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A Performance Evaluation of a Lean Reparable Pipeline in Various Demand Environments

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A PERFORMANCE EVALUATION OF A LEAN REPARABLE PIPELINE IN VARIOUS DEMAND ENVIRONMENTS

THESIS

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Abstract

Lean production and logistics processes were developed in the commercial sector to reduce total system costs of production while simultaneously providing high levels of customer service, increased productivity, and increased worker utilization. In 1993, the Air Force instituted the Lean Logistics program, which successfully implemented some commercial lean principles, enabling a reduction in the total reparable asset material requirement for the Air Force reparable asset pipeline. The Air Force is attempting to further implement lean production principles into depot repair in hopes of further enhancing reparable asset pipeline cost and customer service performance. However, the failure of reparable assets, which determines demand for Air Force depots can be extremely erratic and difficult to predict. A primary criticism of lean systems is their vulnerability in volatile demand environments. Therefore, the implementation of a full-scale lean approach to depot repair may not be conducive to operational success.

The purpose of this research is evaluate whether the Air Force reparable pipeline operating under lean production and logistics principles can effectively support operational requirements in various demand environments. In an attempt to answer the research objective, multiple Arena simulation models of a "lean" reparable asset pipeline operating under various conditions were developed. A full factorial experimental design was employed and multivariate analysis of variance (MANOVA) was utilized to assess the effects of differing levels of demand variability, base and depot supply levels, and the use of premium transportation on cost and stockage effectiveness response variables.

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A PERFORMANCE EVALUATION OF A LEAN REPARABLE ASSET PIPELINE IN VARIOUS DEMAND ENVIRONMENTS

I. Introduction

Background

In the decade following Operation Desert Storm, Air Force logistics leaders have continually reevaluated logistics processes in efforts to provide better combat support. The 1980s were a resource-rich environment characterized by large inventories of spare parts and plentiful manning at both base and depot levels (Hallin, 1998:13). The end of the Soviet threat, highlighted by the fall of the Berlin Wall, marked the end of the resource-rich environment the United States military enjoyed throughout the Cold War era (Hallin, 1998:13). The 1990s were characterized by both reduced inventory levels and significantly reduced spare parts procurement (Oliver, 2001). The reduced funding level coupled with changes to the Air Force operating environment meant Air Force logisticians needed to find more efficient ways of doing business while maintaining its capability to support the warfighter. In particular, Air Force leaders needed to find ways to reduce cycle times for reparable assets through the repair pipeline or "supply chain" despite reduced inventory and funding.

According to Lieutenant General William P. Hallin, former US Air Force Deputy Chief of Staff for Installation and Logistics, Lean Logistics (LL) was what the Air Force called its first attempts to improve its logistics processes. Established in 1993, the LL program drew on an integrated set of commercial business innovations termed "lean production" by Womack, Jones, and Roos in 1990 in their book *The Machine that Changed the World* (Raney, 1999:1). In the commercial sector, "lean logistics" is commonly referred to as those logistics principles utilized to support lean production. In the Air Force, LL was a formal program instituted in hopes of shortening flow times for reparable assets through the Air Force supply and maintenance system. As explained by Raney (1999) in his research on defining and evaluating Lean Logistics in the US Air Force, LL attempted to create a high velocity logistics infrastructure:

> *A high velocity logistics infrastructure emphasizes speed of processing over mass of inventory. Whereas today it takes, on average, 60 to 90 days for the Air Force logistics processes to turn a reparable component into one ready for issue, a high-velocity infrastructure might produce a repaired component in 5 to 10 days.*

In its attempt to create velocity in the logistics infrastructure, the LL concept proposed to consolidate large portions of assets from base level stocks up to intermediate supply points, to greatly reduce transportation times, and to streamline reparable asset repair in order to decrease total pipeline length (Hill and Walker, 1994:5). Consolidation of assets to intermediate supply points theoretically allowed greater flexibility to asset managers in distributing assets as well as possibly reducing the overall number of assets in the system (Hill and Walker, 1994:5). The reduction in transportation time for shipment from the depot to the base and retrograde shipment of assets from the base to the depot through the use of premium transportation was perhaps the most effectively adopted LL concept. In theory, reducing in-transit time to and from repair should compress the repair pipeline and reduce the total number of assets needed in the system.

LL policy reduced standard total order and ship time from 22 days to less than 3 days utilizing premium transportation (Hill and Walker, 1994:21).

The final major element of the LL concept was to streamline the depot repair cycle process. This consisted of both changing depot induction process and changing the basic repair system philosophy. Before LL, item managers met on a quarterly basis to determine which assets would be inducted into repair for that quarter (Hill and Walker, 1994:6). LL proposed the use of the Distribution and Repair in Variable Environments (DRIVE) system on a biweekly basis to establish a prioritized list of assets that would most improve overall fleet fully mission capable aircraft (Hill and Walker, 1994:6). By instituting a more frequent review of assets for induction into repair, the system became more responsive to the needs to the warfighter. DRIVE was later replaced by the more powerful Execution and Prioritization of Repair Support System (EXPRESS). The second part of streamlining depot repair cycle process was to implement Theory of Constraint and Just-in-Time (JIT) philosophy into depot repair. Traditionally, the depots utilized batch processing methods for reparable assets. By performing maintenance in batches, the depot hoped to capitalize on economies of scale and thus reduce costs of production through minimizing machine changeovers and increasing efficiency through production runs with the same sequence of operations. However, depot repair flow times for assets averaged 54 days, largely due to the time assets waited to be inducted into repair (Hill and Walker, 1994:28). By moving to lean production processes employing just-in-time, smaller or single-piece batches, and reduced work-in-process inventories, the Air Force hoped to reduce depot repair flow time to 10 days (Hill and Walker, 1994:28). In essence, the Air Force wanted depots to become responsive and offer quick throughput rather than seeking local efficiencies achieved through batch production (O'Malley, 1996:2).

Of the three major thrusts of LL, perhaps the most difficult to implement was the introduction of lean production practices into the depot repair shop floor. Popularized by Womack, Jones, and Roos (1990), the lean production concept was developed as the Toyota Production System (TPS) over 30 years in Japan. The systematic elimination of the unnecessary activities and cost, or waste, is the heart of lean production. By effectively introducing the concepts of flow and pull into production, capitalizing on just-in-time inventory and production methodology, the lean producer reduces the cost per unit of production (Duguay et al., 1997:1189). Firms such as Porsche and Pratt & Whitney instituted lean principles and credit the paradigm shift, which allowed both companies to significantly reduce production costs, production cycle times, and production errors enabling improved firm profitability and growth, resulting in the resurgence of their respective organizations (Womack and Jones, 1996).

The United States Air Force has attempted to implement lean production principles at reparable asset depot repair facilities in order to improve depot performance in terms of reduced repair cycle time, reduced repair cost, and improve overall depot productivity. Of those repair depots, the Warner-Robins Air Logistics Center (WR-ALC) has made the most substantial commitment to making the lean conversion although it has yet to become an actual lean organization. There are two confounds to the application of the lean production system into the Air Force reparable asset environment: 1) the actual implementation of a new production approach and philosophy to the organization and 2) whether or not the lean production approach is actually appropriate for the remanufacture/repair environment.

Even in the commercial sector, the implementation of the lean production system is difficult. For companies to successfully implement lean thinking they need to have senior management who clearly support the lean conversion and have an understanding of the difficulties associated with the new direction (Womack and Jones, 1996). Secondly, companies require a change agent to champion fundamental changes in the organization. The change agent and all senior managers must fully understand lean thinking to the extent it becomes second nature (Womack and Jones, 1996:250). Finally, the implementation of lean production often requires the elimination of those individuals and managers who do not embrace the concepts. As Art Byrne, a man with 10 years of experience in creating lean organizations explained, “Lean thinking is profoundly corrosive of hierarchy and some people just don’t seem to be able to make the adjustment” (Womack and Jones, 1996:132). The removal of those “anchor draggers” is essential to enabling the lean conversion to successfully take place (Womack and Jones, 1996:132).

With these factors in mind, it seems the implementation of lean principles into an Air Force repair depot would be doubly difficult. Air Force depot senior leadership changes on a relatively regular basis, resulting in a lack of continuity and possible loss of lean core knowledge. Secondly, reductions in manning, often a part of the conversion to a lean organization, are generally difficult to implement as unions typically exert strong influence and protection for worker positions. This confounds implementation of lean principles at massive depot repairs facilities on two fronts. First, uncommitted workers cannot be easily removed. Secondly, function-oriented unions reduce worker flexibility. Function-oriented unions are those whose members share a particular skill such as machinists, welders, etc. In Japan, the lack of function-oriented unions enabled Toyota to employ their workers on a variety of functions within their production facilities. Operators in these less constrained environments develop a broad spectrum of manufacturing skills which enabled the build up of a total system in the production plant (Ohno, 1988:14). In the United States, function oriented unions restrict flexible employment of workers. Attempts to employ workers in functions outside of their functional expertise may cause intense worker reaction and backlash against attempts to create the lean organization.

The second confound for implementation of the lean production system into the depot environment regards the appropriateness of the lean production principles for the remanufacture environment. The lean production system is the best way to remove cost in production (Womack and Jones, 1996:236). However, there are several factors which indicate the lean production system may be inappropriate for the depot repair environment. First, lean production is dependent upon production leveling to stabilize demand and enable production to occur at a constant rate. The failure of depot level reparable assets, which establishes demand for the Air Force depot facilities, can be extremely erratic and difficult to predict and may not be conducive to production leveling. Secondly, as discussed, the lack of worker flexibility caused by function-oriented unions makes flexible employment of worker resources difficult. In a lean production system, the capability to employ workers in multiple functions is a necessity to maximizing overall system productivity. A third significant factor which increases the difficulty of implementing lean production at repair depots is the diverse nature of the depot workload. Due to the numerous types of reparable assets, shop flows can be quite varied with different production sequences, different machine and skill requirements (Hill and Walker, 1994:17). The lean production approach seeks to arrange production steps in sequence so the product moves in continuous flow from raw material to finished good. The diversity of assets and their varied production sequences may be an impediment to successful lean production implementation.

Problem Statement

Lean production and logistics processes were developed in the commercial sector to reduce total system costs of production while simultaneously providing high levels of customer service, increased productivity, and increased worker utilization. Institution of the Lean Logistics program successfully implemented some commercial lean principles, enabling a reduction in the total reparable asset material requirement for the Air Force reparable asset pipeline. The Air Force is attempting to further implement lean principles into depot repair facilities in hopes of further reducing the total material requirement of the reparable asset pipeline and enabling a repair on demand methodology. However, one of the primary criticisms of lean systems is their vulnerability in volatile demand environments. Typically, successful implementation of lean production principles results in production cost reduction, significant productivity increases, and better manpower and resource utilization. However, due to the unique reparable asset environment with characteristics such as erratic demand, diverse production flows, and less than ideal worker flexibility, the actual application of the lean production system may not be appropriate and may not provide the benefits commercial production and manufacturing organizations have realized.

Research Question

The purpose of this research is evaluate whether the Air Force reparable pipeline operating under lean production and logistics principles can adapt effectively in order to support operational requirements in various demand environments. In an attempt to answer the research question, a reparable asset pipeline utilizing lean production and logistics principles will be modeled to demonstrate its effectiveness in support of operational requirements under numerous conditions. The lean reparable pipeline model is a multi-echelon, pull system in which the depot ships assets to individual bases upon demand while simultaneously signaling depot maintenance to induct parts into repair for replenishment of the depot stock level. Thus, the depot maintenance function within the model employs a repair on demand methodology. The depot production (repair) capacity is established according to a predetermined output rate which matches expected customer demand. A lean depot maintenance function would have limited capability to make adjustments to depot output if customer demand changed. This research seeks to demonstrate how this notional model performs in terms of total system cost and stockage effectiveness rate under numerous conditions to include changing demand variability levels, differing stock levels, and premium transportation use.

Investigative Questions

In order to successfully meet the research objective, the following investigative questions must be addressed:

1. How can the reparable asset pipeline be modeled operating under lean production and logistics principles?
2. How well does the lean reparable asset pipeline perform in terms of average total system cost per demand and stockage effectiveness under different demand environments?
3. Can non-premium transportation be used without negatively effecting lean reparable asset pipeline performance?
4. How do differing depot and base stock levels effect the performance of the lean reparable asset pipeline?

Methodology

In order to answer the first investigative question, an extensive literature review will be utilized to gain an in depth knowledge of the commercial industry concept of lean production and the Air Force reparable asset pipeline. Once the key characteristics of the lean production system and reparable pipeline are understood, a simulation model will be developed to model the Air Force reparable pipeline operating under the major lean production principles. The simulation is appropriate because it is an inexpensive method of comparing alternatives, allows us to actually view the physical flow of the production and logistics processes, and has the capability to handle stochastic situations (Bowersox and Closs, 1989:134). Additionally, because computer simulations can be built in blocks, breaking down complete processes into manageable and understandable proportions, it enables decision makers to learn about system structure and how individual components affect model performance (Disney et al., 1997:176). Once this simulation model is developed, the model will be run using different levels of input factors of interest in order to gain insight and answer the research questions.

Summary

Chapter I of this thesis has provided the reader an overview of the research effort, the problem statement and objective of this research, and the proposed investigative questions and related methodology which will lead to the successful accomplishment of the research objective. Chapter II presents an in depth review of the existing literature on this subject. Chapter III describes the development of the model and data used to meet the research objective. Chapter IV provides the findings of the study and Chapter V provides conclusions and presents areas for further research.

II. Literature Review

Introduction

This chapter reviews the terminology used and existing literature concerning this research effort. To begin, the Air Force reparable asset pipeline will be introduced followed by a discussion of the changes in the logistics processes which resulted from Lean Logistics (LL), a program inspired by the commercial industry lean production approach. Finally, a brief primer on the mass production approach followed by a more comprehensive discussion of lean production as defined by the Toyota Production System to include history, key concepts, and its associated production characteristics will be discussed in order to provide an understanding of the magnitude of change associated with the implementation of the lean production approach.

Reparable Asset Pipeline

Reparable or recoverable assets are aircraft parts or major components which can be repaired in order to return the weapon system to a serviceable condition. Examples of reparable assets are expensive components such as brake assemblies, avionics, or engine fuel controls that can be removed from aircraft upon failure (O'Malley, 1996:1). Unlike consumable items which are discarded and replaced by new items, the high expense of reparable items makes simple discard and replacement of the item cost prohibitive and therefore necessitates considerable management and repair of those items.

The reparable asset pipeline refers to the logistics (and remanufacture) functions which enable the Air Force's war fighting capability. The "pipeline" analogy is useful to visualize the flow of reparable assets through the logistics system in the same way water flows through a physical pipeline (Hill and Walker, 1994:12). A pipeline has the physical qualities of routing, volume, and length. Routing shows the actual sequence of movement for assets through the various processes of the logistics system, volume refers to the quantities of assets in the system, and length refers to the time involved in moving assets from one point to another within the system. In general, smaller pipelines result in better support at lower costs (O'Malley, 1996:8). For instance, reliability improvement programs reduce failure rates and shrink the pipeline volume by reducing the number of items in the pipeline (O'Malley, 1996:8). The end result is a lower total requirement of that particular reparable asset and thus a decreased cost of support.

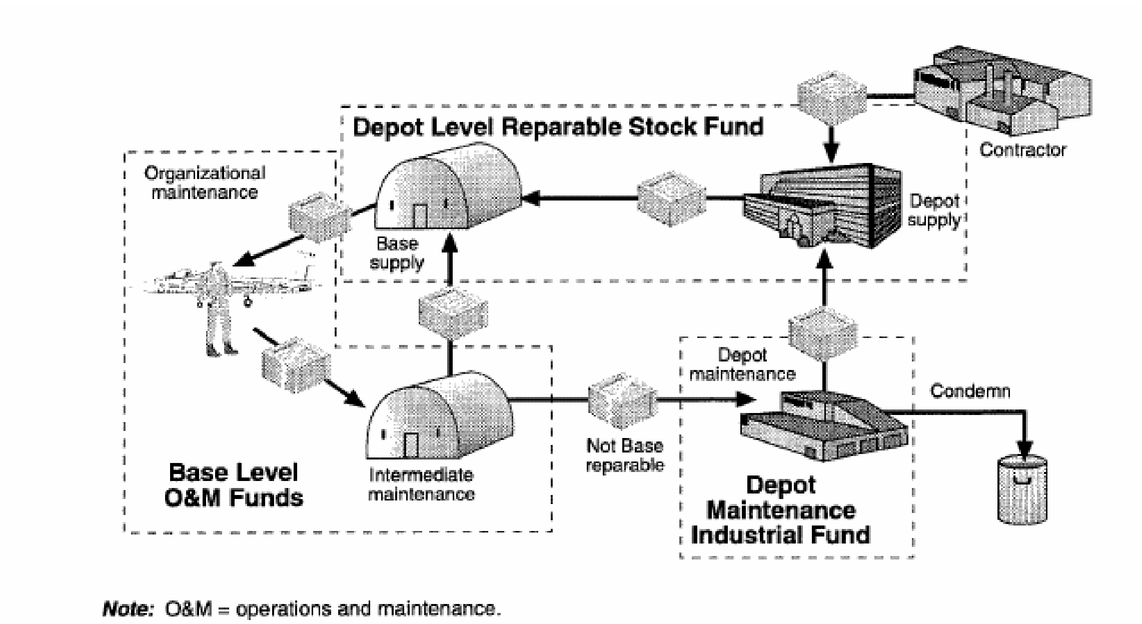


Figure 1. Reparable Asset Pipeline (O'Malley, 1996:3)

Figure 1 above depicts the various functions and flow of assets in the Air Force reparable pipeline. Organizational or squadron maintenance removes a failed reparable asset from the weapon system and sends the failed carcass to base intermediate maintenance. If the base maintenance function has the capability to repair the asset, they do so and upon repair completion, return the asset to base supply. Upon removal of the failed reparable asset, organizational maintenance requests a replacement from the inventory held at base supply. If no replacement is available, the aircraft is NMCS (not mission capable—supply) until a serviceable unit can be produced by base maintenance or one is received from depot supply.

The depot pipeline segment operates similarly to the base pipeline segment. Air logistics centers or depots have both repair and supply functions as seen in the base pipeline segment. Reparable asset failures which are beyond the capability of base maintenance capability are returned to the depot for repair. When the asset is shipped to depot, the base simultaneously requests a serviceable unit from depot supply, which is satisfied immediately if possible. If depot supply does not have the requested reparable asset, they must either wait for depot maintenance to produce the part or attain assets through the acquisition channel. At depot maintenance, returned reparable assets are inspected, deemed repairable and fixed, or are determined to be beyond depot repair capability and are condemned and discarded. Upon depot repair, assets are stocked at depot supply to replenish the inventory position.

Lean Logistics

Lean Logistics was a set of several process and management initiatives which sought to decrease overall pipeline length by reducing transportation and repair times. The stated objective of LL was to "maximize operational capability by using high-velocity, just-in-time processes to manage mission and logistics uncertainty in-lieu of large inventory levels—resulting in shorter cycle times, reduced inventories and cost, and smaller mobility footprint" (Briggs, 1996).

The LL concept arose as a way for the Air Force to meet fiscal challenges imposed by reduced repair and inventory funding after the Gulf War (Hill and Walker, 1994:22). Acting on a request by the Air Force logistics directorate, in February 1993, the RAND Corporation of California provided a presentation on how some modern business practices could be applied to Air Force reparable pipeline processes in order to minimize resource investments (Hill and Walker, 1994:22-23). The ideas pulled largely from the integrated set of business innovations termed "lean production" by Womack, Jones, and Roos in 1990 (Raney, 1999:1) and thus, likely led to the "Lean Logistics" term being coined.

According to Colonel Arthur Morrill (1997), Executive Officer, Air Force Deputy Chief of Staff for Logistics, the Two-Level Maintenance (2LM) concept holds the most prominent position in the LL architecture. With implementation beginning 1 Oct 1993, 2LM essentially removed a level of repair capability from the intermediate base level and relocated it back to the Air Force depot (Morrill, 1997). The initiative was meant to improve operational focus while also reducing the Air Force mobility footprint. The program was successful in reducing some 4,430 intermediate maintenance manpower positions, as well significantly reducing equipment purchase requirements (Morrill, 1997). Additionally, the program successfully enabled a reduction in the Air Force mobility footprint by relieving units of the need to deploy intermediate maintenance equipment and personnel in support of deployed operations (Morrill, 1997).

Where 2LM is perhaps the most well known change instituted under LL, there were several other profound initiatives which had considerable effect on the reparable asset pipeline. Among those were proposal to consolidate large portions of assets from base level stocks to intermediate supply points, to greatly reduce transportation times, and to streamline reparable asset repair in order to decrease total pipeline length (Hill and Walker, 1994:5). Consolidation of assets to intermediate supply points theoretically allowed greater flexibility to asset managers in distributing assets as well as possibly reducing the overall number of assets in the system (Hill and Walker, 1994:5). The reduction in transportation time for shipment from the depot to the base and retrograde shipment of assets from the base to the depot through the use of premium transportation was perhaps the most effectively adopted LL concept. Current Air Force policy calls for all reparable items to move via premium transportation. In theory, by reducing the time assets are in transport to and from repair, the repair pipeline is effectively shortened, reducing the total number of assets needed in the system. However, recent studies have suggested the Air Force overuses premium transportation and alternatives such as scheduled truck routes within CONUS should be assessed (Masciulli, Boone, and Lyle: 2002).

The final and perhaps most difficult element of the LL concept was to streamline the depot repair cycle process. This consisted of both changing depot induction process and changing the basic repair system philosophy. Previous to LL, item managers would meet on a quarterly basis to determine which assets would be inducted into repair for that quarter (Hill and Walker, 1994:6). Under the Management of Items Subject to Repair (MISTR) process, item managers would utilize worldwide consumption data to compute the expected number of quarterly failures for the items they managed and pass that information onto depot-production management specialists (Glazer et al., 2002:77). They in turn would coordinate with applicable depot-repair shops to determine whether depot-repair shop capacity existed to repair the expected number of reparable failures (Glazer et al., 2002:77). Due to the fact depot repair shops repaired a wide variety of reparable assets, production management specialists often had to negotiate quarterly repair quantities less than the expected number of failures (Glazer et al., 2002:77). A number of problems arose from the MISTR process. First, due to the volatile nature of reparable asset failure patterns, negotiated repair quantities were frequently too low or too high (Glazer et al., 2002:77). Thus, when negotiated quantities were too low, mission capability suffered and when negotiated quantities were too high, depot capacity was consumed on unneeded items at the expense of others (Glazer et al., 2002:77). Secondly, even if the MISTR negotiated quantity was exactly right, the process only ensure the negotiated quantity would be produced sometime during that period and thus was not linked to demand.

LL proposed the use of the Distribution and Repair in Variable Environments (DRIVE) system on a biweekly basis to establish a prioritized list of assets that would most improve overall fleet fully mission capable aircraft (Hill and Walker, 1994:6). By instituting a more frequent review of assets for induction into repair, the system became more responsive to the needs to the warfighter. DRIVE was later replaced by the more powerful Execution and Prioritization of Repair Support System (EXPRESS) under the Depot Repair Enhancement Program (DREP).

The second part of streamlining depot repair cycle process was to reduce reparable asset repair flow time (the time from receipt of the asset at the depot to the time the asset is available for issue as a serviceable unit). Traditionally, the depots utilized batch processing methods for reparable assets. By performing maintenance in batches, the depot hoped to capitalize on economies of scale and thus reduce costs of production through minimizing machine changeovers and increasing efficiency through production runs with the same sequence of operations. In this way, depot management sought the most efficient use of depot repair and management resources. However, as a result of this repair methodology, depot repair flow times far exceeded actual hands on repair time as parts waited for repair until a batch quantity is accumulated. This contrasted with base repair flow times which often approximated hands on repair time because efficient utilization of resources was not a primary consideration (Raney, 1999:17). By moving to lean production processes (not necessarily fully embracing the Toyota Production System) with characteristics such as just-in-time, smaller or single-piece batches, and reduced work-in-process inventories, the Air Force hoped to reduce depot repair flow time near actual hands on repair time. In essence, the Air Force wanted depots to become responsive and offer quick throughput rather than seeking local efficiencies achieved through batch production (O'Malley, 1996:2).

Initial Lean Logistics programs resulted in incremental performance improvement in terms of repair flow time reduction and responsiveness. In an effort to attain major performance improvement, DREP was implemented by Air Force Material Command in 1996 (Glazer et al., 2002:77). The program sought to improve depot repair by allowing customer "pull" to drive repair to improve responsiveness (achieved through EXPRESS utilization), by changing shop organization from a functional to a production orientation, and improving material support among other changes (Caudill, 2003). DREP resulted in a reduction in shop flow days by 40% at WR-ALC (Intergraph, 2002). In an effort to further improve depot repair performance, WR-ALC is seeking full implementation of the lean or Toyota Production System. In order to understand the magnitude of change involved in implementation of the lean production paradigm into the depot environment, the following sections provide background on the mass and lean production approaches.

Mass Production

Mass production is the dominant production paradigm utilized by production organizations throughout the world today to include the United States, Europe, and Japan. The production paradigm emerged during the nineteenth century as an outgrowth of the Industrial Revolution (1770-1800) and became the dominant mode of manufacturing in the United States by 1890 (Duguay et al., 1997:1183).

The main focus of mass production is to reduce per unit production costs via increased volume of production (economies of scale). Some resulting characteristics of this approach include batch and queue methodologies, long production runs, large specialized equipment and machinery, and the emphasis on keeping machines and production running (Dennis, 2002:6). In the production environment, this leads to large work-in-process and finished goods inventories despite the fact there may be no customer to buy the product (Dennis, 2002:6). Another consequence of the batch and queue method is a rise in defect rates due to the fact a machine may replicate defects throughout the batch before the defects are caught (Dennis, 2002:6). Other characteristics of mass production include improved production primarily through innovation directed by experts and managers, labour execution of production tasks under management supervision, and adversarial relationships with suppliers as firms seek to get the best deals through competition among suppliers (Duguay et al., 1997:1184-1185); although, the current ideas of supply chain management and strategic partnerships with suppliers may be changing this characteristic.

Over time, firms utilizing mass production grew in size, increasing productive capacity and speed, in addition to complexity in operations (Duguay et al., 1997:1183). The new organizational complexity as well as excess production capacity during depression years highlighted the need to address organization, coordination, and control issues and ushered in the era of "scientific management" and the ideals of Frederick W. Taylor (Duguay et al., 1997:1183). Scientific management sought to find the "one best way" to complete a task, also known as standardized work (Dennis, 2002:2). Some more of Taylor's innovations included reduced cycle times, time and motion studies as a tool to develop standardized work, and the use of measurement and analysis for process improvement (Dennis, 2002:2-3). Taylor's system was based on separating planning from production and consequently widened the gap between production planners and actual production workers (Duguay et al., 1997:1183). Although it was not the intent of Taylor, his ideas became synonymous with mindless dehumanizing work (Dennis, 2002:2).

Another figure central to the emergence of the mass production approach was Henry Ford (1863-1947), the pioneer of the American automobile industry who is credited with creation of the first assembly line. Ford sought to produce and sell automobiles that common people could afford, an unrealized ambition until the 1908

Ford Model T (Dennis, 2002:3). This was accomplished through successful introduction of several innovations into automobile production. First, Ford successfully attained interchangeability of parts and ease of assembly, a concept pioneered by Eli Whitney in musket manufacturing. By standardizing parts and reducing the number of parts in engine and other systems, the assembly process was simplified (Dennis, 2002:3). Next, the number of actions required by workers was reduced and parts were delivered to the work area, reducing worker walk time. These actions helped reduce cycle times from hours in 1908 to minutes in 1913 (Dennis, 2002:3). Lastly, Ford hit upon the idea of an assembly line bringing the car past stationary workers (Dennis, 2002:3). This again reduced worker walk time while linking sequential processes (Dennis, 2002:3). Additionally, this innovation forced slower workers to speed up and faster workers to slow down, increasing overall stability in the production pace (Dennis, 2002:3).

Ford's innovations greatly reduced human effort needed to assemble the vehicle and resulted in huge cost savings, catapulting Ford to industry leadership and fully ushering in the era of mass production (Dennis, 2002:4). United States industrial strength, built on mass production, became a major advantage for the United States. During the Second World War, American industry's ability to adapt to military applications, and produce items such as airplanes and radars in large volumes through mass production enabled American mastery of the skies and provided a significant strategic military advantage (Duguay et al., 1997:1186).

In the 1950s, US industrial performance and the mass production paradigm was so highly esteemed, European and Asian producers went to the United States in order to learn about mass production (Duguay et al., 1997:1186). Among those was Eiji Toyoda, a Japanese engineer who visited the Ford Rouge plant in Detroit in the Spring of 1950 (Dennis, 2002:6). Toyoda's family had founded the Toyota Motor Company in 1937 which had produced 2,685 automobiles in its 13 years of existence (Dennis, 2002:7). In contrast, the Rouge plant was producing 7,000 vehicles per day (Dennis, 2002:7)! Upon returning to Japan, Eiji and his production genius Taiichi Ohno, concluded that mass production would not work in Japan (Dennis, 2002:7). There were several reasons for this conclusion. First, the Japanese market for automobiles was significantly different than in America. Japanese market place restrictions required production of small quantities of numerous varieties due to low demand in the postwar period (Ohno, 1988: xiii). For example, large trucks were required to transport produce to markets, small trucks were needed by farmers, luxury cars were desired for the elite, and small cars were needed for Japan's narrow roads (Dennis, 2002:7). Secondly, in the wake of World War II, the Japanese economy was starved for capital and a huge investment in sophisticated machinery, a characteristic of mass production, was impossible. Eiji and Ohno believed improvements could be made to the American mass production system and the Toyota Production System (TPS) or the lean production system was what they developed.

Cost Reduction Through Lean Production

Lean production utilizes a different approach to cost reduction than that of mass production. Rather than capitalizing on economies of scale, lean production seeks to eliminate wasteful activities in the production organization and its processes, effectively reducing the cost of production. As explained by Pascal Dennis (2002:14) and summarized in equations 1 and 2, firms used to be able to determine price by adding the typical industry profit margin to the cost of production to establish their product price. In most cases, all costs and desired profit were simply passed along to the consumer in price, who more often than not paid it. However, in today's business environment where consumer power is strengthened by their access to information, prices are often fixed or falling and profits are determined solely by the firm's ability to reduce costs—the goal and strength of lean production.

Old: *Cost + Profit Margin = Price* (1)

New: *Price (fixed) – Cost = Profit* (2)

The term "lean" was popularized by the book, *The Machine that Changed the World*, by James Womack, Daniel Jones, and Daniel Roos in 1990 (Dennis, 2002:13) but is based on the Toyota Production System (TPS) and the teachings of Taiichi Ohno. In the wake of WWII, then President of Toyota Motor Company, Toyoda Kiichiro felt the survival of the Japanese automobile industry was contingent of catching up with American productivity (Ohno, 1988: 3). The understood ratio of the time was that on average, it took 9 Japanese workers to produce the same amount as 1 American (Ohno, 1988:3). Finding it unlikely Americans could exert 10 times the physical effort as Japanese workers, Ohno surmised there had to be waste in Japanese production processes and the elimination of this waste could result in the productivity increase of 10. This idea marked the beginning of the Toyota Production System and lean production (Ohno, 1988:3).

Waste.

In production, waste refers to all elements of production that only increase cost without adding value (Ohno, 1988:54). Taiichi Ohno found seven common forms of waste in organizations and termed them as follows: overproduction, waiting, transporting, too-much machining (overprocessing), inventories, moving, and making defective parts and products (Ohno, 1988:129). Later, Womack and Jones (1996) refined the terms: production of items not yet desired, individuals in a downstream activity waiting for the upstream activity to deliver, unnecessary transport of goods, unneeded processing steps, excess stock, unnecessary movement of employees, and mistakes needing rectification (Womack and Jones, 1996:15). They also added goods and services which do not meet the needs of the customer as an eighth form of waste (Womack and Jones, 1996:15). Through the systematic elimination of these wasteful activities, organizations become lean and can effectively reduce the cost per unit of production (Duguay et al., 1997:1189).

Most lean practitioners explain that only five percent of activities in typical production operations truly add value to the product (Dennis, 2002: 20). Value-added work is those activities which actually involve processing or changing the actual shape or character of the product (Ohno, 1988:57). Jones and others (1997:154) contend 35 percent of work is often necessary non-value added activity, or as defined by Dennis (2002), auxiliary work. These are activities which do not add value but are essential under present working conditions such as removing received parts from containers or walking to pick up items (Ohno, 1988:57). The remaining 60 percent of the activities of a typical production firm are likely to be unnecessary, wasteful activities (Jones et al., 1997:154). This percentage may seem high and unrealistic but closer examination of the common forms of waste in organizations may help to confirm the charge.

Forms of waste.

Mistakes needing clarification take various forms such as order input errors, raw material or subcomponent defects, or production defects and are clearly wasteful activities in that they consume raw material, labor, and time resulting in excess cost with no contribution to profit. For instance, order input errors result in the production of goods which do not satisfy the desires of the customer. The result is the waste of the raw materials and labor utilized to create the unwanted good, the need to consume additional labor and resources to rectify the mistake, as well as delay to the customer in finally receiving the order. Raw material and subcomponent defects result in delays to production, additional cost in transporting material back to suppliers, and the need to carry additional material on hand to ensure continual production. Like order input and raw material errors, production defects result in excess cost through the actions necessary to rectify the mistake as well as decreased customer satisfaction if the production error reaches the end customer. However, these mistakes also contribute to waste in other ways.

Excess processing steps such as inspection or quality control steps are often instituted in order to control or reduce production errors. The inspection of raw materials or subcomponents from suppliers is one such example. These activities add cost to the final product as labor is utilized in the inspection process although no actual production utility was added by the inspection—meaning the material has not advanced in the production process of becoming the finished good. It is intuitive that if these mistakes could be controlled through the value-added production activities, these excess processing steps could be eliminated. A related but slightly different view of excess processing is overprocessing (Dennis, 2002:23). Overprocessing is a form of waste when the producer does more than the customer wants and is willing to pay for (Dennis, 2002:23). For instance, by designing highly innovative and technologically superior features into a product which have no value to the customer.

Excess movement of personnel and equipment and *excess transportation of goods* are common and closely related forms of waste resulting from poor work place ergonomics and design. Poor ergonomic design reduces worker productivity and quality as well as negatively affecting safety (Dennis, 2002: 22). Ergonomic factors such as posture, force, and repetition contribute to over 50% of workplace injuries in North America (Dennis, 2002:22). Additionally, many factory floors are cluttered and unorganized causing workers to waste time locating and retrieving tools necessary to complete jobs. Even when factories are clean and orderly, their production layout still contributes to waste of human effort. The ideal lean production layout would allow minimal movement of employees and goods as the raw materials flow through the production process to become the finished good. This concept of flow will be discussed in greater detail later. However, in many production facilities, goods do not follow a direct path through production and the total distance traveled by the raw material to become the finished good is significantly greater than necessary. For instance, oftentimes, due to batch and queue processes, large amounts of work-in-process materials are produced and moved to intermediate storage locations rather than proceeding directly to the next step in production. This excess movement of employees and equipment and transportation of goods requires labor as well as equipment, time, and storage space, all of which add cost to the final product.

Waiting by downstream activities for upstream activities to deliver is another of the seven original forms of waste identified by Taiichi Ohno. Clearly, a portion of your production line being idle due to delays in upstream activities is costly as labor costs are incurred while no production activity is actually being performed. Waiting occurs when there is extensive work-in-process due to large batch production, equipment problems, or defects requiring rework (Dennis, 2002:22). This is one of the chief reasons firms have often valued large raw material and work-in-progress inventories so as to ensure production activity.

Excess stock, or inventory, are unnecessary raw materials, parts, and WIP which cause a firm to incur associated inventory carrying costs to include building and maintenance of warehousing facilities as well as inventory management, energy, and labor expenses. Ohno (1988:15) explains people naturally feel more secure with a considerable amount of inventory but the industrial society must develop the courage and good sense to procure only what it needed when it is needed in the right quantity.

Ohno (1998:15) felt the *production of goods not yet desired,* or overproduction as he originally termed it, was the most terrible waste in business. Overproduction leads to *excess stock* and the associated costs discussed above. Additionally, overproduction can lead to production workload irregularities, warehouse space limitations, and the necessity to discount finished goods below normal in order to move inventory. In some industries, producers may need to make modifications to already finished goods in order to satisfy customer desires, again adding cost to the final product. In sum, overproduction is the root cause of several types of waste in the organization (Dennis, 2002:23).

Goods and services which do not meet the needs of the customer is the eighth form of waste as identified by Womack and Jones (1996:15). As discussed earlier, the creation of a product which does not match expectations and desires of the customer will require firms to modify existing finished goods or necessitate an entirely new product to fully satisfy customer expectations. And from the customer perspective, the only purpose of the production firm is to create products which meet customer expectations. Therefore, firms need to work harder at understanding the desires of their customers. Dennis (2002:24) terms this form of waste as knowledge disconnection meaning that the company is not in tune with its customers (or possibly with its suppliers or within the company itself). Increased production flexibility and customization of products are signs that an increasing number of firms are beginning to understand this concept.

With knowledge of some typical wasteful activities of production firms as a backdrop, we begin to understand that each and every activity a firm performs has an impact on the cost of the good or service being produced, whether or not any actual value was added by each successive step. The most effective way to eliminate waste and ensure value is added with each successive step of production is by implementing the key production principles of *flow* and *pull* into production.

Flow and Pull.

Flow means that the individual product flows continuously through production with no stoppages. Conventional thinking or the "common sense" approach is to operate in batch and queue production in order to maximize compartmental efficiency (Womack and Jones, 1996:21). However, a more efficient way to operate is to produce a product from raw material to finished good continually (Womack and Jones, 1996:22). Productions steps should be arranged in sequence with the product moving in single piece flow without any buffers in between processes (Womack and Jones, 1996:60). In order to accomplish this, tools and machines must be right-sized to fit into the production process. This may equate to a simpler, less automated, or slower machine (Womack and Jones, 1996:60). In order to ensure continuous flow, all machines and personnel must be capable; meaning they are in the proper condition to run and all parts must be made exactly right (Womack and Jones, 1996:60). Visual controls and other techniques can be utilized to ensure quality is maintained (Womack and Jones, 1996:61). The end objective is to totally eliminate all stoppages in an entire production process (Womack and Jones, 1996:61).

Pull means no one upstream should produce a good or service until a customer has ordered it (Womack and Jones, 1996:67). In order to understand the logic and challenge of pull is to start with the real customer expressing a demand for a real product and to work backwards through all the steps required to bring the product to the customer (Womack and Jones, 1996:67). The result of flow and pull in your production organization is a reduction in the time required from concept to launch, sale to delivery, as well as production from raw material to finished product (Womack and Jones, 1996:24). A newly lean firm can expect a reduction of product development by 50%, order processing by 75%, and physical production by 90% (Womack and Jones, 1996:24). This results, not only in the initial reduction of inventory, but allows the firm to produce what the customer wants, when they want it. This allows for the firm to eliminate sales forecasting and allows the customer to pull products. This also eliminates the creation of undesired products which must be pushed onto customers, often at discounted rates (Womack and Jones, 1996:24).

Elements of Lean Production

Although conceptually basic, the actual achievement of flow and pull in production operations is difficult. Achievement requires the implementation of several critical elements which in total make up the lean production concept. Figure 2, from the book *Lean Production Simplified* by Pascal Dennis presents a pictorial framework of the key elements of the lean production concept. Dennis presents the lean production system as a house in which the roof is customer focus whose goal is to achieve the highest quality product, at the lowest cost, in the shortest time by continually eliminating waste. The foundation of the structure and thus the lean production concept entail the elements of stability and standardization. The walls of the structure are supported by the critical elements of just-in-time and *jidoka*, the Japanese word for autonomation, or automation with a human touch. Finally, according to the Dennis (2002) model, involvement is presented as the heart of lean production. Using the framework Dennis has established combined with the thoughts of other lean practitioners, the critical elements and production characteristics of lean production will be defined.

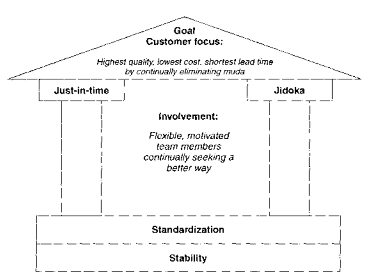


Figure 2. Lean Production Elements (Dennis, 2002)

Stability.

A stable foundation among the firm's personnel, machinery, material, and work methods are necessary to establish and maintain flow and pull in production. Dennis (2002:27) calls this stability in the 4Ms: man, machine, material, and method, which are the tools the firm utilizes to produce a product. The lean production system operates on the premise that it should not produce products until they are requested by the customer, and once requested, should be produced immediately. Therefore, inconsistencies or wide variability in production due to worker mistakes, material defects, machine breakdowns, or inefficient work methods would cause the failure of the production system. Thus, the elimination of variation and stability among the 4Ms is a critical element of lean production. Stability is achieved through the concepts of visual management, the 5S system, and Total Productive Maintenance.

Visual management. Visual management is the first concept utilized to achieve stability for lean production. As the lean production paradigm calls for the elimination of all wasteful activities or activities which do not add value to the product, standard production safety mechanisms like work-in-process inventory are removed. With these safety buffers of production disruptions removed, the production line is vulnerable to varied work stoppages. Consequently, the lean production approach is dependent on instantaneous communication of undesirable conditions. In order to ensure this instantaneous communication, the lean production workplace is visual in nature where the work environment is self-explaining, self-ordering, and self-improving (Dennis, 2002:28). The visual workplace allows for management on the basis of exceptions where deviations from standards are immediately obvious (Dennis, 2002:27). Taiichi Ohno called this visual control or management by sight (Ohno, 1988:129) where Dennis (2002:28) terms it visual management.

5S system. Practicioner Hiroyuki Hirano developed the 5S system, a tool which enhances stability and supports just-in-time production (Dennis, 2002:27), and the second conceptual element of stability. The 5Ss'stand for sort, set in order, shine, standardize, and sustain which together form a system of workplace organization and standardization which supports visual management (Dennis, 2002:43).

The first element of the 5S system is to sort out what you don't need. People have a tendency to hold on to formerly useful goods just-in-case they will be useful later (Dennis, 2002:30). However, oftentimes these items accumulate and the workplace becomes overrun with stuff such as work in process, scrap, equipment, or parts which impede the flow of work (Dennis, 2002:29). This clutter necessitates additional floor space, shelf space, and people to manage the items (Dennis, 2002:30), all of which are undesirable in a waste free production line.

Set in order, the second element of the 5S system, seeks to organize the remaining stuff of your shop floor to minimize wasted motion (Dennis, 2002:31). The first step is to position your equipment and supplies in a way to enable flow and material movement. The next step is to create and utilize visual systems, visual devices that convey information at a glance (Dennis, 2002:33). Visual indicators are like street signs, only telling information (Dennis, 2002:33). Visual signals grab attention like traffic lights (Dennis, 2002:33). Visual control limits behavior like parking lot lines. The final visual device, guarantees, allow only the correct response like the automatic pump shut off at a gas station (Dennis, 2002:33). The objective of the visual system is to create a work place which talks to workers. Information such as dangerous areas and protective clothing requirements are immediately and continuously communicated to workers (Dennis, 2002:35).

The next element, shine (and inspect) means to ensure the workplace is clean and orderly (Dennis, 2002:33). This is done through the establishment of standards which determine what will be cleaned, how the cleaning will be accomplished, who will perform the cleaning, and what the acceptable level of cleanliness is (Dennis, 2002:33). Understood cleaning targets, methods, schedules and responsibilities ensure all members take pride in the work place and inspect and clean machinery (Dennis, 2002:34). This regular upkeep improves machine performance and help support machine stability (Dennis, 2002:34).

The first three 5S elements have created a clean, orderly workplace which communicates to workers (Dennis, 2002:34). The fourth element, standardize, means to create standards for measuring and performing our work which will allow us to maintain the gains we made from our first three elements (Dennis, 2002:34). For instance, a tailored scoreboard measuring the firm's 5S condition helps ensure upkeep is continued (Dennis, 2002:35).

The final 5S element is sustain which seeks to ensure 5S occurs continually and becomes the company's normal way of doing business (Dennis, 2002:35). Sustainment is accomplished though promotion, communication, and training of 5S standards which create and sustain team member involvement in the 5S process. Successful implementation of the 5S system introduces team members to the language of lean production and lays a foundation for future lean activities (Dennis, 2002:36).

Total Productive Maintenance. The final conceptual element of stability is total productive maintenance (TPM). TPM enables firms to achieve machine stability and effectiveness by assigning basic maintenance work to production team members (Dennis, 2002:36). It creates a mindset in which operators are responsible for their equipment. As a result workers perform more preventative maintenance and less fire fighting, meaning greater equipment availability (Dennis, 2002:38).

Dennis (2002:38) explains there are hundreds of hidden and minor failures which foreshadow an accident or major breakdown (Dennis, 2002:40). For instance, a machine may have loose nuts and bolts which at the current time have no negative effect on the function of the machinery. However, overtime these loose nuts and bolts may allow vibration which causes bearing deterioration (Dennis, 2002:40). This deterioration may result in minor work stoppages such as overheating in the motor. Eventually, if unchecked, this leads to complete breakdown in the equipment such as when the motor eventually burns out. TPM listens for those anomalies like loose bolts and nuts and corrects them before a breakdown (Dennis, 2002:41). Thus, high equipment availability is a necessity and characteristic of the lean production firm.

Standardized Work.

Standardized work is the second foundational element of lean production as established by Dennis in Figure 1. Standardized work represents a playbook of the easiest, safest and most effective ways of doing things as we currently know now (Dennis, 2002:47). Unlike the unwritten assumption of industrial engineering practice that there is one best way to perform a task or function, standardized work provides the best way only at a particular point in time providing workers a basis for improvement for future design of work (Dennis, 2002:47). Standardized work is composed of three elements: work sequence, in process stock, and takt time (Dennis, 2002:51). Work sequence, also termed work procedure by the Japanese Management Association (1989), defines the order in which work is done in a given process. In essence, work sequence provides the worker with the exact way they should do their work (Japanese Management Association, 1989:104). By creating this standard work sequence, firms avoid seeing workers performing tasks in different ways or even the same person performing the same task in different ways (Japanese Management Association, 1989:103). The end result is the elimination of mistakes which could arise by workers forgetting the process or performing it out of sequence. In-process stock establishes the acceptable level of work-in-process stock per process (Dennis, 2002:51). The final element of standardized work, takt time, is a technique instrumental in matching demand with production scheduling (Womack and Jones, 1996:53) as well as a critical element in the production leveling concept to be discussed later.

As a production system in which inventories are eliminated and products must be produced precisely at the correct time to satisfy customer demand, there must be a technique or mechanism in place to match the rate of production with the rate of sales, or demand (Womack and Jones, 1996:53). Takt time is this technique, essentially telling workers how frequently a product must be produced in order to satisfy the rate of demand. At Toyota, the customer or sales record serves as the indication of demand and therefore, establishes the production plan. Takt time is defined precisely at a given point in time in relation to demand and should be adjusted as demand changes (Womack and Jones, 1996:56). It should be noted that among lean practitioners, there are slight differences in the definition of takt time. Taiicho Ohno (1988:60) defined takt time as the length of time, in minutes and seconds, it takes to make one piece of product. Japan Management Association (1989) defined this measurement as either cycle or tact time. Dennis (2002) chooses to make a clear distinction between takt (or tact) and cycle time. He defined the actual time required to make a product as cycle time and defined takt time as how frequently to make a product in order to satisfy the established demand. According to Dennis (2002:51), the goal is to synchronize takt and cycle time to the greatest extent possible. Essentially, this means production cells of people, machines, materials, and methods should be adjusted in order to synchronize the number of products produced with the number of products required. Womack and Jones (1996:56) point out the physical pace of work never changes and therefore, when takt time changes signaling demand change, increases or decreases in productivity need to be accomplished by adjusting the size of the team accordingly (Womack and Jones, 1996:63).

Table 1. Takt Time Formulation (Japanese Management Association, 1989:53)

	Month	Day (480 minutes, 20 work days	Takt Time
A Car	4,800 units	240 units	2 min
B Car	2,400 units	120 units	4 min
C Car	1,200 units	60 units	8 min
D Car	600 units	30 units	16 min
E Car	600 units	30 units	16 min
	9,600 units	480 units	1 min

To illustrate the concept of takt time, I present an example from the book *Kanban: Just-In-Time at Toyota*. In the table 1 above, there are five varieties of cars with different required quantities for the month. In total, 9600 units must be produced for the month. The total number of each variety of product (vehicles) to be produced, as indicated in the second column, is established based on the expected number that will be purchased based on the sales record. The number to produce per day is established by dividing the total number of each type of vehicle required the month by the number of work days per month and is shown in the third column. Next, the daily operating time is divided by the required quantity per day to provide the takt time. The takt time for each vehicle type is shown in the fourth column.

$$Takt = Daily\ Operating\ time\ /\ Required\ Quantity\ per\ day \quad (3)$$

The notion of takt or cycle time is in essence the timing with which production must occur to precisely satisfy the demand established by the customer. Timing is essential in the sense that if products are produced too late orders may be cancelled and if produced to early, enormous inventories build up resulting in waste (Japanese Management Association, 1989:50).

Production leveling.

As takt time is the technique utilized to match production with demand, there must also be a mechanism in place to smooth demand itself in order to allow production to occur at a relatively steady rate. This technique is known as production leveling or load smoothing. In any industry, demand is seldom steady. There is normally some amount of variation in demand and in some industries great variation in demand. Despite this variability, many firms set the capacity of the workplace to handle a peak work demand and not an average value (Japanese Management Association, 1989:45). The result is underutilization of personnel, machines, and material when the amount of work required for peak demand is not present (Japanese Management Association, 1989:46). Alternatively, if the workplace continues to produce at peak capacity despite the lack of corresponding demand, the waste of overproduction occurs (Japanese Management Association, 1989:46). Thus, the most efficient condition occurs when the amount of work can be distributed equally meaning it can occur at an even pace and not at fluctuating levels (Japanese Management Association, 1989:47). This is the basis of the load smoothing or production leveling concept—eliminate the peaks and valleys in work load.

There are essentially two levels of load smoothing or *heijunka* which occur in the lean production system. The micro-level of load smoothing eliminates workload peaks and valleys by equalizing both quantities and types in production, an essential element to successful just-in-time operations (Japanese Management Association, 1989:50). This is accomplished by producing in accordance with takt time as described previously. For instance, take the 5 vehicle varieties shown in Table 1. A standard production line may seek to produce all Car As, followed by Car Bs, and so forth in order to avoid changeovers. However, this could lead to long lead times for those customers who want goods not currently being assembled, a large investment in finished goods to offset the lead time, as well as swelled WIP inventory as raw materials and parts are used in batches (Dennis, 2002:78). Alternatively, the lean production line seeks to produce individual or small lots of each variety of vehicle in the frequency indicated by the takt time. This technique distributes production volume and product mix evenly over time meaning shorter lead time, smaller finished goods and WIP inventory, and less unevenness and strain experienced by operators (Dennis, 2002:79).

The macro-level of load smoothing involves gradual adjustment of the production plan once demand changes occur (Japanese Management Association, 1989:55). For instance, if there are major differences in required production quantities from month to month, the production line is again placed in a situation in which it must cope with major fluctuations in workload. For instance, if the production plan calls for the production of 100 units a day in one month but 150 units a day the next, the line may not be able to respond. Therefore, if changes in the production plan are necessary, they should be built into the plan gradually so the production line can accommodate the changes.

With the foundational elements of lean production established, we can move to discussion what has traditionally been viewed as the two pillars of lean production (Ohno, Japanese Management Association) or the two walls of lean production as defined by the Dennis (2002) model, just-in-time and autonomation.

Just-in-Time.

Just-in-time (JIT) means producing the right item at the right time in the right quantity (Dennis, 2002:65) and constitutes the skeletal structure and starting point of the Toyota Production System (TPS) (Ohno, 1988:92). The TPS, or lean production is a system in which the production steps are arranged in sequence with the product moving in a continuous flow from raw materials to finished good. Just-in-time is an ideal state in the flow process, when the parts needed for a process arrive precisely at the time they are needed and only in the amount that is needed (Ohno, 1988:4). Thus, just-in-time is the ideal approach in achieving the concept of pull in production. The conventional view of production is to supply materials from an earlier process to a later process (Ohno, 1988:5). However, operating under this view would lead the earlier process to produce without regard to later processes resulting in waste and excess inventory. This means the possibility of numerous parts piling up at the later process, which in turn means workers spending time storing and hunting for parts rather than producing (Ohno, 1988:13). Rather, as Womack and Jones (1996:71) explain, the just-in-time approach espouses "don't make anything until it is needed, and then make it very quickly."

In order to achieve just-in-time, a new perspective is required. The American supermarket was impetus for the idea of viewing earlier steps in the production process as a store and helped enable just-in-time (Ohno, 1988:25). A supermarket is where a customer gets what is needed, when it is needed, and in the amount needed. Compared with Japan's traditional turn of the century merchandising method in which goods were peddled door to door, the supermarket eliminates labor being wasted carrying goods door to door which may not sell and keeps buyers from buying extra unwanted items (Ohno, 1988:26). By looking at the production flow in reverse, we see the later process (the shopper) goes to the earlier process (the supermarket) and communicates exactly what part or material is needed, in the right quantity, at the exact time (Ohno, 1988:26). If and when the later process withdraws a part, the earlier process will logically make only precisely what was withdrawn (restock) and waste is thus eliminated. Since, no production occurs until the customer (or later process) requests it, overproduction is effectively eliminated.

Dennis (2002:70) points out JIT is dependent on quick machine changeovers, which allow rapid response to daily customer orders and minimizes waiting, as well as the foundational elements of stability and standardized work established earlier. Quick machine changeovers are especially important in the lean production system due the elimination of batches in production equating to the significant increase in the necessary number of machine changeovers. According to Womack and Jones (1996:69) machines should be in production 90% of the time and be in changeover 10% of the time. In a system in which a machine changeover is feasible to occur after each single product is produced, it becomes clear quick changeovers are a necessity.

Kanban.

The method of communication which controls the amount of production in the Toyota just-in-time system is the *kanban* (Ohno, 1988:5). In other words, kanban is the way the just-in-time system is managed (Ohno, 1988:33). Also inspired by the supermarket system, the kanban was first adopted in the Toyota machine shop around 1953 and was utilized company wide 10 years later (Ohno, 1988:34). The kanban comes in different forms but is essentially a means of indication (Ohno, 1988:5), or a system of visual tools that synchronize and provide instructions to suppliers and customers, allowing the TPS to move smoothly (Dennis, 2002:70). According to the Japanese Management Association (1989:85), the kanban has two primary functions. First, it serves as a work order giving information concerning what and when to produce, in what quantity, by what means, as well as how to transport it. This information is all succinctly located on the kanban providing all necessary information at a glance (Japanese Management Association, 1989:85). Secondly, the kanban moves with actual material. As the actual material and kanban move together, overproduction is eliminated, priority in production is clear, and control of material is simplified (Japanese Management Association, 1989:86).

A kanban can also be thought of as the customer saying, “Please make me…” or a system of gears that synchronizes production with the pacemaker process. According to Dennis (2002:72), “Pacemaker” is the point of connection with the customer or the process at which production is scheduled. At Toyota the final assembly line is the starting point and pacemaker process as defined by Dennis (2002). The production plan with the desired types and quantity of cars, and due dates goes the final assembly line where requirements are then passed backwards through the manufacturing process via the kanban (Ohno, 1988:5). As a result, in TPS only one production schedule is needed making the accommodation of customer demand changes more easily accommodated than mass production firms which must reschedule each point in the production process (Dennis, 2002:72). The kanban system is a tool which enables the just-in-time system to operative smoothly. However, if kanban tools are utilized incorrectly, they may prevent the firm from reaching the goals for which they were created (Japanese Management Association, 1989:87). Therefore, there are rules or preconditions for operating kanban. Slightly different from the rules originally espoused by Ohno (1988), Japanese Management Association (1989) and Dennis (2002) provide the following six rules for kanban: (1) never ship defective parts, (2) subsequent process comes to withdraw, (3) produce only the quantity withdrawn, (4) level production, (5) use kanban to fine tune production, and (6) stabilize and strengthen the process.

Never ship defective parts. Production of defective parts means investing materials, equipment, and labor for goods which cannot be sold—waste. By observing this rule, processes which have just produced a defective product can immediately discover them. Additionally, problems in the process are immediately called to everyone's attention so immediate rectification can occur so subsequent processes are not affected by the defect. The second pillar of lean production, *jidoka* or automation with a human touch is a key component in eliminating defectives in the just-in-time system and will be discussed later in this chapter.

Subsequent process (customer) withdraws only what is needed. Critical for the elimination of waste, this rule has direct connection with the just-in-time concept. This rule means customers or subsequent processes come to withdraw parts and materials at the time and in the quantity needed and ensures earlier processes do not supply to subsequent processes. As we move from the notion of supplying to withdrawing, three corollaries to this rule must be present: no withdrawal without a kanban, a kanban always accompanies an item, and withdraw only the indicated parts in the indicated quantity. By following this rule, we effectively eliminate the waste of producing too many, producing to early, or the producing of the wrong part—all typical in standard production operations.

Produce only the quantity withdrawn by the customer. A natural extension of rule 2, this rule ensures production of only the exact quantity withdrawn by the subsequent process. The rule is predicated on the condition that the process restricts itself to the absolute minimum inventory possible. Due to this fact, two operational guidelines must be observed: produce no more than the number of kanbans and produce in the sequence in which kanbans were received. By observing the second and third rules, the entire production process can function in unison, much like a single conveyor.

Level Production. As has been established through the concepts of stability and load smoothing, just-in-time operations work best when production can occur at a stable, even pace. Again, the system operates with subsequent processes withdrawing parts and material from the previous process. If the subsequent process withdraws in a fluctuating manner, the previous process will need to maintain excess capacity or produce early in order to satisfy demand. Ofcourse, these wasteful activities cannot be tolerated in a lean production organization. Therefore, the kanban system requires subsequent processes to withdraw from previous process with consistency—in the same manner, in same interval, and in about same amount (Japanese Management Association, 1989:57). If implemented successfully, the fourth rule effectively guarantees an adequate supply for subsequent process as well as achieving the production as inexpensively as possible (Japanese Management Association, 1989:92).

Use kanban to fine-tune production. This rule, also related to the load smoothing concept, means the kanban system cannot be utilized to respond to major changes in required production output. As discussed by Ohno (1988:49), the kanban system essentially serves as the information system for all parts of the production line upstream of the pacemaker process. In a constantly fluctuating market, the production line must have the capability to adjust to schedule changes. Since the production line only responds to kanbans and does not have detailed schedules beforehand, within limits, the production line can make fine adjustments automatically (Ohno, 1988:51). However, major production changes must be accounted for in the production plan or pacemaker process as discussed in production leveling.

Stabilize and strengthen the process. The final kanban rule means to seek continuous improvement in all processes.

Autonomation.

Frequent line stoppages due to high defect rates make flow and pull impossible, causing kanban systems to collapse and productivity to implode (Dennis, 2002:90). The second pillar of lean production system as defined by Taiicho Ohno (1988:6), autonomation or "automation with a human touch" is a critical element in eliminating line defects. Autonomation describes machinery that can sense when abnormalities occur and turn themselves off, thus preventing the production of defective products (Ohno, 1988:6). In describing the same concept, Dennis (2001) concentrates on the Japanese term for automation, *jidoka,* which effectively means that if the worker feels they are making a defect they must immediately stop the line (Japanese Management Association, 1989: 72). As such, Dennis' conceptual definition focuses not only on machinery but intelligent workers and machines which together identify errors and take corrective actions (Dennis, 2002:89).

Sakichi Toyoda, the company founder created the concept when he invented a loom that stopped automatically when the thread snapped, or when thread was no longer in the loom (Japanese Management Association, 1989:70). Since machines only need human attention when the machine stops, a worker can attend several machines at once, reducing numbers of operators and increasing production efficiency (Ohno, 1988:7). In the case of the automatic loom, after its invention workers could handle up to 20 looms

(Japanese Management Association, 1989:71). Additionally, machine stoppages focus attention on problems ensuring they are corrected immediately so improvement occurs (Ohno, 1988:7). The autonomation or jidoka concept was further developed and extended by Shigeo Shingo (Dennis, 2002:90). Statistical methods emphasized by Deming are based on the expectation of defects (Dennis, 2002:90). Shingo espoused the true goal should be zero defects and to this end, invented the *poka-yoke*, or a simple, inexpensive failure-proofing device as a method of preventing defects (Dennis, 2002:90).

Standardized work, visual management, and the 5S system are all methods utilized to improve human reliability (Dennis, 2002:90). Despite these practices, human errors are all but impossible to eliminate. Common errors range from missing processing steps, processing errors, wrong or missing parts, and faulty machine operations among other mistakes (Dennis, 2002:92). Despite the inability to eliminate human errors, poka-yoke devices can still enable the elimination of production defects (Dennis, 2002:91).

Poka-yoke devices are essentially foolproofing mechanisms which incorporate automatic inspection into the production process. Despite the fact inspections are increased, poka-yokes actually reduce the worker's physical and mental burden by eliminating their need to constantly check for common errors (Dennis, 2002:91). This can be accomplished because poka-yokes can detect abnormal situations before they occur and shut down the machine or deliver a warning to prevent the production defect from occurring (Dennis, 2002:94). Or, if a defect does occur, a poka-yoke can stop the production line to prevent future errors (Dennis, 2002:91). Some examples of poka-yokes include a light sensor which stops or prevents a drilling operation when it fails to detect the requisite number of holes in a work piece or a machine that will not start until the piece is correctly positioned (Dennis, 2002:94). Poka-yokes can detect work piece or work method deviations, as well as deviations from some fixed value. For instance, work piece deviations or abnormalities in weight, dimensions, or shape of the product can be detected with sensing devices (Dennis, 2002:94). Work method deviations detect errors in standard motions through the use of photoelectric sensors or counters (Dennis, 2002:95). For example, a photoelectric sensor may count the number of times a worker's hand breaks a beam and if the requisite number of counts is not reached, parts must be missing (Dennis, 2002:95). An example of a poka-yoke which observes deviation from fixed value is a welding machine that will not work until after a weld tip is changed upon reaching the requisite number of uses (Dennis, 2002:95).

Involvement.

The final element of the lean production system as established by Dennis (2002) is that of involvement. Involvement essentially means that workers are continually engaged in activities which further and improve the production environment. The conceptual premise comes from the fundamental respect of the lean production system for the production workers or humanity in general and thus seeks to provide challenging and fulfilling work. Rather than push down upon workers the correct method of accomplishing tasks, workers are challenged with the task of improving operations. For example, the lean foundational elements/tools of standardized work, the 5S system, and Total Productive Maintenance are all involvement techniques (Dennis, 2002:19). Additionally, suggestions from workers on workplace improvements are valued and encouraged in the lean production system. The goal of involvement activities is to improve production, quality, safety and environment, and morale through solving problems, reducing hassles, reducing risk, and improving team member capability (Dennis, 2002:103).

Lean Production Summary.

According to Dennis (2002:144), the lean production system cannot and should not be precisely defined. However, he and other lean practitioners do provide guidance in helping to understand the goals, principles, major elements, and characteristics of the lean production system which the author has attempted to lay out in this chapter. The primary goal of lean production is to lower production costs, and is accomplished through elimination of wasteful activities which do not add value to the customer. Dennis (2002) explains providing products of the highest quality and in the shortest time frame are also primary goals of the lean production system. These goals are accomplished via the implementation of the principles of flow and pull into production. With these principles successfully implemented, raw materials move in continuous flow through the production process to become finished goods in synchronization with customer demand. In this way, all forms of waste to include overproduction are effectively reduced or eliminated. As Ohno (1988:96) explains, the underlying idea is that in the marketplace, each customer buys a different car (product) and therefore, in production, cars (products) should be manufactured one at a time. The principles of flow and pull are accomplished through establishment of the major elements of lean production to include stability, standardization, just-in-time, autonomation, and involvement as defined in the literature review. Some of the resultant characteristics of lean production system include low product cost, high product quality, low defect rates, high equipment reliability, safe work environments, close or integrated supplier relationships, as well as increased production flexibility.

Summary

This chapter reviewed the terminology and concepts concerning this research effort. The Air Force reparable asset pipeline and Lean Logistics (LL) program were discussed. Next, the mass and lean production approaches and their associated principles were discussed. Together, these concepts provide a theoretical foundation for development of a lean reparable asset pipeline model. The next chapter of this thesis explains the methodology followed to develop the lean reparable pipeline model to ensure the reader is afforded a clear understanding of the model.

III. Methodology

Introduction

The purpose of this chapter is to present the process used to develop the model of a lean reparable asset pipeline and to provide the methodology proposed to answer the research investigative questions. The chapter begins with a discussion of the system of interest and the key assumptions utilized to model that system. Next, a discussion on how the problem is formulated and the key performance measures to evaluate the problem are presented. Next, the chapter discusses the use of simulation and Arena simulation software as the appropriate methodology and tools for this research. Finally, the experimental design and statistical methods utilized during the experiment are discussed.

System of Interest—Lean Reparable Asset Pipeline

The lean reparable asset pipeline model does not model an actual system. It is a simplified version of the Air Force reparable pipeline introduced in Chapter II of this thesis, operating under parameters established by the key lean principles gathered in the literature review. The system modeled incorporates three operational bases with established stock levels. Each base utilizes assets in their aircraft fleet. Upon failure, reparable assets are removed from the weapon system and are sent to depot maintenance. This differs from the reparable asset pipeline model presented in Chapter II in which failed carcasses were first sent to base intermediate maintenance where, if the base intermediate maintenance function had the capability to repair an asset, they did so. This model operates under the 2LM concept in which the failed assets are removed from the aircraft by the base maintenance function and is sent immediately to depot maintenance. Figure 3 presents the conceptual model of the lean reparable pipeline modeled.

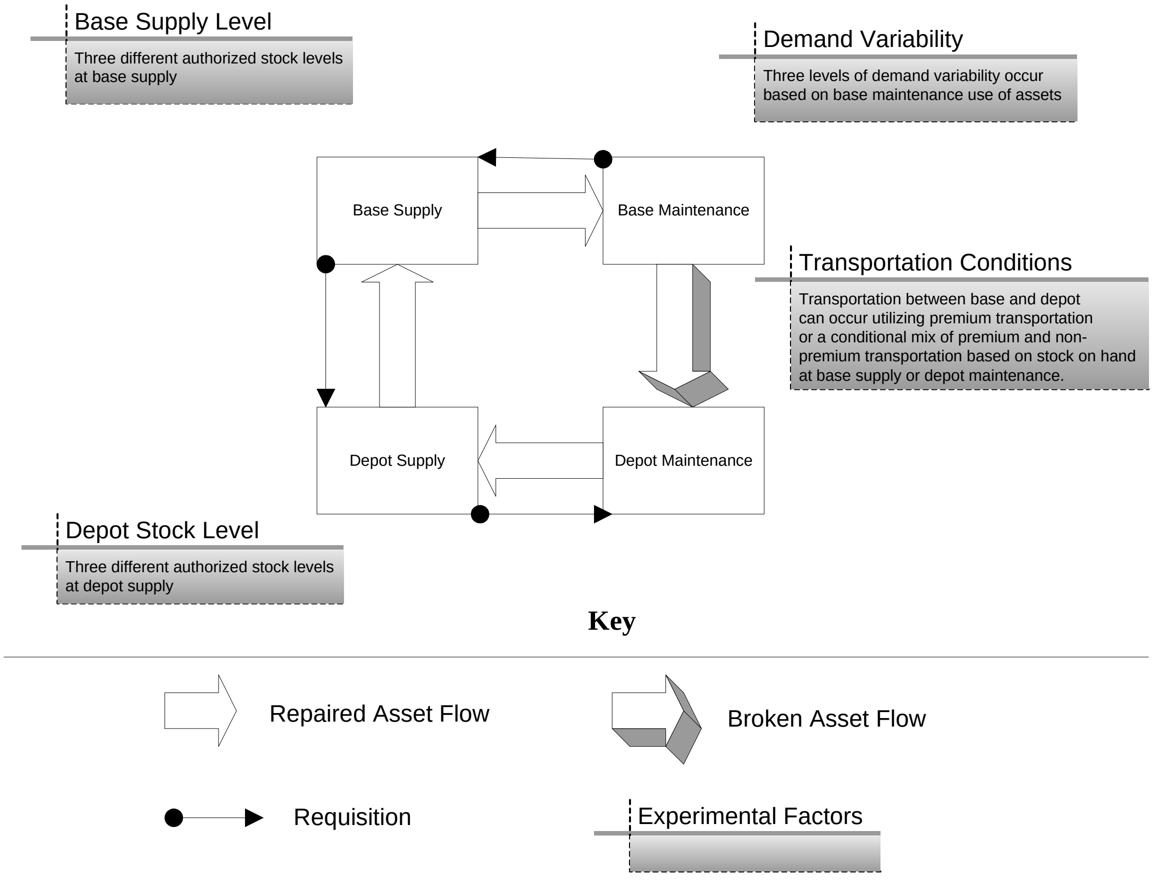


Figure 3. Lean Reparable Pipeline Conceptual Model

Within the lean reparable pipeline, the failure of asset at the base maintenance function creates a pull signal in the system. As indicated by the requisition arrows in Figure 3, when an asset fails, base maintenance signals for a replacement asset from base supply, base supply requests an asset from depot supply to replenish its stock level, and depot supply requests depot maintenance induct and repair an asset to refill the depot supply stock level. The flow of assets occurs in the opposite direction. Base maintenance sends the failed reparable carcass to depot maintenance. Repaired assets flow from depot maintenance to depot supply to base supply and ultimately to base maintenance for actual use of the asset.

There are three key features or assumptions with the lean reparable asset pipeline model which differentiates it from the actual Air Force reparable pipeline system. First, the model is not designed to model the real system. Rather, the system is meant to model the reparable pipeline with its repair function operating under lean principles of *pull* and *just-in-time* production. As discussed in the literature review, *pull* means no one upstream should produce a good or service until a customer has ordered it (Womack and Jones, 1996:67) and *just-in-time* means producing the right item at the right time in the right quantity (Dennis, 2002:65). Therefore, the model utilizes repair on demand methodology in which parts are inducted into demand based on orders from Depot Supply. Another overriding lean principle that must be demonstrated by the depot maintenance portion of the lean reparable pipeline model is a relatively steady output (repair) rate in concert with expected customer demand. As discussed in the literature review, when inventories are eliminated and products must be produced precisely at the correct time to satisfy customer demand such as in a lean system, a mechanism such as *takt* time which matches the rate of production with the rate of demand is necessary. The notion of takt or cycle time is in essence the timing with which production must occur to precisely satisfy the demand established by the customer. This is typically done in production organizations by appropriately sizing the production team. This model will assume an appropriately sized production team to match a preset demand rate. Therefore, this model will exhibit the characteristic of relatively stable and level depot output. This differs significantly from the reality of present day repair output of the Air Force depots.

Secondly, the model does not seek to model the Air Force reparable pipeline in its entirety. The model is a simplification of the actual system. In the lean reparable pipeline model, only three bases are modeled where in actuality there are significantly more locations to include bases and deployed locations with which the Air Force pipeline must extend and service. Also, this model only looks at one item, an F-15 radar warning receiver, radio frequency tuner 56C Shop Replaceable Unit (SRU) as opposed to all items which depots must repair and stock. Looking at one item should be sufficient in modeling the major outcomes of the lean production and logistics environment and allows for less complicated model construction. Additionally, the simulation model is not intended to model the in depth effects and characteristics of the lean production approach on the production floor. Instead, the model is intended to represent the only major routing paths and processes of the actual system in order to present the macro level effects of the lean approach on overall system performance.

Finally, it is assumed that there is no lateral resupply between bases or cannibalization. Cannibalization is removing a part from one aircraft already awaiting parts for another asset in order to repair an aircraft. Both practices occur in the real world operation of the Air Force fleet. However, in order to simplify model construction, these two real world pipeline features will not be accounted for.

Formulating the Problem

The purpose of this thesis research is to investigate whether the Air Force should utilize lean production and repair on demand techniques as its overarching repair philosophy. Some elements of the lean production system should be relatively easy to implement into a repair depot. Air Logistics Centers are capable of implementing stability elements of Total Productive Maintenance and the 5S system. Successful implementation of these principles could net immediate benefits such as increased machine availability and more efficient work methods. However, true benefits of the lean production system can only be realized through full implementation of its principles (Dennis, 2002:17). The successful implementation of flow and pull into the depot repair process could equate to substantially improved productivity, responsiveness, and production efficiency. However, some factors suggest it may be difficult to implement lean production to depot repair and achieve the same level of success as commercial production operations.

Lean production is dependent upon production leveling to stabilize demand and enable production to occur at a constant rate. The failure of depot level reparable assets, which establishes demand for the Air Force depot facilities, can be extremely erratic and difficult to predict and may not be conducive to production leveling and a constant, efficient repair operation. A further complicating factor is the diverse nature of the depot workload. Although flexibility is a natural strength of the lean production system and one aspect of flexibility is the ability to produce diverse product varieties--as market diversification increases, production leveling becomes more difficult (Ohno, 1988:39). As the success of the lean production system is dependent on smoothing the demand volume to eliminate variation in production, in a volatile environment in which demand volume is highly variable or significant market diversification is present, the lean production system may not be equipped to successfully operate in this environment. McCurry and McIvor (2002:77) contend the lean production system may actually become "extremely fragile" to the impact of change. Due to the varied type of reparable assets, shop flows can be quite diverse with different production sequences, different machine and skill requirements (Hill and Walker, 1994:17). Further, assets in repair typically must be tested, repaired, and then retested creating a cyclic production sequence. The diversity of assets and their varied production sequences may be an impediment to the lean production operation which seeks to arrange production steps in sequence so the product moves in continuous flow from raw material to finished good.

This research assumes successful implementation of lean production principles in the depot repair function despite the difficulties discussed. Since true implementation of a lean system means creation of a pull system which is synchronized with customer demand, it follows that a model which could demonstrate how the lean reparable pipeline would perform under several customer demand conditions is a worthy endeavor to study. Air Force reparable asset failure patterns are highly volatile meaning a relatively unstable customer demand signal for the depot (Blazer et al., 2002:77). Consequently, perhaps a significant complication for level production in Air Force depots exists. Accordingly, an experiment which demonstrates model performance under differing demand conditions as well as other related pipeline factors such as base and depot stock levels and transportation use was created.

Simulation

Since the 1960s, a variety of Operations Research methods have been utilized to analyze production/distribution processes and solve associated problems (Riddalls et al., 2000:969). In their journal article entitled, "Modeling the dynamics of supply chains", Riddalls, Bennett, and Tipi (2000) review and evaluate various methods to model and analyze production-inventory-distribution systems. Among the most prominent of those methods include continuous time differential equation models, discrete time differential models, and discrete event simulation models.

Their research found that both continuous time differential equation models and discrete time differential models considered systems on the aggregate level and thus did not possess the capability to consider individual entities or products in system. As a result, these methods are not suited for production processes in which individual entities have an impact on the fundamental state of the system (Riddalls et al., 2000:971). Other limitations include the models' inability to deal with the stochastic nature of demand variance and the effect of system delays (Bertulis, 2002:12).

Discrete event simulations emerged in order to address the deficiencies of the differential equation and discrete time differential models. Simulations allow users to actually view the physical flow of the production process where raw materials progress through resources and inventories to become finished goods. Further, simulation models can accurately portray actual system phenomena such as individual entity queue behavior (i.e. balking, blocking, swapping, etc.), inter-arrival time, and variable service speed that would make differential equations incomprehensible (Riddalls et al., 2000:974). Another critical advantage of simulation models is their capability to handle stochastic situations (Bowersox, 1989:134). Uncertainty and variance are typical considerations in production and logistics systems and as a result, models of these systems must be able to incorporate probability to accurately portray the system. Simulation can effectively model variants such as customer demand, processing and distribution times, resource failure rates, and storage capacities. Finally, because computer simulations can be built in blocks, breaking down complete processes into manageable and understandable proportions, it enables decision makers to learn about system structure and how individual components affect model performance (Disney et al., 1997:176). These factors make simulation modeling an ideal methodology for applying alternative operating rules and characteristics to a depot repair pipeline and comparing relative levels of performance.

Arena Simulation Software.

This experiment utilizes Arena 5.0 Standard Edition Simulation Software for the development and analysis of the lean reparable pipeline model. Arena utilizes modeling constructs called modules arranged in a number of templates such as "Basic Process" and "Advanced Process" based on different related purposes of each module within the template. In general, models are constructed by dragging and dropping modules into a model window and connecting them to indicate the flow of entities through the simulated system (Law and Kelton, 2000:215). Arena is a Rockwell Software package used by more than 6,000 users worldwide. The software has been successfully utilized by numerous companies to include Dow Chemical, United Parcel Service, Ford, and General Motors and has achieved a premier standing in the modeling industry (Rockwell Automation, 2000:4). The Arena lean reparable pipeline simulation model, supporting logic, and associated data sources can be seen in Appendix A of this thesis.

Performance Measures of Interest

In a simulation study, there are normally several performance measures on interest. The model for this study is primarily concerned with two performance measures: (1) Average Total Pipeline Cost per Asset Demanded—which is the total of inventory, inventory holding, repair, and transportation costs divided by the total base organizational maintenance demands; and (2) Stockage Effectiveness rate—which is the percent of times that parts requests from base organizational maintenance can be satisfied from stock levels at base supply. The average total pipeline cost per asset demanded performance measure provides an indication of the efficiency of the reparable asset pipeline. As discussed in the literature review concerning lean production and the LL program, the primary reason in implementing lean techniques is to reduce costs while meeting operational requirements. Indeed, the most significant way to reduce costs would simply be to reduce repair output, transportation, and/or inventory. However, the level of customer service must be considered. The stockage effectiveness rate provides an indication to the level of customer service provided by the system. Air Force personnel commonly discuss system performance in terms of aircraft availability. However, due to the fact this model is primarily concerned with the reparable pipeline in terms of ability to supply parts in a cost effective and timely manner, stockage effectiveness provides the greatest indication of customer service for the purposes of this experiment.

Experimental Design

The experimental design for a simulation experiment provides for a method of deciding which particular model configurations to simulate so the desired information can be obtained with the least amount of simulation (Law and Kelton, 2000:623). In addition to the response variables of interest (performance measures), the analyst must determine the input parameters or factors of the study. Factors can be classified as controllable, representing those actions controllable by managers in the corresponding real world system or uncontrollable, representing factors in the real world system outside of managerial control (Law and Kelton, 2000:623). We have both controllable and uncontrollable factors of interest in this experiment of the reparable asset pipeline. The three primary controllable factors of interest in this experiment are authorized base stock level, authorized depot stock level, and transportation utilized. The uncontrollable factor of interest is base demand variability. In actuality, this factor is controlled by the distribution selected to model the variability but it is termed uncontrollable since it is not under managerial control in the real world system. Within each of the four factors, there are several levels of interest. The purpose of our model is to study the two response variables, average total pipeline cost per asset demanded and overall base stockage effectiveness, in response to the three controllable factors and one uncontrollable factor. Table 2 below lists the factors and their assigned levels for the planned experiment.

Table 2. Experiment Factors and Levels

FACTORS	LEVELS
Demand Variability	1 - Stable 2 - Mild Variability 3 - High Variability
Base Stock Level	1 - 1 Asset 2 - 2 Assets 3 - 3 Assets
Depot Stock Level	1 - 6 Assets 2 - 7 Assets 3 - 8 Assets
Transportation	1 - All Premium Use 2 - Conditional Use of Less Than Premium

The factor *demand variability* has 3 levels: stable, mild, and high variability. The model simulates reparable asset demand at each base with a module which processes the asset for a length of time. Once the module completes processing of the asset, a demand signal is created. A normal distribution with a mean of 72 hours was utilized to determine processing time. In this way, the three bases will combine to form a depot demand signal of approximately 30 assets per 30 work days. In order to vary processing time and thus the demand, differing levels of the distribution's standard deviation will be specified. The model will use a standard deviation of 12 hours for the stable system, 24 hours for the mildly variable system, and 48 hours for the highly variable system.

The *Base Stock Level* factor has three levels established as 1, 2, and 3 assets. In general, reparable assets are expensive and thus the Air Force attempts to reduce stockage levels to the greatest extent possible. Although a zero stock level could have been specified, by definition, the stockage effectiveness performance measure could not have been utilized. Rather than create another performance measure such as average time until order fulfillment, the base stock levels of 1, 2, and 3 will be utilized for this model.

The *Depot Stock Level* factor will utilize levels of 6, 7, and 8 assets to simulate authorized stock levels at the wholesale supply function. These levels were arrived at after performing multiple pilot runs of the model. It was desirable for the model to achieve a stockage effectiveness rate of nearly 100% at maximum base and depot stock levels at the minimum demand variability level. This would provide a performance benchmark for the system at higher demand variability levels.

The *Transportation* factor will have two levels, all premium transportation use and conditional use of ground transportation. Current Air Force policy calls for all reparable items to move via premium transportation. The Air Force supply community generally uses the term *premium* to indicate fast transportation where the Air Force transportation community generally interprets *premium* as overnight air (Masciulli et al., 2002:4). For the purposes of this study, level 1 of the transportation factor will be defined as the use of standard overnight air shipment. Level 2 of the transportation factor includes conditional use of slower ground transportation. If the depot supply function at a base has a stock level of 1 or greater, shipment of assets from the depot to those bases will occur via ground transportation. For shipment of assets from the base to the depot, assets will travel via ground transportation, if there are more than 3 assets waiting to be repaired. Rates and transit times for premium and ground transportation are based on Federal Express Standard Overnight and Federal Express Ground service respectively.

Figure 4 presents a representation of our experiment. The factors described above represent inputs into the lean reparable pipeline model, while the response variables of interest are outputs of the model.

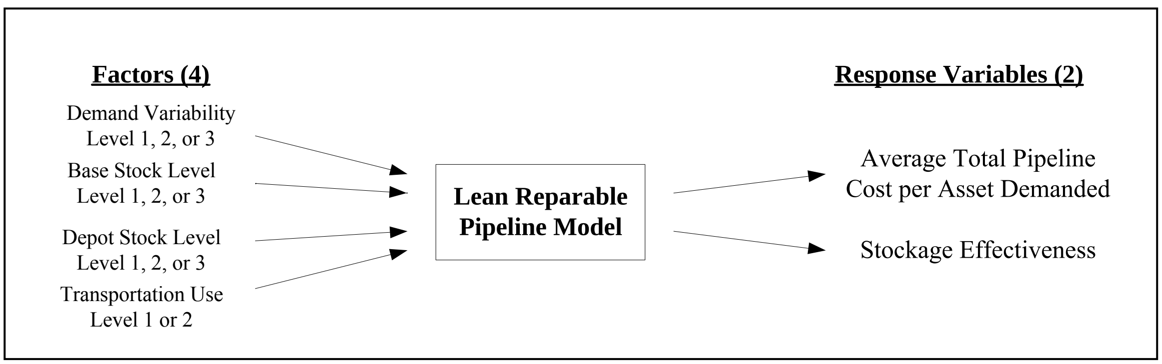


Figure 4. Lean Reparable Pipeline Experiment

Figure 5 below presents the design matrix which will be utilized to evaluate the complete factorial experiment. The numbers represent individual design points.

Base Stock Level		Low						Med						High					
Depot Stock Level		Low		Med		High		Low		Med		High		Low		Med		High	
Transportation Use		Prem	Cond	Prem	Cond	Prem	Cond	Prem	Cond	Prem	Cond	Prem	Cond	Prem	Cond	Prem	Cond	Prem	Cond
Demand Variability	Stable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	Low Var	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
	High Var	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54

Figure 5. Design Matrix for the Factorial Design

Multivariate Analysis of Variance.

Analysis of variance (ANOVA) is used to analyze the effects of independent variables on a dependent variable (Neter et al., 1985:522). "In multifactor studies, analysis of variance models are employed to determine whether different factors interact, which factors are the key ones, which factor combinations are "best," and so on" (Neter et al, 1985:523). Factor influence is made up of *main effect* and *interaction* components (McClave et al., 2001:850). Main effect refers to the direct effect of each factor on the dependent performance measure whereas interaction refers to factors combining to effect the dependent performance measure. Multivariate analysis of variance (MANOVA) is essentially ANOVA with multiple dependent variables (Barker and Barker, 1984:15). By using MANOVA, it will be determined what system factors are directly influencing or combining to influence the lean reparable pipeline model in terms of the two individual performance measures. An alternative and commonly used method of analysis would be to perform separate ANOVA analyses for each individual dependent variable. However, the presence of multiple dependent variables introduces the possibility of varying degrees of correlation between the dependent variables, thus making MANOVA a more appropriate method of analysis (Barker and Barker, 1984:15).

Efficient Frontier.

When comparing the performance of each design point or factor level combination, one must evaluate the design point on two competing performance indicators. As discussed, the two competing objectives are to reduce total system cost while at the same time maximizing stockage effectiveness. The relative importance of each of the two performance indicators depends on numerous factors which must be evaluated by the decision maker. For instance, an operationally focused individual may regard stockage effectiveness as the most important factor where a financial manager may see cost reduction as the most important factor. An approach similar to the efficient frontier will be utilized to graphically illustrate which factor level combinations perform best among the two performance indicators. This approach has been utilized by McMullen (2001) in research attempting to find solutions to a combinatorial sequencing problem with two objectives of interest. Figure 6 provides an example of what the efficient frontier model will look like.

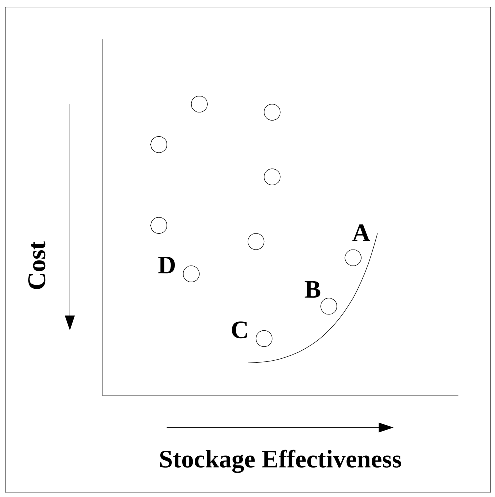


Figure 6. Efficient Frontier

The two axes in Figure 6 represent the two performance measures of interest, cost and stockage effectiveness. As indicated by the arrows, the desirable outcomes are to reduce cost and to increase stockage effectiveness. The ten circles indicate resultant cost and stockage effectiveness values of individual factor-level combinations. The curved line represents the efficient frontier. Only circles A, B, and C located near the efficient frontier line should be considered. For instance, circle A provides the highest level of stockage effectiveness. If cost is taken into consideration making circle A undesirable, circle B or circle C represent appropriate factor-level combinations because they reduce cost but still achieve the best levels of stockage effectiveness. Circle D does not represent an appropriate factor-level combination because both circles B and C have less cost and better stockage effectiveness. This technique will be utilized to display which model factor-level combinations perform the best for both performance measures within each demand environment. Since the demand environment is an uncontrollable factor, we will formulate three separate efficient frontier models for each individual demand environment. This will enable us to find the appropriate combination of controllable factors to utilize within each demand environment.

Output Analysis.

With regard to output analysis, simulations are generally referred to as either terminating or nonterminating systems. Based on the nature of the system, the procedures for output analysis of the model may differ. Generally, terminating simulations are those in which there is a "natural" event that specifies the length of the run, whereas nonterminating systems have no natural event to specify run length (Law and Kelton, 2000: 502-503). Additionally, with terminating systems we are generally interested in the model performance up to or at the predetermined stopping point whereas with nonterminating systems we are interested in the behavior of the system in the long run. The performance measures of interest in this study are both long run type measures: average total pipeline cost per asset demanded and stockage effectiveness of the system thus indicating a nonterminating, or steady state simulation.

In order to estimate the long run characteristics of the system, appropriate decisions concerning run length and the number of replications had to be determined.

The procedures outlined by Banks, et al. (2001) on output analysis for steady-state simulations were followed for this experiment. In determining run length in a steady state simulation, there are two critical considerations. First, bias in the point estimator due to artificial or arbitrary conditions should be eliminated or minimized to the greatest extent possible. There are two primary methods of removing initialization bias. One method termed intelligent initialization involves beginning the simulation in a state which is representative of the long-run conditions. The second primary method of removing initialization bias is to run the model until the model reaches steady state initial conditions (termed initialization phase) and then begin actual data collection. Due to the model logic which requires initial start up to establish cost elements and stock levels in the system, these initialization procedures were not possible. Since bias can be severe if run lengths are short, we specified a stopping point which allowed for the model to reach and operate a significant amount of time in steady state condition based on the stockage effectiveness performance measure. This was accomplished by performing pilot runs while observing a graphical presentation of the stockage effectiveness performance measure. A run length of 1560 days was established. This value simulates the pipeline operating for approximately 6 years in business days. It is assumed that the length of the run has reduced initialization bias to a negligle level for the stockage effectiveness performance measure. Normally, each performance measure should be examined for initialization bias (Banks, et al., 2001:426). However, due to the method in which the average total pipeline cost per demand measure is calculated, this was not possible. The measure is taken at the end of each model run and therefore, a graphical presentation of the cost measure was not available for examination.

Once the initialization bias has been reduced to a negligible level, the level of desired precision for the point estimator must be determined. Precision was established at $1.00 for the average total pipeline cost per asset demanded measure and .001 for the stockage effectiveness measure. The specified precision (ε) can be achieved by either increasing the number of replications (*R*) or increasing run length (Banks, et al. 2001:434). Pilot runs consisting of 30 replications were performed on all design points for both performance measures. As an example, runs calculation for cost and stockage effectiveness performance measures for design point 13 (demand variability level 1, base stock level 3, depot stock level 1, transportation level 1) was performed in the following manner:

$$R \geq (t_{0.0125,R-1} S_0 / \varepsilon)^2 = (2.364 \text{ x } 3.44177 / 1.50)^2 = 29.4 \quad (4)$$

$$R \geq (t_{0.0125,R-1} S_0 / \varepsilon)^2 = (2.364 \text{ x } .000469 / .001)^2 = 1.2 \quad (5)$$

The resultant value gave the number of runs required to estimate the average total pipeline cost per demand and stockage effectiveness with a precision of $1.50 and .1% and individual alpha values of .025. Design point 13 proved to be the design point which needed the most runs. As shown in equations above, all resultant runs calculations showed the level of precision specified for all performance measures were achieved within the 30 replications. Therefore, no additional runs were needed beyond the initial 30 runs to accomplish our stated level of precision. Despite the stated accuracy of 97.5% for each performance measure, due to the fact we have two performance measures, the resultant number of runs provide an overall level of accuracy of 95% as explained by the Bonferroni Inequality (Law and Kelton, 2000:542).

Summary

This chapter presented the process taken in the development of the model of a lean reparable asset pipeline and provided the methodology proposed to answer the research investigative questions. The chapter began with a discussion of the system of interest and the key assumptions utilized to model the system. Next, a discussion on how the problem was formulated and the key performance measures to evaluate the problem were presented. Finally, the experimental design and proposed statistical analysis methods were introduced. Chapter IV will present the final phase of this research effort in which model performance will be evaluated against numerous factors and levels using statistical analysis tools.

IV. Results and Analysis

Overview

The objective of this research was to develop a simulation model of a reparable asset pipeline operating under lean production characteristics of pull, just-in-time production, and steady depot output rate and evaluate its performance under different demand variability environments. To this point, the research discussed the general characteristics of the Air Force reparable pipeline, the Air Force Lean Logistics program, and the lean production system and its associated principles as defined under the Toyota Production System. Together, these elements of the literature formed the framework from which the lean reparable pipeline model is constructed. We also introduced discrete event simulation and discussed its merit as an appropriate methodology in estimating performance of a system under different system conditions. Chapter III demonstrated how the lean reparable pipeline model was developed and introduced the proposed methods of statistical analysis. This chapter details the final phase of the research in which an experiment was conducted, observing the lean reparable pipeline model under different base demand variability levels, authorized depot and base stock levels, and transportation rules.

Model Results

In total, 30 replications each, of the 54 separate models, representing all factor-level combinations were run for a simulation length of 1580 days. The resultant mean performance measures are displayed in Table 3 and 4 (see Appendix C for a table with both response variables for each design point). Initial analysis of these resultant values support model validity. First, as expected, stockage effectiveness improves and costs per asset demanded increases as stock level increases within each demand variability level.

Table 3. Model Stockage Effectiveness Performance Results

Base Stock Level		Low						Med						High					
Depot Stock Level		Low		Med		High		Low		Med		High		Low		Med		High	
Transportation Use		Prem	Cond	Prem	Cond	Prem	Cond	Prem	Cond	Prem	Cond	Prem	Cond	Prem	Cond	Prem	Cond	Prem	Cond
Demand Variability	Stable	0.937	0.940	0.961	0.962	0.973	0.972	0.981	0.977	0.989	0.989	0.986	0.982	0.993	0.989	0.994	0.998	0.995	0.994
	Low Var	0.880	0.881	0.913	0.914	0.926	0.927	0.955	0.944	0.969	0.958	0.967	0.964	0.975	0.964	0.982	0.976	0.978	0.973
	High Var	0.790	0.789	0.815	0.813	0.826	0.826	0.917	0.901	0.935	0.914	0.939	0.924	0.957	0.948	0.965	0.958	0.970	0.959

Table 4. Model Cost Performance Results

Base Stock Level		Low						Med						High					
Depot Stock Level		Low		Med		High		Low		Med		High		Low		Med		High	
Transportation Use		Prem	Cond	Prem	Cond	Prem	Cond	Prem	Cond	Prem	Cond	Prem	Cond	Prem	Cond	Prem	Cond	Prem	Cond
Demand Variability	Stable	7012.92	7011.58	7052.30	7045.43	7091.83	7076.40	7151.37	7108.59	7192.90	7146.72	7233.09	7183.09	7283.78	7231.57	7326.56	7282.12	7369.23	7312.34
	Low Var	7021.11	7016.54	7056.25	7050.69	7091.98	7081.62	7157.68	7118.03	7195.84	7155.32	7237.29	7189.96	7286.07	7236.08	7333.14	7283.21	7374.36	7316.96
	High Var	7043.61	7039.76	7077.39	7071.04	7105.22	7103.44	7178.02	7142.47	7217.71	7180.42	7253.82	7213.13	7311.48	7270.88	7350.30	7310.26	7390.14	7343.75

Second, when comparing treatments with identical stock levels but differing demand variability levels, Figure 7 shows that as expected, stockage effectiveness is more strongly affected by demand variability at lower stock levels than at higher stock levels.

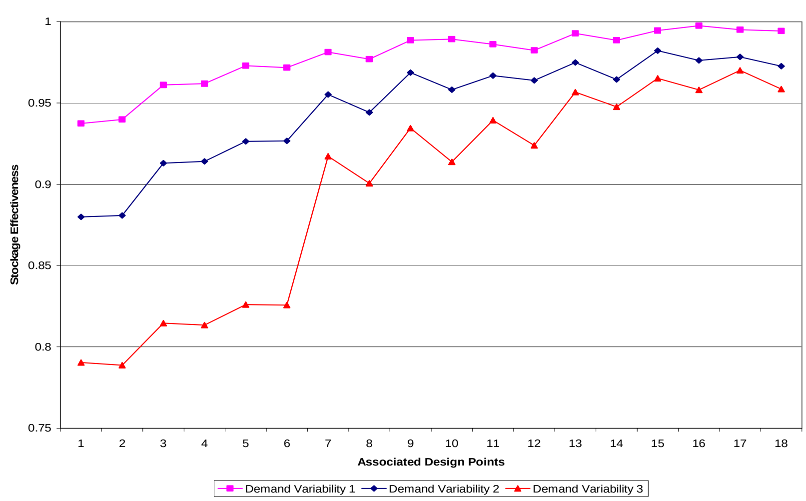


Figure 7. Demand Variability Effect on Stockage Effectiveness

In Figure 7, the line labeled "Demand Variability 1" represents design points 1-18. The line labeled "Demand Variability 2" represents design points 19-36 and design points 37-54 are represented by "Demand Variability 3". As the chart indicates, at design point 1, 19, and 37 (far left) where stock levels are lowest, the different demand variability causes great separation in the points. However, as you move to the right where stock level increases, the design points move closer together indicating less effect on stockage effectiveness due to the demand variability.

Next, when comparing treatment pairs in which the transportation factor is changed, as expected, the total pipeline cost per asset demanded always decreases when conditional use of non-premium transportation is used. Again, this is an observation that is consistent with expectations. However, in terms of stockage effectiveness, there are 6 design points which show better performance by the treatment utilizing non-premium transportation over premium transportation (design points 2, 4, 10, 17, 20, and 24). Four of these occurrences are in demand variability level 1 and two are in demand variability level 2. The largest difference among these 6 design points from their associated premium transportation treatment pair is .00309. It is expected that this difference is not significant. If not significant, it seems to support the notion that at low demand variability, the conditional use of non-premium transportation has a neglible effect on stockage effectiveness.

Multivariate Analysis of Variance

Initial analysis of the model results indicates model validation. Formal analysis of model results using Multivariate Analysis of Variance (MANOVA) was performed to test for the significance of the main and interactions effects on the two response variables. SPSS statistical software was utilized to perform the MANOVA. There are two basic statistical assumptions for MANOVA that should be satisfied: multivariate normality of distribution and homogeneity of dispersion matrices (Barker and Barker, 1984:26). Normality of distribution and homogeneity were checked using SAS JMP 5.0.1.2 statistical analysis software. Nonnormality was found in a number of treatment distributions at the lowest variability level. This was caused by a number of individual treatment runs reaching stockage effectiveness levels of 100%. Departures from the homogeneity assumption were also found. Despite these departures, in light of MANOVA's robustness in dealing with departures from normality and homogeneity (Barker and Barker, 1984:26), MANOVA was still performed.

Table 5 presents the results of the multivariate tests of the MANOVA. Full results of the SPSS MANOVA output are displayed in Appendix B. The results showed each of the main effects and all two factor interactions were significant base on an alpha value of .05. No three or four factor interactions proved to be significant. Based on these

Table 5. MANOVA Results

MULTIVARIATE TESTS

MAIN EFFECT	P-VALUE
Demand Variability	0.000
Base Stock Level	0.000
Depot Stock Level	0.000
Transportation Use	0.000

TWO FACTOR INTERACTION	P-VALUE
Demand Variability and Base Stock Level	0.000
Demand Variability and Depot Stock Level	0.000
Demand Variability and Transportation Use	0.000
Base Stock Level and Depot Stock Level	0.000
Base Stock Level and Transportation Use	0.000
Depot Stock Level and Transportation Use	0.000

results, we then examined the individual Analysis of Variance (ANOVA) results for the individual two-factor interaction on the two individual performance measures.

Results –Stockage Effectiveness as the Response Variable.

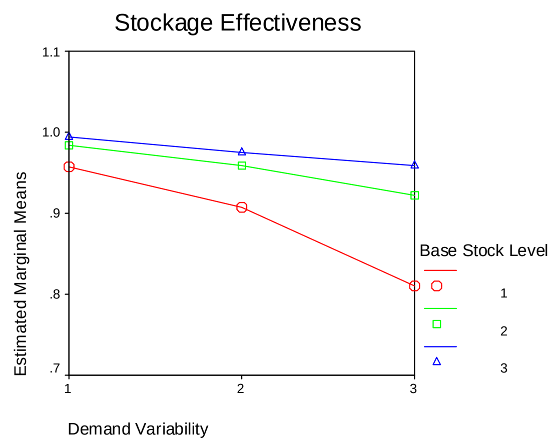
The first part of the experiment discussed uses average base level stockage effectiveness as the response variable with all four factors at their respective levels. Results of the ANOVA are shown in Table 6. ANOVA showed significant interaction between demand variability and base stock level, demand variability and depot stock level, demand variability and transportation use, base stock level and depot stock level, and base stock level and transportation use. Test P-values showed non-significant interaction between depot stock level and transportation use.

Table 6. Stockage Effectiveness ANOVA Results

TWO FACTOR INTERACTION	P-VALUE
Demand Variability and Base Stock Level	0.000
Demand Variability and Depot Stock Level	0.001
Demand Variability and Transportation Use	0.000
Base Stock Level and Depot Stock Level	0.000
Base Stock Level and Transportation Use	0.000
Depot Stock Level and Transportation Use	0.699

Given significant interaction effects on stockage effectiveness, we concentrate our analysis on the nature of those interaction effects. Interaction effects occur when factors act together creating a synergistic effect on the response variable. Figures 8-13 show the estimated marginal means plots of each of the interaction effects on stockage effectiveness. In addition, the figures contain the family-wise confidence intervals for the individual treatment means. These confidence intervals are utilized to determine whether the differences were significant or not.

Figure 8 presents the marginal means plot of the interaction effect of demand variability and base stock level on stockage effectiveness. The slopes of the lines within each plot explain the intensity and direction of the effect as level changes. Visual analysis of Figure 8 indicates the nature of the interaction of base stock level and demand variability on stockage effectiveness. At base stock level 1, increasing demand variability seems to exert greater effect on stockage effectiveness than at higher stock levels. This is supported by the close proximity of the top two lines and the relative



Interaction Factors		95% Family Confidence	
B. Stock Level	D. Variability	Lower	Upper
1	1	0.953357	0.960643
	2	0.903357	0.910643
	3	0.806357	0.813643
2	1	0.980357	0.987643
	2	0.955357	0.962643
	3	0.918357	0.925643
3	1	0.990357	0.997643
	2	0.971357	0.978643
	3	0.955357	0.962643

Figure 8. Variability and Base Stock Level Interaction Effect on Stockage Effectiveness

tightness of the three points at demand variability level 1 and separation of the three points demand variability level 3. Examination of the confidence intervals allows us to make significance determination at any of the treatment levels. Since none of the confidence intervals overlap, we can say with at least 95% confidence that each treatment level is significantly different.

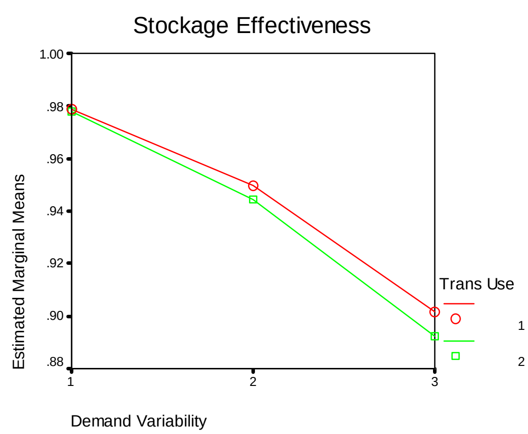
Figure 9 presents the interaction effect of demand variability and depot stock level on stockage effectiveness. The relatively parallel lines demonstrates the nature of the interaction is much the same throughout the levels of each factor. The relative greater slope of the lines from variability level 2 to variability level 3 demonstrates a

Interaction Factors		95% Family Confidence	
D. Stock Level	D. Variability	Lower	Upper
1	1	0.965357	0.972643
	2	0.929357	0.936643
	3	0.880357	0.887643
2	1	0.978357	0.985643
	2	0.948357	0.955643
	3	0.896357	0.903643
3	1	0.980357	0.987643
	2	0.952357	0.959643
	3	0.903357	0.910643

Figure 9. Varibility and Depot Stock Level Interaction Effect on Stockage Effectiveness

more intense effect on stockage effectiveness at the highest variability level. This is likely due to the greater degree of change from demand variability level 2 to level 3 in comparison from demand variability level 1 to 2. Examination of the confidence intervals shows overlap between all treatments of depot stock levels 2 and 3. Therefore, we cannot say we 95% confidence there is a difference in the stockage effectiveness means of stock levels 2 and 3. We can, however, say with 95% confidence that there is a difference in stockage effectiveness at depot stock level 1 from both depot stock levels 2 and 3 across all demand variability levels.

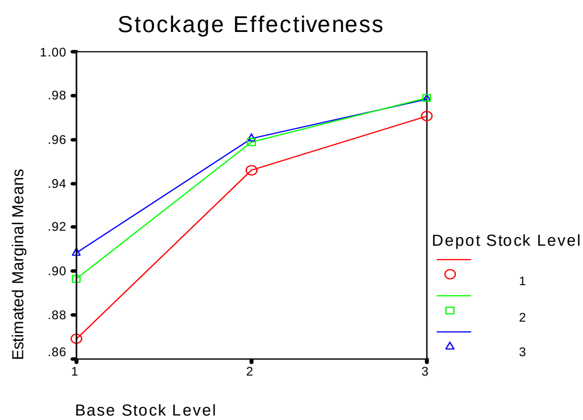
Figure 10 presents the interaction effect of demand variability and transportation use on stockage effectiveness. The fact that the two lines touch at demand variability level 1 demonstrates that there is no significant difference in stockage effectiveness due



Interaction Factors		95% Family Confidence	
Trans Use	D. Variability	Lower	Upper
1	1	0.976131	0.981869
	2	0.947131	0.952869
	3	0.899131	0.904869
2	1	0.975131	0.980869
	2	0.942131	0.947869
	3	0.889131	0.894869

Figure 10. Variability and Transportation Interaction Effect on Stockage Effectiveness

to differing transportation levels at low levels of variability. Since the confidence intervals overlap at variability levels 1 and 2 for both transportation factor levels, we cannot say with 95% confidence that there is a difference between stockage effectiveness between transportation levels at stable and low variability. However, as demand variability increases to level 3, the interaction with transportation level 2 creates a significant decrease in stockage effectiveness.



Interaction Factors		95% Family Confidence	
B. Stock Level	D. Stock Level	Lower	Upper
1	1	0.866357	0.873643
	2	0.892357	0.899643
	3	0.904357	0.911643
2	1	0.942357	0.949643
	2	0.955357	0.962643
	3	0.956357	0.963643
3	1	0.967357	0.974643
	2	0.975357	0.982643
	3	0.974357	0.981643

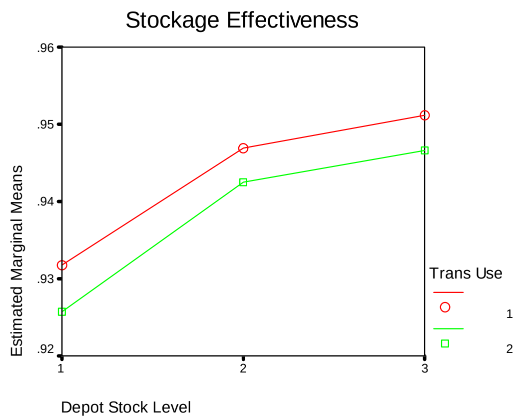
Figure 11. Base Stock Level and Depot Stock Level Interaction Effect on Stockage Effectiveness

Figure 11 shows interaction among the base and depot stock level factors on stockage effectiveness. The separation of the three lines and their respective confidence intervals at base stock level 1 indicate significant differences of stockage effectiveness with all depot stock levels. However, at higher base stock levels, the significant effect diminishes as indicated by the tightness of the top two lines and overlapping of the confidence intervals. Inspection of the confidence intervals shows there is no significant difference in depot stock levels 2 and 3 at base stock levels 2 and 3. This seems to make intuitive sense since the main effect of the base stock level appears to be much stronger than main effect of the depot stock level. This is due to the fact a change of one level in base stock equates to a change of 3 assets in the system whereas a change of one level in depot stock is only a change of 1 asset in the system.

Interaction Factors		95% Family Confidence	
Base Stock	Trans Use	Lower	Upper
1	1	0.888131	0.893869
	2	0.888131	0.893869
2	1	0.957131	0.962869
	2	0.947131	0.952869
3	1	0.976131	0.981869
	2	0.970131	0.975869

Figure 12. Base Stock Level and Transportation Use Interaction on Stockage Effectiveness

Figure 12 demonstrates that at low levels of base stock, there is no significant difference in stockage effectiveness caused by transportation. However, as base stock level increases, transportation use does become significant as conditional non-premium transportation use reduces stockage effectiveness. This is likely to occur because the institution of non-premium transportation use is far less likely to occur at base stock level 1. However, as stock level increases, the use of non-premium transportation increases and thus the possibility of a stock out during the longer transit time increases. It should be noted that the difference in treatment means at base stock level 3 is smaller than the difference at base stock level 2. This seems to demonstrate that if stock level increased further, the difference would again become insignificant.



Interaction Factors		95% Family Confidence	
Depot Stock	Trans Use	Lower	Upper
1	1	0.929131	0.934869
	2	0.923131	0.928869
2	1	0.944131	0.949869
	2	0.939131	0.944869
3	1	0.948131	0.953869
	2	0.944131	0.949869

Figure 13. Depot Stock Level and Transportation Use Interaction on Stockage Effectiveness

Figure 13 depicts the depot stock level and transportation use interaction on stockage effectiveness. As discussed previously, effects test p-value demonstrated the interaction effect of these two factors to be insignificant. The relatively parallel nature of the lines of the marginal means chart appears to show a lack of interaction. The confidence intervals of the two lines at depot stock levels 2 and 3 demonstrate significance of the treatment means cannot be determined with 95 % confidence. However, at depot stock level 1, there is a significant difference in stockage effectiveness between the two treatments for transportation use.

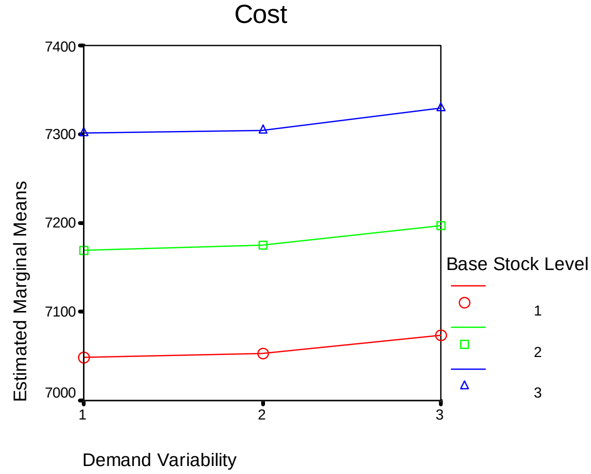
Results –Cost per Asset Demanded as the Response Variable

The second part of the experiment presents average total pipeline cost per asset demanded as the response variable with all four factors at their respective levels. ANOVA results for the two factor interactions on the cost performance measure are displayed in Table 7. Due to the effects test indicating significant interaction effects, we again concentrate our analysis on the nature of those interaction effects as we did with stockage effectiveness. Figures 14-19 show the estimated marginal means plots of each of the interaction effects on cost as well as the family confidence intervals for the individual treatment means.

Table 7. Cost ANOVA Results

TWO FACTOR INTERACTION	P-VALUE
Demand Variability and Base Stock Level	0.040
Demand Variability and Depot Stock Level	0.000
Demand Variability and Transportation Use	0.000
Base Stock Level and Depot Stock Level	0.000
Base Stock Level and Transportation Use	0.000
Depot Stock Level and Transportation Use	0.000

Figure 14 presents the marginal means plot of demand variability and base stock interaction effect on cost. The relatively parallel lines between each base stock level shows that there is a relatively small level of interaction between the two factors on cost. This is likely the reason for the relatively high p-value (<= .04) of these two factors on

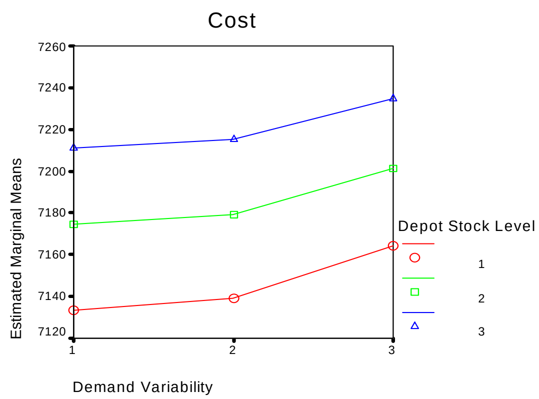


Interaction Factors		95% Family Confidence	
B. Stock Level	D. Variability	Lower	Upper
1	1	7045.48	7051.34
	2	7050.10	7055.97
	3	7070.48	7076.34
2	1	7166.36	7172.23
	2	7172.75	7178.62
	3	7194.66	7200.53
3	1	7298.00	7303.86
	2	7302.04	7307.90
	3	7326.54	7332.40

Figure 14. Base Stock Level and Demand Variability Interaction Effect on Cost Measure

the interaction effects test. Confidence intervals tell us that with at least 95% confidence, all mean cost results are significantly different for each treatment level. Based on the low (although significant) level of interaction between the two factors, we can conclude that the significant difference in cost means is mainly due to main effect of base stock increasing system cost at successive levels. Due to the changing slopes of the curves, we also see that as variability goes up, it causes an increase in mean cost. These two factors interact only slightly relative to the interaction effects between other factors on the cost measure.

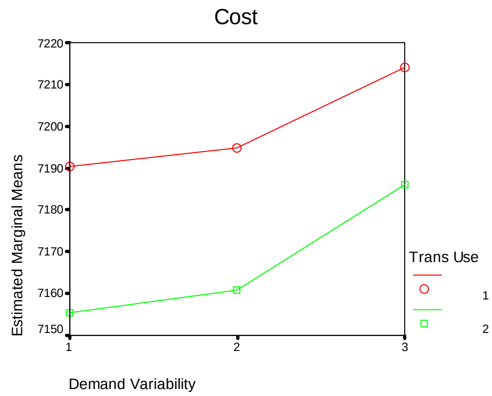
Figure 15 presents the marginal means plot of the interaction effect on cost of the demand variability and depot stock factors. The plot shows the nature of the interaction between demand variability and depot stock level is very similar to the nature of the interaction between demand variability and base stock level. Since we see the distance between the plots at the lowest level of variability is slightly wider than the width of the plots at the highest level of variability, we see that the effect of a depot stock level increase on cost diminishes slightly as demand variability increases. In general, we again see that the main effects of higher depot stock levels and higher demand variability equates to higher cost.



Interaction Factors		95% Family Confidence	
D. Stock Level	D. Variability	Lower	Upper
1	1	7130.37	7136.23
	2	7136.32	7142.18
	3	7161.44	7167.30
2	1	7171.41	7177.27
	2	7176.14	7182.01
	3	7198.25	7204.12
3	1	7208.06	7213.93
	2	7212.43	7218.29
	3	7231.99	7237.85

Figure 15. Depot Stock Level and Demand Variability Interaction Effect on Cost Measure

Figure 16 presents the marginal means plot of the interaction effect on cost of the transportation use and demand variability. Based on examination of the confidence intervals, we see there is significant difference in mean cost at the different treatment levels. Again, we see relative parallel lines showing the level of interaction although significant, is not the main reason for the significant difference in the treatments means.

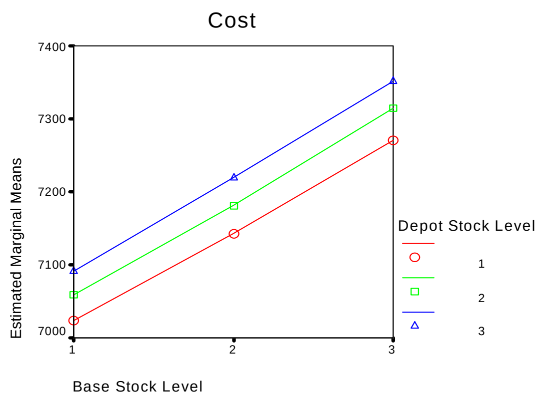


Interaction Factors		95% Family Confidence	
Trans Use	D. Variability	Lower	Upper
1	1	7188.55707	7192.32693
	2	7192.97307	7196.74293
	3	7212.30307	7216.07293
2	1	7153.43107	7157.20093
	2	7159.05007	7162.81993
	3	7184.24407	7188.01393

Figure 16. Transportation Use and Demand Variability Interaction Effect on Cost Measure

We attribute the main effects of higher demand variability and premium transportation use as leading to higher cost. We also see that although the conditional use of non-premium transportation (level 2) saves cost in comparison with all premium transportation, its cost reduction effect diminishes at higher levels of demand variability. This is demonstrated by the relative tightness of the plot at demand variability level 3 compared to demand variability level 1.

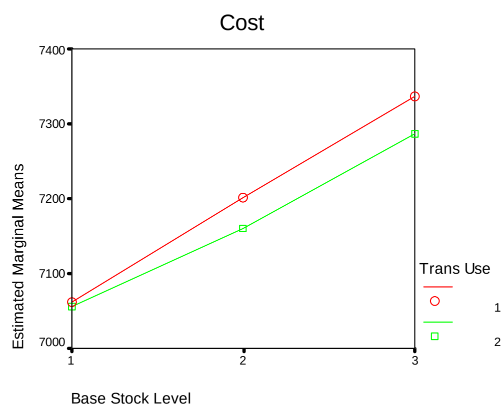
The marginal means plot of the interaction effect on cost of the base stock level and depot stock level is shown in Figure 17. Based on examination of the confidence intervals, we see there is significant difference in mean cost at the different treatment levels. Like the previous plots, we see relative parallel lines showing the level of interaction although significant, is not the main reason for the significant difference in the treatments means. We attribute the main effects of increased base and depot stock levels as the primary reasons for higher costs. This makes intuitive sense in that additional assets will lead to greater inventory and holding costs with all other factors held constant. Interaction likely occurs due to the relative mix of base and depot assets at different levels.



Interaction Factors		95% Family Confidence	
B. Stock Level	D. Stock Level	Lower	Upper
1	1	7021.32	7027.19
	2	7055.92	7061.78
	3	7088.82	7094.68
2	1	7139.76	7145.63
	2	7178.55	7184.42
	3	7215.46	7221.33
3	1	7267.04	7272.91
	2	7311.33	7317.20
	3	7348.20	7354.06

Figure 17. Base and Depot Stock Level Interaction on Cost Measure

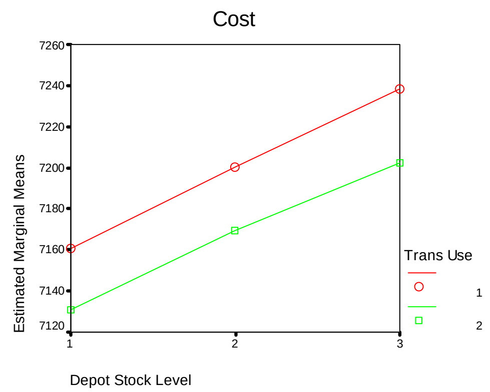
The marginal means plot of the interaction effect on cost of the transportation use and base stock is shown in Figure 18. Based on examination of the confidence intervals, we see there is significant difference in mean cost at each of the different treatment levels despite how close the plots are at the base stock level 1. Based on visual inspection of the plot, we see that at low levels of base stock, the use on non-premium transportation makes a small but significant improvement in cost performance (lower). However, we see by the separation of the points at base stock level 2, interaction causes the performance to improve to a greater degree than at base stock level 1. This cost improvement continues at base stock level 3 although not at the same magnitude as the improvement from base stock level 1 to 2.



Interaction Factors		95% Family Confidence	
Base Stock	Trans Use	Lower	Upper
1	1	7059.52	7063.29
	2	7053.28	7057.05
2	1	7200.08	7203.85
	2	7157.86	7161.63
3	1	7334.23	7338.00
	2	7285.58	7289.35

Figure 18. Base Stock Level and Transportation Use Interaction Effect on Cost Measure

The marginal means plot of the interaction effect on cost of depot stock level and transportation use is presented in Figure 19. Based on examination of the confidence intervals, we see there is significant difference in mean cost at each of the different treatment levels. Based on visual inspection of the plot, we see that at levels 1 and 2 of depot stock, the lines run near parallel but widen from depot stock level 2 to 3. This signifies the conditional use of non-premium transportation interacts with the highest depot stock level to reduce cost.



Interaction Factors		95% Family Confidence	
Depot Stock	Trans Use	Lower	Upper
1	1	7158.79	7162.56
	2	7128.73	7132.50
2	1	7198.38	7202.15
	2	7167.58	7171.35
3	1	7236.67	7240.44
	2	7200.42	7204.18

Figure 19. Depot Stock Level and Transportation Interaction Effect on Cost Measure

Efficient Frontier

The efficient frontier model serves as a method of displaying the experiment results in a manner that conveys tradeoffs involved with each factor level combination. Figures 20-22 present the efficient frontiers to display which model factor-level combinations perform the best for both performance measures within each demand environment. The factor-level combinations are broken into different demand environments due to the demand factor being an uncontrollable variable in the real world system. Figure 20 presents the efficient frontier for demand variability level 1. Each individual design point is annotated with its identifying number.

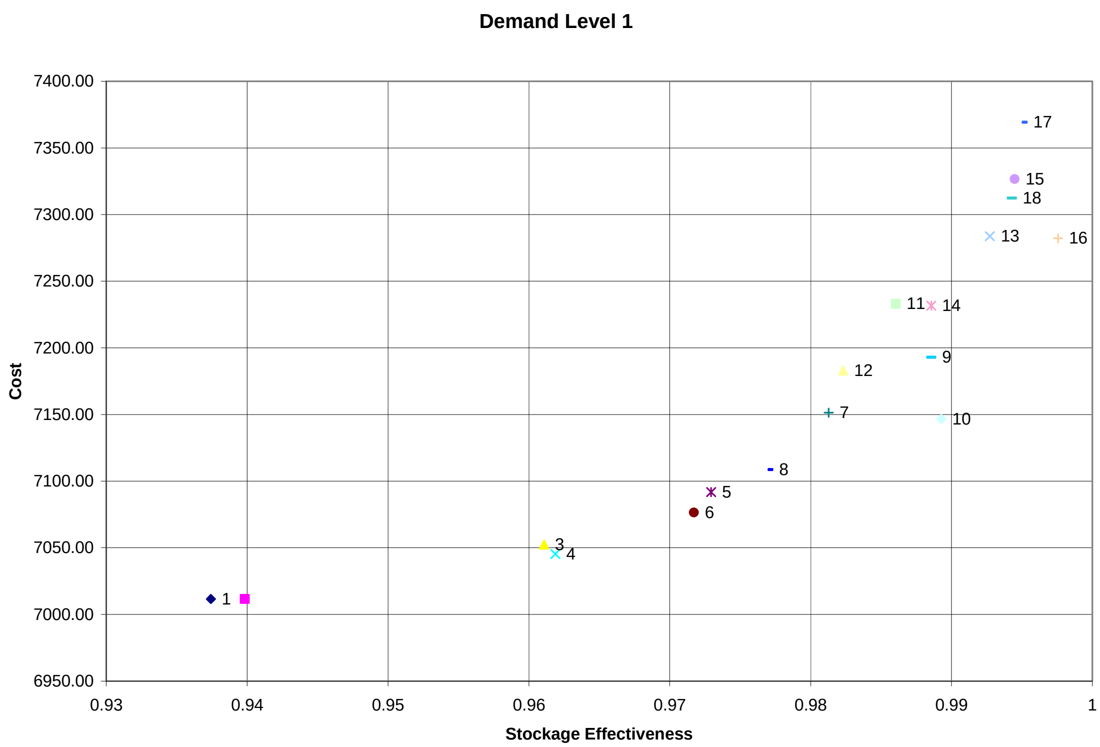


Figure 20. Demand Variability Level 1 Efficient Frontier

Evaluating the efficient frontier within demand level 1, we see a number of trends which will form the basis for the conclusions of this thesis. First, when examining paired factor-level combinations such as design points 1 and 2, we see the even numbered point is lower in cost than its paired odd point. This is attributable to each even numbered point representing factor-level combinations in which conditional use of less expensive, non-premium transportation with all other independent variables being held constant. We also see a general trend of increasing cost difference among successive design point pairs displayed as increasing vertical distance between paired points among successive pairs. This is likely explained by a combination of our interaction effects uncovered by the MANOVA results. Since the interaction effect on cost between transportation use and base and depot stock levels increases at higher stock levels, it makes sense that we see little separation in terms of cost between points 1 and 2 but more separation between 3 and 4.

There is also a general trend among successive design point pairs to increase in cost and stockage effectiveness. For instance, the design point pair made up of design points 3 and 4 has an increased stockage effectiveness and cost per asset demanded than the pair made up of design points 1 and 2. When focusing on cost, comparing all odd numbered design points in which premium transportation is used, each successive design point is higher than its predecessor. This holds constant when comparing each even numbered design point. The increase in cost is attributable to each successive design pair equating to an overall increase in total assets in the system. In general, stockage effectiveness increases with successive design point pairs due to the increase in total assets. These trends are also visible in both Figures 21 and 22, which present the efficient frontier plots of design points for demand variability levels 2 and 3. In general, the greatest differences displayed among the three levels of demand variability is the resultant stockage effectiveness response.

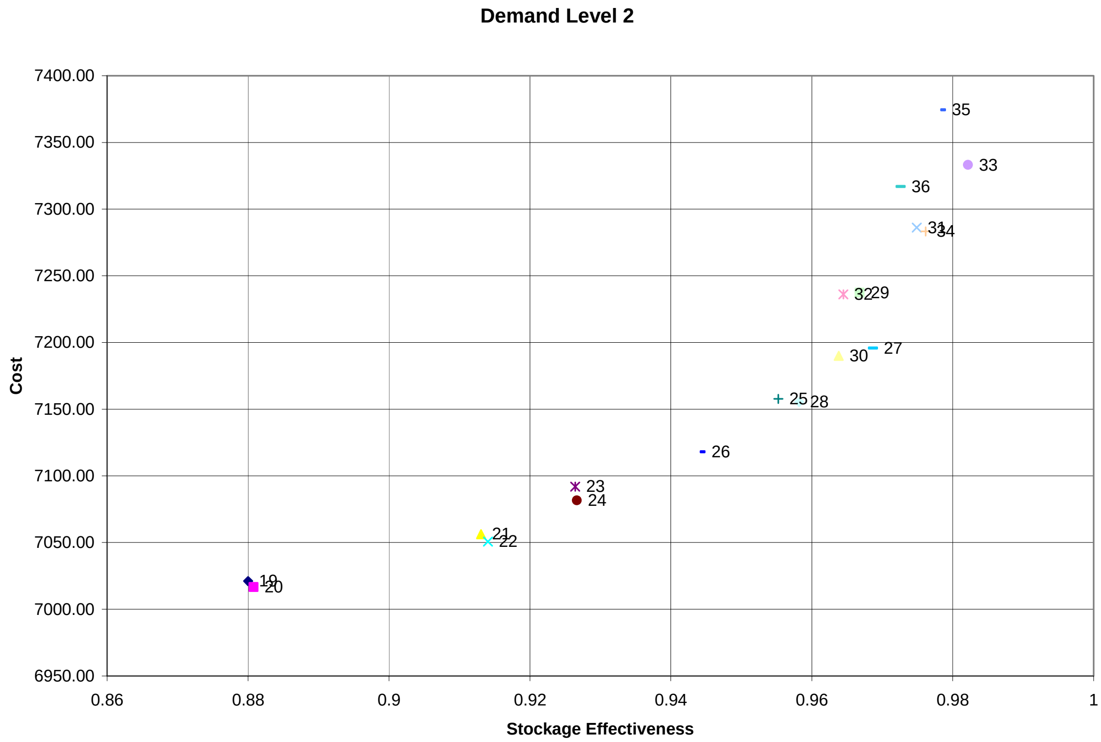


Figure 21. Demand Variability Level 2 Efficient Frontier

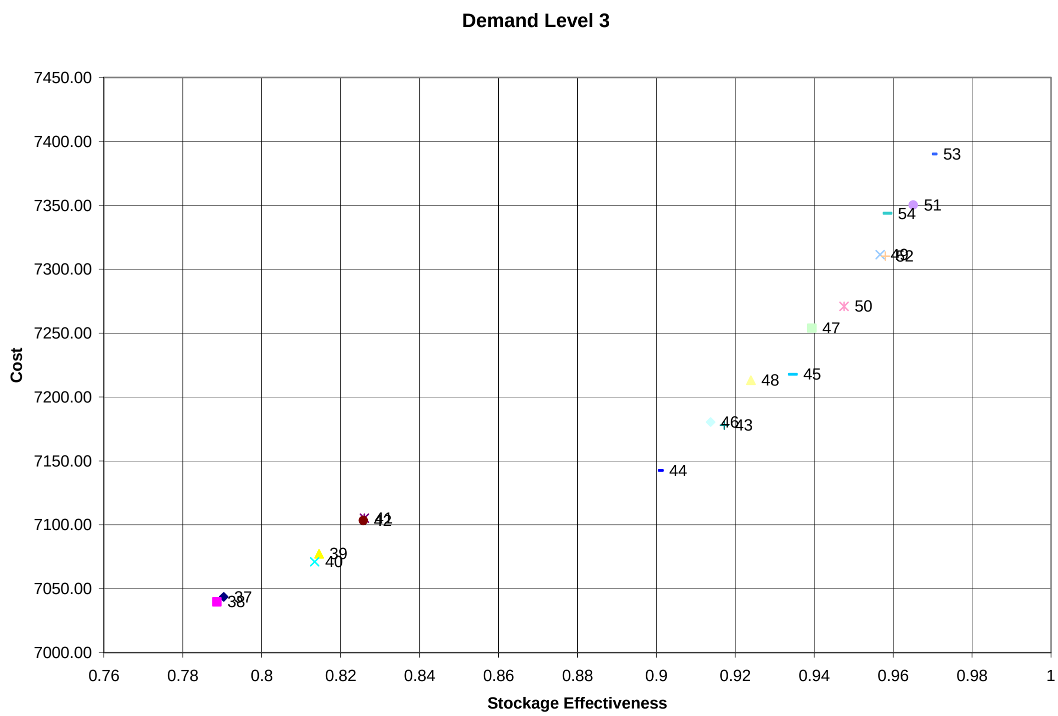


Figure 22. Demand Variability 3 Efficient Frontier

Figure 23 presents the efficient frontier plot of all design points across the three variability levels. Perhaps the most distinguishable characteristic of the plot is the significantly lower stockage effectiveness responses for the factor-level combinations of high demand variability and low stock levels (design points 1-6) and low base stock levels in particular in comparison with treatments with lower levels of demand variability. At higher base and depot stock levels, it appears that the demand variability has less effect on stockage effectiveness although it still combines with other factors to reduce overall effectiveness.

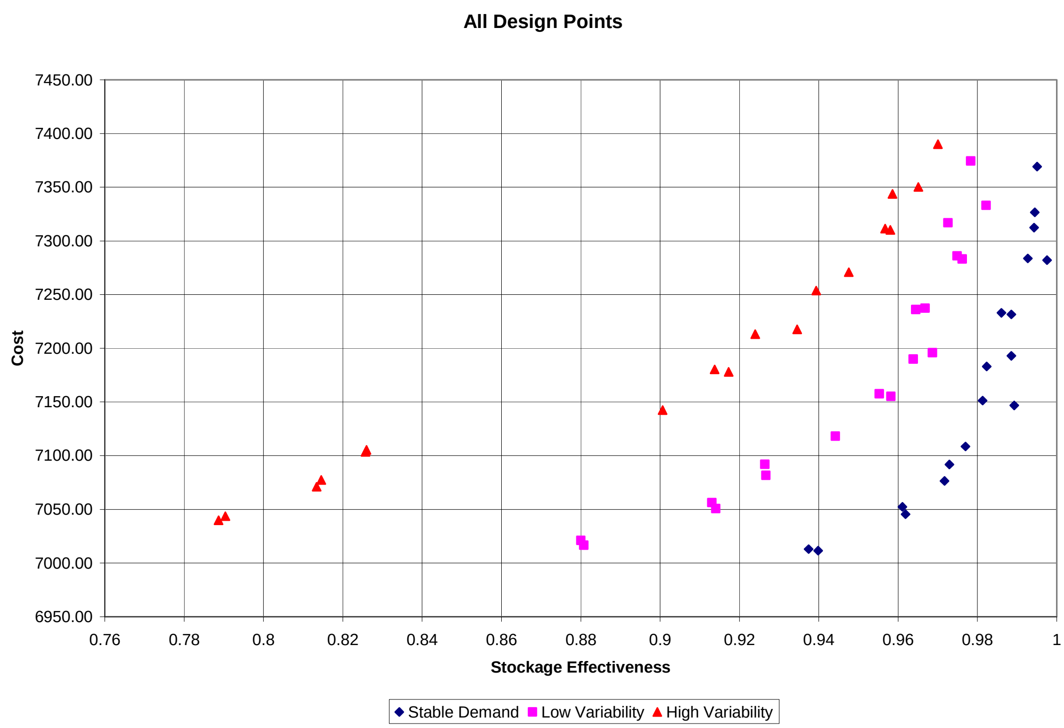


Figure 23. Efficient Frontier of All Design Points

Overall Findings

The experiment accomplished the primary task of evaluating lean reparable pipeline performance in various demand environments. First, the reparable pipeline was modeled in a manner such that the depot repair function operated under two key features: it utilizes repair on demand methodology and exhibits a relatively stable rate of production. Repair on demand methodology is mandated for repair of Air Force reparable assets in Air Force Policy Directive 20-3 and mirrors the fundamental lean principle of pull. A relatively steady production or repair rate is both an advantage and limitation that accompanies the implementation of lean principles. It was assumed that the lean repair depot right-sizes its workforce and repair capability in order to capitalize on cost savings associated with lean techniques. Based on this assumption, steady repair rate in concert with the expected base level demand rate was established as a characteristic of the model.

Once modeled, actual system performance in terms of average total system cost per demand and stockage effectiveness was evaluated across differing demand environments. As shown in Figure 23, in general, the lean reparable system performed better across both performance measures at lower demand variability levels. In particular, MANOVA results showed a significant interaction effect of base stock and demand variability levels on stockage effectiveness. Therefore, at low levels of base stock, high levels of demand variability significantly decreased stockage effectiveness. However, as base and depot stock levels rose to their highest levels, the effect of demand variability on stockage effectiveness diminished.

Another key finding of this experiment involved the use of non-premium transportation in the lean reparable pipeline. The Air Force mandates the use of premium, time-definite transportation for reparable assets between bases or deployed sites to and from depot or other sources of repair with a total transportation time of no more than two days. Recent studies have suggested the Air Force tends to overuse premium transportation over more economical sources of transportation, especially when transportation performance among the non-premium and premium transportation modes are equal (i.e. 2-day air versus 2-day ground shipment). This study sought to compare pipeline performance in terms of both cost and stockage effectiveness elements among treatments utilizing premium transportation and those employing conditional use of non-premium transportation. For the purposes of this study, premium transportation exhibited a transportation time of approximately 1 day as opposed approximately 2 days for non-premium transportation. This difference in transportation time ensured there was a transportation performance advantage for premium transportation. This study sought to determine whether the conditional use non-premium transportation could be utilized in the lean reparable pipeline in order to save on transportation costs without damaging stockage effectiveness performance.

Among treatment pairs in which only transportation level was changed, those treatments utilizing conditional use on non-premium transportation always performed better in terms of cost. This cost performance was normally very small at the lowest level of base and depot stock but generally increased as stock levels increased regardless of demand variability level. The MANOVA results showed significant interaction effects between transportation use and both base and depot stock levels on cost performance.

Generally, as base and depot stock levels increased, the effect of non-premium transportation increased resulting in lower costs per asset demanded. In managerial terms, this is because at low stock levels, non-premium transportation is used less than at higher stock levels due to the conditions set for non-premium use. Since, its use occurs less, the effect of conditional non-premium transportation on cost is less than at higher levels of stock. MANOVA results also showed that at higher demand variability levels, non-premium transportation had less of a cost reducing effect. Table 8 illustrates the cost per demand saved among each design point pair due to the conditional use of non-premium transportation as well as the estimated savings over the 6 year time period with the number of demands held constant for each factor level. Savings range from just over $2,000 to nearly $88,000.

Table 8. Non-Premium Transportation Estimated Savings

DESIGN POINT PAIR	COST DIFFERENCE	ESTIMATED SAVINGS
1-2	$1.34	$2,045.44
2-4	$6.88	$10,501.23
5-6	$15.43	$23,565.88
7-8	$42.78	$65,338.77
9-10	$46.18	$70,541.44
11-12	$50.00	$76,378.70
13-14	$52.21	$79,752.20
15-16	$44.43	$67,870.96
17-18	$56.88	$86,887.86
19-20	$4.57	$6,981.33
21-22	$5.56	$8,494.23
23-24	$10.37	$15,838.00
25-26	$39.65	$60,564.52
27-28	$40.52	$61,888.04
29-30	$47.33	$72,295.55
31-32	$49.99	$76,349.13
33-34	$49.93	$76,263.58
35-36	$57.39	$87,666.91
37-38	$3.85	$5,876.74
39-40	$6.36	$9,707.95
41-42	$1.77	$2,710.15
43-44	$35.55	$54,302.88
45-46	$37.29	$56,956.46
47-48	$40.68	$62,143.02
49-50	$40.60	$62,012.60
51-52	$40.04	$61,161.70
53-54	$46.39	$70,858.55

Whereas the use of non-premium transportation generally led to a cost savings among all treatment levels, its effect on stockage effectiveness differed depending primarily on base stock level and demand variability. MANOVA results showed that at low levels of base stock, there was no significant difference on stockage effectiveness due to transportation use but as base stock level increased to factor level 2, conditional non-premium transportation use reduced stockage effectiveness. The difference in treatment means at base stock level 3 was smaller than at base stock level 2 but was still statistically significant. This was likely due to the fact, non-premium transportation was seldom used with a base stock level of one and therefore no significant difference in stockage effectiveness could have occurred. However, as the base stock level rose to two, the use on non-premium transportation went up and increased the likelihood and occurrence of backorders. At base stock level 3, the additional asset placed at base level served as additional safety stock at the base reducing the number of backorders in comparison to base stock level 2. The second major interaction effect occurred between demand variability and transportation use. At low levels of demand variability, the use of non-premium transportation did not have a significant effect on stockage effectiveness in comparison with premium transportation use. However, as demand variability increased, non-premium transportation did significantly reduce stockage effectiveness in comparison with all premium use.

Therefore, in terms of stockage effectiveness, the use of non-premium only had a statistically significant effect at higher levels of demand variability and higher levels of base stockage levels. Examination of the efficient frontier plots (Figures 20-22) show tight clustering of the three lower level design pairs indicating there is virtually no managerial significant effect on stockage effectiveness when base level stock is 1 across all demand variability levels. In terms of managerial significance, Table 9 shows the number of backorders attributable to non-premium transportation in the 6-year simulation period, based on the average number of demands across all levels. In the low demand variability level, we see the maximum number of backorders due to conditional use of non-premium transportation is less than 7 backorders in 6 years. The highest number of backorders attributed to non-premium transportation is nearly 32 backorders.

Table 9. Non-Premium Transportation Estimated Effect on Stockage Effectiveness

DESIGN POINT PAIR	STOCKAGE EFFECTIVENESS DECREASE	ESTIMATED BACKORDER INCREASE
1-2	-0.00241	-3.7
2-4	-0.00080	-1.2
5-6	0.00121	1.9
7-8	0.00429	6.5
9-10	-0.00072	-1.1
11-12	0.00372	5.7
13-14	0.00416	6.4
15-16	-0.00309	-4.7
17-18	0.00076	1.2
19-20	-0.00076	-1.2
21-22	-0.00100	-1.5
23-24	-0.00022	-0.3
25-26	0.01105	16.9
27-28	0.01048	16.0
29-30	0.00297	4.5
31-32	0.01040	15.9
33-34	0.00603	9.2
35-36	0.00572	8.7
37-38	0.00172	2.6
39-40	0.00115	1.8
41-42	0.00026	0.4
43-44	0.01664	25.4
45-46	0.02081	31.8
47-48	0.01541	23.5
49-50	0.00914	14.0
51-52	0.00707	10.8
53-54	0.01146	17.5

Therefore, in terms of managerial significant findings, we see that across all demand variability levels, costs savings can be substantial with the use of non-premium transportation while seemingly making little difference in terms of stockage effectiveness. For assets which may fall into the stable demand category, significant cost savings can be acquired through the use of non-premium transportation with little risk of effecting stockage effectiveness. For higher levels of demand variability, there is increased risk of reducing stockage effectiveness through the use of non-premium transportation. However, the maximum number of backorders which occurred in 6 years, due to conditional use of non-premium transportation was 32. Aggregating 32 backorders over 3 bases over 6 years equates to less than two backorders a year per base. The estimated cost savings at that backorder level was nearly $57,000.

The final finding concerned base and depot stock levels and their effect on the lean reparable pipeline performance. In general, base stock level seemed to contribute to model performance to a greater degree than depot stock level. Base stock level contributed more significantly to cost performance of the model since a change in one level of base stock equated to the addition of 3 assets in the system whereas a change in one level only equated to 1 additional asset entering the system. As major cost elements such as asset material costs and holding costs rise with additional assets, changing base stock levels has a relative greater effect on cost than changing depot stock levels. Also, as discussed previously, base stock level had significant interaction effect with transportation use on overall cost. This is largely attributable to the conditional use of non-premium transportation criteria which is linked to the base or retail stock condition.

In terms of stockage effectiveness, base stock level again seems to have the most significant effect on model performance. At the low base stock level, there is significant interaction with all levels of depot stock on stockage effectiveness. However, as base stock level rises to two assets per base, there is no significant difference on stockage effectiveness due to interaction with the base stock level and depot stock level 2 or 3.

V. Conclusions and Recommendations

Overview of Research

According to Air Force Policy Directive 20-3 (1998):

The objective of Air Force logistics is to maximize operational capability by using high velocity, time-definite processes to manage mission and logistics uncertainty in-lieu of large inventory levels—resulting in shorter cycle times, reduced inventories, and cost, and a smaller mobility footprint.

In an effort to achieve the stated objective, the Air Force has attempted to capitalize on lean production principles utilized in the private sector. Lean Logistics, which started in 1993, was the Air Force's first large scale program aimed at creating a lean reparable pipeline. The program had four primary elements: reduce the mobility footprint through two-level maintenance implementation, reduction of transportation times through use of premium transportation, consolidation of inventory to intermediate stock points, and finally, streamlining of the depot repair process. The most difficult element of LL has been the actual implementation of lean principles into the depot repair process.

In the commercial sector, lean organizations strive to synchronize production with customer demand in an effort to eliminate waste and produce the highest quality products at the lowest cost. Costs are effectively reduced though just-in-time, pull production as opposed to attempting to capitalize on economies of scale such as in mass production. In order to attain full benefits of the lean production approach, organizations further attempt to smooth demand in order to allow production to occur at a steady pace. In the Air Force reparable pipeline, the Air Force depot and associated repair sources represent the production portion of the commercial supply chain. The failure of reparable assets, which establishes demand for the Air Force depot facilities, can be extremely erratic and difficult to predict and presents a confound to production leveling and a constant, efficient repair operation. Therefore, actual implementation of lean production into the depot repair process may not equate to operational success.

This study modeled the Air Force reparable pipeline with the depot repair function operating under lean principles. The associated lean characteristics of repair function were steady repair rate in concert with estimated system demand and repair on demand methodology. Once modeled, a full factorial experimental design was employed and multivariate analysis of variance (MANOVA) was utilized to assess the effects of differing levels of demand variability, base and depot supply levels, and the use of premium transportation on average total pipeline cost per asset demanded and stockage effectiveness response variables. These two performance measures provide an indication of the general level of efficiency and customer service of the pipeline.

Results of the Research

The research showed that the lean reparable pipeline was affected significantly by demand variability, especially at lower stock levels. In general, overall pipeline performance, in terms of both efficiency and customer service measures, was reduced as demand variability increased. Further, interaction between demand variability and low base stock level caused the lowest levels of pipeline stockage effectiveness. Therefore, in order to attain the same levels of customer service that could be expected in less erratic demand environments, the acquisition of additional assets at the base and overall pipeline stock levels would have to take place. This does not indicate that the pipeline is inappropriate for a highly variable demand environment but that more inventory would be required in the system to attain the levels of customer service as the system in lower variable demand environments.

The research also showed that the conditional use of non-premium transportation could yield considerable cost savings without significantly affecting stockage effectiveness in low demand variability environments. However, as demand variability increased, the conditional use of non-premium transportation increased the number of expected backorders in the system. This finding is managerially significant since the Air Force has many items which exhibit stable or less erratic failure rates. Therefore, for these items, the Air Force could capitalize on less expensive non-premium transportation, even when non-premium transportation has a performance disadvantage to premium transportation, without any effective increase in pipeline length or decrease in pipeline performance. For those items that do exhibit more erratic failure rates, maintaining the Air Force policy of shipping reparable items by premium transportation may be appropriate.

Limitations of the Research

The results of this research are based on the performance of a notional pipeline simulation model. Since, the lean reparable pipeline is not a system that actually exists, the use of simulation allowed for the performance estimation of the existing reparable pipeline operating under the proposed condition of steady repair output. However, the simulation model is a simplification of the actual reparable asset pipeline, which limits the validity of the model. Conceptually, if a model is valid, it can be used to make decisions about the system similar to those decisions that would be made if it were feasible to experiment with the actual system itself (Law and Kelton, 2000:265). The actual system has considerably more locations, more assets, and more processes than are modeled in this simulation. Additionally, the use of a normal distribution, although sufficient to model changes in the levels of demand variability, may not be accurate in comparison with the actual system behavior.

Future Research

The model utilized for this research featured three bases providing the system demand signal for the depot repair facility. Notional distributions were utilized to model demand variability in order to examine pipeline performance under those different demand environments. Future researchers may wish to expand the model to include more locations and obtain actual demand data to more accurately model the actual Air Force pipeline. Model validity could be increased further by modeling more elements of the system to include maintenance and supply processing times for assets.

A key assumption utilized within this model was the depot repair function repaired assets in a constant rate in concert with the expected average demand. The model did not allow for increases or decreases in production rate in response to sustained increases or decreases in demand. In the Air Force, sustained demand changes could occur as the result of operational changes. Future researchers could change the model to allow small, incremental changes in the production rate as can occur under lean production through increasing capacity, increasing manpower and equipment, or extending operating hours. Once the new model is developed with incorporated changes, the experiment should be conducted again. Additionally, research could expand the experimental design to include levels of flexibility in repair.

This research modeled the Air Force reparable pipeline with the depot repair function exhibiting characteristics espoused by lean principles. In actuality, the implementation of lean principles may be extremely difficult for Air Force depots. The actual implementation of any new wholesale production approach into an organization is difficult. Even if the lean production system were perfectly tailored to operate in the depot repair environment, the actual implementation of such a radical change in mindset may never be successfully accomplished. In addition to the problems associated with changing the production approach, there are other considerable obstacles that must be considered. For instance, repair shop flows are generally more cyclical than manufacturing shop flows as items must inspected, repaired, re-inspected, and in some cases re-repaired in contrast with manufacturing production which generally has a more linear flow. Additionally, worker flexibility is generally limited in the Air Force civil service community, a considerable confound to attaining the full benefits of lean principles at an Air Force depot. The examination and modeling of actual depot repair shop flows with real asset demand, resource, and production data could provide insight into how lean production could be utilized in the Air Force depot. Modeling a depot repair cell in its current state and under lean principles could not only provide information regarding advantages or disadvantages in performance under the two approaches, but also lead to solutions for successful implementation.

We hope future researchers will continue in the efforts regarding implementation of lean techniques into depot repair and the Air Force reparable pipeline. We sincerely hope this research adds to the Air Force community's knowledge regarding lean techniques and the reparable pipeline and in some way leads to future improvement in pipeline performance.

Appendix A. The Arena Model and Supporting Logic

Model Development

The lean reparable pipeline simulation model is designed to simulate the general characteristics of the Air Force reparable pipeline supplying one item, an F-15 radar warning receiver, radio frequency tuner 56C Shop Replaceable Unit (SRU) to three bases, with depot maintenance operating under a lean, repair on demand philosophy. There are four major sections of the lean reparable model to include (1) Tyndall Air Force Base (AFB), Eglin AFB, and Seymour Johnson AFB; (2) depot supply; (3) depot maintenance; and (4) the data collection and supporting submodels and modules. In the Air Force, F-15 56C SRUs are repaired and distributed through Warner Robins Air Logistics Center (WR-ALC) in Georgia. Although not explicitly stated in the model like the other base locations, the location of the depot supply and maintenance is WR-ALC. The following section will discuss the construction and key assumptions utilized for each section of the model.

Bases.

The model contains three bases which represent the customer or retail level in the reparable pipeline. There are two critical functions that each base needed to perform in order to accurately portray its role in the reparable pipeline. First, a base supply function needed to store and provide assets to maintenance, the ultimate customer, as well as place orders for replenishment assets from depot supply. Second, the bases needed to model the maintenance or consumption portion of the base which utilizes assets. Figure A-1 presents the simulation model representing Tyndall AFB. The two other bases modeled, Eglin AFB and Seymour Johnson AFB, are modeled in the exact same manner.

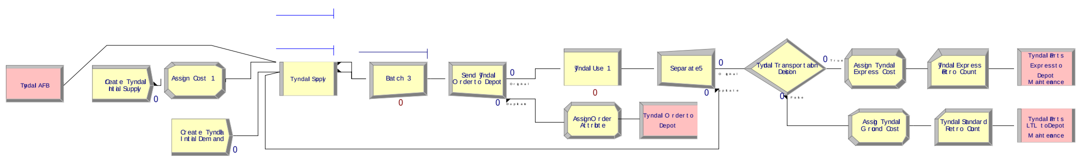


Figure A-1. Tyndall AFB

As seen in Figure A-1, each base begins with an Arena Basic Process Create module which creates the initial inventory level for radar warning receiver assets at the base. By changing the entities per arrival, the established stock level for each base can be manipulated. Arrivals from this Create module occur at simulation time 0.0 and occur only once during the simulation. All other entities which represent actual radar warning receiver assets are created in the depot supply portion of the model which will be discussed in the next section of this appendix.

The entities flow from the Create module to an Arena Basic Process Assign module which enables the programmer to assign individual attributes, variables, and other characteristics to each entity which enters the module. In Arena, attributes provide a method of individualizing entities (Kelton, Sawdowski, and Sawdowski: 2002:25). For instance, individual entities can be assigned attributes or characteristics such as due dates or priorities which are unique to that particular entity. In this particular Assign module, each entity is assigned an entity picture. In the case of Tyndall AB, the assets are assigned an entity picture of a yellow ball. Throughout the model, different entity pictures are assigned to entities as their status and location changes in the model. In general, this animation helps the model operator and user to visualize the flow of assets through the model as well as helping ensure entities are flowing in their intended manner. Entities in the Eglin and Seymour Johnson AFBs are assigned red and green balls respectively. As the entity pass through the Assign module, a *Product Cost* variable is also assigned. As each entity enters the Assign, they increment the *Product Cost* variable. In Arena, a variable differs from an attribute in that variables are not tied to the individual entity but instead pertain to the system at large (Kelton et al., 2002:26). The *Product Cost* variable represents the total material cost of all assets in the system. *Product cost* will be discussed in greater detail in the data collection section.

The entities which represent actual assets next flow into one of two queues entering an Advanced Process Match module which represents the inventory holding section of the base supply unit. The Match module brings together entities waiting in separate queues, matches them based on criteria established by the programmer and then releases one entity from each queue to be matched (Rockwell Software, 2000). The matched entities are synchronized to depart from the module at the same time. This Match module serves the purpose of matching customer orders with inventory assets in base supply. The second queue entering the Match module arrives from a Create module. The create module creates one order entity at time 0.0 of the simulation run. After this occurrence, all future entities arrive from an Advanced Process Separate Module which will be discussed later. These order entities arrive at the second queue into the Match module where they wait to be matched with an inventory asset from the first queue. Essentially, if there are no assets in the queue (on the shelf) the order will wait in second queue until a part become available. Likewise, if there are assets on the shelf but no orders from the organizational maintenance, asset entities will remain in the first match queue.

After orders and assets are matched and exit the Match module, they flow to an Arena Basic Process Batch module. The Batch module serves the purpose in this portion of the model of ensuring the requested asset which has now been "pulled off the shelf" was authorized to do so by an order from the customer. A Batch module is a grouping mechanism which permanently or temporarily joins entities depending on the needs of the model. In this model, the batch is defined as permanent representing the permanent joining of the order request and the asset. Features of the Batch module will be discusses further in the Depot Supply portion of this appendix.

After entities leave the Batch module they enter an Arena Basic Process Separate module. The Separate module is utilized to create duplicate entities or clones which are exact replicas of the original entity (Kelton and others: 2002:352). Once a duplicate entity is created, it can be manipulated to perform other functions within the model. In this case, the duplicate entities are created in order to provide a demand signal to depot supply. As the radar warning receiver entity leaves the Match module (the supply shelf) to satisfy the base maintenance demand, a demand for a replacement asset to replenish the base stock is generated. The duplicate entity serves as this demand signal. While the original entity travels to a Process module to satisfy the flightline demand, the duplicate entity flows to an Arena Basic Process Assign module. Here, the duplicate entity is assigned numerous characteristics which identify it as an order for a replacement asset for its particular base. In the case of Tydnall AFB, the duplicate entity is assigned an entity type of *Order* and an entity picture that resembles a report. This signifies that the entity is no longer an actual asset but an order for a replacement asset. The Assign module also assigns an attribute entitled *Base* with a specified value. Each base is provided with a unique *Base* attribute value which ensures each order is fulfilled and sent to the appropriate destination. The *Base* attribute values are shown in Table A-1.

Table A-1. Base Attribute Values

LOCATION	VALUE
Depot	1
Tyndall AFB	2
Eglin AFB	3
Seymour Johnson AFB	4

The *Base* attribute will be discussed further in the depot supply section. Once the order entity has passed through the Assign module, it then enters an Arena Advanced Transfer Route module. In this model, all base orders are routed to the depot supply station. It is assumed that orders are routed electronically and instantaneously to depot supply and therefore the route time is assumed to be zero.

The original entity which entered the Separate module travels to an Arena Basic Process, Process module entitled *Tyndall Use 1* which is being utilized to represent the maintenance or demand portion of the system. When the module is busy processing an entity, it signifies all demands as being satisfied (no aircraft needs an asset). When the module has completely processed an entity, it becomes idle and awaits a replacement asset from the Match module. The rate at which the Process module processes the entity is manipulated by the modeler and in essence simulates customer demand rate. By increasing the standard deviation of the processing time's normal distribution, demand variability increases.

Once the Process module completes processing an entity, the asset which represents a failed reparable asset moves into another Separate module. This module creates a copy of the entity and sends the entity to the order queue of the match module signaling the need to send a replacement asset to the process module. The original entity moves to an Arena Basic Process Decide module shown in Figure A-2. The Decide module enables entities to make decisions based on conditions or probabilities. Depending on the level of the Transportation factor, entities will either all pass through the premium express shipment path or pass through either the premium or ground transportation path based on a conditional factor. During transportation factor level 1 when all premium transportation is used, the decide module sends 100% of asset down the premium transportation path.

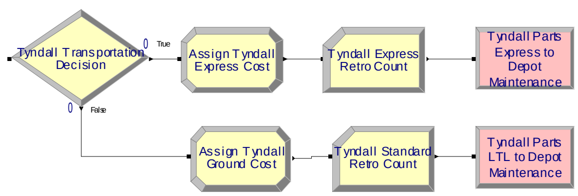


Figure A-2. Shipment Decision and Transportation Modules

For transportation factor level 2, entities utilize ground transportation if the number of assets in the awaiting repair queue in the depot is greater than or equal to 3 assets. The logic behind this decision criteria is that if the depot produces at a rate of roughly 1 asset per 24 hours and there are three or more assets waiting at the depot, the use of premium transportation is unnecessary.

After passing through the decision module, entities enter an Assign module where the entity is assigned a new entity picture of an airplane or truck depending on the mode of transportation back to the depot maintenance station for repair. Additionally, a variable entitled *Transportation Cost* is incremented as the asset which will be shipped to the depot for repair will cause the system to incur the cost of transporting the asset back to the depot maintenance station. After the Assign module, the entity moves to an Arena Advanced Transfer Route module. The Route module routes the entity to a station identified by the model developer. In this model, each failed asset entity moves to the depot maintenance station. The Route module enables a route time to be specified which indicates how long it takes for the entity to arrive at the destination. Route times and costs used for this model are shown in Tables A-3 and A-4 respectively.

Table A-3. Transportation Time Distributions

TRANSPORTATION TIME	
PREMIUM	GROUND
TRIA (22, 24, 28)	TRIA (44, 48, 52)

The units for the Transportation times shown in Table A-3 are hours and are based on Federal Express Standard Overnight and Ground service levels between the zip codes of the destination bases. All route times are the same between each base. Transportation costs shown in Table A-4 are also based on Federal Express Standard Overnight and Ground service levels.

Table A-4. Transportation Costs (Federal Express, 2004)

	TRANSPORTATION COST	
ROUTE	PREMIUM	GROUND
Depot -T yndall AFB	19.16	3.91
Tyndall AFB - Depot	19.16	3.91
Depot - Eglin AFB	20.16	4.91
Eglin AFB - Depot	19.16	3.91
Depot - Seymour Johnson AFB	25.99	3.91
Seymour Johnson AFB- Depot	25.99	4.36

Depot Supply.

The depot supply station is the intermediate supply point for all customers in the pipeline. The station must receive and store inventory from depot maintenance, ship inventory to replenish base stock levels, and request assets from depot maintenance to replenish depot stock levels.

As in the base portion of the model, the depot supply portion of the model begins with a Create module, which creates in the initial depot inventory level. A specified number of entities are created at simulation time 0.0 which signifies the authorized depot inventory level. Entities then flow into an Assign module which assigns an entity picture of a box. The box entity picture helps the model developer and users to visualize the assets as inventory with no assigned recipient at this stage in the model. The Assign module also assigns a *Base* attribute value of *1* to these entities signifying that these entities are depot assets. Finally, as entities pass through the Assign module, as in the base portion of the model, assets increment a *Product Cost* variable indicating additional system material cost of the assets entering the system.

Upon leaving the Assign module, entities arrive at one of two queues entering a Match module. As in the base portions of the model the Match module brings together entities waiting in separate queues, matches them based on criteria established by the programmer and then releases one entity from each queue to be matched (Rockwell Software, 2000). This Match module serves the purpose of matching customer orders with inventory assets in depot supply. The second queue entering the Match module arrives from an Arena Advanced Transfer Station module, *Depot Supply*. This Station module is the destination module in which order entities (discussed in the base section of the model) arrived from the three bases. These order entities arrive at the second queue into the Match module where they wait to be matched with an inventory asset from the first queue. Essentially, if there are no assets in the queue (on the shelf) orders will back up in the second queue until parts become available (as shown in Figure A-3 below). Likewise, if there are assets on the shelf but no orders from the bases, asset entities will remain in the first match queue.

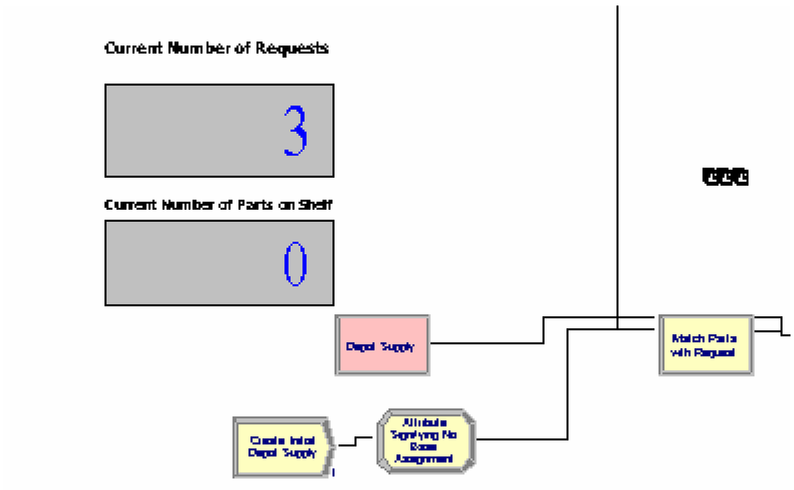


Figure A-3. Depot Backorders

After orders and assets are matched and exit the Match module, they flow to a Batch module. The Batch module serves the purpose in this portion of the model of ensuring the requested asset which has now been "pulled off the shelf" is identified for the proper destination according to the requesting base. As discussed previously, the Batch module is a grouping mechanism which permanently or temporarily joins entities depending on the needs of the model. Within the Batch module, the modeler specifies Save Criterion which determines how the user defined attributes of the individual entities entering the batch module will affect the resulting attributes of the batched representative entity (Rockwell Software, 2000). The Save Criterion specified for this model is *Product* which multiplies the values of the user-defined attributes and assigns the product to resulting batched entity. The only user-defined attributes of the entering entities were the *Base* attribute values. All inventory assets entities entering the Batch module have the *Base* attribute value of 1. The order entities entering the Batch module have their *Base* attributes of 2, 3, or 4 depending on the base from which they originated. Therefore, the resulting *Base* attribute value of the batched item equals the original value of the order entity. This attribute will be utilized later in the model to determine the destination of the entity.

In the same manner in which orders were created in the base portion of the model, a Separate module is utilized to create an order signal from the depot supply station to the depot maintenance station. The Separate module creates a duplicate entity and sends it to an Assign module which assigns the entity a *Depot Order* entity type and a "report" entity picture. The entity is also assigned a *Base* attribute value of 1, signifying it is being requested by depot supply. This order entity is then sent to a Route module which sends the entity to the Depot Maintenance station.

The original asset entity departs the Separate module and arrives at a Decide module. In this case, the Decide module routes the entity based on the value of the entity's *Base* attribute. If an entity arrives at the decide node and its *Base* value does not equal 2, 3, or 4 it is routed to Arena Basic Process Record and Dispose modules. The Record module tallies the number of entities arriving into the module and the Dispose module disposes of any entities which enter into it. These two modules serve as a check to ensure the match and batch portions of the model are operating correctly. If the model is operating as intended, there should not be any entities arriving at the Record and Dispose modules.

From the Decide module, the asset entities are routed to one of three other Decide modules. As in the base portions of the model, these Decide modules are utilized to determine which type of transportation will be utilized. Under Transportation factor level 1, all assets utilize premium transportation. Under Transportation factor level 2, entities utilize ground transportation if there is an asset in the destination base's supply queue. The logic behind this decision module is that if there is an asset on the shelf at supply and on average the base demands one asset every 72 hours, then a transit time of 48 hours should be acceptable even if the part on the shelf is demanded just after ground transportation has been utilized. The Assign modules assign yellow, red, and green ball entity pictures to the assets depending on their corresponding base. The *Transportation Cost* variable is also incremented based on the cost of sending the asset to its destination base. Entities flow through an Arena Basic Process Record module which counts the number of entities entering the node. This is a data collection module which helps the modeler get an insight into system behavior. Next, the entities are sent to a Route module which sends the assets to the appropriate base with a prescribed route time based on the times listed in Table A-3. The entities arrive at a Station module at the individual bases which is the connected the individual base's Match module queue representing the base supply shelf.

Depot Maintenance.

Depot Maintenance represents the repair capability for depot level reparable items. Within the lean reparable pipeline model, the depot maintenance portion of reparable pipeline deviates significantly from the actual system. For the purposes of this research, the depot maintenance portion must operate according to the overriding principles of lean production. Principles like *Pull* meaning no one upstream should produce a good or service until a customer has ordered it (Womack and Jones, 1996:67) and J*ust-in-time* meaning producing the right item at the right time in the right quantity (Dennis, 2002:65) must be demonstrated by the model. Therefore, the model does not utilize batch or mass production techniques but repair on demand methodology in which parts are inducted into demand based on orders from Depot Supply.

Another overriding lean principle that must be demonstrated by the Depot Maintenance portion of the lean reparable pipeline model is a relatively steady output (repair) rate in concert with expected customer demand. As discussed in the literature review, when inventories are eliminated and products must be produced precisely at the correct time to satisfy customer demand such as in a lean system, a mechanism such as *takt* time which matches the rate of production with the rate of demand is necessary. The notion of takt or cycle time is in essence the timing with which production must occur to precisely satisfy the demand established by the customer.

The actual Arena model of the depot maintenance portion begins with a Station module which receives both order entities from depot supply and reparable asset entities from the individual bases. From this station module, the entities enter a Process module called Depot Maintenance. Typically, entities entering into Process modules undergo standard processing within the module. An alternative option for processing is Submodel type processing which enables the modeler or user to define more complex and hierarchical logic for processing within the specified Process module (Rockwell

Software, 2000). The Depot Maintenance Process module is a submodel with the logic for actual depot maintenance processing contained within it.

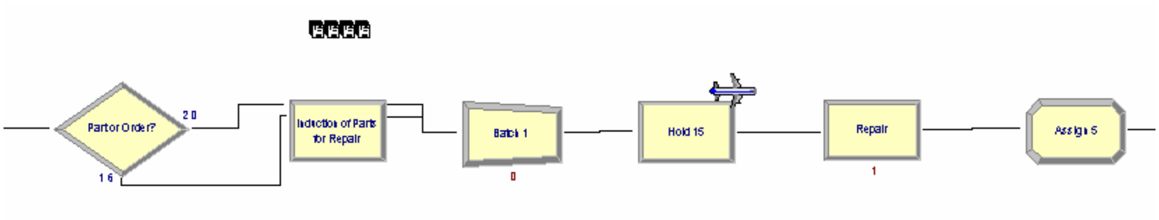


Figure A-4. Depot Maintenance Process Submodel

As shown in Figure A-4, inside the Depot Maintenance Process Submodel, entities arriving from the Station module arrive at a Decide module which separates the entities into two paths based on the condition of whether or not the entity type matches Depot Order. In this ways, order entities are sent along one path and reparable asset entities are sent along the other. Each path leads to separate queues entering the same Match module. The Match module operates in the same manner as the other Match modules in the base and depot supply portions of the model. The Match module matches order entities and reparable asset entities. In essence, the module serves to match an actual request for an asset from the depot with a carcass that is available to be repaired. Figure A-4 shows four requests waiting to be matched with a carcass. The matched entities are released from the Match module into a Batch module which simply serves the purpose of permanently joining the order and asset entities into one.

Next, the joined entity moves to a Hold module which captures entities and holds them until a certain external signal or condition is satisfied and signals the release of one entity. After the release of an entity, all other entities in the queue of the Hold module will be held until the external signal or condition is again satisfied. The release condition for this Hold module is when the following Process module, entitled *Repair,* work-in-process equals zero. This means that the Process module has completed the processing of an asset and has become idle waiting for another asset to process.   This Process module symbolizes the actual repair function. Assets can only pass through the repair function one at a time.   The *Repair* Process module simulates the depot repair production rate which is aligned with the depot demand rate. It should be noted that in the real world system, a depot has demand generated from not only the bases of which it services but from internal customers within the depot.   However, for the purposes of this model, all depot demand is generated from the three bases within the model. In this model, on average, each base requires 1 asset per 72 hours which equates to a depot production rate of 1 asset per 24 hours. The actual distribution used in the model is TRIA (23, 24, 25). This symbolizes the relative stable level of production of the lean repair function discussed in Chapter III of this thesis.

Once entities have passed through the *Repair* Process module, they enter an Assign module. Here, entities are given an entity picture of a box to symbolize a part with no predetermined customer and a *Base* attribute of 1. The entities also increment a *Repair Cost* variable which adds to the total system cost of operation of the pipeline. From the assign module, the entities depart the Depot Maintenance Process submodel and flow to the Match module of the Depot Supply portion of the model, symbolizing parts on the shelf.

Data Collection and Supporting Submodels

In addition to the major portions of the model simulating the operation of the reparable pipeline, there are a number of submodels and statistic calculators utilized to collect meaningful data from the simulation. These Arena Submodel modules are different from the Process module with submodel type processing utilized to model the depot maintenance function. The Arena Submodel modules are attached from the Object menu of Arena and act as stand alone models, separate from the actual entities flowing through the reparable pipeline. The model components essential to provide the model's two performance indicators are presented.

Base Stockage Effectiveness Calculator Submodel.

The Base Stockage Effectiveness Calculator submodel collects data regarding base backorders and stockage effectiveness of the reparable pipeline for the three bases in the model. A backorder is created anytime base maintenance requests an asset from base supply but there are no assets on the shelf at base supply to support the request. Stockage effectiveness refers to the percent of occurrences when requisitions from base maintenance are satisfied from on hand stock at base level supply or in essence, total requisitions minus backorders divided by total requisitions.

$$\textit{Stockage Effectiveness} = \frac{\text{Total Requisitions} - \text{Backorders}}{\text{Total Requisitions}} \quad \text{(A-1)}$$

For the purpose of this model, average stockage effectiveness serves as the sole evaluation of system customer service performance.

The submodel has two primary functions. First, a section of the submodel counts the number of backorders which occur during the course of the simulation. A second section of the submodel calculates the stockage effectiveness based on the number of backorders counted during the first section of the submodel. This is repeated for each individual base. The total number of backorders for all three bases and the average stockage effectiveness rate is displayed on the main pane of the reparable pipeline model.

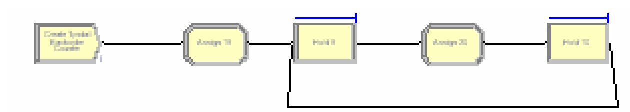


Figure A-5. Base Backorder Counter

As shown in Figure A-5, the backorder counting function begins with a Create module which creates a backorder counter entity specific to the individual base. A maximum of one entity is created. In the case of Tyndall AFB, this entity travels to an Assign module which creates a variable entitled *Tyndall Backorder* with an initial value of zero. This variable will be utilized to count the total number of backorders the system generates for the individual base. The total amount of backorders for the system will be calculated by summing all base backorders. After passing through the Assign module, the entity travels to a Hold module where it waits for the condition that the number in the base's order queue of the Hold module to be greater than the number in the asset queue of the Hold module. This condition equates to the maintenance function requesting an asset and the base supply function being unable to satisfy the request due to having no stock on shelf. When this condition occurs, the entity is released from the Hold module and travels to an Assign module. Here, the variable *Tyndall Backorder* is incremented by the value of one. Next, the entity travels to another Hold module which holds the entity until the condition that the work in process number of the base's *Tyndall Use 1* process equals one. Once this condition occurs, the entity is released back to the initial Hold module where it awaits another backorder occurrence. In this manner, the entity travels in a loop, incrementing the Backorder variable until the end of the simulation run. This occurs for all three bases in the same manner. The stockage effectiveness calculation is completed in the Advance Process Statistic portion of the model. The variable is calculated by taking the total number of entities entering all three base Process modules (total demands) minus the number of backorders for the bases and dividing the difference by the total number of demands. As shown in Figure A-7, this value is displayed on the main pane of the model using the Variable object from Arena's Animate tool bar. The total system backorders are displayed in the same manner.

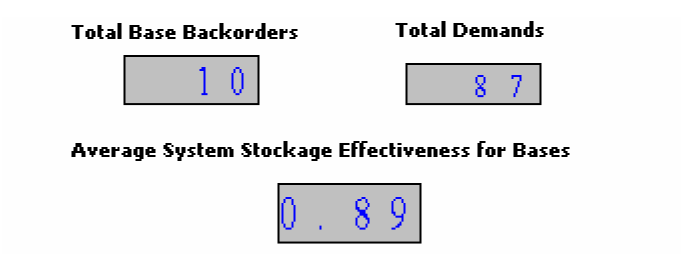


Figure A-7. Performance Indicator Animation

Average Total Pipeline Cost per Asset Demanded.

The total pipeline cost is the total inventory, repair, inventory holding, and transportation costs of supplying assets to the customer. The average total pipeline cost per asset demanded is the total pipeline cost divided by total base demands and serves as the primary indication of pipeline efficiency for this model. Inventory costs refers to the cost of the actual inventory of the assets in the system. The standard price of the asset was utilized as the cost of inventory for this asset. Repair cost refers to the cost in material and manpower to repair an asset. For the purpose of this model, each item is assigned the repair cost which represents an average cost to repair each item. This value is based on the Latest Repair Cost established by AFMC.

Typically, total logistics costs are thought to be made up of several components to include transportation costs, warehousing costs, order processing and information exchange costs, lot quantity costs, and inventory carrying costs (Douma and Goldsby, 2002). For the purposes of this model, the only logistics costs that will be considered are transportation and holding (inventory carrying) cost. Transportation costs are described in Table A-4. No data could be found concerning how the Air Force calculates holding costs for reparable items. However, the Department of Defense directs a 10% cost of capital be applied to all investment decisions (Blazer et al., 2002: 9). Cost of capital refers to the opportunity cost of investing in inventory of this particular item and therefore not being able to use the money for other purposes. Other Air Force holding cost components include obsolescence, deterioration and loss, handling, transportation, storage, taxes, and insurance (Blazer et al., 2002:9). The Air Force typically uses 15% per year as the holding cost for consumable items. It is assumed for this model that holding costs are 12% per year based on the assumption obsolescence and loss occurs at a smaller rate for reparable items. Order processing charges and warehousing costs will be assumed to be contained in the holding costs. Lot quantity costs are not applicable in the model as reparable assets are generally shipped in single quantity due the relative cost of the item and urgency of need. Therefore, total pipeline cost of the reparable asset pipeline model is the sum of total system inventory, repair, transportation, and holding costs. All other costs are described below in Table A-5.

Table A-5. Model Costs

COST TYPE		
Inventory Cost	$43,755.60	per asset
Repair Cost	$6,687.00	per asset
Holding Cost	12% x Inventory Cost x # years	

The Average Total Pipeline Cost per Asset *Demanded* submodel calculates the total pipeline costs divided by total number of assets demanded. The different elements of this cost are calculated at different times during the simulation run. The inventory costs are created at the initial start of the model run while the transportation and repair costs are continually incremented throughout the run of the model. The holding costs are calculated at the end of the simulation run. Holding costs for each base are calculated in a similar fashion as the backorder submodel. A Create module creates one entity at time *tfin,* which means at the end of the simulation run. This entity enters an Assign module which assigns a holding cost variable for that particular portion of the model. In all, there are five locations in which holding costs are computed: each of the three bases, depot supply, and depot maintenance. The holding cost variable is calculated by multiplying the average number in the asset holding queue by the holding cost calculation factor listed in Table A-5. The average total pipeline cost per asset demanded is calculated using the Statistic module which sums all system costs and divides the number by the total number of assets demanded.

The total pipeline cost variable is defined as the sum of the variables *Material Costs, Repair Costs, Transportation Costs,* and *Inventory Carrying Costs.* As the entity passes through the Assign module, the total pipeline cost is calculated and the entity is disposed of. The total pipeline cost is displayed using the Variable object from the Animate toolbar.

Appendix B. MANOVA Results

Multivariate Tests

Effect		Value	F	Hypoth df	Error df	Sig.
Intercept	Pillai's Trace	1.000	950148256.220	2.000	1593.000	.000
	Wilks' Lambda	.000	950148256.267	2.000	1593.000	.000
	Hotelling's Trace	1192904.277	950148256.267	2.000	1593.000	.000
	Roy's Largest Root	1192904.277	950148256.267	2.000	1593.000	.000
VARIABIL	Pillai's Trace	.989	779.724	4.000	3188.000	.000
	Wilks' Lambda	.035	3431.679	4.000	3186.000	.000
	Hotelling's Trace	26.488	10542.378	4.000	3184.000	.000
	Roy's Largest Root	26.462	21090.425	2.000	1594.000	.000
BASESTOK	Pillai's Trace	1.360	1695.380	4.000	3188.000	.000
	Wilks' Lambda	.003	13365.644	4.000	3186.000	.000
	Hotelling's Trace	200.190	79675.767	4.000	3184.000	.000
	Roy's Largest Root	199.614	159092.745	2.000	1594.000	.000
DEPSTOK	Pillai's Trace	.978	762.507	4.000	3188.000	.000
	Wilks' Lambda	.050	2776.397	4.000	3186.000	.000
	Hotelling's Trace	18.567	7389.660	4.000	3184.000	.000
	Roy's Largest Root	18.537	14774.027	2.000	1594.000	.000
TRANS	Pillai's Trace	.855	4700.087	2.000	1593.000	.000
	Wilks' Lambda	.145	4700.087	2.000	1593.000	.000
	Hotelling's Trace	5.901	4700.087	2.000	1593.000	.000
	Roy's Largest Root	5.901	4700.087	2.000	1593.000	.000
VARIABIL * BASESTOK	Pillai's Trace	.802	266.572	8.000	3188.000	.000
	Wilks' Lambda	.200	492.529	8.000	3186.000	.000
	Hotelling's Trace	3.995	795.083	8.000	3184.000	.000
	Roy's Largest Root	3.993	1591.408	4.000	1594.000	.000
VARIABIL * DEPSTOK	Pillai's Trace	.109	22.983	8.000	3188.000	.000
	Wilks' Lambda	.891	23.619	8.000	3186.000	.000
	Hotelling's Trace	.122	24.255	8.000	3184.000	.000
	Roy's Largest Root	.120	47.756	4.000	1594.000	.000
VARIABIL * TRANS	Pillai's Trace	.142	60.724	4.000	3188.000	.000
	Wilks' Lambda	.858	63.151	4.000	3186.000	.000
	Hotelling's Trace	.165	65.581	4.000	3184.000	.000
	Roy's Largest Root	.164	130.940	2.000	1594.000	.000
BASESTOK * DEPSTOK	Pillai's Trace	.453	116.613	8.000	3188.000	.000
	Wilks' Lambda	.548	139.811	8.000	3186.000	.000
	Hotelling's Trace	.824	164.030	8.000	3184.000	.000
	Roy's Largest Root	.823	327.940	4.000	1594.000	.000
BASESTOK * TRANS	Pillai's Trace	.661	393.569	4.000	3188.000	.000
	Wilks' Lambda	.342	566.296	4.000	3186.000	.000
	Hotelling's Trace	1.919	763.936	4.000	3184.000	.000
	Roy's Largest Root	1.915	1526.455	2.000	1594.000	.000
DEPSTOK * TRANS	Pillai's Trace	.056	22.872	4.000	3188.000	.000
	Wilks' Lambda	.944	23.189	4.000	3186.000	.000
	Hotelling's Trace	.059	23.505	4.000	3184.000	.000
	Roy's Largest Root	.059	46.844	2.000	1594.000	.000

a Exact statistic

b The statistic is an upper bound on F that yields a lower bound on the significance level.

Tests of Between-Subjects Effects

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	steffec	4.786	25	.191	660.278	.000
	cost	19681946.302	25	787277.852	6752.460	.000
Intercept	steffec	1433.851	1	1433.851	4945208.871	.000
	cost	83599697086.462	1	83599697086.462	717032232.272	.000
VARIABIL	steffec	1.826	2	.913	3149.478	.000
	cost	227691.593	2	113845.797	976.452	.000
BASESTOK	steffec	2.097	2	1.048	3615.393	.000
	cost	17357740.236	2	8678870.118	74438.423	.000
DEPSTOK	steffec	.122	2	6.111E-02	210.746	.000
	cost	1511231.972	2	755615.986	6480.897	.000
TRANS	steffec	1.019E-02	1	1.019E-02	35.149	.000
	cost	424356.872	1	424356.872	3639.697	.000
VARIABIL * BASESTOK	steffec	.665	4	.166	573.243	.000
	cost	1170.476	4	292.619	2.510	.040
VARIABIL * DEPSTOK	steffec	5.365E-03	4	1.341E-03	4.626	.001
	cost	2562.938	4	640.734	5.496	.000
VARIABIL * TRANS	steffec	4.880E-03	2	2.440E-03	8.416	.000
	cost	3860.042	2	1930.021	16.554	.000
BASESTOK * DEPSTOK	steffec	4.935E-02	4	1.234E-02	42.547	.000
	cost	9147.179	4	2286.795	19.614	.000
BASESTOK * TRANS	steffec	6.194E-03	2	3.097E-03	10.681	.000
	cost	141097.104	2	70548.552	605.093	.000
DEPSTOK * TRANS	steffec	2.077E-04	2	1.039E-04	.358	.699
	cost	3087.890	2	1543.945	13.242	.000
Error	steffec	.462	1594	2.899E-04		
	cost	185846.481	1594	116.591		
Total	steffec	1439.099	1620			
	cost	83619564879.245	1620			
Corrected Total	steffec	5.248	1619			
	cost	19867792.783	1619			

a R Squared = .912 (Adjusted R Squared = .911)
b R Squared = .991 (Adjusted R Squared = .990)

Appendix C. Model Performance Measure Results

DESIGN POINT	FACTOR 1: Level of Varability	FACTOR 2: Base Stock Level	FACTOR 3: Depot Stock Level	FACTOR 4: Transportation Use	RESPONSES Stockage Effectiveness	RESPONSES Per Demand Cost
1	1	1	1	1	0.9374	7012.92
2	1	1	1	2	0.9398	7011.58
3	1	1	2	1	0.9611	7052.30
4	1	1	2	2	0.9619	7045.43
5	1	1	3	1	0.9729	7091.83
6	1	1	3	2	0.9717	7076.40
7	1	2	1	1	0.9813	7151.37
8	1	2	1	2	0.9770	7108.59
9	1	2	2	1	0.9886	7192.90
10	1	2	2	2	0.9893	7146.72
11	1	2	3	1	0.9860	7233.09
12	1	2	3	2	0.9823	7183.09
13	1	3	1	1	0.9927	7283.78
14	1	3	1	2	0.9886	7231.57
15	1	3	2	1	0.9945	7326.56
16	1	3	2	2	0.9976	7282.12
17	1	3	3	1	0.9950	7369.23
18	1	3	3	2	0.9943	7312.34
19	2	1	1	1	0.8800	7021.11
20	2	1	1	2	0.8808	7016.54
21	2	1	2	1	0.9131	7056.25
22	2	1	2	2	0.9141	7050.69
23	2	1	3	1	0.9264	7091.98
24	2	1	3	2	0.9267	7081.62
25	2	2	1	1	0.9552	7157.68
26	2	2	1	2	0.9442	7118.03
27	2	2	2	1	0.9687	7195.84
28	2	2	2	2	0.9582	7155.32
29	2	2	3	1	0.9668	7237.29
30	2	2	3	2	0.9638	7189.96
31	2	3	1	1	0.9749	7286.07
32	2	3	1	2	0.9645	7236.08
33	2	3	2	1	0.9822	7333.14
34	2	3	2	2	0.9761	7283.21
35	2	3	3	1	0.9783	7374.36
36	2	3	3	2	0.9726	7316.96
37	3	1	1	1	0.7904	7043.61
38	3	1	1	2	0.7887	7039.76
39	3	1	2	1	0.8146	7077.39
40	3	1	2	2	0.8134	7071.04
41	3	1	3	1	0.8260	7105.22
42	3	1	3	2	0.8257	7103.44
43	3	2	1	1	0.9173	7178.02
44	3	2	1	2	0.9006	7142.47
45	3	2	2	1	0.9346	7217.71
46	3	2	2	2	0.9138	7180.42
47	3	2	3	1	0.9394	7253.82
48	3	2	3	2	0.9240	7213.13
49	3	3	1	1	0.9567	7311.48
50	3	3	1	2	0.9476	7270.88
51	3	3	2	1	0.9651	7350.30
52	3	3	2	2	0.9580	7310.26
53	3	3	3	1	0.9700	7390.14
54	3	3	3	2	0.9586	7343.75

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Vita

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His first assignment was at Luke AFB, Arizona where he served as Flight Commander, Vehicle Maintenance Flight, 56th Transportation Squadron from June 1997-June 1999. While stationed at Luke, he led his flight to an Outstanding rating during the 1998 Air Education and Training Command Operational Readiness Inspection. In July 1999, he was assigned to the 633d Air Mobility Support Squadron (Air Mobility Command) at Kadena AB, Japan. He served in numerous capacities to include Officer in Charge, Air Freight, Officer in Charge, Passenger Service, and Flight Commander, Combat Readiness Flight. In August 2002, he entered the Graduate School of Engineering and Management, Air Force Institute of Technology. Upon graduation, he will be assigned to Headquarters, U.S. Air Forces in Europe at Ramstein, Germany.

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14. ABSTRACT

Lean production and logistics processes were developed in the commercial sector to reduce total system costs of production while simultaneously providing high levels of customer service, increased productivity, and increased worker utilization. In 1993, the Air Force instituted the Lean Logistics program, which successfully implemented some commercial lean principles, enabling a reduction in the total reparable asset material requirement for the Air Force reparable asset pipeline. The Air Force is attempting to further implement lean production principles into depot repair in hopes of further enhancing reparable asset pipeline cost and customer service performance. However, the failure of reparable assets, which determines demand for Air Force depots can be extremely erratic and difficult to predict. A primary criticism of lean systems is their vulnerability in volatile demand environments. Therefore, the implementation of a full-scale lean approach to depot repair may not be conducive to operational success. The purpose of this research is evaluate whether the Air Force reparable pipeline operating under lean production and logistics principles can effectively support operational requirements in various demand environments. In an attempt to answer the research objective, multiple Arena simulation models of a "lean" reparable asset pipeline operating under various conditions were developed. A full factorial experimental design was employed and multivariate analysis of variance (MANOVA) was utilized to assess the effects of differing levels of demand variability, base and depot supply levels, and the use of premium transportation on cost and stockage effectiveness response variables.

15. SUBJECT TERMS

Lean Logistics; Air Force reparable pipeline; Supply Chain Management; Lean Production; Discrete-Event Simulation; Simulation; Arena; MANOVA; Multivariate Analysis of Variance

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