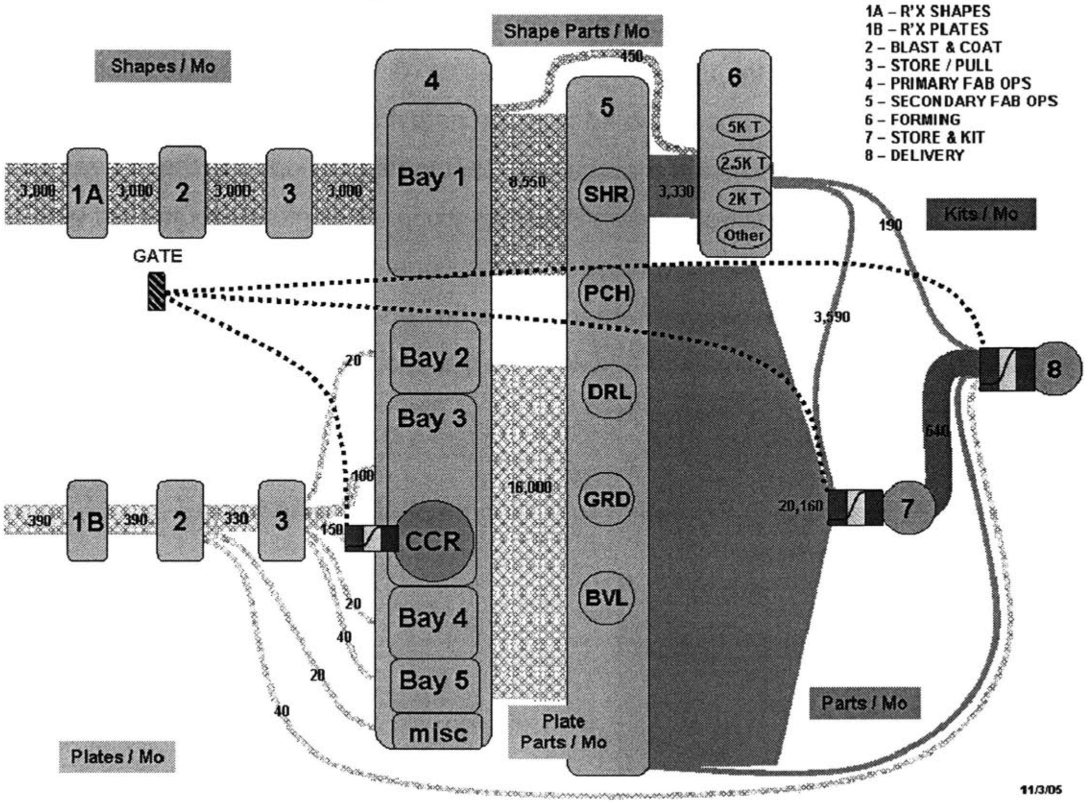
The team made suggestions as to how the CCR could be exploited. A few team members took ownership of the suggestions and formulated new policies and plans to put in place. Some examples of exploit ideas were to align the crane and preventive maintenance crew schedules under the condition that the CCR be given top priority. Once the plans were in place, they were presented to senior management for approval. Figure 5-F outlines a few of the plans that were constructed during this step.

**Figure 5-F: Exploit Plans**

1) Ensure DNC data is dropped in time to support continuous burning.
2) Quality control before material arrives at CCR.
3) Accuracy control SPC.
4) Align crane support to give priority to the constraint.
5) Managing down time for cleaning.
6) Operator training / qualifications.
7) Considerations for 2nd & 3rd shift operations.
8) Priority for equipment breakdowns.
9) Critical spare parts on hand.
10) Consumable replacement.
11) Predictive Maintenance.
12) Investigate layoff operation to minimize impact on burning.
13) Rules for routing to L08B, particularly rules for jobs to offload during forward view conditions.

There was concern that not all jobs were accounted for if Structural Fabrication focused solely on jobs routed through the CCR. It was decided that there should also be buffers placed in strategic locations to account for these jobs. In referring to Figure 5-G, the team decided that there should be two additional buffers placed in front of *Store and Kit* (7) and *Delivery* (8). These buffers were now considered as secondary constraints and would only create a signal to the material release zone if the finished good did not pass through the CCR. Figure 5-G depicts the CCR and the secondary constraints.

Figure 5-G: Buffer Locations



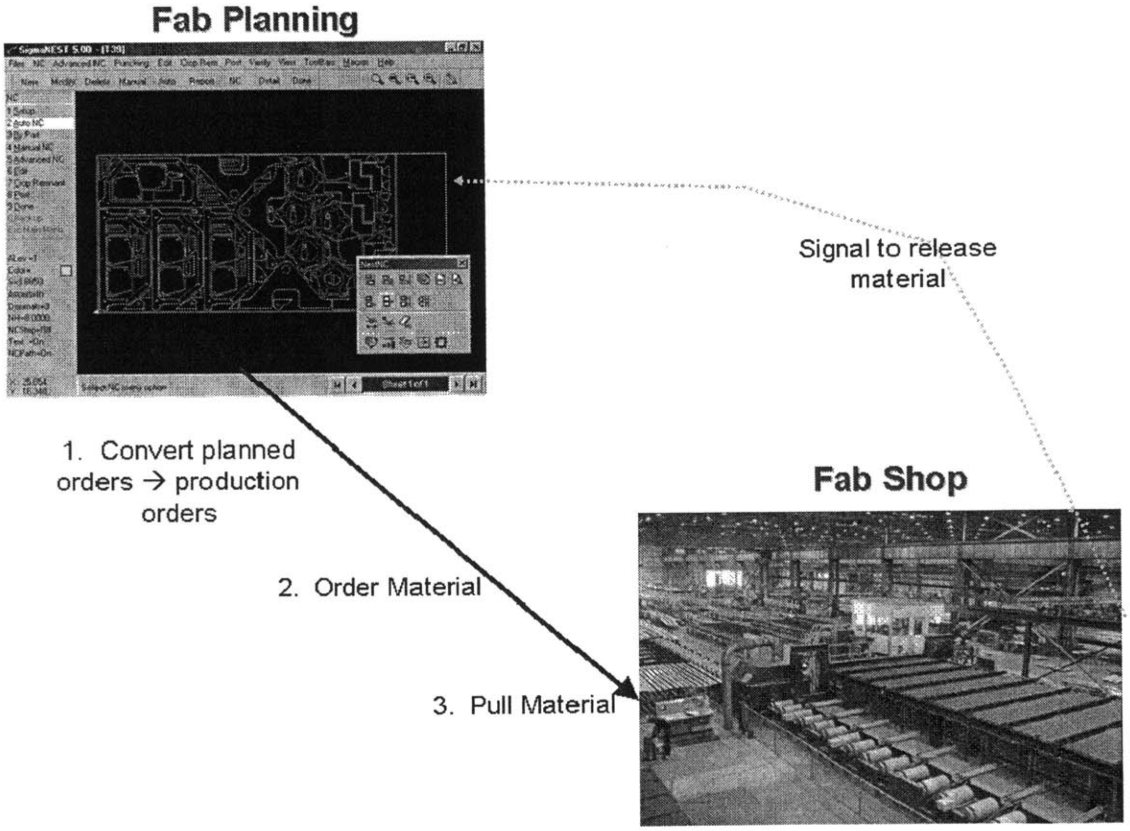
## 5.2.5 Decide on Scheduling Rules for the Drum

Thus far, steps 1 and 2 of the Five Focusing Steps were accomplished; *identify* the constraint and develop a plan to *exploit* it. The following steps in the design phase revolve around step 3: *subordinate* all else to the constraint. Subordinate includes ensuring that material is released at the pace (drumbeat) at which the constraint can consume it, no other work center should outrun the constraint, and the alignment of metrics to encourage this behavior. Preparation for this step takes diligence and time, but is absolutely necessary in the design process.

Deciding on rules for scheduling the drum was a complex task because Structural Fabrication's job shop environment meant that there were several different rules and exceptions to consider. Fortunately, lead time data had been gathered from a similar effort that was attempting to improve the manner in which Structural Fabrication was scheduled. We were able to use the lead times calculated by that team to establish rules for scheduling the constraint.

Prior to establishing the scheduling rules the team needed to decide upon a "gate" for the material release. The *gate* is the point at which the inventory would be held until it was requested from the customer. In other words, this was the division between push and pull production – material would only be released from the gate if there was a signal from constraint or buffer areas. The team determined that the gate should be positioned at the conversion process owned by the Structural Fabrication Planning group. This group would hold onto the planned orders for Structural Fabrication and upon the signal from the constraint (based on buffer location and rope length) planned orders would be converted into production orders. Once the order was converted, it was to flow through the shop as quickly as possible. Figure 5-H illustrates one example of this approach.

**Figure 5-H: Process Flow from the Gate to the Shop**



Once the gate was positioned, the next step was to designate which processes would dictate lead times for each buffer. For example the two processes that designated lead times for the CCR were *material ordering* and *material pull*. The lead times for each of the processes combined was equivalent to the rope length for that buffer. The buffers at the end of the workflow (named secondary constraints) had a variety of rope lengths because material could go through many different resources or very few resources before it reached the buffer.

The rules were established with the idea that as production was able to supply its customer with kits or parts as requested, the rope lengths could be shortened to help achieve the desired reduction in inventory and operating expense.

### 5.2.6 Establish Buffer Sizes

Similar to the rope lengths that allot time to allow production orders to reach their destination buffer, buffer sizes add to the production lead time. Buffers are placed in locations that require protection to prevent the CCR from starving or to protect the customer. These buffers are monitored to provide information concerning the health of the production system.

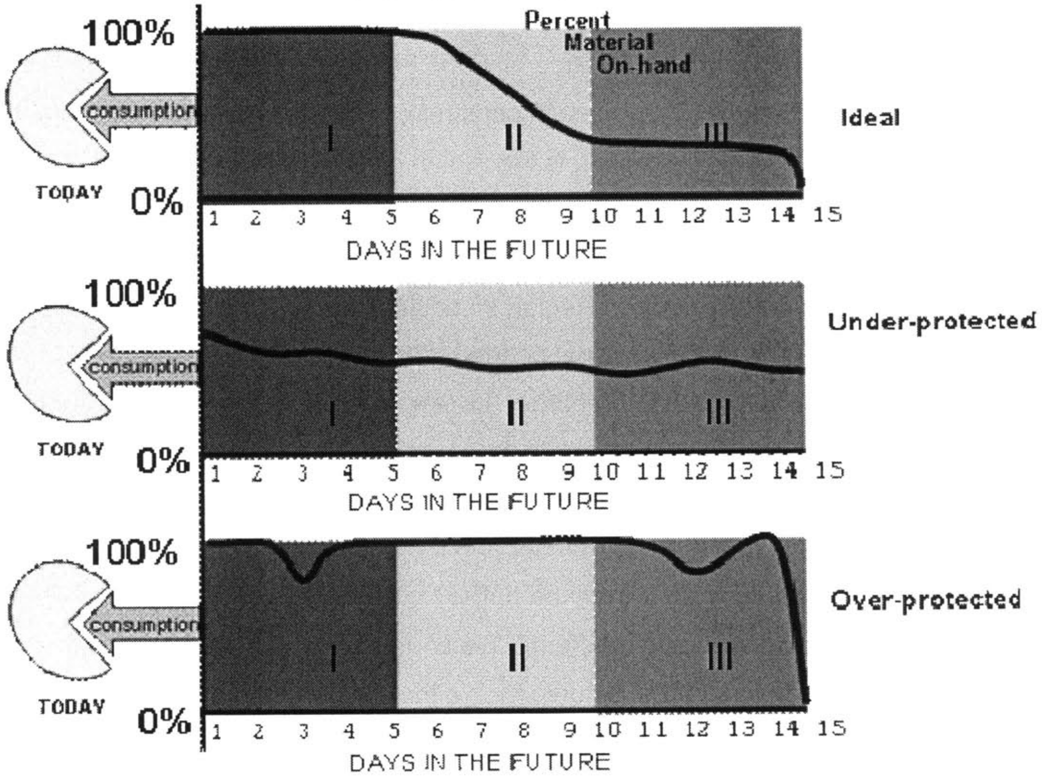
(See Figure 5-I.) The buffer in front of each constraint is broken into three equivalent regions. Region I (also know as the red region) is the region just before the constraint. Regions II and III (yellow and green) precede Region I. There is an S-curve in each buffer that represents the level of material that should be on hand at the buffer. Region III of the buffer should have 20-30% of the material needed. Region II should have 50-60% of the material on hand. Region I should have 100% of the material needed. This curve is based on the probability that material will be received at the buffer. For example, if the buffer is 15 days and each region is 5 days, there is a 20-30% probability that material will be received 11 to 15 days before it is consumed at the constraint. Should the material on hand meet the S-curve, then the production system is performing in a healthy manner and the buffer size and rope length are appropriate. (Rope length is the lead time from the buffer to the material release zone. These are depicted as the dashed lines from each buffer to "Gate" in figure 5-G.) However, if the material on-hand exceeds the levels of the S-curve then either the buffer can be sized smaller or the rope length can be made shorter. A production system that is unable to have material on hand with the probabilities described in the S-curve is either unhealthy or requires adjustment to its buffer sizes or rope lengths. Recall that the goal of the system is to reduce inventory so rope lengths and buffer sizes should be kept as short and small as possible.

Figure 5-I illustrates three conditions of a 15 day buffer. The first buffer represents the ideal condition. The black line represents the percentage of material on hand. The second buffer represents an under-protected buffer as regions II and III are starved of the material they need to keep the constraint 100% utilized. The last buffer illustrates an over-protected buffer in

which each region has too much material and either the rope length or buffer size should be decreased to reduce the amount of work in process (WIP) inventory.

There are three actions a buffer manager should take when the buffer is under-protected: watch, plan, and act. If there are "holes" in region III of the buffer (the material on hand does not add up to 25% of the material required), these items should be watched. If the holes persist in region II of the buffer, then the buffer manager should make an action plan in case the inventory is not available in region I of the buffer. Therefore, if holes exist in region I, production should act on the plan made by the buffer manager.

**Figure 5-I: Buffer Conditions**[1]



The Structural Fabrication team decided on a buffer size measured in days of inventory and based upon the current amount of inventory that resided at each constraint. It was understood that these buffers could be squeezed or expanded as necessary. Figure 5-J illustrates the size of the buffer chosen at the CCR, LO8B, relative to the upstream and downstream operations. (Actual numbers were masked for proprietary reasons.) Rope A is

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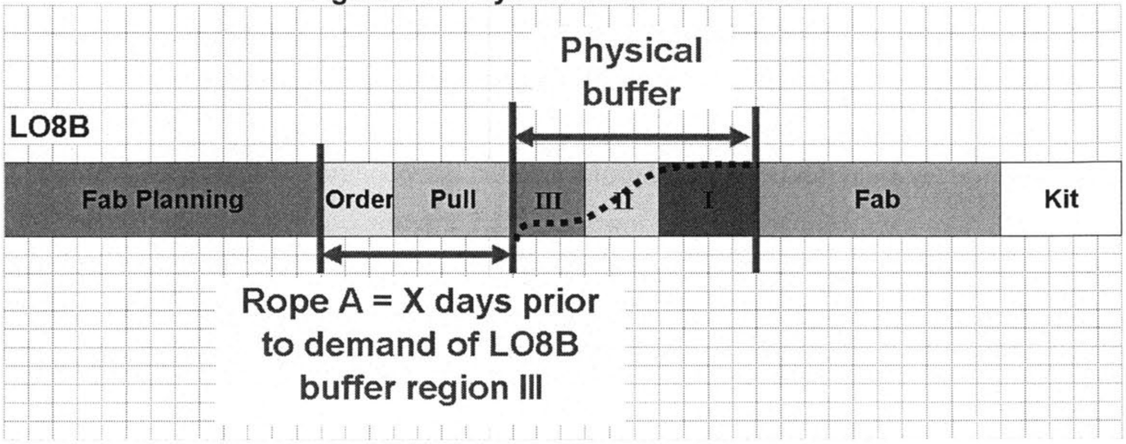
[1] Courtesy of S. Holcomb of Northrop Grumman Corporation.

delineated as the time to order and bring material into the shop. This represents the time required for material to flow from the gate to region III.

Figure 5-J: Physical Buffer at the CCR



## 5.2.7 Tie the Rope

Tying the rope encompassed defining the material gating process, defining the users of the material release and their needs, defining calculations and necessary changes to information systems and reports in order to provide a material release signal, making and testing these changes, and documenting the design. The team designed the pilot system using a combination of Microsoft Access and Microsoft Excel.

The material gating process was defined and initial users of the material release signal were identified. This was helpful in understanding user requirements, data sources, data format, and the proposed harvest method for the scheduling system. From this step, calculations were defined based on the rope lengths and buffer sizes identified in previous steps. (See section 5.2.6 for more detail regarding rope lengths and buffer size calculations.)

The author's assigned project duration did not make it through the completion of this step. The remaining steps describe what the team planned to complete the implementation design.

Once calculations were entered into the desired information system the team would test the new system along with the current system to ensure that no gaps in information existed. Throughout the process, design of the system should be documented for the benefit of future users of the system and to facilitate any upgrades to the system.

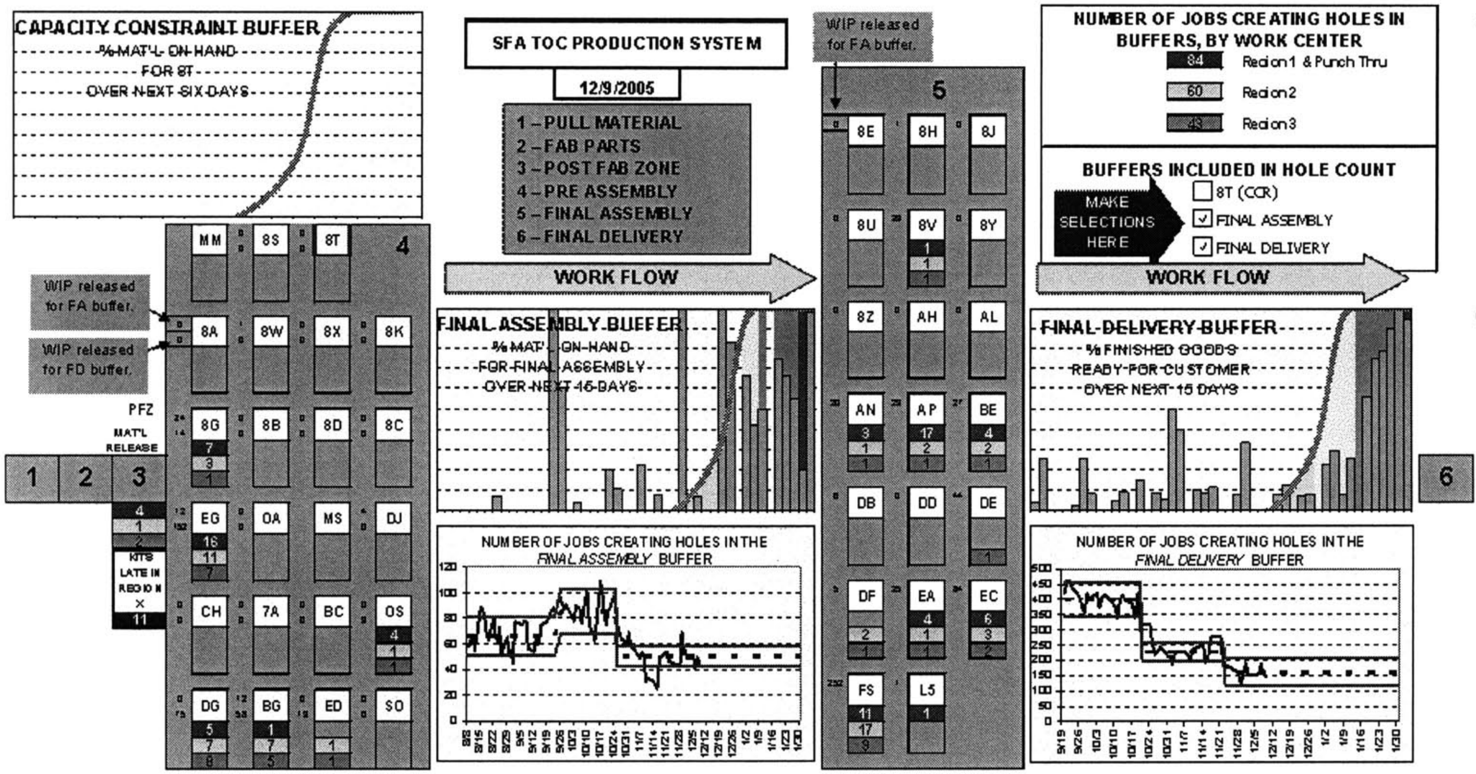
### 5.2.8 Define Buffer Management

Buffer management is an important activity in understanding how well the production is performing and whether the correct scheduling rules are in place. Because Structural Assembly had traveled up the learning curve and defined buffer management in their environment, the design team was able to use the lessons learned by Structural Assembly and adapt them for Structural Fabrication. The number of "holes" in the buffer was a metric that Structural Assembly used to understand trends and take action to improve work centers that had previously created holes in the buffer. The buffer should be monitored with the understanding that certain conditions warrant certain actions. To recap, the reasons for an under-protected buffer should be mitigated by researching the problem suppliers that continuously create holes in the buffer. To resolve an over-protected buffer, the buffer size or rope length could be shortened (see figure 5-I). For a more detailed description of the different buffer conditions, see section 5.2.6.

The buffer management dashboard provides a tool for Production Control supervisors to visibly see where the flow stopped and take necessary action. "The TOC has provided work flow visibility that Structural Assembly has not seen in the past," was a comment made by the Production Control manager who was pleased with the dashboard created to manage the buffer. Figure 5-K is a snapshot of the dashboard used in Structural Assembly.

To correlate the dashboard used in Structural Assembly to Structural Fabrication, the system will be described. Work flows from left to right. Boxes 1, 2, and 3 are operations completed by Structural Fabrication. The gate, or material release, in this system is the post fab (fabrication) zone. The boxes following the post fab zone are the pre-assembly work centers. The CCR in this case, was the pre-assembly work center titled 8T. 8T is a robotic welder that performed operations such as welding stiffening onto plates. The buffer condition for 8T is located in the upper left corner of the dashboard. Since 8T was demobilized for repairs at the time this dashboard was printed, there was no material in front of 8T and thus the buffer was empty. Once the pre-assembly work centers completed a job, the work flowed to the final assembly work centers. The condition of the final assembly buffer is shown in the center of the dashboard. Just below the buffer, there is a trend of the number of holes in the buffers over time. There were limits based on averages and standard deviations of the number of holes to understand whether the process was in or out of control. Once the final assembly was built, it flowed into another buffer called final delivery. Final delivery was a buffer that protected the customer from late deliveries. The buffer condition is shown at the right hand side of the dashboard. Historical trends of the buffer condition were captured just below the buffer shown.

# SFA TOC PRODUCTION CONTROL SYSTEM – FA & FD



Foot-printed Final Assembly is under protected & finished pre-assembly WIP is excessive.

The downstream customer is under protected. WIP is excessive.

Figure 5-K: Buffer Management Dashboard used in Structural Assembly

Similar to Structural Fabrication, Structural Assembly had three buffers: a CCR, a final assembly buffer, and a final delivery buffer. The bars in each buffer represented actual material on-hand ready to be consumed by each constraint. Bars that fell beneath the S-curve represented holes in the buffer. Bars to the left of the S-curve represented material that was released too early. Structural Assembly was still experiencing the growing pains of their new system. The trends below each buffer showed that the conditions were improving as they became more experienced at how to improve upon their new performance measures.

Buffer management in Structural Assembly was executed by Production Control. Since the pilot implementation they have done the following:

- Monitored the material release to the buffer signal.
- Drained WIP from the system.
- Shortened rope length to reduce WIP.
- Monitored and acted on source of buffer holes.
    - Problem codes were tracked to document the reason behind the hole.
    - Work center behavior that could be creating the holes was researched to provide understanding.
- Systematically analyzed the cause of the buffer holes with a focus group.
- Implemented appropriate work center metrics.
- Rescheduled orders to match true customer demand.

From these lessons the Structural Fabrication design team defined the role of the buffer manager, metrics, and actions the buffer manager should take to correct holes or "problem" work centers.

### 5.2.9 Define Desired Behaviors

(This step was not completed during the author's assignment and therefore is documented as tasks the design team has planned.) The design team has planned to consider the different functions and how their roles will change with the new system. Desired behaviors will be defined for Production Control, work centers, and management. The new performance measures will be discussed and defined by the design team. Each of these behaviors will be incorporated into a "Start – Stop – Continue" list that defines behaviors that production will start, stop, or continue in response to the new method of scheduling production.

### 5.2.10 Create an Implementation Action Plan

Once each of the above steps is complete, the design team can go forward with creating an implementation action plan. The design team will consider each stakeholder involved in the process and ensure that all concerns are addressed prior to implementing Drum-Buffer-Rope. The implementation action plan should include details for scheduling drum, managing customer demand, making buffer size changes, buffer management process, information system changes, material release changes, reports, metrics, training, and implementation barriers and enablers. Most of these items were completed in the steps leading to the action plan. The action plan is a tool to ensure that each stakeholder in the new process has been trained and understands the changes that new system will create. Similarly the plan can be used as a tool to communicate to the workers, supervisors, managers, suppliers, and customers of Structural Fabrication that a new process will be implemented.

### 5.2.11 Communicate and Reinforce Desired Behaviors

The change will continue to be communicated once the implementation goes live. The design team will change work center display boards to replace current metrics with recommended TOC metrics. In order to change the metrics effectively, the performance agreements that Manufacturing Process Owners (MPO's) and Manufacturing Process Leaders (MPL's) are held to should be modified to augment the new metrics. The design team will also work with MPO's and MPL's to communicate the TOC DBR desired behaviors to the workforce.

### 5.2.12 Document System Design

Finally, the design team will ensure that all steps completed throughout the design and pilot implementation are documented. This will help new employees get up to speed and help employees outside of the design team understand changes made to the system and why those changes were made.

## *5.3 Results*

Results for the implementation described above will not be seen until after this paper is released (results expected in 2007). Results are projected to be similar to the Structural Assembly's implementation. Six months after implementation, DBR in Structural Assembly was showing improving cost trends and a reduction in WIP in 2005.

# 6 Managing Change

The most important aspect of implementing a change is managing the change to ensure that the organization is aligned and wants to "pull" the change through rather than feeling as though the change is "pushed" upon them. This is important in order to gain buy in at all levels of the organization. Furthermore, it is equally important that the change is managed in a way that it can be sustained through changes in management, employees, suppliers, or customers. Sustainable change will allow the true benefits of change to be realized. This next section discusses the author's views on how to effectively manage a new process improvement that requires changes in policies, metrics, information systems, and various functions.

## *6.1 Organizational Alignment*

In order to carry out any change in a system, the leadership within the system needs to understand what to change, what to change to, and how to accomplish the change. Once the senior leadership has agreed upon and is "on board" with the change proposed, it is much easier to implement each of the changes in policies and metrics that must augment the prescribed implementation. Ideally, one should align each stakeholder in every function of the organization with what needs to be changed, what to change to, and how to cause the change. However, in large organizations the amount of time and effort to educate and align each of these functions would be overwhelming. In these instances, it would be more beneficial to **align the leadership** in one division of the organization and pilot the change. This would allow other organizations to understand the change and how the change helped to achieve the goal of the process improvement. When pilots are used to implement change, it is important that data is gathered on the state of the system before the change and that the same data is gathered after the change. In other words, results should be recorded and reported to every part of the organization often. This will serve as an education tool for the organization and aid in adopting the lessons learned from the pilot to future implementations.

Whether the entire organization or a pilot is required to implement a change, it is paramount that the rank and file employees are aligned with the change. One way to do this is to include front line supervisors in the decision making process. While the benefit of alignment is achieved, the drawback is that the time to make decisions increases at the risk of missing an opportune moment. Another approach to further align the workforce would be to include a subset of the rank and file in the implementation design process. This would help to ensure that the employees who will adopt the change are educated about the improvement and can help educate the rest of the workforce about the changes that will be required to make the implementation a success. Ultimately, **creating or identifying the need for the change** prescribed is paramount to aligning the organization. This will be described more in the next section.

## *6.2 Pulling Change*

If time permits, the ideal method of implementing a new process improvement would be to create a "pull" for change. In her book *True Change*, Jan Klein [18] describes the difference between pulling and pushing change in an organization. Pulling change is defined as creating the desire and need for the change among shop level employees. Whereas, pushing change is change that is forced upon the shop level employees with little understanding by rank and file as to why the new change is in place. It was determined that pulling change is an easier approach to adoption than pushing change. Furthermore, the help of the shop level employees in the change initiative will create a more swift and sustainable change.

The first step in educating the employees about the change is to **establish the current state of the system**. Gathering data such as the current inventory levels, examples of the problem to be solved (i.e. the lack of synchronization in building an assembly), and other measures will help illustrate the current system. Moreover, understanding the difficulty in managing the current state of production is essential to tap into pulling the change.

Next, the **perceived future state** should be established assuming the process improvement is implemented and has reached a steady state. Perceived results should be illustrated in the form of the current and proposed metrics. This is designed to not only illustrate the benefits but also to refute any metrics that are ineffective in measuring performance in the new system. In the case of a TOC implementation, performance measures such as inventory, operating expense, throughput, and synchronization should be communicated to those expected to adopt the improvement. Understanding how this improvement will help the shop level supervisors and senior leadership, again, is the conduit that will create the pull for change.

Taking the time to establish a pull for change can be the tipping point that drives the implementation into success. Finally, if available, a similar application should be shared with the stakeholders. If the current state and future state of a similar environment can be related, the process improvement gains more credibility among the workforce.

## *6.3 Creating a Sustainable Change*

As mentioned in section 6.2, a sustainable change is created by pulling the change. Creating the pull for change helps every level of the workforce to understand the new system and will help ensure that the right actions at each level are taken to attain a sustainable change.

Conjointly, **changes to policies and performance measures** need to be robust and adopted across each function of the organization. In order to change the policies and performance measures, however, the implementation team must first identify the measures and policies in place that are in conflict with the new regime. This task requires the insiders of the organization to step back and think as outsiders. If available, it helps to include outsiders in the team to aid in this process. The difficulty in this task is to understand the reasons behind policies (if any) and then come up with new policies that better fit the new system. The creation of new policies is often overlooked which forces the workforce to resort to the old policies once again. Similarly, performance measures need to be evaluated and revised if they conflict with the new system and new metrics need to be established.

Finally, the change should be incorporated in each of the business processes that the change affects. In today's business environment this implies an approach that changes the rules and assumptions in the information or data system(s) that control these processes and replaces them with the new rules. Otherwise if the rules are not replaced, numerous interfaces that alter the data output from the system to incorporate the new rules will need to be established to output the necessary information needed by each function. Either way, **change to the information system(s)** should not be overlooked as this is a critical key to providing a more sustainable adoption.

# 7 Conclusions

In an industry such as shipbuilding, the cultural acceptance of change is difficult. Newport News Shipbuilding has survived for over a century using age-old practices – what incentives do they have to change? With maritime law that protects them from foreign competition one struggles with why a shipyard needs to change. In recent years, however, the Navy has recently recognized the incentives that cost-plus[1] contracts encourage and how this has allowed U.S. shipbuilders to fall behind their foreign competitors. The Navy's most recent Virginia Class Submarine (VCS) contract was set at a fixed price to discourage high construction costs seen in the past. A recent excerpt from Defense Daily highlights that there is some dispute as to why U.S. shipbuilding has such astronomical costs as compared with shipyards abroad:

> *The United States shipbuilding industry has come under sharp scrutiny over the past year as Navy costs for building new ships, in particular the DD(X) destroyer, have soared. Industry has countered those charges saying costs have increased because the Navy is buying fewer ships and it's nearly impossible [to] win international work against foreign shipyards that are subsidized by their governments [1].*

Even so, there were striking differences captured through studies that compare U.S. shipbuilding to Asian and European competition.

> *[Rep. Gene Taylor (D- Mississippi)] said he's told Northrop Grumman shipyard operators in his district that they must adopt practices used by overseas shipbuilders, such as laser cutting, bar coding and robotics. He said he was amazed that European builders used bar codes to track where every piece of steel will go on a 1,200-foot ship before it's assembled [1].*

Furthermore, the termination of the US Construction Differential Subsidy[2] in 1981 reduced the ability of US shipyards to compete successfully for commercial shipbuilding contracts with foreign shipyards – many of which are subsidized by their governments [8].

While the industry has changed since the Cold-War era, the shipbuilding culture (many third and fourth generation welders and fitters) has yet to catch up. The recent pressure from the Navy has created incentive for change as U.S. shipyards heed the Navy's threat of accepting competitive bids from foreign ship builders. Communicating this sense of urgency is no easy feat when the production cycle time of a Nuclear Aircraft Carrier is seven years and

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[1] Pre-determined percentage of profit added to the total cost of an incentive program.
[2] Federal shipbuilding assistance program.

there is uncertainty as to the Navy's need for more than 11 aircraft carriers in the 21st century [19].

Change in any large organization is difficult to tackle. More recently, however, change has been embraced as the shipyard understands that they could one day lose their Navy contracts to foreign competition. This success of this implementation will signify that the shipyard is ready to accept the change it needs to remain in business. A similar effort to implement pull in the Structural Fabrication Shop was attempted in 1996 and later scrapped after management turnover.

Even though it seems as if the need for change is urgent, I heard frustrations during informal conversations among employees who were not confident of the new change. Some individuals were ready to embrace the change while others were skeptical of this initiative and were uncertain it was the correct approach. It is crucial, therefore, to continue to communicate the reasons behind the change to every level within the organization. Additional enablers of a successful adoption are discussed in the next section.

## *7.1 Enablers of a Successful Drum-Buffer-Rope (DBR) Adoption*

Enablers of a successful implementation of DBR in an environment such as the Structural Fabrication Shop include understanding what to change, what to change to, how to create the change, creating organizational alignment, assigning resources dedicated to the effort during the transient state, information system support, discarding the old policies and metrics (that create a conflict in the desired behavior) and replacing them with new policies and metrics, and continuing to educate all of the stakeholders.

First and foremost, the organization should understand the reason behind the TOC DBR adoption. This can be accomplished by answering the three questions asked in the TOC thinking process (TP):

- What to change?
- What to change to?
- How to accomplish the change?

Once these three questions are identified and understood by each level of the organization, then the process improvement implementation can be carried out.

In order to manage the change at each level, the appropriate authority to change policies and performance measures must be awarded to the stakeholders tasked with implementing the change. This will enable the projected results to be achieved and support a sustainable adoption of the change. Furthermore, the stakeholders tasked with implementing the change should be allotted the appropriate resources to successfully implement and adopt the change. To ensure that this transient state is not too long and taxing on the organization's resources, the information system(s) should incorporate the new business processes set in place.

As mentioned in section 6.3, policies and performance measures need to be scrutinized and evaluated by the implementation team to understand whether or not they are in conflict with the goal the process improvement is trying to achieve. Again, the discipline of not only discarding old policies but of implementing new policies is paramount.

Finally, taking the time to continually educate members of the organization about the successes and failures of the implementation will pay dividends in the sustainability of the change and in the further adoption by other areas of the organization.

## *7.2 Evaluation and Recommendations*

This next section contains the author's evaluation and recommendations for the implementation of DBR at Northrop Grumman Newport News. Given the scope of the current implementation in Structural Fabrication and Assembly, the author will comment specifically on her observations in this area.

In general, attacking the lack of synchronization between work centers with SFA is an important problem to resolve. In weighing the options of which method (push, pull, or a hybrid of the two) is most appropriate, the author agrees that TOC DBR is the best application of pull in SFA's inherent job shop environment. Further, the division between push and pull production internal and external to SFA should be clearly established and understood by Production Control during the transient state of implementation. Once a steady state is achieved, the further rollout of pull to other areas and functions should be considered. It may not be necessary in some cases to adopt pull but rather to ensure that the interface between push and pull is managed so that a clear signal to produce is given in both areas.

Further, the adoption should consider how to best incorporate the new policies and performance measures to the interfacing functions of SFA. Functions such as Finance, for example, should understand why the change has taken place, what policies have changed or are implemented, and how they can effectively gather metrics that would augment the change.

Additionally, the implementation effort should continue to focus on "pulling" the change throughout SFA and the rest of NGNN. This includes the continual reporting on the status of the change, progress, and results to areas within and external to SFA. Other measures to pull the change should also be considered. For example, the inclusion of line employees in the design of implementation was a key enabler in the SFA's implementation phase and should be continued in future implementations.

Finally, the change agents within the organization should continue to find venues to educate other areas of the organization about the change and how it has changed the way business is done in SFA. Incorporating sustainable changes in the business processes (via information systems) will be enabled via the education process.

Considering ways to make the change sustainable involves momentum at all levels of the organization. This thesis has explored the positive results that Drum-Buffer-Rope can bring and how these results are achieved. It cannot be emphasized enough that this momentum will be difficult to sustain, but will be necessary to ensure adoption is achieved within the shipyard. The customer is eager to see the ways in which NGNN can reduce cost and add value to the future of the United States Navy. Through this continued drive to improve processes, perhaps ship building can one day be competitive in the United States again.

*"The Navy has both a tradition and a future--and we look with pride and confidence in both directions."* - Admiral George Anderson, CNO, 1 August 1961.

# References

[1] Cahlink, George, 'Reps Postpone Visit To Asian Yards, Concerns Remain About U.S.

[2] Shipbuilding', *Defense Daily,* Potomac: Aug 10, 2005. Vol. 227, Issue 28; pg. 1.

[3] Cohen, Oded and Lepore, Domenico, "Deming and Goldratt." Massachusetts: North River Press, 1999.

[4] Cox, James F. and Spencer, Michael S., "The Constraints Management Handbook." Florida: St. Lucie Press, 1998.

[5] Dailey, Kenneth W., "The Lean Manufacturing Pocket Handbook." DW Publishing, 2003.

[6] Defense News Research, 'Defense News Top 100', 2005, <http://www.defensenews.com/content/features/2005chart1.html> [accessed March 4, 2006].

[7] Di Vincenzo, Mark., 'A New Hope', *Virginia Business Magazine,* March 1997.

[8] Global Security.org 2006, Shipyards. <http://www.globalsecurity.org/military/facility/intro-shipyard.htm> [accessed March 23, 2006].

[9] Goldratt, Eliyahu M., "Beyond the Goal." 2005, Audio Book.

[10] Goldratt, Eliyahu M., "It's Not Luck." Massachusetts: North River Press, 1994.

[11] Goldratt, Eliyahu M. and Cox, Jeff, "The Goal." New York: North River Press, 1986.

[12] Goldratt, Eliyahu M., "The Haystack Syndrome," New York: North River Press, 1990.

[13] Goldratt, Eliyahu M. and Fox Robert E., "The Race." Connecticut: North River Press, 1986.

[14] Hepburn, Richard D., "History of American Naval Dry Docks." Virginia: Noesis, Incorporated, 2003.

[15] Holmes, Lind E., Hendricks, Ann B., "Is TOC for you?", Strategic *Finance,* Montvale: Apr 2005.Vol. 86, Issue 10; pg. 50.

[16] Hopp, Wallace J. and Spearman Mark L., "Factory Physics." The McGraw-Hill Companies, Inc., 1996.

[17] ICAF Staff, 'Shipbuilding Sector Remains Uncompetitive: U.S. Government Should Take Action to Make the Nation's Shipyards More Efficient', *National Defense Magazine.* March 2002.

[18] Klein, Janice A., "True Change: How Outsiders on the Inside Get Things Done in Organizations." California: Jossey-Bass, 2004.

[19] Lerman, David, 'Budget Hard on Shipyard', *Knight Ridder Tribune Business News*. Washington: Feb 7, 2006. pg. 1.

[20] Liker, Jeffrey K., 'Manufacturing Engineering for Lean Manufacturing', Optiprise, Inc. <http://www.optiprise.com> [accessed May 7, 2006].

[21] MARAD, 'Report Survey of U.S. Shipbuilding and Repair Facilities', 2003, <http://www.coltoncompany.com/shipbldg/statistics/yards.htm> [accessed Jan 24, 2006].

[22] Norfolk Naval Shipyard, 'NNSY History', 2006, <http://www.nnsy1.navy.mil/History/HISTORY.HTM> [accessed March 4, 2006].

[23] Northrop Grumman Corporation, 'Northrop Grumman 2004 Annual Report', 2004, <http://www.northropgrumman.com/images/annual_report/2004_noc_ar.pdf> [accessed March 4, 2006].

[24] Northrop Grumman Corporation, 'About Us', 2006 <http://www.northropgrumman.com/about_us/about_us.html> [accessed March 4, 2006].

[25] Pitcher, Michael, 'Examining Just-In-Time and Theory of Constraints', Society for Manufacturing Engineers, 2005.

[26] 'Sales of U.S. Shipyards Since 1980', <http://www.coltoncompany.com/shipbldg/statistics/yardsales.htm> [accessed Jan 24, 2006].

[27] Shephard, John Jr. and Spolsky, Harvey, 'Five Shipyards Too Many: The Pentagon Should Focus on Paring Down Private-Sector Facilities', *The Washington Post.* November 8, 2005. Page A19.

[28] Stein, Robert E., "The Theory of Constraints, Applications in Quality and Manufacturing." New York: Marcel Dekker, Inc., 1997.

[29] Stein, Robert E., "Re-Engineering the Manufacturing System: Applying the Theory of Constraints." New York: Marcel Dekker, Inc. 2003.

[30] Thompson, Loren, B., 'U.S. Shipbuilders: The Tide Begins to Turn', *Sea Power Magazine.* April 1, 1999.

[31] Woeppel, Mark J., "Implementing the Theory of Constraints." Florida: St. Lucie Press, 2001.

[32] Womack, James P., Jones, Daniel T., "Lean Thinking." New York: Free Press, 2003.