Applying Factory Physics to Manual Assembly at an Aerospace Fabrication Site

by

Joseph G. Konefal

Bachelor of Science in Mechanical Engineering, Duke University, 2005

Submitted to the MIT Sloan School of Management and the Institute for Data, Systems, and Society in Partial Fulfillment of the Requirements for the Degrees of

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Abstract

The assembly of welded reservoirs at the Boeing Tube Duct, and Reservoir Center (TDRC) is a traditional batch and queue operation that relies heavily on manual craftsmanship. The production system experiences high variability in cycle times, high use of overtime, and poor on-time performance. The value provided by the system to Boeing and its customers is characterized by considering the associated costs of late delivery, inventory, labor, and opportunity cost. To understand the system's performance, the system's processes are mapped and modeled using discrete event simulation. The simulation is used to evaluate the benefits of changes to staffing, overtime implementation, and shop floor control. Based on the results of the simulation, lead times are increased to stabilize delivery and a CONWIP system is implemented to improve productivity and reduce overtime costs. Subsequent production data show that these changes are effective and that this framework provides successful strategies for value characterization, system stabilization, cost reduction, and increases in value creation.

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Glossary of Terms

Bottleneck – The resource that determines the capacity of a production system.

CONWIP – Shop floor control method that constrains the work-in-process, or WIP, in a series of production processes.

Customer Service Level – The ratio of the number of instances demand for a product is satisfied on time to number of instances the product is demanded.

Drum-buffer-rope – Shop floor method that uses the bottleneck, or system constraint, to set the pace of the system (drum), ensures sufficient WIP in front of the bottleneck to keep it utilized (buffer), and ties together all processes that precede the bottleneck (rope).

Kanban – Shop floor control method that uses cards to constrain the WIP in a single production process.

Operation Time – The sum of process time and setup time.

Order Cycle time – Actual time from release to completion for a production order.

Order Lead Time – Scheduled time from release to completion for a production order.

Process Time – Time to complete a given process.

Setup Time – Time required to set up a tool or machine to begin a process.

Shared Work Center – Work center that contains an operation or set of operations that are shared by multiple product lines.

Shared Work Center Cycle Time – Time between completion of prior operation and completion of final shared work center operation for a given order.

Work Center – Area composed of work stations and factory personnel dedicated to a specific type of product.

Work Station – Location within a work center where a particular operation is performed.

1.0 Introduction

This Chapter is an overview of this research including the problem, research motivations, objectives, and methodology.

1.1 Problem Statement

The Boeing Tube Duct, and Reservoir Center (TDRC) supplies components to airplane programs. The assembly of hydraulic reservoirs at the TDRC is a traditional batch and queue operation that relies heavily on manual craftsmanship. The system experiences high variability in cycle times, high use of overtime, and poor on-time performance. The objective of this work is to identify and implement a scheduling, staffing, shop floor control, and performance management strategy that stabilizes and optimizes system performance and provide a foundation for continuous improvement. Stabilizing the system is defined as ensuring consistency of product delivery and customer satisfaction. Optimizing the system is defined as maximizing the value provided by the production system to Boeing and its customers. Improvement is defined as an increase in the value that the production system provides.

1.2 Motivation

Boeing Commercial Airplanes (BCA) is facing increased competition in the aviation marketplace. To meet this challenge, BCA has identified several "Keys to Winning". This work addresses two of these items, delivery discipline and competitive pricing, as related to the production of hydraulic reservoirs. Stabilizing the hydraulic reservoir production system improves delivery discipline. Optimizing the system reduces costs and allows for more competitive pricing and also provides an approach for characterizing and quantifying that can be used to guide continuous improvement efforts. Continuous improvement allows for reduction in costs due to increased throughput and/or reduced capacity, lead time, and inventory.

In addition to increasing the TDRC's and BCA's delivery discipline with respect to hydraulic reservoirs, this work provides a framework for improving performance of a production system that can be applied elsewhere at Boeing Fabrication.

1.3 Methodology

The project is performed in four phases: value characterization, system modeling, control improvements, and implementation.

Value characterization is performed by identifying and assessing the costs associated with the performance of the production system. This effort includes interviews with factory management and customers and analysis of costs associated with inventory, labor, and late delivery. In this instance, the customers of the production system are the Boeing airplane programs and are therefore internal to Boeing. The opportunity cost of the people, equipment, and other infrastructure that is used by the production system is also considered.

The system modeling phase involves developing a discrete event simulation of the reservoir production system. The scope of this model includes all processes and workers in the reservoir work center. Process times are input based on worker feedback and manufacturing data. Worker absenteeism is modeled based on attendance records. Quality non-conformances and rework are modeled as rework loops at appropriate locations. Rejection rates are input based on manufacturing data. Logic in the model triggers worker overtime based on traditional management practice. Support activities are modeled as additional cycle time according to a distribution based on manufacturing data. The model is capable of performing various forms of scenario and sensitivity analysis. It is benchmarked using historical production data. As part of this phase, the simulation model is used to determine the manufacturing lead times that ensure customer satisfaction.

In the control improvements phase, the benefits of changes to shop floor control, such as work-in-process (WIP) control, cross-training, work prioritization, and overtime strategies are determined using the simulation model. These benefits are compared to any associated costs, and improvements are recommended accordingly.

The implementation phase includes the development of management tools to implement new staffing, lead time, and control measures and evaluate their effectiveness. These tools display key work status and performance indicators. They are monitored, with daily follow-up to encourage operator problem solving to improve system performance. The system's performance is evaluated to determine whether the predicted improvements materialize.

2.0 Background

This Chapter provides relevant background on The Boeing Company, the TDRC, and hydraulic reservoirs.

2.1 Boeing

Boeing is the world's largest aerospace company and leading manufacturer of commercial jetliners and defense, space and security systems. The company has two primary business units: Boeing Commercial Airplanes (BCA) and Defense, Space & Security.

BCA currently manufactures the 737, 747, 767, 777 and 787 families of airplanes and the Boeing Business Jet range. The 747, 767, 777 and 787 families are assembled and delivered in Everett, Washington [1].

Boeing Fabrication provides key manufacturing and assembly capabilities and technologies to BCA. Fabrication has 11 manufacturing sites across three countries. The Auburn, Washington Fabrication site has eight manufacturing business units, including the TDRC.

In addition to production operations, Fabrication works with Engineering to develop new manufacturing capabilities that enable the introduction of new product development concepts.

2.2 Tube, Duct and Reservoir Center

The TDRC produces tubes, aluminum and hard-metal welded duct assemblies, dip-brazed assemblies, hydraulic reservoirs, and hydraulic units for BCA programs. The tubing and ducts are used in several different systems and applications on the airplanes. The hydraulic reservoirs store hydraulic fluid that actuates critical aircraft systems such as landing gear and flight controls. The TDRC also provides out-of-production spares and critical emergent parts for final assembly. The factory contains several critical manufacturing capabilities, such as tube bending, pullouts, welding, heat treatment, chemical treatment, and paint.

2.3 Hydraulic Reservoirs

Hydraulic reservoirs supply hydraulic fluid to the hydraulic power system. The hydraulic power system operates several mechanical devices on an aircraft. A cross-section sketch of a hydraulic reservoir and its key components is provided in Figure 2-1. The reservoirs are fabricated by making and joining three separate parts, an upper weld assembly (upper), a lower weld assembly (lower), and a gravity trap (g-trap).

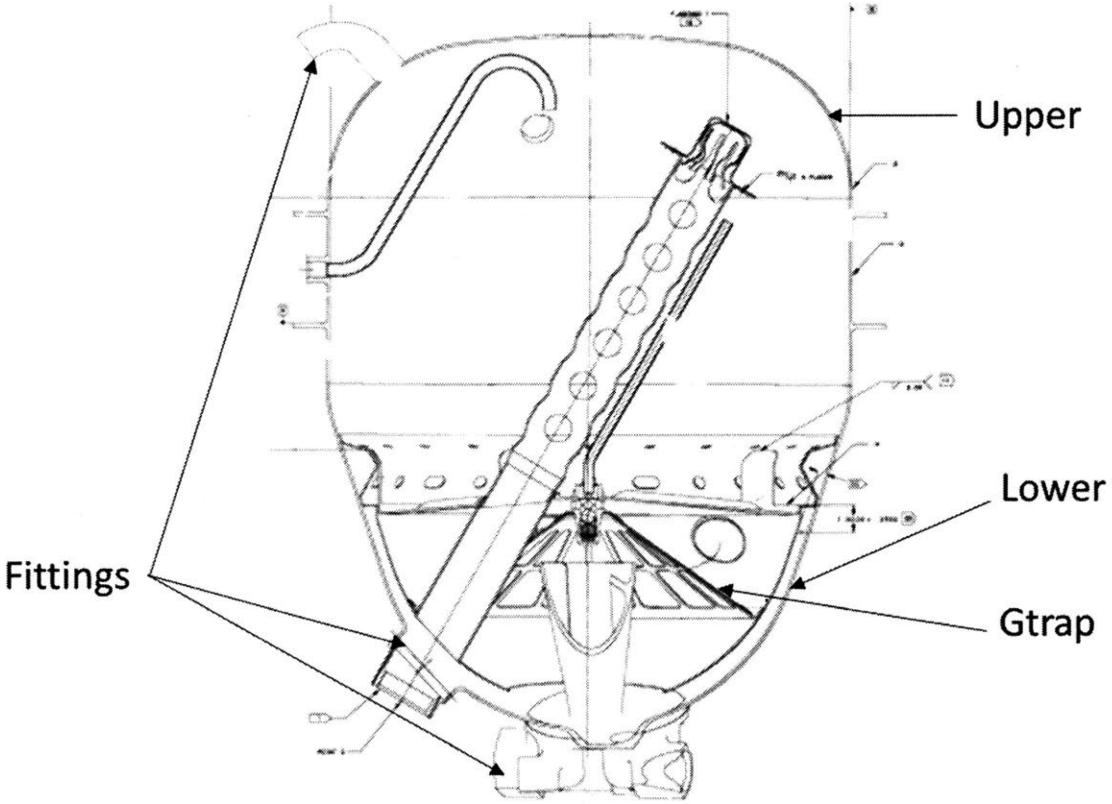


Figure 2-1. Hydraulic Reservoir Cross-Section

The upper and lower parts are assembled from aluminum forgings, which are supplied to the TDRC by an outside vendor. The forgings are trimmed and then annealed. For certain part numbers, rings are welded on the forgings with a girth weld. Fittings are attached to the forgings by drilling out holes in them, pulling out penetrations, setting up the fitting and then welding. The welds are then inspected via x-ray. Next the parts are heat treated, formed back into shape (straightened), deoxidized, and checked for hardness. Finally, the fitting welds are inspected via dye penetrant testing. Throughout this process, geometric inspections are performed.

The g-trap is fabricated by initially deoxidizing the supplied parts, followed by a series of assembly steps that include riveting and welding.

A reservoir is assembled by starting with an upper, lower, and g-trap. First, the upper and lower are fitted up to determine any trimming that is required to yield an appropriate reservoir height.

The upper is then trimmed while the g-trap is fitted and welded into the lower. The upper and lower, with g-trap inside, are then fitted and welded together. The new girth weld is inspected via x-ray and dye penetrant testing and then heat treated. The assembled piece is then checked for material hardness, pressure tested, dried, and painted. Following painting, brackets and other components such as a relief valve and site glass are installed on the reservoir.

Table 2-1 shows reservoir part numbers and corresponding upper, lower and g-trap part numbers for different airplane programs. For the 747, a shipset includes four reservoirs. The 767 has two distinct shipsets, one for the freighter 767 and one for the tanker 767. A 777 shipset consists of three reservoirs.

Table 2-1. Reservoirs and Part Numbers

Program	Takt Time (M-Days)	Reservoir Part Number	Takt Time (M-Days)	Lower Part Number	Takt Time (M-Days)	Upper Part Number	Takt Time (M-Days)	Gtrap Part Number	Takt Time (M-Days)
777	2.5	271W3104-1	2.5	271W3105-3	2.50	271W3105-2	2.50	271W3106-5	2.22
		271W3108-8	2.5	271W3109-3	1.25	271W3109-2	1.25	271W3110-6	1.25
		271W3108-11	2.5						
767 Tanker	20	271T5212-63	20	271T5211-15	5	271T5211-3	10	271T5219-15	5
		271T5212-64	20			271T5211-4	10		
		271T4521-7	20	271T4522-9003	20	271T4522-2	20	271W3106-5	-
767 Freighter	20	271T5212-59	20	271T5211-15	-	271T5211-3	-	271T5219-15	-
		271T5212-60	20			271T5211-4			
		271T0115-12	20	271T4551-9	20	271T4551-10	20	271T0110-10	20
747	20	271U3001-11	20	271U3110-9013	10	271U3110-2	10	271U3110-4	10
		271U3001-12	20						
		271U3002-16	20	271U3210-9016	10	271U3210-2	10	271U3210-4	10
		271U3002-19	20						

2.4 Summary

In summary, the TDRC, a factory within Boeing's Fabrication Division, provides tubes, ducts, and reservoirs to the Boeing airplane programs. The scope of this work is limited to the production of the hydraulic reservoirs for the 777, 767 and 747 programs. A work center in the TDRC is devoted to these products. Three subassemblies, the lower, upper, and g-trap, are assembled at the TDRC. The final assembled reservoir is then assembled from the three subassemblies. The 777 reservoirs are the highest volume products under consideration. A shipset of 777 reservoirs (one large reservoir, two small reservoirs) is produced every 2.5 manufacturing days, compared to shipsets of 767 and 747 reservoirs, which are produced monthly.

3.0 Key Concepts and Literature Review

This Chapter provides a description of key operations management and manufacturing concepts that are pertinent to the work described herein. A review of relevant research and literature is also included.

The introduction of the industrial revolution and machine technology brought with it the need to develop methods of managing production processes that take place in factories. Over the last two hundred years, several manufacturing management strategies and theories have been proposed [2]. Two relatively recent proposals are theory of constraints (TOC) and factory physics.

3.1 Theory of Constraints

Gupta and Boyd contend that TOC "provides a broad framework for viewing the relationship between operations management and the whole firm" and "that TOC concepts address many of the traditional concepts of operations management from a more unified perspective" [3]. TOC focuses on the constraints of a system and aims to exploit those constraints to increase the rate at which the goal of the organization is achieved. In a for-profit manufacturing organization, the goal of the firm is not simply to reduce cost but to "make more money" [4]. In TOC, the term "bottleneck" is replaced by "constraint". TOC defines a constraint as anything that limits a firm's ability to increase the rate at which it achieves its goal.

Goldratt [4] provides five steps for managing a system's constraints:

1. Identify the system's constraint, or resource that determines the capacity of the system.
2. Decide how to exploit the system's constraint (determine how to improve the capacity of the constraint).
3. Subordinate the rest of the system to the decisions made above (prioritize this strategy).
4. Elevate the constraint (prioritize communication of the constraint's status).
5. Go back to Step 1.

TOC proposes drum-buffer-rope (DBR) as a shop floor control methodology [5]. DBR is shown pictorially in Figure 3-1. In this approach, the "drum" provides the cadence, or rate, of the system. The drum is therefore the system's constraint. The "buffer", which is work-in-process, protects the drum against any disruptions due to variability. It is important that a buffer be in front of the constraint so that it is not starved. Starving the constraint starves the throughput of the entire system. The rope is the mechanism that moves materials through the system in unison, tying the drum together with upstream processes. In other words, materials is pulled into the system by the rope at the rate at which the drum is beating, or producing. Therefore, the production schedule must be compatible with the capacity of the drum.

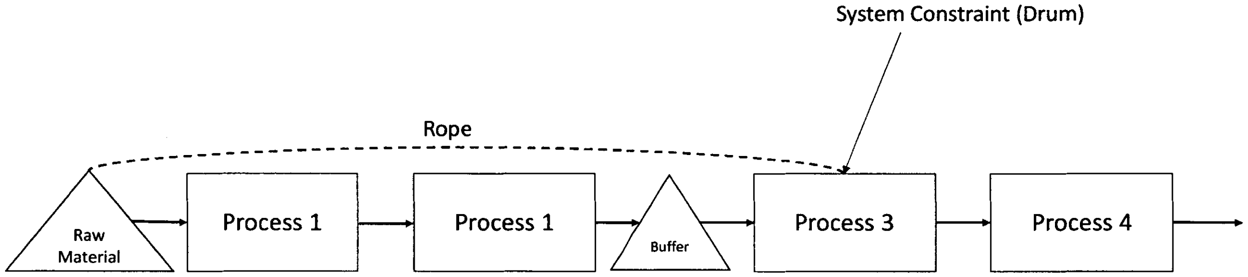


Figure 3-1. Drum-Buffer-Rope

TOC prioritizes three measures in order of importance: throughput, inventory, and operating expense. Because throughput is most important, TOC recognizes the need for excess capacity at processes that are not constraints [2]. The required amount of excess capacity required is dependent on the amount of variability in the production process.

In TOC, the purpose of inventory (raw material, WIP or finished goods) is to protect the throughput of the system. Having too little inventory can starve the constraint or other resources. Too much inventory takes up space and complicates movement and tracking of materials in the factory. For firms that make to stock and compete on order lead times, higher finished goods inventory increases a firm's competitiveness. For firms that make to order and compete on order lead times, higher WIP increases cycle times and decreases the firm's competitiveness.

3.2 Factory Physics

Factory Physics [6] is a textbook that attempts to provide a basis for the behavior of manufacturing systems and an approach for managing them. The text presents several "laws" of factory physics, one of which addresses variability [7]. The more variability in a manufacturing system, the poorer the system performs. The presence of variability requires the use of buffers to achieve consistent output. In a manufacturing system, buffers can take one of three forms: 1) capacity, 2) lead time (or WIP), and 3) finished goods inventory [8].

As an example of how these buffers are related, consider the curve shown in Figure 3-2, which shows cycle time as a function of utilization. All manufacturing systems behave in accordance with this figure. Cycle time increases with respect to utilization. In other words, as the capacity buffer decreases, (utilization increases) a larger lead time buffer is required. This increase is non-linear, and at a certain point, becomes highly unstable and difficult to predict. The point at which this occurs is dependent on the amount of variability in the system. The more variability, the lower the utilization at which this instability occurs.

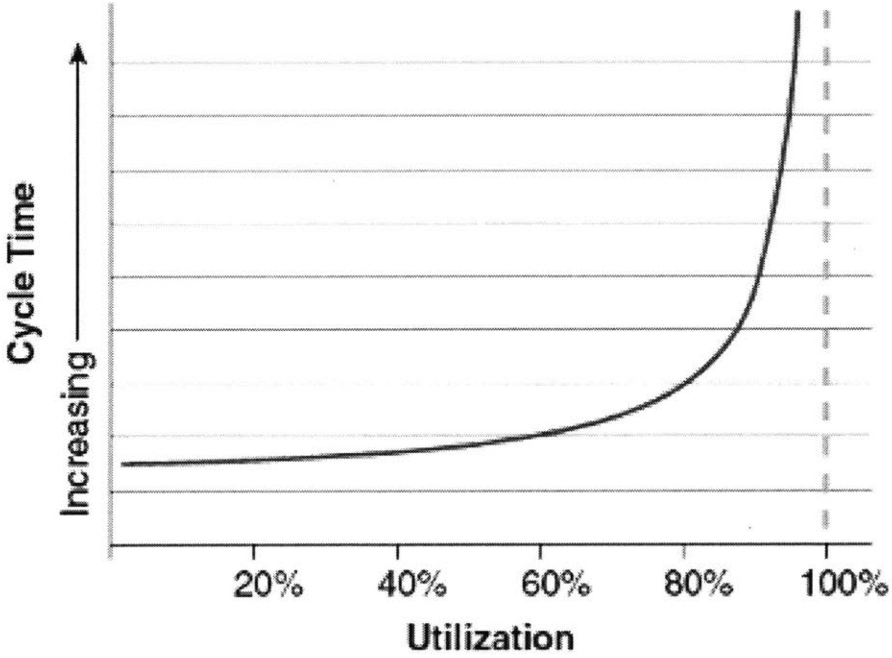


Figure 3-2. Cycle Time vs. Utilization in a System with Variability [8]

The optimal type and amount of buffer are dependent on the nature of the manufacturing system and its customers. Therefore, it is important to define and quantify value as it exists relative to the manufacturing system. Then, one can analyze the system and choose the right buffers to maximize the rate at which value is output from the system. This concept is no different from the recommended strategy of TOC, which is to provide sufficient capacity and inventory buffers to ensure desired throughput, so as to maximize the rate at which the goal (making money) of the system is achieved.

As part of the factory physics approach, Spearman, Woodruff and Hopp propose a CONWIP, or constrained WIP, system as an effective shop floor control method [9]. Push systems, in which orders are pushed onto the shop floor by a materials resource planning (MRP) or enterprise resource planning (ERP) system, are very popular in U.S. factories. The TDRC, in fact, uses an ERP system. Pull systems, which authorize production based on the performance of the system, are less popular. The most well-known pull system is a Kanban, in which cards are used to limit the WIP of a particular part number between one production process and the next. A CONWIP system is similar to Kanban in that WIP is limited and is therefore a pull system. In a CONWIP system, however, production authorization is not part specific and is not necessarily based on the WIP between two production processes. CONWIP systems can limit WIP between multiple production processes. A basic CONWIP system is shown in Figure 3-3. Work can be scheduled and "pushed" to the start of the system based on demand using an MRP or ERP system, but release of work is authorized according to the output of the last process in the CONWIP loop.

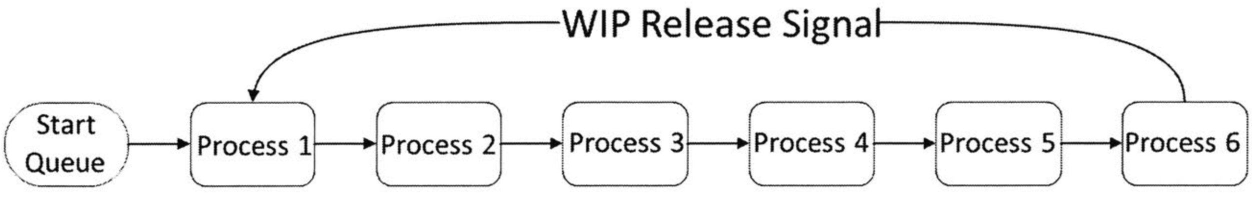


Figure 3-3. CONWIP

In a CONWIP system, a maximum WIP level, m, is determined and applied. The appropriate m level can determined by analysis (simulation) or by simply setting a level and evaluating its effectiveness. Choosing an m level that is too low will reduce throughput too much. Choosing an m level that is too high will result in unnecessarily high inventories. Spearman, Woodruff and Hopp recommend setting an m level that is higher than what might seem necessary and then lowering it from there.

A capacity shortage trigger, or r value, is also applied. This is the size of the start queue at which additional capacity (usually overtime) is applied.

CONWIP has several advantages versus a traditional push MRP system. First, cycle times for orders are more predictable. Second, limiting WIP causes work to amass at the bottleneck and may starve non-bottleneck activities. This phenomenon encourages cross-trained workers to spend less time overproducing on non-bottleneck activities and instead move to more productive work. Finally, CONWIP provides immediate feedback on a system's capacity, allowing for targeted additional capacity and other problem solving, if necessary.

3.3 Summary

Both TOC and the factory physics approach provide production management methodologies that emphasize the following:

- Understanding the value that the system is trying to maximize.
- Determining and providing appropriate buffers (staffing, order lead time) that maximize value creation.
- Implementing a shop floor system that effectively paces and manages the system's constraints.

The work described herein will integrate TOC and factory physics by implementing these concepts.

4.0 Value Characterization

This Chapter describes the approach used to determine the value provided by the welded reservoir production system to Boeing. Value is broken down into four categories: delivery, inventory, labor, and opportunity.

4.1 Delivery

The value of delivery is defined as the cost saved and/or revenue gained by Boeing as a result of reliably delivering a quality product. There are several costs associated with late delivery of a reservoir. These include:

1) Expediting – The TDRC has a staff of expediters that track and communicate the progress of late work orders through the factory and out to the customer. Each airplane program, or customer, has an additional staff of expediters with similar responsibilities.
2) Overtime – Late work often requires overtime labor, either at the TDRC or at airplane assembly, to catch up on schedule.
3) Waste – Late products to the airplane assembly line can delay other tasks, thereby reducing the utilization of mechanics and wasting their time.
4) Delayed cash flow and revenue recognition – If reservoir is late enough, it can delay the airplane delivery schedule, which delays cash transfers and revenue recognition.
5) End-customer dissatisfaction – Airlines that receive aircraft late will be more likely to turn to other options for their next fleet of planes.
6) Increased Program Lead Times – To compensate for chronically late delivery of certain parts, airplane programs increase order lead times and buffers, which ties up capital and requires additional storage.
7) Loss of Work Statement – To find a more reliable source of reservoirs, the airplane programs may turn to a more expensive external supplier, thereby increasing costs for Boeing.

A quality non-conformance found on a delivered reservoir has similar types of consequences, though the magnitude can be much greater depending on the timing of the discovery of the defect.

To understand these costs, representatives from materials management, supply chain, and production management for both the TDRC and the airplane programs were engaged. From these discussions, it was determined that the effects of late delivery are very extensive and difficult to quantify, but the cost vs. number of days late increases exponentially.

Rather than attempt to quantify the value of supply reliability, the approach used herein is to treat supply reliability as a constraint. In other words, customer satisfaction (the right part, with the right quality, at the right time) must always be achieved. This will avoid or reduce many of the costs associated with poor supply reliability. It also focuses factory management by providing a primary goal (customer satisfaction) and then allowing other aspects of value to be considered separately.

4.2 Labor

The cost of labor required to produce the demanded amount of reservoirs is considered when assessing the value of labor. In this analysis, the cost of labor is assumed to be $50/hour. For a staff of 15 operators and mechanics working 40 hours a week, 48 weeks a year, this equates to $96,000 annually in labor costs per employee, or $1.44 MM in total labor costs. This value is an approximation to demonstrate the magnitude of labor cost relative to other costs described in this chapter. It does not account for other factors such variation in the amount of leave taken or use of overtime labor. In this evaluation, overtime labor costs twice that of standard labor, or $100/hour.

4.3 Inventory

The cost of holding inventory includes the opportunity cost of the tied up capital, the cost of storage, and the cost of obsolescence. An annual inventory holding cost rate of 10.5% is assumed. The cost of storage is very low and is not considered. The cost of obsolescence is nearly zero and not considered because each ordered part has a committed customer. Therefore, a rate of 10.5%, a rate that is typically used by Boeing and one that is in line with costs of capital for large industrial companies, is assumed. The average material cost for a reservoir is approximately $20,000. Therefore, the average inventory holding cost for a reservoir is:

$$C_I = \$20{,}000 * 10.5\% = \$2100 \; per \; reservoir \; per \; year$$

The average lead time for the welded reservoir production system is 5.25 weeks. The daily demand is 1.7 reservoirs per manufacturing day (mday). Therefore, the average WIP is:

$$WIP_{ave} = 5.25\, weeks * 5\frac{mday}{week} * 1.7\frac{reservoirs}{mday} = 45 \text{ reservoirs}$$

The approximate holding cost associated with reservoir WIP is therefore:

$$C_{I\_WIP} = C_I * WIP_{ave} = \$94{,}500\, per\ year$$

4.4 Opportunity

The opportunity cost associated with the welded reservoir production system is the value that could be added (or cost saved) by putting a resource currently employed in the production of welded reservoirs toward an alternative pursuit. Such resources could include machines, employees, or floor space. In this analysis, the value added due to increased available floor space is considered. This resource has the most value that can be transferred to other opportunities. This is because it allows Boeing to take advantage of all the different knowledge and capabilities at the TDRC, including materials management, supplier management, manufacturing engineering, and quality engineering, in making use of available space.

The potential value, or opportunity cost, of floor space at the TDRC was estimated by considering a new statement of work. The TDRC was in the process of proposing to take on 787 tubing production. These tubes are currently being produced by an outside vendor at a cost, C_{vendor}, of approximately $10 MM per year. The estimated cost for the TDRC to produce these tubes, using Boeing cost estimating methods, C_{fv}, is approximately $7 MM per year. This estimate includes depreciation expenses for tube bending machines and other capital equipment required for the statement of work. It also, however, includes fixed costs of the TDRC that currently exist, such as engineering and maintenance staff. Based on discussions with TDRC management, a conservative estimate is that 80% of the $ 7 MM cost estimate is variable and the other 20% is fixed. Therefore, the actual additional cost to Boeing by introducing the 787 tubing statement of work is:

$$C_{TDRC} = C_{fv} * 80\% = \$5.6\, MM/year$$

The value to Boeing from moving the 787 tubing statement of work from an outside vendor to the TDCR is therefore:

$$V_{787} = C_{TDRC} - C_{Vendor} = \$4.4\ MM/year$$

The required floor space to implement the 787 tubing statement of work with an entirely new set of machines and tooling, F_{787}, is approximately 2500 square feet. Based on the 787 tubing opportunity, the value of floor space at the TDRC is then:

$$V_F = \frac{V_{787}}{F_{787}} = \$1760\ per\ sq.ft.per\ year$$

In reality, the value provided by available floor space for an opportunity is a step function, where the value of the opportunity is zero until a certain amount of space is available. At that point, the value increases from zero to the value of the project. For the 787 tubing statement of work, if 2499 square feet of space or less are available, the value of that space is zero. If 2500 square feet or more are available, the value is $4.4 MM per year.

In this assessment, however, the value provided by opportunities for the TDRC to use its space is assumed to increase linearly with each available square foot. This approach is used to provide a generic value for space in the TDRC and to increase the incentive for factory managers to optimize their use of space. The 787 tubing statement of work is a representative opportunity. Other opportunities may require less space. Therefore, managers should always be looking to decrease usage of space. This approach provides a value that can be used to trade off of other management decisions.

This analysis only considers the cost of the floor space occupied by the reservoirs as they are worked. Therefore, increases in order lead time increase WIP, which increases floor space, or opportunity, cost. Decreases in order lead time decrease WIP, which decreases this cost. Based on review of the reservoir storage containers, each reservoir in-process is assumed to occupy 15 square feet of floor space. The approximate opportunity cost of a single reservoir held in inventory is therefore:

$$C_O = V_F * 15 = \$26{,}400\ per\ year$$

The approximate opportunity cost of the reservoir WIP is therefore:

$$C_{O\_WIP} = C_O * WIP_{ave} = \$1{,}188{,}000\ per\ year$$

4.5 Summary

Delivery reliability, either due to a missed schedule or poor quality, is the highest priority for the airplane programs as customers of the welded reservoir production system. Customer service is therefore treated as a constraint and other costs are minimized from this starting point. Labor costs are the largest and most apparent costs associated with the production system. Inventory costs are more than an order of magnitude smaller. The significance of opportunity cost, as estimated here, is comparable with labor cost. This cost, however, is not as visible to TDRC management and is more difficult to quantify.

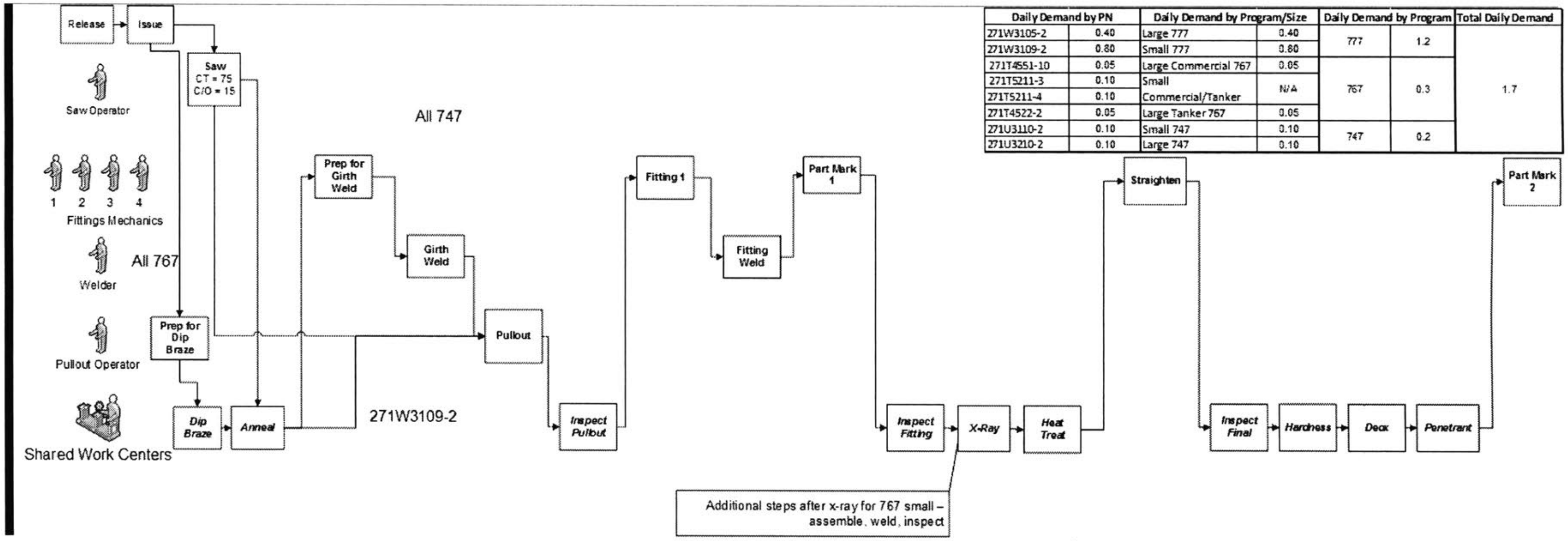
5.0 Welded Reservoir Value Stream – Current State

This Chapter describes the current state of the manufacturing operations required to produce welded reservoirs within the TDRC. Key sources of variability in the value stream are identified and discussed. Current system performance characteristics are defined.

5.1 Key Manufacturing Operations

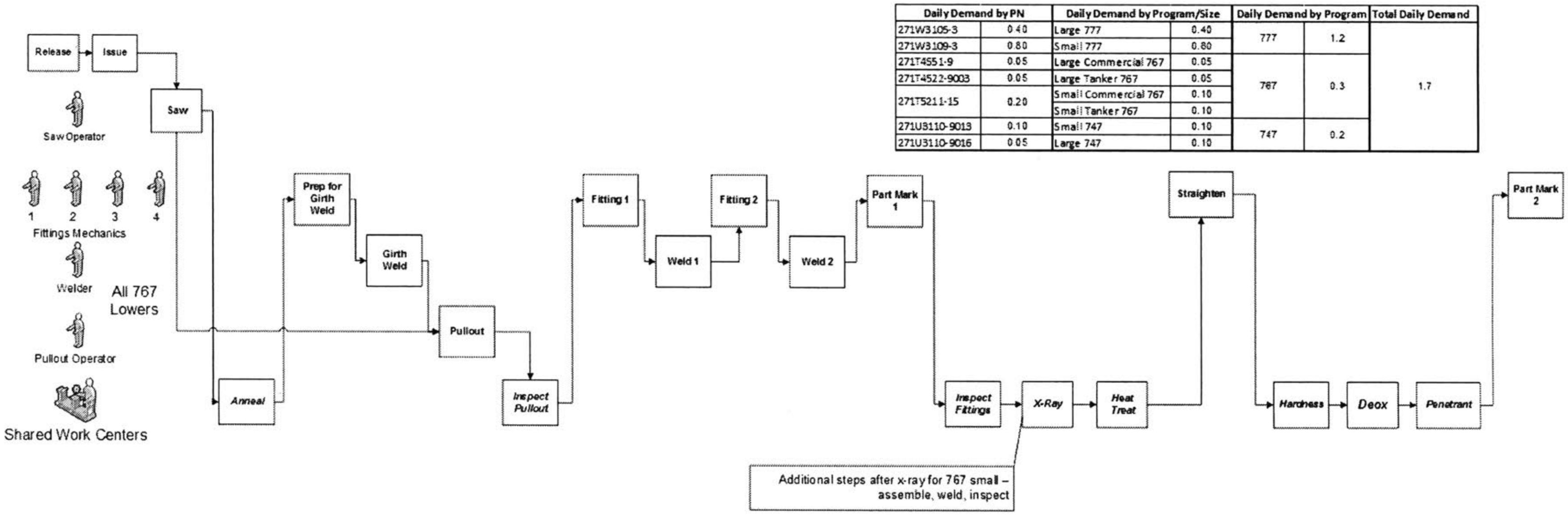
Charts that describe the flow of operations for the processes used to produce uppers, lowers, and closeouts are shown in Figure 5-1, Figure 5-2, and Figure 5-3. The charts also include daily demand by part number. The workflow described in these charts is used in a simulation of the welded reservoir manufacturing system (see Chapter 6).

Key operations are listed and described below. The operations are divided between those that are performed in the welded reservoir work center and those performed in shared work centers. Figure 5-1, Figure 5-2, and Figure 5-3 indicate this distinction among different operations. For welded reservoir work center operations, the figures specify the worker with primary responsibility for each particular operation.



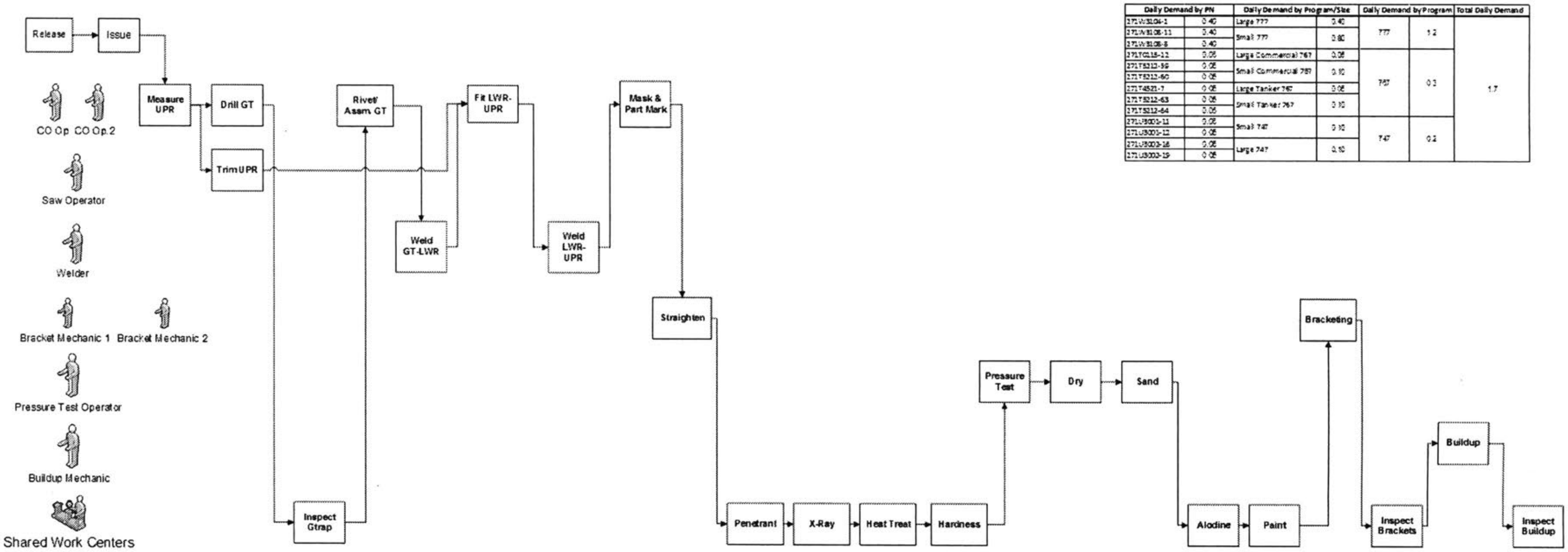
Daily Demand by PN		Daily Demand by Program/Size		Daily Demand by Program		Total Daily Demand
271W3105-2	0.40	Large 777	0.40	777	1.2	1.7
271W3109-2	0.80	Small 777	0.80			
271T4551-10	0.05	Large Commercial 767	0.05	767	0.3	
271T5211-3	0.10	Small Commercial/Tanker	N/A			
271T5211-4	0.10					
271T4522-2	0.05	Large Tanker 767	0.05			
271U3110-2	0.10	Small 747	0.10	747	0.2	
271U3210-2	0.10	Large 747	0.10			

Figure 5-1. Upper Weld Assembly Flow of Operations



Daily Demand by PN		Daily Demand by Program/Size		Daily Demand by Program		Total Daily Demand
271W3105-3	0.40	Large 777	0.40	777	1.2	1.7
271W3109-3	0.80	Small 777	0.80			
271T4551-9	0.05	Large Commercial 767	0.05	767	0.3	
271T4522-9003	0.05	Large Tanker 767	0.05			
271T5211-15	0.20	Small Commercial 767	0.10			
		Small Tanker 767	0.10			
271U3110-9013	0.10	Small 747	0.10	747	0.2	
271U3110-9016	0.05	Large 747	0.10			

Figure 5-2. Lower Weld Assembly Flow of Operations



Daily Demand by PN		Daily Demand by Program/Size		Daily Demand by Program		Total Daily Demand
271W3104-1	0.40	Large 777	0.40	777	1.2	1.7
271W3108-11	0.40	Small 777	0.80			
271W3108-8	0.40					
271TC115-12	0.05	Large Commercial 767	0.05	767	0.3	
271T5212-59	0.05	Small Commercial 767	0.10			
271T5212-60	0.05					
271T4521-7	0.05	Large Tanker 767	0.05			
271T5212-63	0.05	Small Tanker 767	0.10			
271T5212-64	0.05					
271U3001-11	0.05	Small 747	0.10	747	0.2	
271U3001-12	0.05					
271U3002-18	0.05	Large 747	0.10			
271U3002-19	0.05					

Figure 5-3. Final Reservoir Assembly (Closeout) Flow of Operations

5.1.1 Work Center Operations

Trim – An operator uses a fixed saw to trim the upper and lower forgings that are provided from vendors. The operation includes measuring the height of the forgings to determine the appropriate location of the trimming operation, setting up the trimming fixture, and the actual trimming process with the saw. For certain assembly orders, the saw is also used to trim the upper to ensure a proper fit-up with the lower section.

Pullout – An operator drills holes in the upper and lower domes and then uses pneumatic cylinders to pull out penetrations to engineering specifications. These operations are performed on a large fixture that is place on top of the domes. The fixture has holes for drilling and pulling out in the appropriate locations depending on the part number.

Welding – Welding is used to join cylindrical shells (girth welds) and to attach fittings to pullouts. Girth welds are performed using a dedicated machine, while fitting welds are applied by hand.

Fittings – Mechanics use customized tooling to place fittings onto the pullouts of lowers and uppers. Once the geometry is correct, the fittings are tack-welded in place and delivered to the welder.

Part Mark – At various points, mechanics affix markings to parts to indicate part number and order number.

Straighten – A mechanic uses tooling to remove distortions that occur in assemblies after they undergo heat treatment.

Closeout Operations – Closeout operations consist of all actions required to join the upper, lower, and g-trap. This includes:

- Assessing the fit between the upper and lower and delivering the upper to the saw for trimming (certain part numbers only)
- Drilling, riveting and fitting the g-trap inside the lower and delivering the lower/g-trap to the welder for welding
- Fitting the upper and lower/g-trap together and delivering the assembly to the welder for welding

Pressure Test – Pressure testing is performed to ensure the mechanical integrity of the reservoir pressure boundary. Water is pumped into the reservoir up to a pressure of 125 psig. After testing, the reservoir is rotated via machine and allowed to drain. The reservoir is then hooked up to a drier for two hours to ensure that all surfaces are dry.

Bracketing – Brackets are fastened onto the flanges of the reservoir. These brackets are used for installation of the reservoir inside the airplane.

Build-up – Final markings and devices, including a sight glass and a safety relief valve, are installed on the reservoir during build-up.

5.1.2 Shared Work Center Operations

Release – A capacity planner releases a subassembly (upper, lower, g-trap) or assembly (747, 767, 777 reservoir) order. This release is performed in accordance with the start date of the order. The start date of the order is determined based on the order lead time. For example, if a particular g-trap has an order lead time of 6 days, then the start date for an order of that g-trap would be 6 manufacturing days prior to the planned finish date. For each part number, there is a three manufacturing day time buffer between the finish date and the actual customer need date.

Issue – A material mover issues requested material for an order. This operation occurs after the release of an order to issue initial materials. It also may occur at other times when additional parts require issue. For example, brackets are issued prior to the bracketing operation for reservoir assemblies.

Quality Inspections – A quality inspector is dedicated to the welded reservoir production work center and performs inspections at various points. These inspections ensure appropriate geometries, orientations, and assembly.

Anneal – Annealing is performed to increase the ductility and reduce the hardness of the upper and lower material, making it more workable and allowing for downstream pullout processing to occur. As part of this process, each of the trimmed upper and lower forgings is placed in a furnace and heated for four hours. The parts are cooled for an additional ten hours.

X-Ray – Each weld is examined via x-ray to ensure that no defects that could harm the structural integrity or fatigue life of the weld are present.

Heat Treat/Age – After welding, assemblies are heat treated to stress-relieve welds. This operation is performed in a furnace where parts of batched and then heated for up to six hours.

Hardness Testing – Heat treated parts are cooled back to room temperature and then tested to ensure that the hardness of the material is sufficient. This ensures that material strength has not been lost due to heat treatment.

Penetrant Testing – Each weld is examined via dye penetrant testing to ensure that no defects that could harm the structural integrity or fatigue life of the weld are present.

Tank Lines – After heat treatment and hardness testing, uppers and lowers are cleaned, or deoxidized, using a series of chemical treatments. Prior to painting, reservoirs are given alodine chemical treatment.

Painting – Assembled, pressure-tested reservoirs are painted in a booth prior to bracketing.

5.2 Manufacturing Personnel

Table 5-1 provides a list of manufacturing personnel in the welded reservoir work center. The table includes the operator or mechanic's primary task and other tasks for which he/she is cross trained.

Table 5-1. Manufacturing Personnel Task Priority

Operator/Mechanic	Primary Task	Secondary Task	Tertiary Task
Welder	Welding	-	-
Saw Operator	Saw	-	-
Pullout Operator	Pullout	-	-
Fittings Mechanic 1	Fittings	-	-
Fittings Mechanic 2	Fittings	Weld Prep	-
Fittings Mechanic 3	Weld Prep	Fittings	-
Fittings Mechanic 4	Straighten	Fittings	-
Gtrap Mechanic	Gtraps	Fittings	Weld Prep
Team Lead	Part Mark	-	-
Closeout Mechanic 1	Closeouts	-	-
Closeout Mechanic 2	Closeouts	-	-
Bracket Mechanic 1	Bracketing	Buildup	-
Bracket Mechanic 2	Bracketing	-	-
Pressure Test Operator 1	Pressure Test	-	-
Buildup Mechanic 1	Buildup	Pressure Test	-

5.3 Key Sources of Variability

Based on observation and feedback from operations personnel, three critical sources of variability in the welded reservoir production system are:

1. **Absenteeism** – Vacation time is planned and limited by management. Sick time and family leave, however, are unplanned and can disrupt production. Many operators have multiple decades of experience and have accumulated a large amount of sick time. In addition, operators without sick time are free to take unpaid family leave without providing warning to management.
2. **Shared Work Center Cycle Time** – Operators and production managers feel that there is uncertainty as to when processing of a part in a shared work center will take place and when that part will return to the welded reservoir work center. This concern is valid, as other work centers compete with the welded reservoir work center for shared work center capacity. Inconsistencies in performing and prioritizing work in shared work centers leads to added cycle time variability. For example, if work in another work center is

farther behind than welded reservoir orders, a shared work center may prioritize the late work. Other shared work centers, however, may prioritize work according to first in first out (FIFO).

3. **Rework due to failed weld inspections** – X-ray and dye penetrant inspections of lower fitting welds occasionally reveal unacceptable weld cracking. These findings result in rework, which ties up operator and welder capacity and increases the cycle time and cycle time variability of the lowers.

5.4 Current Performance Characteristics

In this section, cycle time distributions, customer service level, and overtime usage for January 4, 2016 through June 6, 2016 are provided. Table 5-2 provides average cycle time, cycle time standard deviation, and coefficient of variation, and customer service level for the small 777 and large 777 reservoirs. Figure 5-4 shows cycle time cumulative distribution for small 777 and large 777 reservoirs. The percentage of tasks completed on weekends is used to represent overtime usage. This value is approximately 5%.

Table 5-2. Product Cycle Time Statistics and Service Level

Product	Average Cycle Time (days)	Standard Deviation (days)	Coefficient of Variation	Service Level
777 Small	33.4	4.3	0.13	0.40
777 Large	39.1	3.5	0.09	0.30

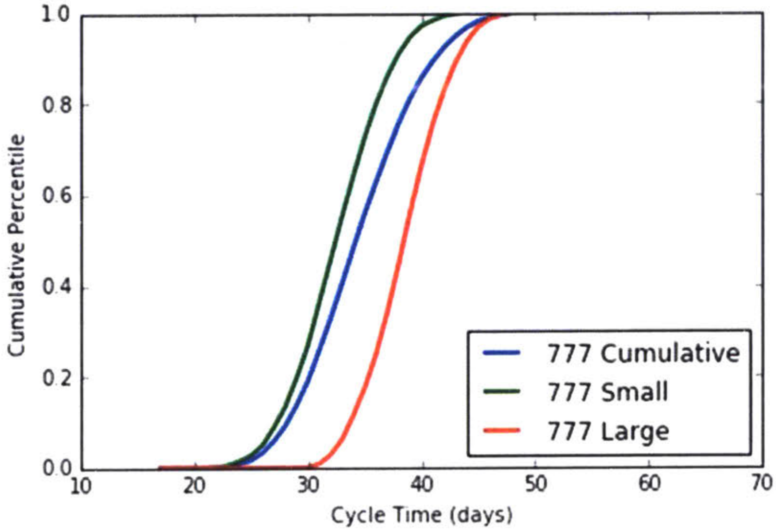


Figure 5-4. Cycle Time Cumulative Distribution

5.5 Summary

The current state of the welded reservoir production system includes a complex workflow through several operations. Approximately half of these operations occur in the welded reservoir production area. This area is devoted to welded reservoirs and contains fifteen workers (operators, mechanics, and welders). Absenteeism among these workers is a significant source of variability in the production system. The other half of the operations takes place in shared work centers. The cycle time through these shared work centers is another significant source of variability in the process flow. Rework due to failed weld inspections that occur at share work centers (dye penetrant inspection and x-ray inspection) is the final significant source of variability that is considered in this work.

6.0 Production System Simulation

This Chapter describes the development of a discrete event simulation of the welded reservoir production system. This simulation is intended to be a tool for determining the effect on value made by changes to the production system.

6.1 Approach

A discrete event simulation of the welded reservoir production system is developed and analyzed using Process Simulator 2014 – Professional, Version 9.2.4.2624, Copyright © 2002-2015 ProModel Corporation. The scope of the model includes release, assembly of details (uppers, lower, and g-traps) and closeouts. The purpose of the model is to evaluate the effect of changes to labor deployment, overtime usage, and shop floor control within the welded reservoir work center on the required labor usage and customer service level (given a specified order lead time). The resultant labor usage and order lead times are converted into a "total cost" value using the value characterizations of labor, inventory, and opportunity described in Chapter 4.

The model, shown in Figure 6-1, simulates process times, capacities, labor requirements, and the distribution of available labor for activities in the welded reservoir work center. Shared work center operations are included in the simulation but only as waiting times. The process times, capacities, and labor associated with shared work centers are not included. Rather, a waiting time probability distribution is applied for each shared work center operation. This approach does not affect the accuracy of the simulation but rather limits its utility by not allowing for the evaluation of changes to shared work centers. It is reasonable given the purpose of the model, which is to evaluate changes to the welded reservoir work center.

Using this model, orders are pushed into the simulation according to the rate of demand. 747 and 767 products are simplified. Though there are multiple part numbers for a 747 or 767 lower, upper, g-trap, and closeout, only one generic part number is considered for each product type for each of these programs. This simplification is reasonable because process flows and process times are similar for the grouped products. Therefore, four types of parts are considered (small 777, large 777, 747, and 767).

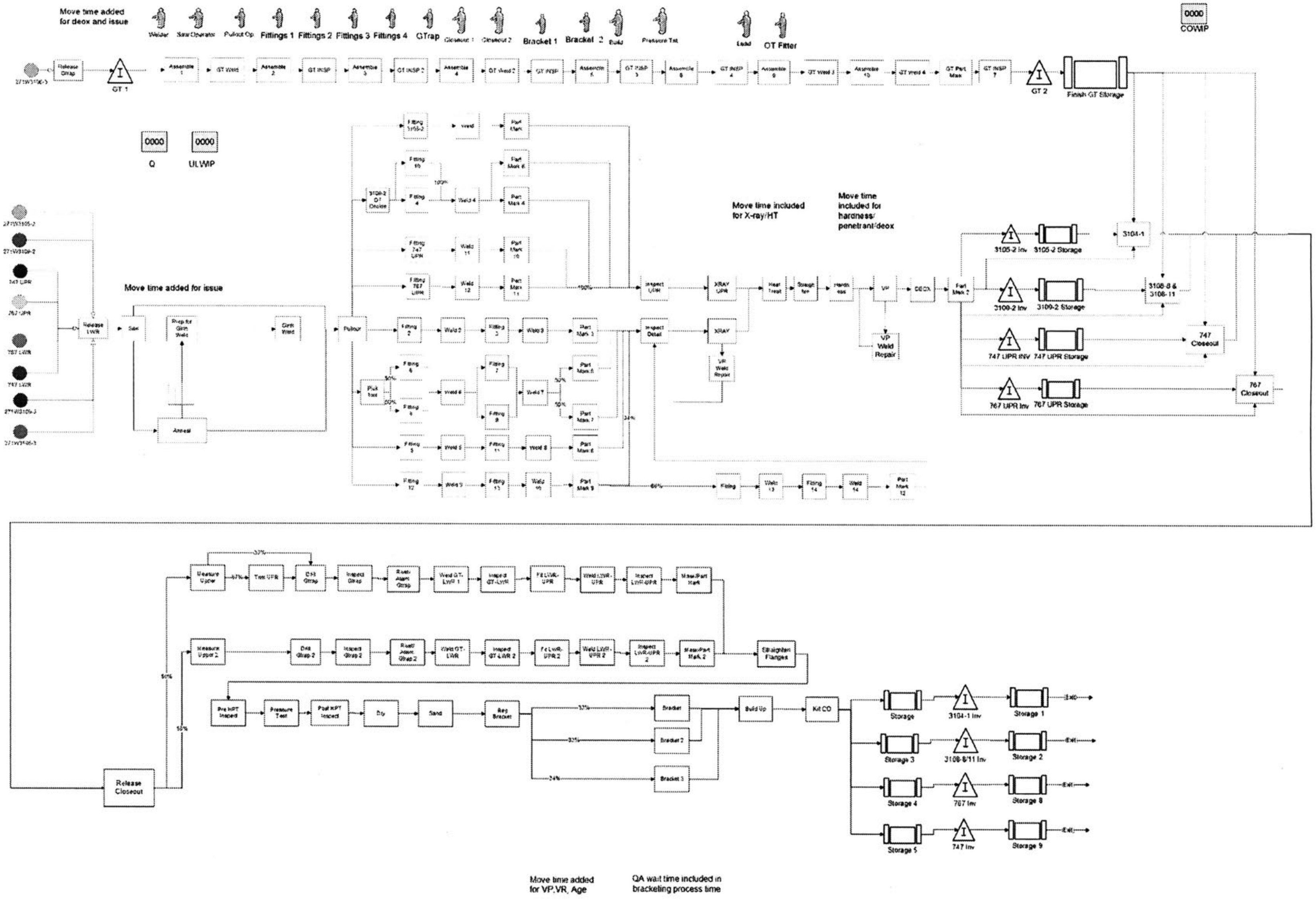


Figure 6-1. TDRC Hydraulic Reservoir Production Simulation

Process times, provided in Section 6.2.1, are input for work center operations as deterministic values. Using deterministic values is not completely realistic but is a reasonable approximation. The variability of an individual operation is small relative to other contributors to system variability. For example, an operation may take 30 minutes one time and 35 minutes the next, but the much bigger concern is whether the operator actually present that day (especially when he is absent one or two days out of ten).

Shared work center operations are modeled as additional cycle (waiting) time according to a distribution based on manufacturing data (see Section 6.2.1). Manufacturing personnel within the welded reservoir work center are included in the model and given shift and task assignments in accordance with cross-training priorities provided in Table 5-1. The three key aspects of system variability (absenteeism, shared work center cycle time, and rework due to quality non-conformances) are included in the model. Worker absenteeism is modeled based on attendance records and input as provided in Section 6.2.2. Shared work center operation cycle times are input in accordance with Section 6.2.1. Quality non-conformances and rework are modeled as rework loops at appropriate locations. Rejection rates are input based on manufacturing data as described in Section 6.2.3. Logic is implemented into the model to trigger worker overtime based on traditional management practice as described in Section 6.2.4.

Orders are pulled out of the system according to the rate of demand, delayed by certain lead time. The model is simulated for one year of production ten times. The number of times a reservoir is not available is determined, and a service level is calculated according to the following equation:

Service Level = $\frac{D-N}{D}$

Where:

D – Total number of finished goods demanded by customer

N – Number of times finished goods are not available when demanded by customer

A baseline case is developed to simulate current system performance. In Section 6.3, this case is used to benchmark the model's ability to effectively predict the relationship between service level and order lead time against production data.

6.2 Inputs

Inputs to the discrete event simulation model used in the baseline case are provided in this section.

6.2.1 Operation Details

Table 6-1 lists each reservoir work center operation and several associated performance characteristics that used as inputs in the discrete event simulation. These include:

- Personnel required
- Tools/machines required to perform operation
- Average Setup Time – Setup times are determined via discussion with operators and observation. New setups are required for all activities. No batching takes place in the welded reservoir work center.
- Average Process Time – Process times are determined by subtracting setup time from operation time.

Operation times are estimated using production data and validated based on discussion with operators and observation. Operation times are not readily available in existing production data because the available production data contain the time completions of operations but do not contain starts of operations. Also, shift times and breaks complicate this calculation. Using production data from January 4, 2016, through March 26, 2016, operation times are estimated as follows:

1. For each operator that performs the specific operation, determine the time between the completion of the previous operation performed by that operator and completion of the current operation by that operator.
2. Average each of these times, with the exception of times greater than 8.5 hours (length of a shift) and less than 5 minutes. The long times are not considered to remove the effect of work stoppage due to the end of a shift. The short times are not considered to remove the effect of operation batching. Operation batching occurs when operators indicate completion of multiple tasks on a work order at the same time even though those operations were completed at different times in the operation sequence.

3. Correct for non-productive time – Each of these operations is performed by operators on a shift that lasts 8.5 hours. However, due to scheduled breaks, meetings, and training, Boeing management estimates that approximately 7 hours of productive work are expected each shift. Therefore, each average time is adjusted by a factor of approximately 7/8.5 = 0.82. This approach is not exact, as some operations will be more affected than others by breaks in work, but it provides a reasonable estimate for the purposes of the simulation.

Table 6-1. Reservoir Work Center Operation Details

Operation Type	Machines, Tools, and Personnel Required	Specific Operation	Part Type	Setup Time (min)	Process Time (min)
Trim	1 saw required and available, 1 operator required, capable of processing one part at a time	-	All Uppers and Lowers	25	65
			Large 777 Closeout	15	45
Pullout	1 pullout station required and available, 1 operator required, capable of processing one part at a time	-	Uppers	15	30
			Lowers	30	105
Welding	1 weld booth and welder required per part, 1 weld booth and welder available	-	All Closeouts	0	30
			All Uppers and Lowers	0	24
Fittings	1 fitting tool required per part, 1 fitting tool available per part with exception of 271W3109-2 and 271W3109-3 (2 fitting tools available per part), 1 mechanic required per part	-	All Uppers and Lowers	30	150
Part Mark	1 mechanic required per part	-	All Uppers and Lowers	10	65
			All Closeouts	5	55
Straigthen	1 tool and 1 mechanic required per part, 1 tool available	-		10	30
Closeout	1 mechanic required per part	Measure Upper	All Closeouts	30	45
		Drill/Fit Gtrap	All Closeouts	10	50
		Fit LWR/UPR	777 Closeouts	10	150
			747 Closeouts	30	210
			767 Closeouts	30	180
Pressure Test	1 mechanic required per part (mechanic is idle during "Dry" portion of the operation)	Pressurize	All Closeouts	30	90
		Dry	All Closeouts	5	120
		Sand	All Closeouts	0	60
Bracketing	1 tool and 1 mechanic required per part, 1 tool available per part	-	Small 777 Closeout	0	300
			Large 777 Closeout	0	450
			747 Closeout	0	540
			767 Closeout	0	480
Buildup	1 mechanic required per part	-	All Closeouts	0	180

Table 6-2 lists each support operation and several associated performance characteristics that are used in the discrete event simulation. These include average cycle time and approximate cycle time distribution. The characteristics are determined by considering production data from January 4, 2016 through June 6, 2016. Cycle time distributions are curve fit using @Risk in Microsoft Excel to one of the following distributions that Process Simulator is capable of modeling:

- Exponential
- Lognormal
- Gamma
- Weibull

Table 6-2. Support Operation Details

Operation	Average Cycle Time (hrs)	Distribution Type	Special Parameters
Release	N/A	25	
Issue Upper/Lower	25	Exponential	
Issue Closeout	25	Exponential	
Issue Fittings	15	Exponential	
Issue Gtrap	41	Exponential	
Inspection	1.2	Exponential	
Anneal	Note 1	Note 1	
X-Ray	23	Lognormal	Standard Deviation = 68 hours
Heat Treat	66	Weibull	gamma = 1.5, k = 73
Age	26	Lognormal	Standard Deviation = 15 hours
Hardness Testing	60	Gamma	k = 3, theta = 20
Penetrant Testing	14	Exponential	
Tank Lines	27	Lognormal	
Paint	14	Exponential	

Note 1 – Anneal cycle time is not considered in the simulation because the characteristics of anneal are modeled in more detail. On Monday through Thursday, all uppers and lowers that go through the trim process during first shift are annealed during second shift and available by 10 AM the following manufacturing day. Uppers and lowers trimmed on Friday are anneal on Monday and available by 10 AM on Tuesday.

6.2.2 Absenteeism

Absences by operators and mechanics are modeled as exponentially distributed events with a mean-time-to-absence (MTTA) and a mean-time-to-return (MTTR). MTTA is the average time between absences for a given worker. Absences due to vacations are considered separately from absences due to personal leave with separate MTTA and MTTR values. MTTR is the average length of the absence. MTTR values are assumed to be similar for each employee, whereas MTTA values are unique to each employee because some employees take more time off than others.

Attendance records from January 1, 2016, through September 16, 2016 are used to calculate MTTA and MTTR values for each employees. MTTR values for vacation and personal leave are calculated according to the following equation:

$$MTTR = \frac{\sum_i DA_i}{\sum_i NA_i}$$

Where:

i – Employee number (1 through 14)

DA – Total number of days absent for a given employee *i* in attendance record

NA – Total number of leaves of absence taken by a given employee *i* in attendance record

The MTTR value for vacation is approximately 3 days. The MTTR value for personal leave is approximately 1 day.

MTTA values for each operator and mechanic for vacation and personal leave are calculated according to the following equation:

$$MTTA_i = \frac{DT * MTTR}{DA_i}$$

Where:

DT – Total number of work days in attendance record

Table 6-3 provides MTTA values for each operator and mechanic for vacation and personal leave.

Table 6-3. MTTA Values

Operator/Mechanic	Employee Number	MTTA (Personal Leave)	MTTA (Vacation)
Welder	Note 1	Note 1	Note 1
Saw Operator	1	8.9	83.6
Pullout Operator	2	84.0	38.7
Fittings Mechanic 1	3	23.7	35.6
Fittings Mechanic 2	4	41.6	55.3
Fittings Mechanic 3	5	11.0	124.6
Fittings Mechanic 4	6	6.7	62.6
Gtrap Mechanic	7	33.6	50.4
Team Lead	8	20.7	35.6
Closeout Mechanic 1	9	12.7	Note 2
Closeout Mechanic 2	10	20.7	124.6
Bracket Mechanic 1	11	41.0	164.0
Bracket Mechanic 2	12	15.0	55.0
Pressure Test Operator 1	13	9.4	Note 2
Buildup Mechanic 1	14	Note 2	24.0

Note 1 – MTTA values are not calculated for the welder because there is additional welder capacity from other work centers that is used when the welder in the welded reservoir work center is absent. Therefore, in the simulation, the welder is never absent.

Note 2 – In this instance, leave was not taken during the time period under evaluation. Therefore, an MTTA value is not considered here.

6.2.3 Quality Defects and Rework

Defects are consistently found in fitting welds on lowers via x-ray and dye penetrant inspection. Non-conformance reports from March 3, 2016 through August 31, 2016 were examined to determine the likelihood of finding a defect on a lower fitting weld. Of the 193 lowers that were produced during this timeframe, dye penetrant inspection discovered defects in 35, or 18%, of these orders. X-ray discovered defects in 13, or 7%, of these orders. These percentages are used as inputs in rework loops in the model, shown in Figure 6-2.

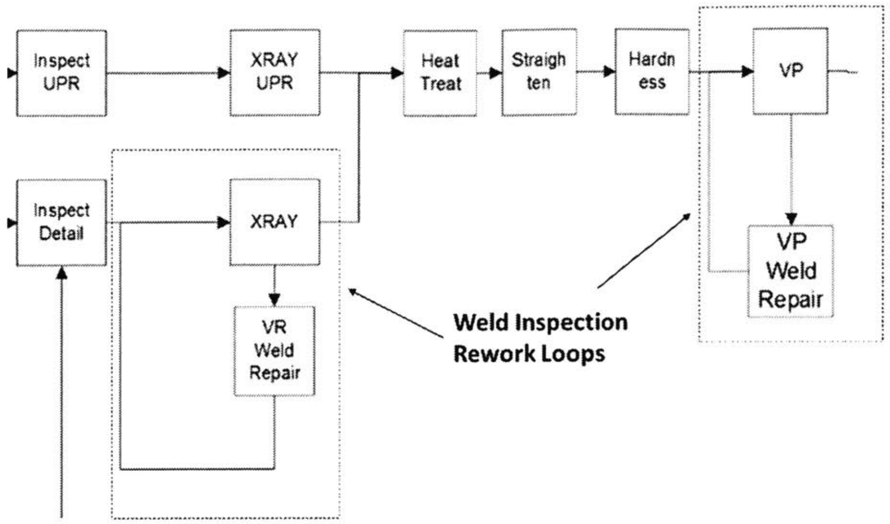


Figure 6-2. Weld Inspection Rework Loops

The average calendar time required to perform rework for weld defects was 49 hours (for both penetrant (VP) and X-Ray (VR)). This value is input into the model.

6.2.4 Overtime Implementation

Overtime labor is used in the welded reservoir production system when orders begin to back up. There is not a standard operating procedure with respect to the application of overtime, but in general, weekend overtime usage occurs every three to four weeks with about two-thirds of the staff present. The work center manager attempts to get workers with the needed skills to attend when overtime is used. Personnel, however, cannot be forced to work overtime and, in addition, if the manager makes overtime available, he/she must make it available to all employees in the work center. Therefore, the exact personnel used is primarily based on availability of the staff and not on which skills are needed. This approach is modeled by choosing ten of the fifteen staff members at random and making them available every third weekend for one and a half shifts.

6.3 Benchmarking

To yield useful results, the model should effectively predict the relationship between service level and order lead time. To benchmark the model, the results of the baseline discrete event simulation are compared to production data from January 4, 2016 through June 6, 2016. The average, standard deviation, and overall distribution of order cycle times are compared. Then the model's ability to accurately predict the relationship between order lead time and service level is determined by comparing expected service levels at various order lead times.

6.3.1 Cycle Time Comparison

Table 6-4 provides a comparison of average cycle times for 777 reservoirs. The table shows that there is less than 10% agreement between the simulation and the production data with respect to cycle time.

Table 6-4. Benchmarking - Average Cycle Time

Product	Average Cycle Time (days)		% Difference
	Data	Simulation	
777 Small	33.4	36.4	8.2%
777 Large	39.1	37.0	-5.7%
777 Combined	35.3	36.6	3.6%

Table 6-5 provides comparisons of standard deviation and coefficient of variation (the ratio of standard deviation to average). Figures 6-3, 6-4, and 6-5 shows cumulative distributions of cycle time for small 777 reservoirs, large 777 reservoirs, and 777 reservoirs in total, respectively. The table and the figures show that the simulated cycle distribution has a larger spread, or standard deviation, than the production data exhibit. This is mostly due to the higher amount of long cycle time orders that occur in the simulation. The simulation predicts a measureable amount of 777 reservoirs (~10%) with a cycle time greater than 45 days, whereas the production data show that less than 1% of 777 reservoirs have a cycle time greater than 45 days. This wider distribution on occurs because the simulation does not account for expediting. When orders are late, they are tagged with "counters" and prioritized above other orders. The TDRC uses this approach in both the welded reservoir work center and the shared work centers. Expediting results in fewer extremely late orders. For example, an order that requires rework due to weld defects will likely not wait as long for heat treatment or bracketing. Expediting, however, does not improve average cycle time, as it also results in fewer extremely late orders. It does not, therefore, change customer service level, as the customer is not concerned with any one particular order but rather with a particular part. Expediting also has the unwanted effect of masking variability in the system so that it cannot be addressed. Excluding expediting will not alter the manner in which the system responds to changes in staffing or shop floor control plan.

Table 6-5. Benchmarking – Standard Deviation and Coefficient of Variation

Product	Standard Deviation (days)		Coefficient of Variation	
	Data	Simulation	Data	Simulation
777 Small	4.3	7.6	0.13	0.21
777 Large	3.5	7.6	0.09	0.21

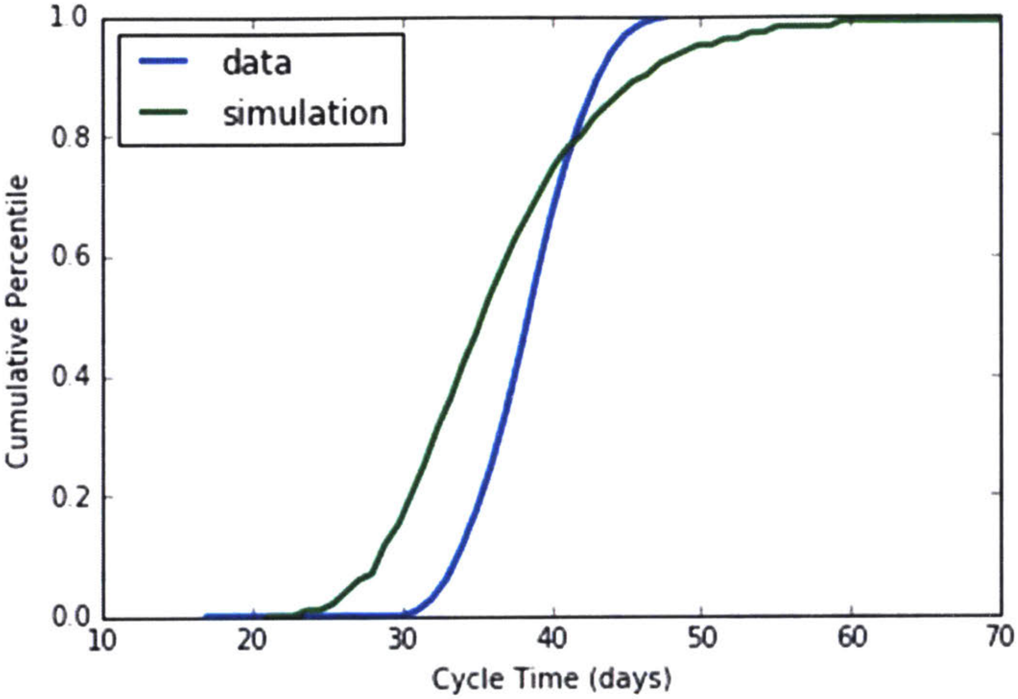


Figure 6-3. Cycle Time Cumulative Distribution for Large 777 Reservoir

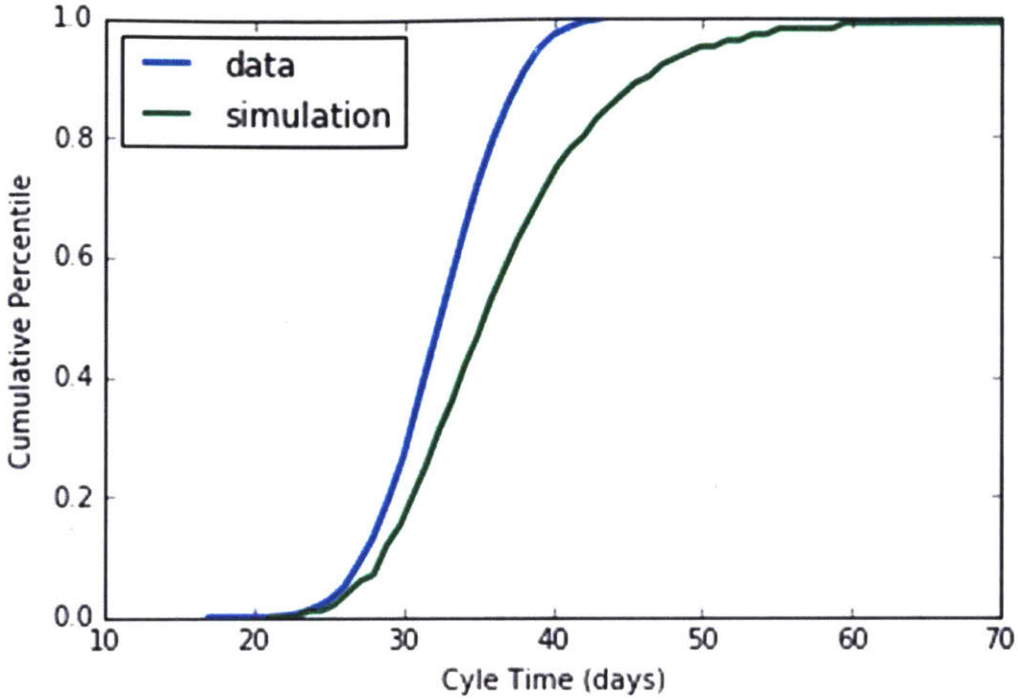


Figure 6-4. Cycle Time Cumulative Distribution for Small 777 Reservoir

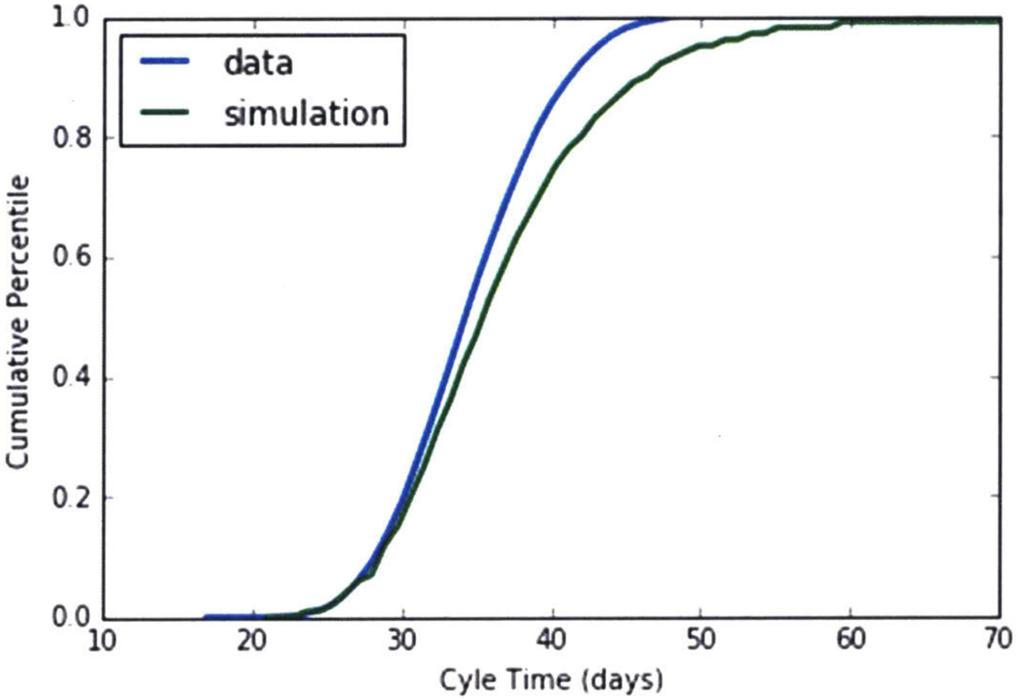


Figure 6-5. Cycle Time Cumulative Distribution for 777 Reservoirs

6.3.2 Service Level vs. Order Lead Time

Table 6-6 provides a comparison between the predicted service levels and actual service levels obtained from production data given the original order lead times. The table shows that the simulation provides similar results.

Table 6-6. Benchmarking – Standard Deviation and Coefficient of Variation

Product	Order Lead Time (weeks)	Service Level	
		Data	Simulation
777 Small	5.25	0.40	0.41
777 Large	5.25	0.30	0.34

To assess the sensitivity of order lead time to service level and the accuracy of the model in predicting the appropriate relationship between order lead time and service level, the adjustment to order lead time required to yield identical service levels is determined. For both the small 777 and large 777, this value is 0.1 weeks, or approximately 2% of the order lead time in the model. Resultant order lead times vary by much larger amounts (0.5 to 1.25 weeks in length) in the evaluation in Chapter 7. Therefore, the error in the model associated with the relationship between order lead time and service level is acceptable, and the simulation provides a useful prediction of system performance that can be used to assess system changes.

6.4 Summary

A discrete event simulation of the welded reservoir production system is developed and benchmarked for evaluating work center changes. Specifically, the model accurately assesses changes to labor deployment, overtime usage, and shop floor control within the welded reservoir work center on the required labor usage and customer service level (given a specified order lead time). The critical outputs of the model are labor usage and order lead times. In Chapter 7, these outputs are converted into a "total cost" value using the value characterizations of labor, inventory, and opportunity described in Chapter 4.

7.0 Shop Floor Improvements

This Chapter describes changes to the manufacturing system, such as WIP control, cross-training, staffing, and overtime implementation that are evaluated using the simulation model. As listed in Table 7-1, six cases are considered. Case 1 uses baseline inputs described in Chapter 6. Case 2 is an ideal scenario in which all mechanics, operators, and welders are fully cross-trained and move to work accordingly. This ensures a completely balanced production system. While this case is not feasible in reality, its results are used for comparison to other cases. In Case 3, the least utilized staff member in Case 1 is removed from the production system. In Case 4, a staff member is added to support the bottleneck activity. In Case 5, the least utilized staff member is cross-trained to support the bottleneck activity. In Case 6, a CONWIP system is implemented between the start of release of upper and lower orders and the fittings process. As discussed in Section 4.1, supply reliability is treated as a constraint. For each case, a 95% service level is maintained. Costs are compared, and insights are drawn.

Table 7-1. Simulation Cases

1	Baseline with increased lead times to ensure customer satisfaction
2	Fully balanced staffing (full cross- training).
3	Remove least utilized staff
4	Add staff at the bottleneck
5	Cross-train least utilized staff to support bottleneck
6	Implement CONWIP system

Details regarding the implementation and results for each case are provided in this Chapter.

7.1 Baseline with Increase Lead Times

For the baseline case, order lead times are increased from those used in the benchmarking analysis until a 95% service level is achieved. Lead times for both 777 reservoirs (large and small) require an increase from the original order lead times of 5.25 weeks to 6.5 weeks.

Figure 7-1 shows worker utilization for Case 1. The G-trap mechanic, who is cross-trained to assemble g-traps, prepare fittings, and prepare girth welds, is the most utilized worker. All of the fittings mechanics are also highly utilized. The pressure test mechanic, who is not cross-trained and is also supported by the buildup mechanic is the least utilized.

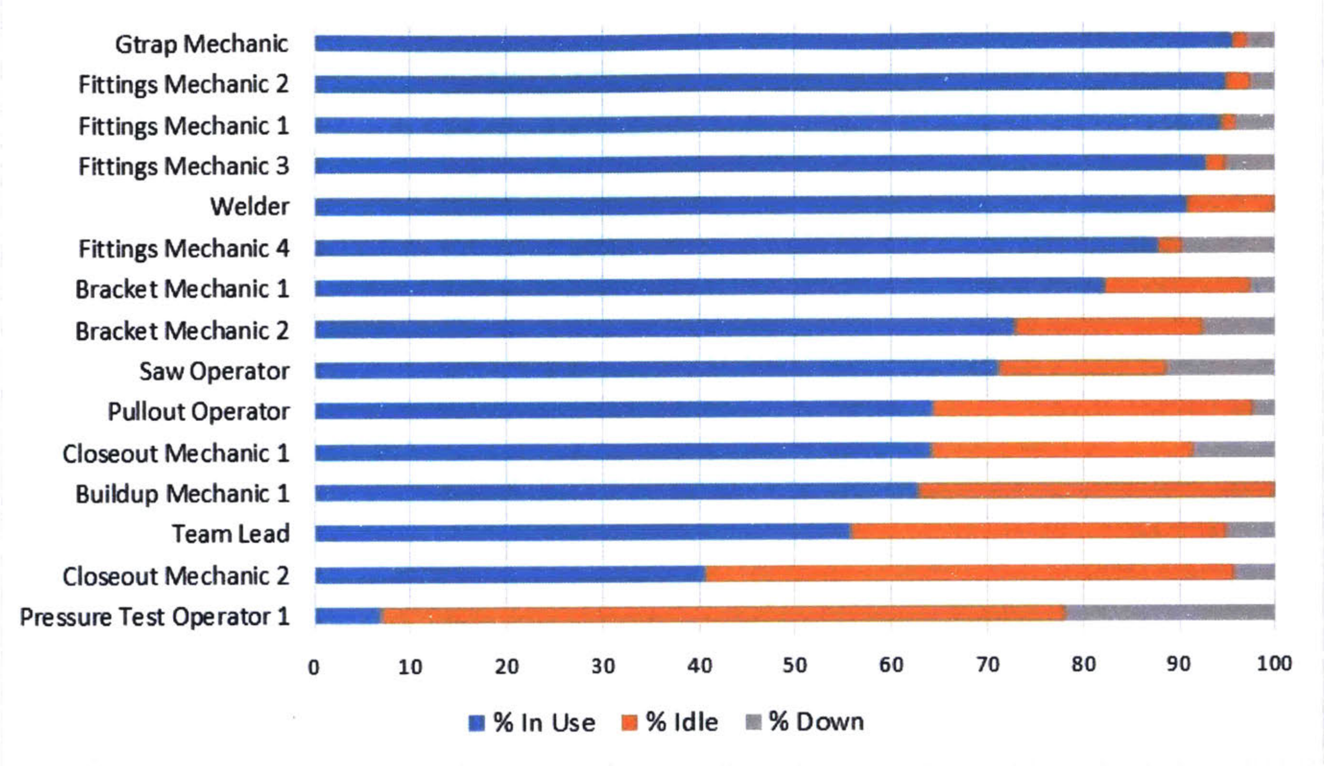


Figure 7-1. Worker Utilization – Case 1 - Baseline

Figure 7-2 shows the estimated annual costs for Case 1. Costs are broken into labor, overtime labor, inventory holding cost, and floor space, or opportunity, cost. Costs are calculated consistent with the bases provided in the value characterization provided in Chapter 4. Specifically,

- A normal labor rate of \$50/hour is used.
- An overtime labor rate of \$100/hour is used.
- An inventory holding cost rate of 10.5% is used.
- A material cost per reservoir of \$20,000 is used.
- A floor space cost of \$1760/ft^2/year is used.
- Each reservoir in-process occupies 10 ft^2 of floor space.

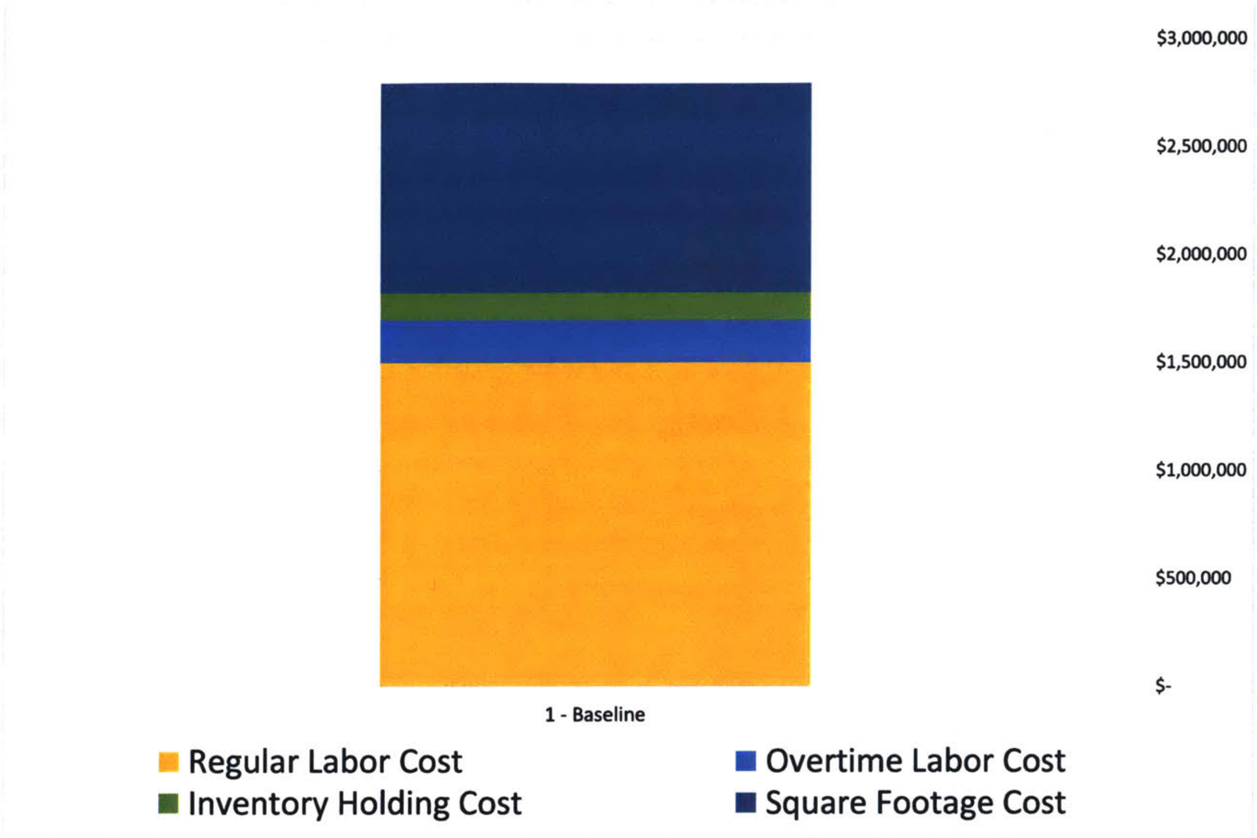


Figure 7-2. Annualized Cost – Case 1 – Baseline Case

7.2 Fully Balanced Staffing

In Case 2, all staff members are cross-trained to perform all tasks. While this scenario is not realistic, it is simulated to provide an ideal, or best-case, scenario to which other changes to staffing and shop floor control can be compared. In Case 2, order lead times can be reduced by half a week from six and one-half weeks to six weeks while still meeting a 95% service level. Figure 7-3 provides a comparison between the costs associated with Case 1 and Case 2. Costs are normalized to 1.0 for Case 1 and adjusted for Case 2 accordingly. The figure shows that overtime labor costs can be eliminated in this scenario. Total costs are reduced by approximately 14%.

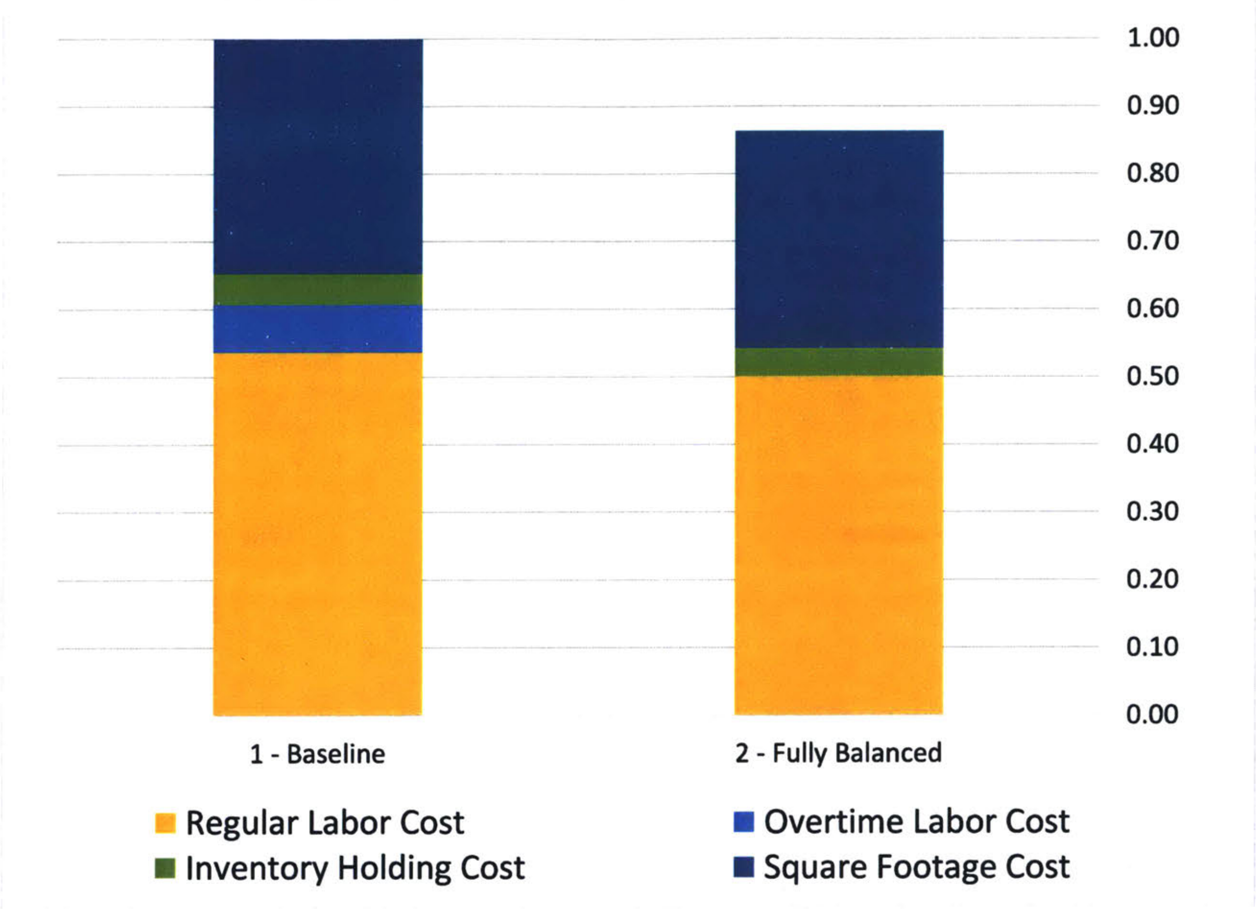


Figure 7-3. Case 1 vs Case 2 Cost Comparison

7.3 Staffing Changes

Cases 3 and 4 show that removing staff does not necessarily reduce total cost and adding staff does not necessarily increase total cost. The resultant total cost is dependent on where staff are removed or added. In Case 3, a staff member is added to prepare fittings. This eases the workload on the highly utilized g-trap and fittings mechanics. In Case 4, the pressure test operator is removed, as he is the least utilized worker. Figure 7-4 provides a comparison between the costs associated with Cases 1 through 4. Costs are normalized to 1.0 for Case 1 and adjusted for the remaining cases. The figure shows that adding staff and removing staff, if done appropriately, can reduce total cost. In Case 3, the added staff member at fittings eliminates overtime labor costs and slightly increases inventory and opportunity costs relative to Case 1 due to increasing order lead times to seven weeks. In Case 4, removing the most underutilized staff member reduces regular labor costs without increasing overtime labor relative to Case 1.

Removing more utilized staff members, however, would result in more required overtime and therefore would increase costs. As with Case 3, Case 4 inventory and opportunity costs increase slightly due to increased order lead times (seven weeks).

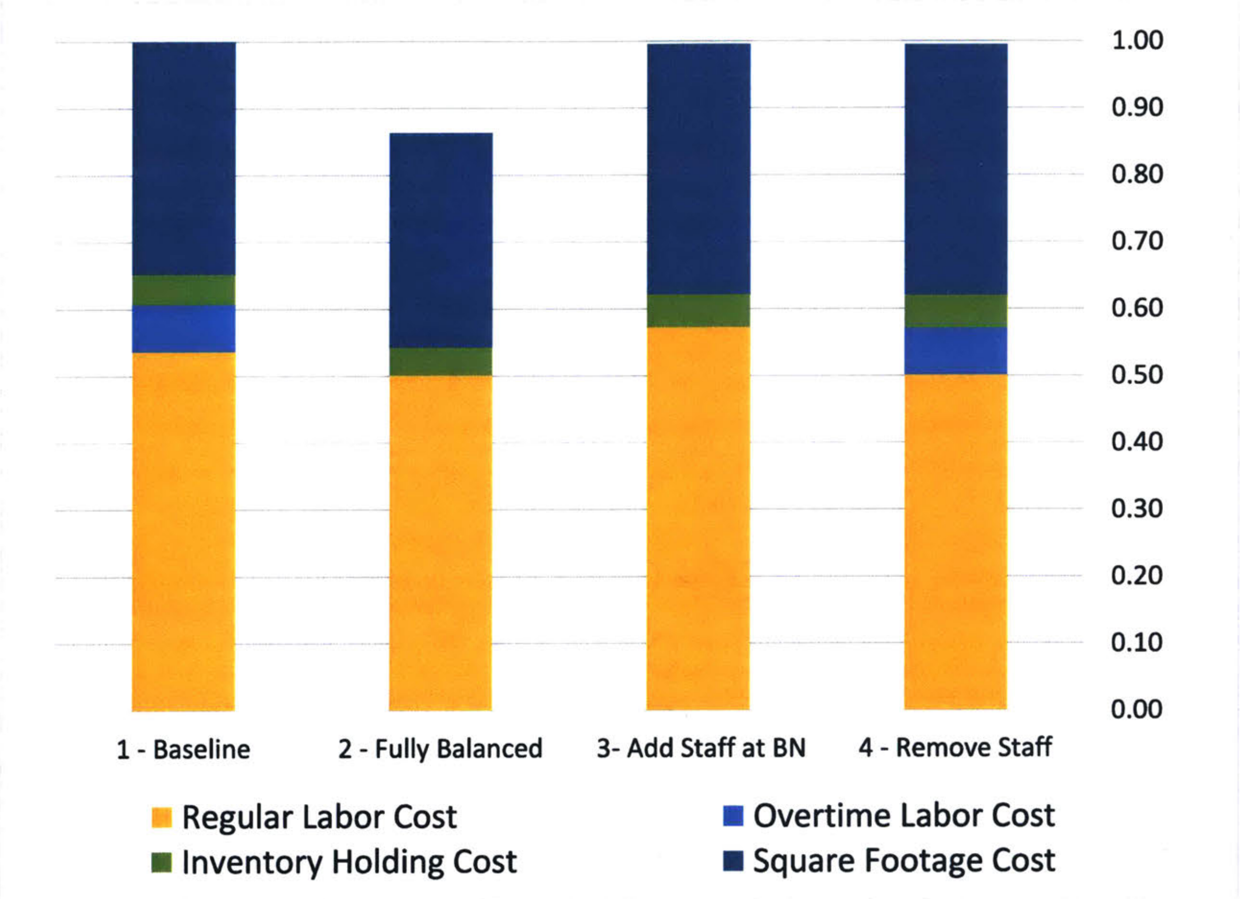


Figure 7-4. Cases 1 through 4 Cost Comparison

7.4 Cross Training

Case 5 shows that targeted cross-training yields better results than either removing or adding staff. In Case 5, the least utilized worker, the pressure test mechanic, is cross-trained to perform the most utilized task (fittings). Figure 7-5 provides a comparison between the costs associated with Cases 1 through 5. Costs are normalized to 1.0 for Case 1 and adjusted for the remaining cases. The figure shows that cross-training reduces costs more than adding or reducing staff. Cross-training the least utilized worker to perform the most utilized task provides more value-added production, eliminating the need for overtime without the need to add staff.

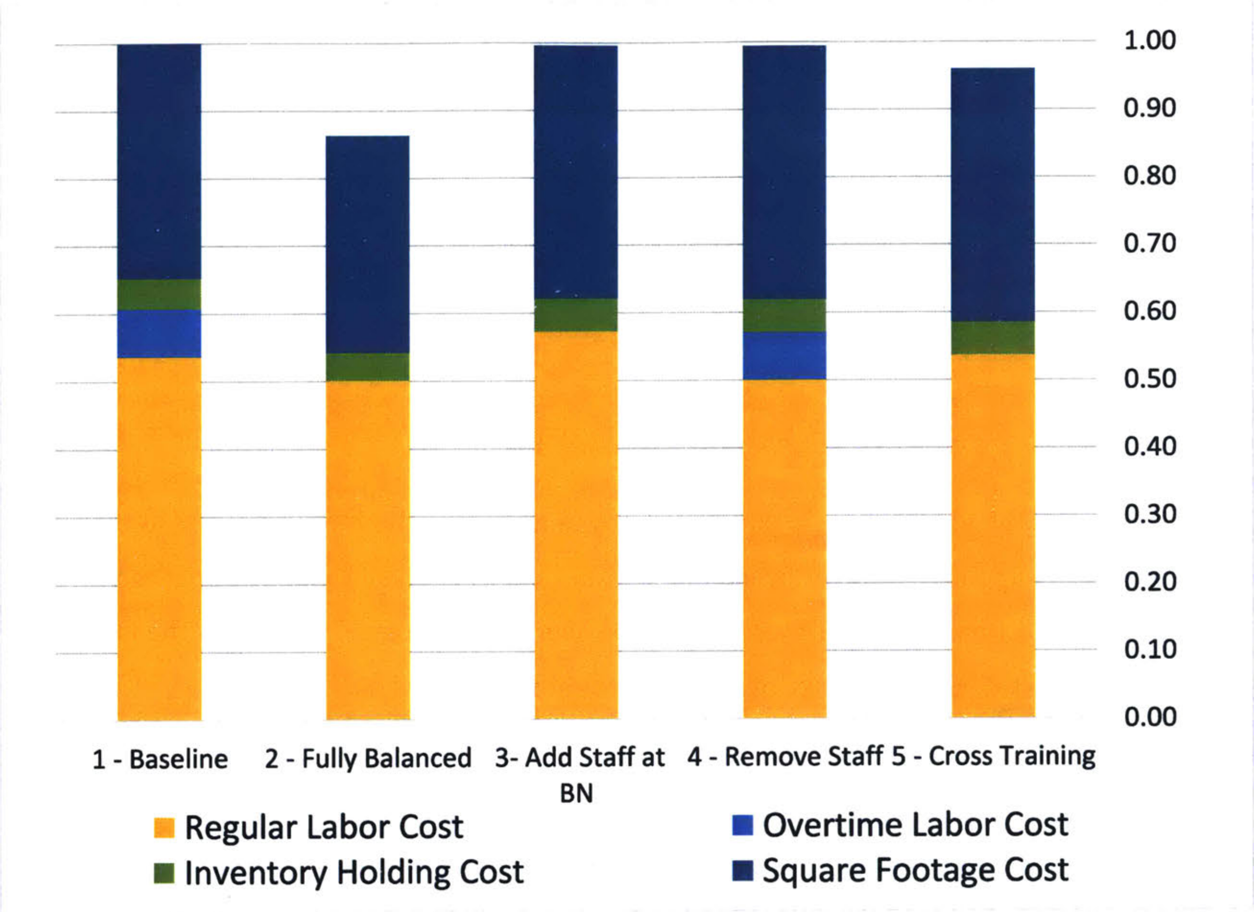


Figure 7-5. Cases 1 through 5 Cost Comparison

7.5 CONWIP

Implementing a CONWIP system reduces the most cost relative to the other strategies that are considered. In Case 6, the lowest utilized staff member is removed, and a CONWIP system is applied between the release of uppers and lowers and the completion of the fittings process, as shown in Figure 7-6. The system provides a simple method for managing the throughput at the fittings process, which is the most utilized, or bottleneck, process. When the late start queue in front of the CONWIP system reaches a certain value (r), overtime is applied. Because welded reservoir production is a one shift operation, overtime can be applied that given day. The manager therefore does not wait until late orders have accumulated due to insufficient throughput. Additional capacity is provided as needed. This is especially useful because absenteeism, which has a direct effect on capacity, is a characteristic of the system with high uncertainty.

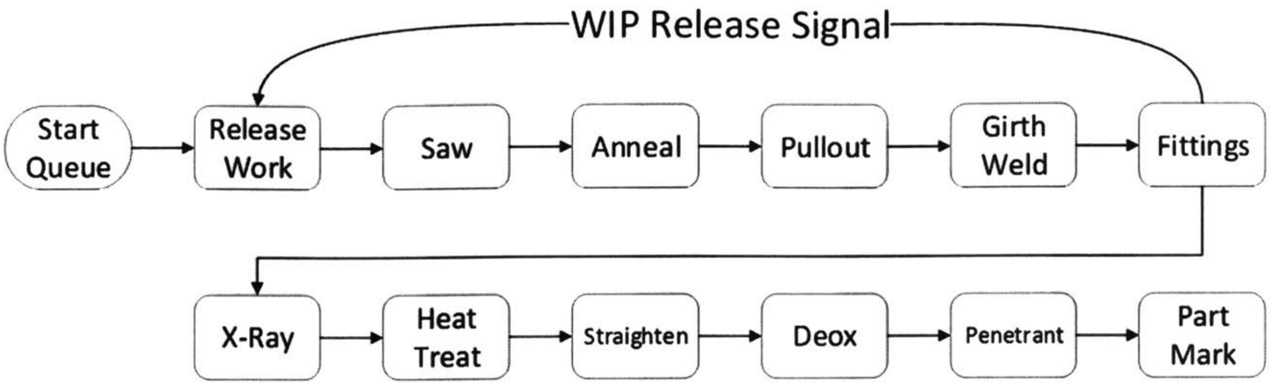


Figure 7-6. Application of CONWIP to Welded Reservoir Production System

In the simulation, up to 4 hours of overtime per day is applied to the fittings process as needed. Overtime is only applied, however, when the late start queue is greater than two (r value = 2). Different m levels (maximum WIP values) are considered. The m level that yields the lowest order lead times with a service level of 95% is determined to be 24.

Figure 7-7 provides a comparison of costs for Cases 1 through 6. The figure shows that both normal labor and overtime labor costs are reduced using the CONWIP system. Order lead times increase from six and one-half weeks in Case 1 to seven weeks. Inventory and opportunity costs therefore increase slightly relative to Case 1.

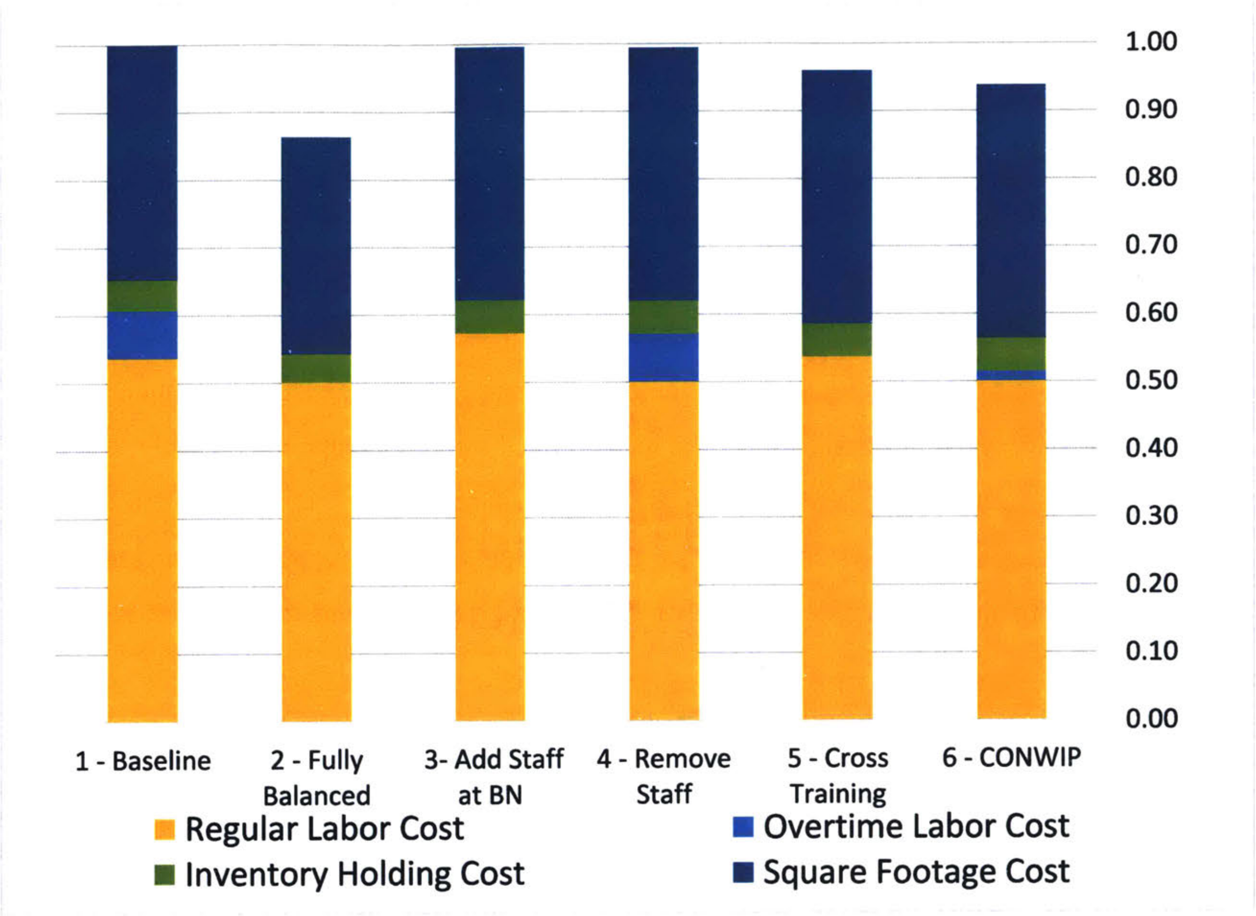


Figure 7-7. Cases 1 through 6 Cost Comparison

7.6 Summary

Simulations of the welded reservoir production system show changes to labor, overtime implementation, and shop floor control will reduce total system costs. Several mechanics work on the fittings process, which is the system bottleneck. Analysis shows that establishing a CONWIP system between the release of uppers and lowers and the completion of the fittings process allows for more efficient use of labor. This system is both effective and simple to incorporate. Therefore, it is chosen for implementation to prove out the results of the simulation analysis.

8.0 Implementation

This Chapter discusses the changes introduced to the welded reservoir manufacturing system and the performance of the system following the implementation of these changes.

Changes to the welded reservoir manufacturing system are implemented based on the results of the simulation. First, total order lead times are increased by one week (orders are scheduled for release a week earlier). The purpose of this change is to increase customer service level. The effectiveness of this change is tracked with the intention of lowering lead times as much as possible once delivery stabilizes. Second, the least utilized staff members, the pressure test mechanic and the closeout mechanic, are cross-trained to support other activities, including fittings. Finally, a CONWIP system that limits the WIP between the saw operation and the fittings is implemented as described in Section 7.5. An m level of 24 and an r value of two are applied.

As part of the CONWIP implementation, an automated System Health Report is developed to provide the work center manager daily updates on the status of the system. An example of a System Health Report is shown in Figure 8-1. This report is displayed on a monitor in the welded reservoir work center for all team members to see and review during their workday.

The report indicates the status of the start queue in the top right corner. The cell is green if the queue is zero, yellow if the queue is one or two, and red if the queue is above two. The red cell is an indication to management that compensatory measures should be taken to increase throughput at the fittings and reduce the start queue. The manager uses his/her discretion as to what measure to apply. It simply be moving a cross-trained worker to fittings from another task. If this isn't possible, then the manager will assign a fittings mechanic to an overtime shift after first shift.

The System Health Report also provides indicators for quality, attendance, throughput, and various buffers. Average work center attendance for the last week is provided. Because attendance is one of the key aspects of system variability, this information is useful and can often explain throughput problems. Also, daily and weekly throughput at different work stations are provided and compared relative to a throughput target that is determined based on demand. Finally, the status of different buffers is provided. Based on his/her knowledge of the work center, the area manager can quickly review the buffer status to ensure that important work stations are not starved and that other station have not been overproducing. Buffers with WIP above the target value indicate either overproduction in the upstream activities or underproduction in the downstream activities. Buffers with WIP below the target values indicate either underproduction in the upstream activities or overproduction in the downstream activities.

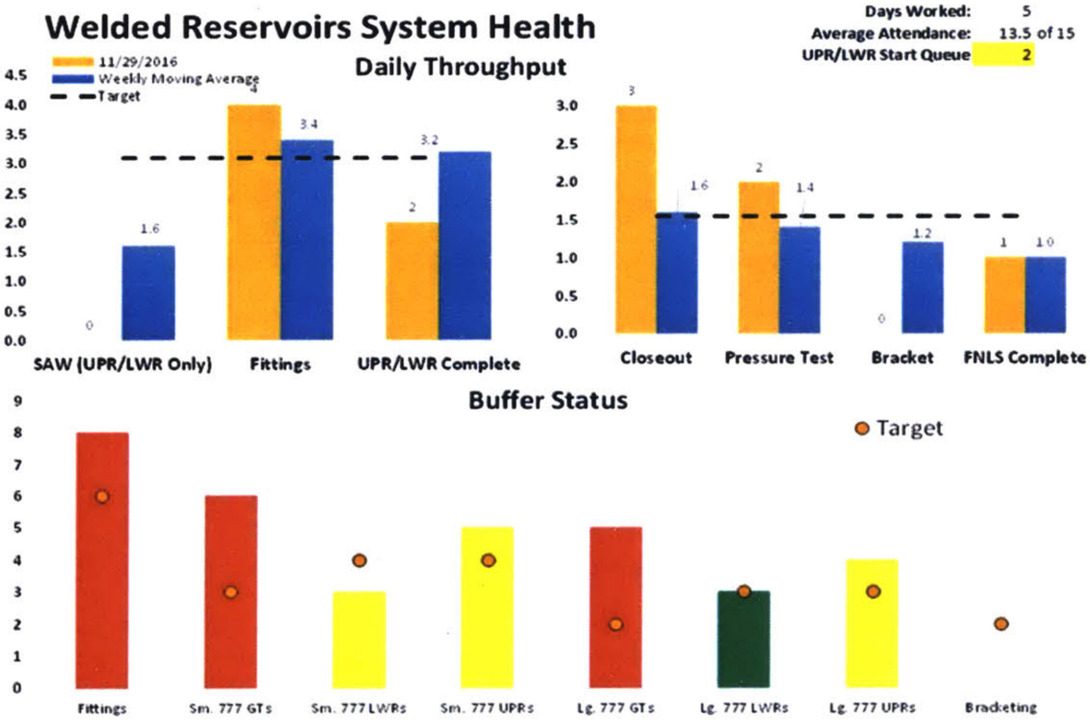

Days Worked: 5
Average Attendance: 13.5 of 15
UPR/LWR Start Queue 2

Figure 8-1. Example Reservoir System Health Report

The limited available data suggest these changes are effective in increasing customer service level and reducing costs. Production data from October 1, 2016 to December 13, 2016 show that customer service level increased from 0.4 to 0.79 for the small 777 models and 0.3 to 0.66 for the large 777 models. In addition, overtime use is down from 5% to 3% during that period.

The data show that cycle times decreased after the changes were implemented but variability of lead times did not decrease. Table 8-1 provides mean, standard deviation, and coefficient of variation results for 777 models prior to and after implementation of the changes discussed above. While mean cycle times decreased by approximately 3 days, cycle time variability did not decrease appreciably. There are two potential explanations for this lack of improvement. First, the CONWIP system was not applied consistently early in its application. At one point, the work center manager released more orders than the system should have allowed. This discrepancy was eventually corrected, but it would have increased cycle time variability. Second, a CONWIP system is in place for the lowers and uppers but is not in place for the final assembly process. Therefore, final assembly orders were still being released to a schedule and not based on a WIP limit. This results in higher cycle time variability, as some orders have to wait for days after being released and some are worked on immediately.

Table 8-1. Cycle Time Prior to and After Implementation of Shop Floor Improvements

Product	Average (days)		Standard Deviation (days)		Coefficient of Variation	
	Before	After	Before	After	Before	After
777 Small	33.4	31.2	4.3	3.8	0.13	0.12
777 Large	39.1	35.2	3.5	3.7	0.09	0.11
777 Combined	35.3	32.4	-	-	-	-

9.0 Summary

This Chapter provides the key conclusions from this work and suggestions for future work.

9.1 Thesis Conclusions

This work provides a methodology for understanding the value provided by a production system, evaluating the effect of changes to that system, and tracking system performance. The key conclusions drawn are related to consideration of the value of supply reliability, consideration of opportunity cost, staffing, meeting delivery targets, and the effectiveness of CONWIP.

The characterization of value in the hydraulic reservoir manufacturing system shows that the value of supply reliability is difficult to quantify. In the case of the reservoirs, supply reliability is the highest priority, but for other types of goods, it may not be. If manufacturers automatically prioritize supply reliability without careful consideration, they may miss opportunities to increase rate at which value is earned.

Opportunity cost is an important consideration but, like supply reliability, is difficult to quantify. A simple calculation that considered the value of factory floor space shows that managers should consider opportunity cost when making decisions. Most of the changes considered in this work are associated with the welded reservoir work center labor force. These changes did not have large effects on required order lead times and therefore did not greatly alter opportunity costs. The consideration of opportunity cost should therefore drive management focus on system changes that can reduce order lead times. The largest of these types of changes include improvements to first pass quality yields and reduction in shared work center cycle times.

The output of manufacturing system with high complexity, manual processes, high rework, high cycle times, and high cycle time variability can be simulated, and buffers can be engineered to meet customer service targets. While it is important to address the aspects contributing to system variability, the simulation approach used in this work provides strategies for stabilizing the system and then starting efforts to improve costs and/or value creation.

As shown in the manufacturing simulations, additions and reductions in staff do not necessarily result in either increases or decreases in cost. Managers should understand the dynamics of their systems to be able to predict the consequence of making staffing changes. The simulation approach used in this work can be used to make such a prediction.

CONWIP is especially effective at capacity management in a highly manual cross-trained assembly. CONWIP provides a simple metric or series of metrics that managers, operators, and mechanics can review and act on in a timely manner.

9.2 Suggestions for Future Work

To continue the progress made in this work, efforts should be made to develop methods that provide a more detailed and accurate characterization of the value provided by similar manufacturing systems and to apply these simulation and shop floor approaches to more of the hydraulic reservoir manufacturing system and other manufacturing systems at the TDRC. With respect to value characterization, developing more complete methods to quantify the value of supply reliability and factory opportunity will allow production managers to develop better metrics and make better decisions. With supply reliability, the actual cost to Boeing versus days of lateness could be calculated and factored into a simulation. For opportunity cost, other assets beyond floor space, such as human capital or manufacturing equipment could be considered. For example, consider other value that a welder or a machining center could add if they had an extra hour or two free each day.

To improve the hydraulic reservoir manufacturing system, consider application of more CONWIP loops. This will provide a more complete and succinct representation of system health. It will also reduce cycle time variability in processes whose WIP are not currently constrained by a CONWIP system.

The methodology that is used to simulate the production of hydraulic reservoirs and evaluate shop floor changes should be applied to other work centers at the TDRC. Most manufacturing processes at the TDRC are similar to reservoir assembly in that they are highly manual and complex with multiple shared work centers and long cycle times. Therefore, this work can be directly applied to improve delivery and reduce costs in other work centers.

Given that shared work centers affect all dedicated work centers at the TDRC, it is recommended that an analysis be conducted at a higher level that includes all TDRC work centers. Using the approach, the interaction between the work centers and their effects on system capacities and cycle times can be better understood.

10.0 References

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