Pursuing Perfection:

Case Studies Examining Lean Manufacturing Strategies, Pollution Prevention, and Environmental Regulatory Management Implications

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DISCLAIMER

The Boeing Company has conducted a thorough review of, and submitted approval on, the content of the Everett and Auburn case studies included in Attachment A and Attachment B of this report, respectively. However, the *findings* articulated in the main body of this report represent Ross & Associates' interpretation of the Boeing case studies and do not necessarily represent the opinions of the Boeing Company.

Table of Contents

Executive Summary

Background

In working with regulated industries over the past eight years, many EPA regulatory reinvention initiatives have recognized an emerging and very real redefinition of the manufacturing landscape. Largely, this movement has arisen in the context of today's increasingly competitive "immediate" global market, requiring companies to conceive and deliver products faster, at lower cost, and of better quality than their competitors. Lean manufacturing is a leading manufacturing paradigm of this fast-paced market economy, with a fundamental focus on the systematic elimination of waste that holds the potential to produce meaningful environmental results.

Realizing that this waste-focused paradigm shift held the potential to create positive environmental outcomes, EPA authorized this study of Corporate Environmental Management and Compliance, designed to analyze corporate business strategies and environmental management approaches and to assess the presence of waste elimination patterns similar to those observed in previous reinvention efforts. This project entailed the analysis of five "assembly" case studies and two "metal fabrication" case studies at the Boeing Company, an enterprise that has adopted, and is in the process of implementing, Lean Manufacturing principles. The case studies describe various Lean efforts at Boeing's Auburn Machine Fabrication Shop and its Everett airplane assembly plant, and demonstrate how Boeing implements and utilizes Lean strategies in its manufacturing settings. The case studies also describe various resource productivity gains associated with the identified Lean activities, and several obstacles encountered by the Company in its efforts to implement specific Lean projects.

What Is Lean Manufacturing?

In its most basic form, Lean Manufacturing is the systematic elimination of waste by focusing on production costs, product quality and delivery, and worker involvement. In the 1950s, Taiichi Ohno, developer of the Toyota "just-in-time" Production System, created the modern intellectual and cultural framework for Lean Manufacturing and waste elimination. Ohno defined waste as "any human activity which absorbs resources but creates no value." Largely, Lean Manufacturing represents a fundamental paradigm shift from traditional "batch and queue" mass production to production systems based on product aligned "single-piece flow, pull production." Whereas "batch and queue" involves mass-production of large inventories of products in advance based on potential or predicted customer demands, a "single-piece flow" system rearranges production activities in a way that processing steps of different types are conducted immediately adjacent to each other in a continuous and single piece *flow*. If implemented properly, a shift in demand can be accommodated immediately, without the loss of inventory stockpiles associated with traditional batch-and-queue manufacturing.

While Japanese manufacturers embraced Lean as their biggest hope in recovering effectively from a war-torn economy in the 1950's, today companies embrace Lean Manufacturing for three fundamental reasons. First, the highly competitive, globalized market of today requires that companies lower costs to increase margins and/or decrease prices through the elimination of all non-value added aspects of the enterprise. Second, meeting rapidly changing customer "just-in-time" demands through rapid product mix changes and increases in manufacturing velocity in this manufacturing age is key. Finally, goods must be of high and consistent quality. Lean manufacturing facilitates these three goals.

Boeing Case Study Findings

The Boeing case studies provide an interesting window into the dramatic shift in manufacturing paradigms taking place in response to the highly competitive market of the 21st century. Like many companies today, Boeing has placed Lean Manufacturing in the forefront of its efforts to eliminate continually all non-value added aspects of the enterprise and ensure optimal competitiveness. Lean strategies utilized at Boeing have reduced the amount of energy, raw materials, and non-product output associated with its manufacturing processes, and many of these reductions can be translated into important environmental improvements. In fact, Boeing's approach to Lean implementation resembles and significantly expands the pollution prevention cultural elements long advocated by public environmental management agencies. Importantly, the waste elimination culture at Boeing is largely grounded in powerful financial incentives to resource conservation, potentially creating greater likelihood that improvements will occur. At times, however, improvements are not possible or fully realized, particularly those involving changes to "environmentally sensitive" manufacturing processes.

More specifically, a detailed analysis of these Lean Manufacturing case studies (along with supplemental research and review of the literature surrounding corporate environmental strategies, resource productivity and environmental improvement, and pertinent regulatory interactions) revealed the following findings:

- **Lean Manufacturing is Mainstream**. Substantial research and literature exists indicating that American industries are actively implementing Lean Manufacturing as a key strategy for remaining competitive in today's manufacturing environment, and implementation of this manufacturing paradigm shift is taking place across numerous industrial and source sectors. Similarly, the Boeing Company began implementing Lean Manufacturing throughout the Commercial Airplanes Division in February 1996: upon realizing early successes in the endeavor, "leaning" efforts at Boeing have been expanded to the entire company. Boeing's substantial investment in Lean reflects its belief that the strategy plays a critical role in the company's efforts to provide customer responsiveness, reduce costs, and systematically improve operational performance on a continual basis.

- **Lean Produces Significant Resource Productivity Improvements with Important Environmental Improvement and Sustainability Implications**. Through the adoption of a combination of Lean strategies (identifying and retooling the value chain, adopting product-aligned, cross-functional manufacturing, designing for manufacturability, and taking a "whole system view"), Boeing has substantially reduced the amount of energy, raw materials, and non-product output associated with its manufacturing processes. Overall, Boeing has realized resource productivity improvements ranging from 30 to 70 percent when Lean initiatives are implemented, and continues to improve on its overall efficiency and pollution output per unit of production. Results such as these have led many, including Paul Hawken, Amory Lovins, and L. Hunter Lovins in their recent book, Natural Capitalism, to advocate Lean as a strategy that can improve substantially the resource productivity of the economy, and reduce the ecological footprint of our country's economic activity.

- **Lean Produces a Robust Waste Elimination Culture**. During the 1980s and 90s, Public Environmental Management agencies have looked to promote pollution prevention through such means as technical assistance, pollution prevention assessment guidance, and pollution prevention planning requirements. Looking across these initiatives, a common theme emerges: to make sustained pollution prevention progress that moves beyond the "low hanging fruit," a company must create a waste elimination culture. Common elements of such a culture, as identified in agency pollution prevention guidance include: systemic and on-going evaluation of waste that is embraced and implemented by operations personnel; substantial engagement of employees, suppliers, and customers; development and utilization of pollution prevention measures; and a systemic approach to continual improvement. At Boeing, the drive to Lean Manufacturing processes produces (and in fact requires for its success) a highly robust waste elimination culture. The case studies reveal that Boeing employees are making aggressive changes throughout the factory, and accomplishing significant environmental improvements, that are fundamentally similar to those advocated by environmental agency pollution prevention staff. At Boeing, operations personnel run the Lean initiatives. These initiatives begin with a systemic evaluation of waste throughout the entire product value chain, actively engage employees on an on-going basis, depend on and reflect close coordination with customers and suppliers, and develop, track, and publicly display performance metrics. Importantly, these initiatives are also embedded in a continual improvement system that reflects a commitment to "pursue perfection"and the belief that improvements and change are never complete. These Lean "cultural attributes" are highly apparent at the Auburn and Everett facilities.

- **Lean Thinking Brings Powerful Financial Incentives to Resource Conservation and Pollution Prevention Improvement**. Pollution prevention adherents often advocate a "pollution prevention pays" theme to promote more sustainable production behavior. As well, pollution prevention guidance encourages facilities to examine the total costs of polluting behavior to ensure investment decisions are fairly and completely evaluated. This "Total Cost Assessment" approach, according to advocates, can produce a strong business case (e.g., a return on investment commensurate with internal hurdle rate requirements) for pollution prevention. From a financial decision making standpoint, Lean brings to the resource conservation financial equation very powerful cost drivers that move well beyond materials efficiency and avoided regulatory and liability costs. To reduce flow days, for example, Boeing has deployed a web of Lean strategies designed to create a single piece flow, pull production system that delivers optimal first delivered unit quality. The financial and customer responsiveness associated with flow day reductions have made the business case for Boeing, while the Lean strategies to obtain flow day reductions produced the resource productivity improvements so important to the environment. The resource productivity improvements produced ancillary, but not determinative, financial benefits. In fact, in most cases, the financial benefits of resource productivity improvements were not even calculated by Boeing because they were deemed financially insignificant.

- **Environmentally Sensitive Processes are Difficult to Lean**. The meaningful resource productivity improvements seen with Lean Manufacturing can not always occur due to challenging implementation barriers. Perhaps the most stunning finding from the case studies has been Boeing's almost complete inability to apply Lean strategies to environmentally sensitive processes. Operations such as painting, chemical treatment, and drying have proved highly difficult to Lean, and remain at Boeing, for the most part, in their less efficient “batch and queue” functional department configuration. These difficulties result largely from a complex array of technical and regulatory constraints, including lack of necessary process technology, the sometimes prescriptive nature of certain regulations, and the potential uncertainty associated with approving innovative process approaches under such regulations. These factors, when examined at the design phase of a variety of Boeing’s Lean initiatives, were deemed to affect adversely the implementation time, predictability of outcomes, and/or overall cost of the initiatives, often causing Boeing to modify substantially or abandon entirely the effort. Importantly, whereas Boeing has seen improvements ranging from 30 to 70 percent when Lean initiatives are implemented, painting, chemical treatment/testing, and drying processes (the processes, from an environmental standpoint, that would be the most desirable to improve) have not experienced commensurate gains, and represent a potentially significant environmental improvement opportunity foregone.

Implications for Environmental Management Agencies

The findings from these case studies hold important implications for environmental (and other public/worker health) management agencies. In particular, Lean’s strong association with resource productivity enhancements contrasted with Boeing’s almost complete inability to Lean environmentally sensitive processes creates an opportunity for agencies to examine opportunities that can both improve company competitiveness and environmental improvement. In particular, there are three areas where agency action could make a substantial difference:

- To facilitate a company’s Lean conversion process (from a batch and queue function to product aligned, single piece-flow manufacturing) the case studies point to three critical needs: increased regulatory agency receptivity to innovative process change (in particular, the ability to accommodate small scale, flexible, and potentially mobile processes); enhanced regulatory predictability to the likely regulatory constraints such equipment will operate under; and timely (preferably real time) responses to construction and modification actions.

- After the basic Lean conversion takes place, Lean’s continual improvement culture means that modifications to material inputs, product outputs, non-product outputs, equipment, equipment configurations, and operating parameters are likely to be the norm, and result in a manufacturing environment subject to constant, on-going change. In this environment, even minimal regulatory delay holds the potential to erode quickly a process improvement’s financial return, which, in turn, could result in foregoing the resource productivity enhancements associated with the change. In other words, the business case for Lean initiatives is highly sensitive to implementation time frames. Thus, regulatory agencies have a new challenge to keep timely pace with these changes while ensuring enforceability and environmental protectiveness.

- Lean holds the potential to invigorate pollution prevention promotional efforts through important and substantial resource productivity financial drivers that are imbedded in a system driven by and dedicated to the elimination of all forms of waste. Lean thinking also utilizes the language of business and operations, so it is readily accepted by those individuals most connected to the fundamental operations (and operational choices and directions) of the company. Lean thus holds the potential to invigorate pollution prevention promotional efforts that can be even more broadly diffused if environmental agencies' pollution prevention efforts recognize and choose to advocate this concept to companies.

Conclusion

Although based on a limited set of examples, the Boeing case studies suggest that, while Lean thinking is redefining the manufacturing landscape and the way production activities take place on the factory floor, the regulatory system -- which grew up and evolved regulating a batch and queue, mass production environment -- continues to be structured and operate with batch and queue processes in mind and operate itself as a batch and queue enterprise. To the extent that Boeing's experience provides a window into the larger world of American production activities, these case studies can provide an opportunity for environmental regulatory agencies, through responsiveness to Lean initiatives, to create a substantial competitiveness and environmental "win – win" outcome. Assisting to eliminate the barriers to full implementation of Lean, creating the opportunity for Lean thinking to retool environmentally sensitive processes, and aggressively promoting the adoption of Lean thinking holds the potential to support American industry in its efforts to compete globally, make important advances in pollution prevention, and move us more swiftly along the road to a more sustainable form of capitalism.

I. Introduction

A. Purpose

Over the past several years U.S. EPA's Office of Reinvention has been involved in a number of "regulatory responsiveness" initiatives. These include the Common Sense Initiative, Project XL, and Pollution Prevention in Permitting Program (P4). In working with a variety of businesses in the context of these initiatives, certain project participants noted that corporate manufacturing strategies and initiatives often produced substantial resource productivity enhancements (that translate directly into improved environmental performance). At the same time, the responsiveness and continuous improvement aspects of these strategies were driving on-going modifications to operating equipment and operating parameters that could be subject to new environmental permitting and/or modifications to existing permits. This meant that desired changes could be subject to regulatory bottlenecks (in terms of time, uncertainty, and administrative costs) that could constrain responsiveness, continuous improvement, and, ultimately resource productivity gains. This raised the question, "is the environmental regulatory system working at cross purposes with environmentally beneficial manufacturing strategies?"

Realizing the significant potential for achieving environmental results through enhanced resource efficiencies, EPA authorized a study of Corporate Environmental Management and Compliance. This study was designed to analyze company's business strategies and environmental management approaches, and assess the presence of needs and strategy patterns similar to those witnessed in previous reinvention efforts. Early in this project "Lean Manufacturing" was identified as a primary manufacturing strategy often utilized by today's competitive industries. Because of Lean Manufacturing's increasing prevalence in factories, and its potential for producing environmental enhancement through resource productivity, the study focused exclusively on this strategy.

The goal of the project is to help environmental regulators better understand the resource productivity aspects of Lean Manufacturing, and to help public agencies consider environmental management implementation in light of the operational requirements of Lean initiatives in the hope that both significant production and environmental benefits result.

B. Case Study Activities

This project entailed the analysis of five "assembly" case studies and two "metal fabrication" case studies at the Boeing Company, an enterprise that has adopted, and is in the process of implementing, Lean Manufacturing principles. The metal fabrication (Auburn, Washington facility) case studies research included up-front meetings with Boeing Operations staff and Safety, Health, and Environmental Affairs (SHEA) Division. These meetings were followed by a guided tour and detailed explanation of two Lean Manufacturing efforts conducted by Boeing Operations staff in Auburn. The five assembly (Everett, Washington facility) case studies also began with up-front conferences with Operations, SHEA, and Lean Manufacturing staff, followed by tours of the areas within the facility where the Lean case studies were implemented (or, were proposed for implementation). All Boeing staff involved in the project tours reviewed all case study documentation for accuracy.

In addition to direct involvement with the Boeing Company and its Lean endeavors, background research was conducted to understand better the history of Lean Manufacturing as a production strategy and the breadth of Lean Manufacturing adoption across the country. Finally, research involved a review of the literature surrounding corporate motivation for environmental improvement more broadly as well as the resulting regulatory interactions and impacts.

C. What is Lean Manufacturing?

In its most basic form, Lean Manufacturing is the systematic elimination of waste by focusing on production costs, product quality and delivery, and worker involvement. It is defined, in its modern form, by the Toyota Manufacturing system invented by Shigeo Shingo and Taiichi Ohno in the 1950's. While "waste" has always been thought of as an undesirable by-product of most factory production systems, many have also considered this an inevitable "end-of-pipe" control expense on the corporate balance sheet. Henry Ford was one of the first to realize that waste also represents inefficient (and more costly) production processes. Although seeming abundant resources at this time in history prevented a resource conservation mentality specifically, Henry Ford was obsessed with reducing the amount of resources wasted in his automobile manufacturing processes. As a result, Ford mandated the use of every possible bit of raw material, minimizing packaging, and material re-use. Reduced production time -- through the first moving assembly lines and development of products with interchangeable parts -- was also the result of Ford's obsession for maximum production efficiency.[1]

What Ford lacked, however, was a necessary responsiveness to ever changing consumer demands. His production systems meant that he could not produce variety in his automobiles. By the end of the 1920's, therefore, competitors more oriented toward customer demands (and less towards efficiency) dominated the automobile market, and Ford's manufacturing strategies were lost.[2] Japanese manufacturers recovering from World War II were next to catch on to Ford's ideals. In 1950, W. Edwards Deming pitched system-wide quality improvement concepts to Japanese managers. Shigeo Shingo and Taiichi Ohno then exploded these concepts by creating the Toyota "just-in-time" Production System which, like Henry Ford's system, was rooted in a complete understanding of quality improvement and the sources of *waste*.[3] It is Ohno who created the modern intellectual and cultural framework for eliminating waste, defining it as "any human activity which absorbs resources but creates no value."[4]

The success of Japanese manufacturing finally caught on again in America, due largely to the works of

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[1]Romm, Joseph. Lean and Clean Management: How to Boost Profits and Productivity by Reducing Pollution. Kodansha America, Inc., 1994, page 18.

[2]Romm, page 21.

[3]Romm, page 22.

[4]Quoted in: Hawken, Paul; Lovins, Amory; and Lovins, L. Hunter. Natural Capitalism: Creating the Next Industrial Revolution. Little, Brown, & Co: Boston.

James Womack[5] and Daniel Jones.[6] In The Machine that Changed the World,[7] Womack and Jones articulate the ways in which Toyota's Lean production systems can and should be utilized to improve factory performance. In their work, Womack and Jones expanded on Ohno's definition of waste by defining it as "mistakes which require rectification, production of items no one wants so that inventories and remaindered goods pile up, processing steps which aren't actually needed, movement of employees and transport of goods from one place to another without any purpose, groups of people in a downstream activity standing around waiting because an upstream activity has not delivered on time, and goods and services which don't meet the needs of the customer."[8] The 400,000+ readers of this book were quick to request a follow-up that served as a practical guide. In response, Womack and Jones published Lean Thinking,[9] a more practical guide to eliminating waste from production processes. This book explains how to convert waste into value by doing more with less labor, less equipment, less time, less space, and as a consequence, less waste.

D. Why Lean Manufacturing?

Companies embrace Lean Manufacturing for three fundamental reasons. First, the highly competitive, globalized market of the late 20th and early 21st century require that companies lower costs to increase margins and/or decrease prices through the elimination of all non-value added aspects of the enterprise. In other words, companies need to key in on Ford's production efficiency ideals. Second, customer responsiveness is key. This means embracing the notion of production efficiency developed by Ford, but also doing what Ford couldn't: meet rapidly changing customer "just-in-time" demands through similarly rapid product mix changes and increases in manufacturing velocity. Finally, producing desired goods quickly won't maintain a market share if the product isn't of high and consistent quality. Thus, efficiency, responsiveness, and quality are three key goals of Lean Manufacturing.

The likelihood and necessity for Lean Manufacturing -- in the fast-paced global "immediate" information age of the 21st century -- is greater now more than ever. Pressure to reduce the time-to-market cycle will likely continue to intensify for most companies. Out of necessity, companies will need to discover new ways to conceive and deliver innovative products faster than the competition, while maintaining quality and lowering production costs. Thomas Friedman, in The Lexus and the Olive Tree: Understanding

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[5] Advises companies on applying Lean Thinking to operations, and has a research affiliation with the Japan Program at the Massachusetts Institute of Technology in Cambridge, Massachusetts.

[6] Director of the Lean Enterprise Research Center at the Cardiff Business School, University of Cardiff, Wales.

[7] Womack, James P. and Jones, Daniel T. The Machine that Changed the World. New York: Harper-Collins, 1991.

[8] Womack and Jones, page 15.

[9] Womack, James P. and Jones, Daniel T. Lean Thinking: Banish Waste and Create Wealth in Your Corporation. Simon & Schuster, 1996.

Globalization wrote: "...the speed by which your latest invention can be made obsolete or turned into a commodity is now lightening quick. Therefore, only the paranoid, only those who are constantly looking over their shoulders to see who is creating something new that will destroy them and then staying just one step ahead of them, will survive."[10] Michael Porter of Harvard's Business School agrees: "Detailed case studies on hundreds of industries, based in dozens of countries, reveal that internationally competitive companies are not those with the cheapest inputs or the largest scale, but those with the capacity to innovate and improve continually."[11]

This notion is also well understood at the Boeing Company. Their 1999 Machine Fabrication Year End Report mentions the competition (Airbus) specifically, and acknowledges Airbus' increasing ability to build airplanes at less cost, making them a "very capable and aggressive competitor." Their solution: "Velocity and manufacturing innovation is key. We must produce faster and cheaper than our competitors and maintain and improve our quality statistics."

E. How Do Companies Engage in Lean Manufacturing?

To compete successfully, companies will increasingly need to continuously: improve production approaches; engage customer responsiveness needs; cut costs; and improve the quality and functionality of products, while maintaining or lowering prices. Often this strategy requires reducing R&D time frames, constantly experimenting with product formulations and production processes, and rapidly modifying raw material inputs, process equipment, operating parameters, and outputs.

To achieve these ends, Lean Manufacturing promotes a fundamental rethinking of how to produce and deliver goods and services and meet the above production challenges. Largely, this rethinking represents a fundamental paradigm shift from "batch and queue" mass production to production systems based on a product aligned "single-piece flow, pull production" system. Batch and queue systems involve mass-production of large inventories in advance, where each functional department is designed to minimize marginal unit cost through large production runs of similar product with minimal tooling changes. Batch and queue entails the use of large machines, large production volumes, and long production runs. The system also requires companies to produce products based on potential or predicted customer demands, rather than actual demand, due to the lag-time associated with producing goods by batch and queue functional department. In many instances this system can be highly inefficient and wasteful. Primarily, this is due to substantial "work in process" being placed on hold while other functional departments complete their units, as well as the carrying costs and building space associated with built-up "work in process" on the factory floor. **See Figure A.**

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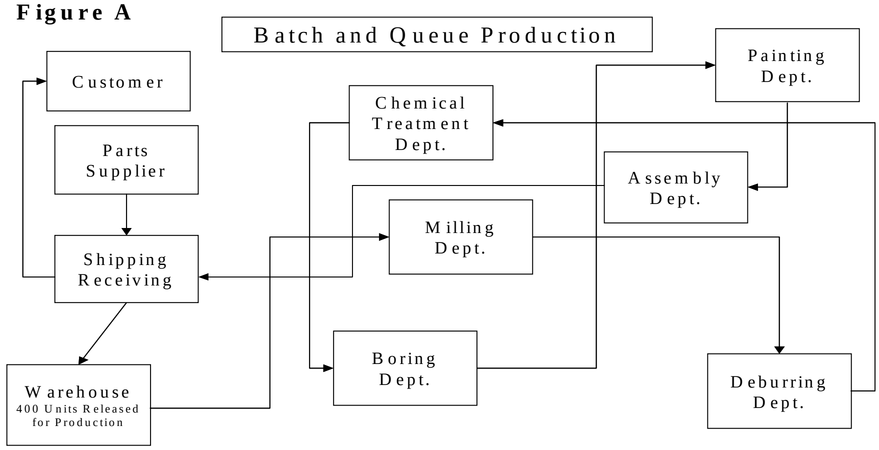
[10] Friedman, Thomas L. The Lexus and the Olive Tree: Understanding Globalization. Thorndike, Me. : Thorndike Press, 1999, page 35.

[11] Porter, Michael E. and van der Line, Claas. *Toward a New Conception of the Environment-Competitiveness Relationship*. Journal of Economic Perspectives, Vol. 9, Number 4 - Fall 1995, page 98.

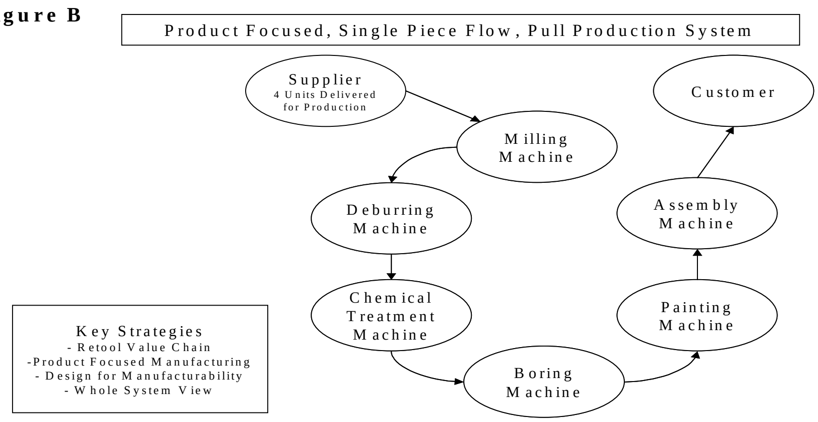
Figure A



As an example, Boeing's Machine Fabrication Manufacturing Business Unit (MBU) was previously organized in a batch and queue production system, where large quantities of goods were produced in a function-driven structure. A complex flow was required to make products under this system, including substantial product travel among functional departments, a large support staff with specific production skills, and the need to acquire large and complex equipment to support a constantly changing volume of goods. Substantial floor space was also dedicated to work in process and functional departments. Operating within this environment generally required six to ten months of product processing time.

Alternatively, Lean aims to rearrange production activities from departments and batches into continuous flow in a way that processing steps of different types are conducted immediately adjacent to each other in "product teams" (i.e., in a continuous and single piece *flow).* **See Figure B.** Under this process, the production floor will wait for the specific customer demand, or *pull,* before producing the product. If Lean is implemented properly, a shift in demand can be accommodated immediately, without the loss of inventory stockpiles associated with batch-and-queue manufacturing. This can eliminate the need for uncertain forecasting as well as the waste associated with unsuccessful forecasting.

Figure B



Boeing's Machine Fabrication Manufacturing Business Unit (MBU) embraced this concept, and transitioned from a batch and queue design where operations were grouped on functional commonality, to a system of production cells where all necessary equipment, people, and resources required to produce a product are grouped into a specific cell. Now there is a single flow through the production process, from one step to the next. Since this change, overall productivity at the plant has improved by 39 percent.

In addition to this paradigm shift from batch and queue to single-piece flow, Lean Manufacturing requires a systematic elimination of all possible forms of non-value-added costs (e.g., waste). In essence, pollution is a manifestation of economic waste and is a sign of production inefficiency, revealing flaws in product design or production processes. It is the unnecessary, inefficient, or incomplete utilization of a resource, or represents a resource not being used to its highest value.[12] This, in turn, can force unnecessary non value-added expenditures in pollution control, clean-up, and/or disposal. Lean Manufacturing zeros in on waste (and, therefore pollution) through a systemic assessment of costs and values associated with a product. This assessment essentially entails four fundamental strategies: embracing a "whole system view;" identifying and retooling the "value chain"; adopting "Product Aligned - Cross Functional" manufacturing; and "Designing for Manufacturability" (DFM). Each strategy is described briefly below.

1. Whole system thinking takes a view of the company's manufacturing system and associated costs as a whole, rather than by functional department. This new way of thinking empowers factory managers to accept higher costs on low value items that may be associated with a given functional department, to produce substantial overall cost savings throughout the production cycle. Companies engaged in Lean Manufacturing are, fundamentally, utilizing new financial decision-making ("whole system") approaches and new powerful cost drivers (e.g., reduced flow days) to eliminate waste. In other words, Lean strives to optimize the entire system, with a focus on strategies that minimize overall production flow days.
For Boeing, one result of the "whole system view" is paying more for lower value components within the system (e.g., raw materials) so that the high value products cost less overall. For example, in Boeing's Machine Fabrication factory, regular bulk ordering of supplies has been eliminated. Although it is cheaper to buy raw materials in large quantities, the costs associated with having the larger quantities on hand increased the overall cost of the finished product.

2. A **value chain** represents "the specific activities required to design, order, and provide a specific product, from concept to launch, order to delivery, and raw materials into the hands of the customer."[13] Evaluation of the value chain means performing systematic assessments of production process steps. Focusing on a production process' value stream can help identify steps which create no value as perceived by the customer and can be eliminated, or steps which create no value and need to therefore be "re-constructed" to reduce unnecessary waste.[14]

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[12]Porter and van der Linde, page 105.

[13]Womack and Jones, Lean Thinking, page 311.

[14]Womack and Jones, Lean Thinking, page 38.

A good example is seen in Boeing's 777 Critical Process Reengineering (CPR) effort. The CPR held a "Link the Flow" workshop, where participants focused on shortening the overall value chain and developed a vision for an ideal shipping process used for seat tracks and floor beams. Previously, 777 seat tracks traveled from Wichita, Kansas to Tulsa, Oklahoma, to Everett, Washington, and 777 floor beams were shipped from Tulsa to Kansas City, Missouri to Seattle to Everett. As a result of the workshop's focus on this inefficient value chain, eight days of travel and three days of receiving and inspection have been eliminated, and each ship set uses 50 percent less transportation.

3. Product-Aligned - Cross Functional Manufacturing addresses inefficiencies of manufacturing systems that are compartmentalized according to function. The separation of groups into design, production, etc. is deemed highly inefficient, and can result in unnecessary trial-and-error processes due to a lack of coordination between the functions.[15] Lean, alternatively, works across manufacturing functions, and is aligned towards specific products. For example, a "Lean Team" was created at Auburn's Machine Fabrication Shop. This team represented various entities throughout the production process, including management, tooling, quality assurance, Safety, Health and Environmental Affairs (SHEA), production staff, programming, and more. Together, this team analyzed and documented factory data associated with quality, cost, delivery, safety and morale, and assessed the production costs associated with the Manufacturing Business Unit (MBU) at Auburn. More specifically, one of the Lean Team's vision was for product/process focused cells, which combined processes and equipment re-located from functional areas, employed multi-skilled personnel, and could be utilized to manufacture and assemble single ship-set quantities. The cell structure addresses problems associated with batch and queue operations, and compartmentalization according to function.

4. Design for Manufacturability. The DFM process optimizes product design such that the design is simplified as much as possible. This may be done by the use of standard parts, elimination of unnecessary components, integration of multiple components, selection of easy to assemble components, etc. These procedures will not only produce a product that is easy to manufacture, but also one that uses less material, is of better quality and is less expensive to produce. DFM often relates product design to all aspects of the manufacturing process in order to optimize manufacturability.

Boeing's Lean efforts with the 777 Overhead Storage Bin Arch provide a good example of DFM. As a result of Lean design, the number of components in the arch has gone from 40 to 26 and the arch is now produced from a monolithic plate instead of numerous sheet metal parts. The Stow Bin Arch cell also incorporates several key Lean tools that have been designed into the manufacturing process, including small, right-sized equipment for specific production operations (e.g., a table top boring mill and tapping machine). As a sub-strategy, *right sizing* is used as a production device that allows for a component to be fitted directly into the flow of products within a product family, so that unnecessary transport and waiting do not occur. For example, there is a right-sized hand drill tool, which requires no flooding lubricants and can be turned off when not in use. The right-sized machines are often built on wheels, increasing production flexibility. Overall, right sizing can result in less energy use, less chemical usage, reduced scrap, and less utilized space. The Stow Bin Arch cell also contains a chaku chaku line for production of

[15] Romm, page 126.

sheet metal clips, brackets, and angles. The line consists of right-sized table top blanking, holing, and tapping machines. This allows an operator to produce only the parts that are needed at a specific time. Overall, DFM enables facilities to reduce costs, design in quality and reliability, and realize increased time to market.

A further example of process redesign for manufacturability is Boeing's *Point of Use* system for chemical materials. This enables the storage of materials where the production process utilizes them, as opposed to the previous system which utilized centralized chemical disbursement centers that entailed frequent machinist travel over substantial distances and greater overall chemical usage and waste. Generally, point of use efforts enable the storage of materials where the production process utilizes them. Boeing controls the amount of chemical inventory and waste on the floor by using minimum/maximum quantities, right-sizing containers, (holding only the necessary amount of material required for a specific application), and limiting each station's quantity of containers. Boeing's key objectives for point of use chemical stations are reductions in machinist travel and better control of the supply, use, and distribution of hazardous materials.

A third sub-strategy, utilized by Boeing in "leaning" inventory processes, is called *kanban*. Essentially, kanban regulates "pull" in the single-piece flow, by signaling upstream production and delivery. For example, to provide better inventory control and decrease damage, the Boeing Everett Wing Responsibility Center (WRC) is implementing a "kanban" cart system. To control the amount of inventory shipped, one set of carts is capable of holding only one set of panels. The WRC's return of an empty cart signals the vendor that Boeing requires another set. For Boeing, this kanban system reduces fiberglass panel inventory from 14 sets to 4.

II. Introduction to the Boeing Case Study Findings

The Boeing Company began implementing Lean Manufacturing throughout its Commercial Airplanes division in February 1996. Lean efforts have since been expanded to the entire Boeing Company.

A key Lean Manufacturing implementation driver for Boeing has been increasing its ability to deliver more value to customers, thereby increasing its competitiveness. The focus of Boeing's Lean effort is continuous elimination of waste in the Company's manufacturing processes, including reducing costs, cycle time, and defects. The Boeing Company is applying Lean Manufacturing principles and strategies to improve and streamline its overall production systems. By using Lean Manufacturing strategies and tools, Boeing is maximizing its production efficiency, and helping to achieve its goal of standard operations, ensuring that employees are doing the right work, the right way, at the right time.

Boeing has based its Lean activities on the principles demonstrated in the Toyota production system and identified in Womack & Jones' <u>Lean Thinking</u>. Among the Lean principles embraced by the Boeing Company are the following.

- *Identify the value stream*: Identify the universe of actions associated with producing raw materials into a finished product.
- *Make value flow*: Ensure that products and processes flow continuously by removing the unnecessary steps in the manufacturing process.
- *Pull value through from the customer*: Work begins only when a customer has requested ("pulls") the product. This approach prevents the production of unwanted or unneeded products.
- *Remove waste*: Eliminate <u>all</u> "non-value added" aspects of the production process.
- *Pursue perfection*: Improve products and processes continuously.

Boeing incorporates these principles into all of the Lean efforts taking place throughout the Company. Boeing believes these principles have resulted in substantial changes in the manufacturing environment and produced significant results.

To implement Lean Manufacturing in different work areas throughout the Company, Boeing has employed several processes. Work area staff begin with conducting a Lean Manufacturing Assessment. The assessment requires that every aspect of a specific work area is examined and its performance evaluated. After staff complete the assessment, they develop an implementation plan. The Implementation Plan includes the Lean Manufacturing strategies, tools, and techniques that staff will implement to improve the work area's production process.

A central component of Lean implementation is employee participation. Boeing utilizes Accelerated Improvement Workshops (AIWs). AIWs are "a rapid learn/do process where the people who do the work reorganize it to achieve major reductions in cost and flow time." The Workshops are 5 days long and combine training, planning, and implementation in a single work week so that rapid improvements can be made on the factory floor. The workshops focus on individual work areas and allow employees to develop and implement significant changes to work procedures, the flow of work, and the machines used for production.

In implementing a key principle of Lean, eliminating waste, Boeing has focused its efforts on many forms of waste, including the following.

- *Complexity:* Reduce or eliminate complex solutions because they tend to produce more waste and are more difficult to manage.
- *Labor:* Eliminate all unnecessary "movement" and steps of people.
- *Overproduction:* Produce only the exact amount of goods the customer wants when the customer wants them.
- *Space:* Conserve space by improving poor arrangement of machines, people, conveyors, or work stations, and storage of excess raw materials, parts, work-in-process, and finished goods inventories.
- *Energy:* Operate equipment and use person-power only for productive purposes.
- *Defects:* Strive to achieve the goal of no rework.
- *Materials:* Convert all materials into products. Avoid scrap, trim, excess, or bad raw materials.

- *Idle materials:* Make sure that nothing sits idle so there is a steady flow to the customer.
- *Time:* Eliminate delays, long setups, and unplanned down time of machines, processes, or people.
- *Transportation:* Eliminate the movement of materials or information that does not add value to the product, such as double and triple handling of goods and needless movement of information.
- *Unsafe acts:* Eliminate dirty, dumb and dangerous acts

Some of the results of Boeing's Lean efforts to eliminate these, and other, forms of waste are highlighted in the Findings below. More detailed findings are included in the Boeing case studies, attached as Appendix A and Appendix B. The case studies describe various Lean efforts at Boeing's Everett airplane assembly plant and Auburn Machine Fabrication Shop, and demonstrate how the Company implements and utilizes Lean strategies in a manufacturing setting. In addition, the case studies describe various resource productivity gains associated with the identified Lean activities, and several obstacles encountered by the Company in its efforts to implement specific Lean projects.

III. Findings

The findings articulated below are based primarily on the results of the Boeing case studies, along with supplemental research and review of the literature surrounding corporate environmental strategies, resource productivity and environmental improvement, and pertinent regulatory interactions. The findings represent Ross & Associates' interpretation of the Boeing case studies and do not necessarily represent the opinions of the Boeing Company.

Finding 1: Lean Manufacturing is Mainstream

Substantial research and literature exists indicating that American industries are actively implementing Lean Manufacturing as a key strategy for remaining competitive in today's manufacturing environment. Lean Thinking and other books that explain the Lean Manufacturing philosophy and processes indicate that implementation of this manufacturing paradigm shift is taking place across numerous industrial and source sectors. For many, Lean has become a fundamental strategy linked to corporate competitiveness and overall economic viability.

The Boeing Company began implementing Lean Manufacturing throughout the Commercial Airplanes Division in February 1996. Some initially saw this as "just another program" that would go away if ignored. It soon became apparent, however, that Lean Manufacturing had important elements not previously addressed in other Boeing manufacturing initiatives, and that these elements should be embraced if the company is to compete effectively. While Boeing realized that increasing market share is important, producing aircraft at lower cost and greater margin is key. Upon realizing early successes in Lean Manufacturing, "leaning" efforts at Boeing have since been expanded to the entire company.

Boeing has now established a corporate level Lean Manufacturing group to support all manufacturing and assembly operations within the commercial aircraft enterprise. Individual divisions have, in turn, established Lean initiatives that, in total, provide coverage to the entire commercial aircraft enterprise. Boeing's substantial investment in Lean reflects its belief that Lean plays a critical role in the company's efforts to provide customer responsiveness, reduce costs, and systematically improve operational performance on a continual basis.

Boeing's experience is highly consistent with, and reflective of, many other U.S. industrial sectors. Dr. Richard Florida's research on environmentally conscious manufacturing has documented the widespread adoption of Lean Manufacturing principles in the automotive industry, and has found substantial evidence of the transition to Lean thinking across a representative sample of the U.S.[16] Lean has also received significant coverage and promotion in major business management publications, such as the Harvard Business Review, and has become a core element of business school curriculum.

These findings indicate that Lean initiatives and thinking have become and will continue to be a staple of the U.S. manufacturing sector. And, as global competitive pressures continue (and increase), production processes will increasingly be converted to operate in conformance with Lean principles.

Finding 2: Lean Produces Significant Resource Productivity Improvements with Important Environmental Improvement and Sustainability Implications

In their recent book, Natural Capitalism, Paul Hawken, Amory Lovins, and L. Hunter Lovins identify broad strategies to achieve a more sustainable, environmentally responsive (and responsible) economy. One particular focus of the book is the substantial inefficiency in our current economy. They discuss the notion of the "ecological footprint," which is determined by calculating the material flow and energy required to support an economy, and note that every product produced and consumed has a hidden history, of environmental impact. As well, the authors argue that traditional capitalism has not accurately measured economic "progress" because measures have not assigned monetary value to natural resources – the basis of all economic activity. Problematically, when natural resources are not considered, the destruction of resources is measured as economic gain, allowing this destruction to continue with increasingly larger footprints. As a first step to addressing this situation, the authors advocate improvements to resource productivity – "rethinking everything we consume: what it does, where it comes from, where it goes, and how we can keep on getting its service from a new flow of very nearly nothing at all – but ideas."[17]

To this end, Natural Capitalism devotes an entire chapter to Lean Manufacturing (which draws heavily on the work of Womack and Jones) and identifies (and advocates) Lean as a powerful resource productivity enhancing system. According to the authors, Lean can improve substantially the resource productivity of the economy; as a result, they endorse and encourage its use as a means to reduce the ecological footprint of our economic activity. "For the first time, we can plausibly and practically imagine a more rewarding

[16] Florida, Richard. *Lean and Green: The Move to Environmentally Conscious Manufacturing*. California Management Review, Vol. 39, No. 1, Fall 1996, page 82.

[17] Hawken et al, page 81.

and less risky economy whose health, prospects, and metrics reverse age-old assumptions about growth: an economy where we grow by using less and less, and become stronger by being leaner."[18]

The Boeing case studies provide further direct evidence that the authors' interest in and advocacy of Lean Manufacturing is well placed. Boeing, through its Lean initiatives, has had substantial success and continues to improve on its "environmental footprint" per unit of production. Overall, Boeing has realized resource productivity improvements ranging from 30 to 70 percent when Lean initiatives are implemented.

At Boeing, the implementation of Lean has represented a fundamental paradigm shift from "batch and queue" mass production techniques to a "single-piece flow, pull production" system dedicated to rooting out all forms of waste (non-value added) from the manufacturing process. Through the adoption of a combination of such Lean strategies such as identifying and retooling the value chain, adopting product-aligned, cross-functional manufacturing, designing for manufacturability, and taking a "whole system view," Boeing has substantially reduced the amount of energy, raw materials, and non-product output associated with its manufacturing processes. More specific examples of resource productivity improvements in each of these areas (energy, raw materials, and non-produce outputs) are provided below.

Energy savings realized through Lean Manufacturing result from efficiencies such as decreased space utilization, decreased transportation, and less product rework. High-level results achieved at Boeing's Machine Fabrication Manufacturing Business Unit indicate that, as a result of Lean, overall space utilized by the MBU has decreased from 650,000 to 450,000 square feet, and 8,000 square feet-worth of temperature controlled atmosphere has been eliminated. This yields across-the-board energy savings on a per product basis, associated with all aspects of building space energy utilization (e.g., heating, cooling, lighting, etc.).

With respect to transportation, Boeing's value chain analysis has produced substantial reductions in the amount of transportation utilized in its manufacturing and assembly activities. The Auburn Machine Fabrication Unit, as a result of using restrike aluminum in its "pickle fork" manufacturing process, has eliminated the need to transport block aluminum to and from California (to undergo stress relieving procedures). At Everett, the re-thinking of the 777 floor grid component delivery process has reduced transportation by 50 percent for each shipset.

Within its factories, Boeing, utilizing cellular manufacturing strategies, has also substantially decreased internal product travel. For example, product travel has decreased anywhere from one to three miles, depending upon the product; overall people travel has been reduced by approximately 34,000 feet; and energy use and maintenance costs have been reduced due to the decrease in truck and forklift use. Much of this movement previously took place using electric or natural gas-powered fork lifts and/or overheard cranes.

Boeing's Lean initiatives have likewise substantially reduced the amount of rework and associated energy requirements conducted in its manufacturing and assembly operations. Prior to implementing Lean, the

[18] Hawken et al., page 143.

Auburn facility experienced a defect rate of 1,200/10,000. Auburn has substantially leaned these numbers to 300/10,000 presently.

Boeing has also seen **raw material savings** associated with improved use of space, better inventory control, decreased defects and scrap rates, use of fewer (or elimination of) lubricants and sealants, and decreased vehicle usage. For example, the Auburn Machine Fabrication shop's Lean efforts have resulted in reductions in raw materials spending by $22 million, and reduced damage and spoilage, resulting in better overall utilization of raw materials. The pickle fork manufacturing process previously machined the part from block aluminum, which generated a significant amount of scrap. The new pickle fork cell utilizes forged, restrike aluminum, which arrives in the approximate shape of the component so less aluminum is scrapped. The cell also incorporates a color coded "visual queue" system to standardize and improve work quality, and to reduce defects, scrap, and wasted raw material.

Also at Auburn, the 777 Stow Bin Arch initiative produced raw material improvements associated with reducing the number of components in the arch from 40 to 26, as the arch is now produced from a monolithic plate instead of numerous sheet metal parts. As mentioned, Boeing has also introduced into the Stow Bin Arch cell a number of small scale, right-sized processes. These include blanking, holing, and tapping which, due to their small scale and intermittent operations, are operated "dry," eliminating the utilization of cutting fluids and flooding lubricants from the process.

Boeing's Lean initiatives also have provided substantial **non-product output improvements** (e.g., scrap associated with defects and off-specification material, packaging material, and material losses) associated with its manufacturing and assembly operations. At the Auburn facility, the MBU has reduced product defects from 1,200/10,000 in 1996 to fewer than 300 presently. Similarly, the MBU has reduced by over 51 percent its quality cost performance measure (measured as total cost of dollars lost due to defects). As well, when Auburn switched to a product-focused cell for the production of 777 pickle forks, the result has been a 100 percent reduction in pickle fork rejection rates, with zero scrap.

At the Everett assembly operation, a variety of Lean initiatives also have substantial impacts on non-product output. The introduction of a "Kanban" cart system to the 747 wing panel inventory and supply system has eliminated utilization of 350 cubic feet of cardboard and bubble wrap packing material per wing ship set, and eliminated rework on the composite parts. Previously, shipping and storing handling damage required fiberglass rework of a significant number of the 140 panels in a ship set. The Everett chemical point-of-use system, a chemical inventory and hazardous waste management Lean initiative designed to improve machinist productivity, has resulted in reducing, on a per plane basis, chemical usage by 12 percent.

Interestingly, Boeing, for the most part, has not tracked, highlighted, or quantified the resource productivity improvements associated with energy, raw materials, and non-product output produced by its Lean initiatives. This is primarily because these improvements have not been part of the core business case for implementing Lean. Other factors (discussed in more detail in Finding 4) such as customer responsiveness, cycle time reductions, and product quality have justified the Lean initiatives, while the resource productivity improvements have come as an ancillary (but insubstantial from a financial standpoint) benefit. This has made it difficult in the context of this report to quantify specifically the environmental improvements associated with Lean while, at the same time, has indicated that Lean brings powerful, competition-based cost drivers to encourage resource productivity improvements.

Finding 3: Lean Produces a Robust Waste Elimination Culture

During the 1980s and 90s, Public Environmental Management agencies have looked to promote pollution prevention through such means as technical assistance, pollution prevention assessment guidance, and pollution prevention planning requirements. Looking across these initiatives at federal, state, and local levels, a common theme emerges: to make sustained pollution prevention progress that moves beyond the "low hanging fruit," a company must create a waste elimination culture. Common elements of this culture as identified in public agency pollution prevention guidance include: systemic and on-going evaluation of waste that is embraced and implemented by operations personnel; substantial engagement of employees, suppliers, and customers; development and utilization of pollution prevention measures; and a systemic approach to continual improvement.

The Boeing case studies indicate that the drive to Lean Manufacturing produces (and in fact requires for its success) a highly robust waste elimination culture. Boeing's approach to Lean implementation mirrors closely, and expands substantially on, the pollution prevention cultural elements long advocated by public environmental management agencies.

At Boeing, operations personnel run the Lean initiatives. These initiatives begin with a systemic evaluation of waste throughout the entire product value chain,[19] actively engage employees on an on-going basis, depend on and reflect close coordination with customers and suppliers, and develop, track, and publicly display performance metrics. Importantly, these initiatives are also embedded in a continual improvement system that reflects a commitment to "pursue perfection" and the belief that improvements and change are never complete.

These Lean "cultural attributes" are highly apparent at the Auburn and Everett facilities. At Auburn, Boeing established a Lean Team comprised of representatives from management, tooling, quality assurance, Safety, Health, and Environmental Affairs (SHEA), production staff, programming, and more. The Team began work by systematically evaluating waste in the Machine Fabrication Shop's processes, developing actions to minimize that waste, measuring the results, developing any additional actions to improve minimization, and continually repeating the cycle. The Team devised an overall Lean approach for the MBU which involved a total conversion of the factory from a batch and queue to single piece flow production environment.

To support continual improvement, Auburn, on an on-going basis, conducts Accelerated Improvement Workshops (AIWs) involving day-long, meetings of product teams to examine opportunities for taking

[19] Lean's and Boeing's definition of waste is very broad and encompassing including: process and product complexity; overproduction; unnecessary space; product defects; idle materials; unnecessary movement; material inefficiency; and injuries.

the next waste elimination step. Approximately 5-10 AIWs are scheduled each month. The MBU held the first AIW in May of 1996 and since that time hundreds of Machine Shop employees have participated.

Auburn also has worked closely with its suppliers and customers to orchestrate a smooth flow of material through the value chain. For example, Auburn has worked with Alcoa, its primary supplier of aluminum, to eliminate bulk ordering and delivery of raw material and to improve manufacturing process efficiencies by switching from block aluminum to forged, restrike aluminum.

At Everett, a similar waste elimination culture is reflected in the Lean initiatives utilized by the Company. Boeing created an overall Lean Group to assist in the development and implementation of Lean initiatives throughout the plant. Programs within the Everett facility invite the Group to participate in specific Lean projects if desired. As well, the different airplane programs, such as the 777 Critical Process Reengineering (CPR) program, have developed their own Lean offices. Specifically, the CPR held a "Link the Flow" workshop to evaluate the supply chain for 777 floor grid components. Working with vendors in Wichita, Tulsa, and Kansas City, the workshop established a substantially more efficient delivery method for the floor grid components. The Wing Responsibility Center (WRC) also created a specially-chartered team that includes the Parts Control Organization, to develop the 747 Line Side Supply and Simplified Ordering System. This involved substantial coordination with a Boeing supplier located in Kent, Washington, who had previously delivered bulk shipments of wing panels to the Everett plant. By working with the vendor, the WRC developed a better, more efficient, and less wasteful inventory ("kanban") control system.

As evidenced above and throughout the case studies, Boeing employees are making aggressive changes throughout the factory, and accomplishing significant environmental improvements that are fundamentally similar to those advocated by environmental agency pollution prevention staff. More broadly, when considered in the context of other waste elimination "cultures," Lean Manufacturing holds the potential to produce particularly sound results. This is primarily due to the fact that Lean manufacturing is "mission driven," based solely on the highly competitive nature of businesses and the need to continuously improve operations in order to drive down costs.

Finding 4: Lean Thinking Brings Powerful Financial Incentives to Resource Conservation and Pollution Prevention Improvement

"Pollution Prevention Pays" has been a consistent theme used by pollution prevention advocates to promote pollution preventing behavior. Pollution prevention assessment guidance and a long list of case studies encourage facilities to examine the total costs of polluting behavior (e.g., unnecessary material loss or utilization, direct regulatory costs, and liability) to ensure pollution prevention investment decisions are fairly and completely evaluated. This "Total Cost Assessment" approach, according to advocates, will often produce a strong business case (e.g., a return on investment commensurate with internal hurdle rate requirements) for resource conservation and pollution preventing behavior.

A consistent theme emerged during the Boeing case studies, however. The business case for undertaking Lean initiatives (and producing the associated resource productivity improvements described earlier) did not rely on these traditional pollution prevention and resource conservation benefits. In fact, in most cases, the financial benefits of resource productivity improvements (e.g., reduced energy, materials, and waste) were not even calculated because they were deemed financially insignificant.

For example, Boeing built the business case for the Everett point-of-use chemical initiative (which produced an 11.6 percent reduction in chemical usage per airplane) around higher machinist productivity. Under the new system, machinists would no longer spend significant amounts of time walking to and from centralized chemical cribs to obtain supplies and deposit waste. The return on investment from machinist productivity enhancements fully justified the change, while the financial benefits from chemical efficiency and waste reduction were deemed unnecessary to the business case.

This example, however, provides only a small glimpse of the cost drivers that Lean thinking brings to improved resource productivity. **From a methodological standpoint**, Lean's "whole system thinking" orientation empowers managers to accept higher costs on low value items (such as raw material inventory) to produce substantial cost savings throughout the entire product value chain. For example, at Auburn, it was common in the past to bulk purchase aluminum raw material to receive a 10 percent (or so) discount. Lean thinking specifically discourages bulk raw material purchasing and utilizes whole system costing to show that the loss of bulk purchasing discounts can be wholly offset by the lower inventory carrying costs associated with a single piece flow-based manufacturing process. (Pollution prevention advocates have long discouraged bulk purchasing because it tends to be highly wasteful due to spoilage, damage, and specification changes from a materials utilization standpoint, and the business case has long been built around material and waste savings.) Lean's whole system thinking, however, brings to the bulk ordering business case substantially larger financial benefits: a reduction in inventory carrying costs throughout the entire product value chain.

From a financial decision making standpoint, Lean brings to the pollution prevention and resource conservation financial equation very powerful cost drivers that move well beyond materials efficiency and avoided regulatory and liability costs. For example, for Boeing, a major driver behind the implementation of Lean thinking has been the reduction in product "flow days." Flow days (also referred to as cycle time) relates to the period of time (measured in days) required to take a product from raw material to customer delivery. At Boeing, (as with many companies) flow days are expensive, with the cost of a product flow day comprised of inventory holding costs, taxes, heating & lighting, and costs associated with capital tied up in the production process. To reduce flow days, Boeing has deployed a web of Lean strategies designed to create a single piece flow, pull production system that delivers optimal first delivered unit quality. The financial and customer responsiveness associated with flow day reductions have made the business case for Boeing, while the Lean strategies to obtain flow day reductions have produced the resource productivity improvements so important to the environment.

As an example, Boeing's Wing Responsibility Center (WRC) has envisioned using small booths or other technologies to replace large scale chemical and painting processes and integrating these processes into a continuous manufacturing cell-based production flow, thus eliminating multiple crane-dependent stabilizer moves in and out of specialized facilities. This would create a one-piece, pull-production system capable of all stabilizer process steps: assembly; sealing; painting; leak testing; and paint and corrosive inhibitor compound (CIC) applications. Although Boeing anticipated that this production realignment would reduce its use and release of environmentally sensitive materials, the financial benefits of these improvements were not calculated. Instead, Boeing built the business case around anticipated reduction in flow days from 16 to 4, and reductions in crane moves from 7 to 5.[20]

As another example, the WRC examined the 767 and 747 wing sealing processes. Previous operations had each 767 and 747 wing craned into one of 12 different positions in the building for internal and external sealing and pressure testing, and chemicals were spread among all 12 positions, and varied depending upon the work being done in each position. The WRC has reconfigured these sealing operations into two moving lines, for 767 and 747 wings. As a result of this "leaning" endeavor, chemical utilization and hazardous waste have been reduced, although it was the reduction in flow days from 13 to 6 for the 747 and from 12 to 6 for the 767 that made the business case.

The whole system thinking and batch-and-queue to single-piece flow paradigm shift, and the accompanying Lean strategies (e.g., product focused cells, design for manufacturability, etc.) are directly linked, as indicated in Finding 2, to the resource productivity gains Boeing has made. In most cases, however, it is the reduction in flow days and inventory carrying costs that anchor the business case for change, with the resource productivity improvements producing ancillary, but not determinative, financial benefits.

Finding 5: Environmentally Sensitive Processes are Difficult to Lean

Probably the most stunning finding from the case studies has been Boeing's almost complete inability to apply Lean strategies to environmentally sensitive processes. Operations such as painting, chemical treatment, and drying (common operations in metal fabrication and assembly activities across all industries) have proved highly difficult to Lean. These operations remain at Boeing, for the most part, in their traditional "batch and queue," functional department configuration.

Boeing's inability to Lean environmentally sensitive operations has resulted from a complex array of technical and regulatory constraints, including lack of process technology that conforms to the right-sized, flexible operational requirements of Lean, the sometimes prescriptive nature of certain building, fire, worker safety, and environmental regulations, and the potential uncertainty associated with approving innovative process approaches under such regulations. These factors, when examined at the design phase of a variety of Boeing's Lean initiatives, were deemed to affect adversely the implementation time, predictability of outcomes, and/or overall cost of the initiatives. This led Boeing to either implement a sub-optimal strategy (from a manufacturing design perspective) where most of a product process was "leaned," while the environmentally sensitive process remained batch-and-queue, or abandon the Lean effort entirely.

Total implementation time is critical to the viability of many Lean endeavors. Obstacles to achieving timely implementation of these activities can, in fact, cause a company to forego the change. For example,

[20]Boeing has this project on hold due to technological and regulatory constraints.

the Wing Responsibility Center (WRC) at Boeing had determined that two parallel lines for wing production (one each for the 767 and 747) would represent an ideal configuration from a manufacturing efficiency standpoint. Boeing determined that this new configuration would require both new building and environmental permitting processes. However, implementation time was also critical to project viability. The anticipated delays associated with conducting these regulatory activities convinced the WRC to align the lines differently (and less optimally), utilizing existing environmental controls.

The time required for regulatory review and the ultimate operational constraints and associated costs placed on the process can be uncertain. This uncertainty is exacerbated, in Boeing's assessment, by the innovative nature of the painting and/or chemical treatment processes they envisioned, and ultimately lead Boeing to modify substantially its original Lean Manufacturing designs. For example, Boeing's Machine Fabrication shop wanted to use small, flexible, right-sized equipment for painting applications (currently, inefficient cell process flow interruptions occur with these painting operations). Because booths required outside venting, federal and local air permitting requirements would apply to this change. Furthermore, there were uncertainties associated with the ability to actually permit this type of "unconventional" process, including the time frame for the review, the costs, and any limitations that might be placed on them. The combination of these uncertainties (along with total construction cost and lack of ideal booth locations) resulted in the abandonment of the effort.

In a number of instances, regulatory requirements dictated a very specific process configuration and technology requirement that would substantially raise the cost of the Lean initiative. For example, the Machine Fabrication Shop had hoped to incorporate chemical processing into their cell structure. As envisioned, the equipment would be small and flexible, and could be right-sized and placed in multiple areas. However, one of several obstacles to implementing a non-batch chemical processing system was Boeing's inability to resolve, in a cost-effective manner, issues raised by the building and fire codes. In fact, Boeing ultimately determined that building and fire codes made moving smaller processing lines to the factory floor cost prohibitive. As with implementation time and uncertainty, the cost of meeting these codes led to significant design changes in the overall Lean strategy and a failure to Lean the environmentally sensitive process.

Boeing's experience is consistent with other researchers' writing on the existing regulatory system's shortfalls in facilitating environmentally beneficial manufacturing innovation. For example, Michael Porter of the Harvard Business School and others have found that firms seeking to market new products or increase manufacturing capacity, even if these changes result in environmental improvements, are often unsure whether they are subject to, or when they will be able to obtain, the necessary regulatory approvals. Such delays and uncertainties reduce projected return on investment, thereby discouraging innovation and turnover of capital stock.[21] EPA staff have as well contributed to this assessment, suggesting that as a

[21]See Porter, Michael & van der Linde, Claas, *Green and Competitive: Ending the Stalemate,* Harvard Business Review, Vol. 73, No. 5, September-October 1995; Stewart, Richard B. *Environmental Regulation and International Competitiveness,* The Yale Law Journal, Vol. 102, 1993; Gray, Wayne B. and Shadbegian, Ronald J. Environmental Regulation and Manufacturing Productivity at the Plant Level. Center for Economic Studies Discussion Paper 93-6, March 1993.

whole, the "system is not structured to reward those who take risks to promote P2 or technology innovation, or those who take the additional time required to explore options for improvements in media."[22]

Boeing's inability to Lean environmentally sensitive processes and incorporate them into its overall single-piece-flow approach has three significant implications for the company, other companies, and the environment. First, the inability to Lean these processes has led to the sub-optimal implementation of Lean strategies. Rather than creating complete single piece flow for its products, Boeing must interrupt product flow and move parts into a batch and queue environment for painting, chemical treatment/testing, and drying. This interruption adds a substantial number of flow days and greater space, raw materials, energy, and inventory management requirements to the production process. In certain instances, the bottlenecks associated with environmentally sensitive processes have completely eroded the business case for Lean, leaving Boeing no choice but to retain traditional production methods. Overall, Boeing's products cost more and take longer to produce than a complete implementation of Lean thinking would otherwise produce.

Second, where Boeing has been able to Lean, substantial resource productivity gains have emerged. As indicated in Finding 2, Boeing has seen improvements ranging from 30 to 70 percent when Lean initiatives are implemented. Painting, chemical treatment/testing, and drying processes (the processes, from an environmental standpoint, that would be the most desirable to improve) have not experienced commensurate gains. Moreover, Boeing has found it challenging to operate these remaining batch and queue processes optimally. They were set up, as all batch and queue functional departments are, to process large volumes of like products during longer production runs. Where Boeing has implemented single piece flow, however, large batches of similar parts are no longer produced.

Third, the environmentally sensitive processes now represent a substantial roadblock to Boeing's complete implementation of Lean principles and the competitive advantages they provide. Thus flow days, and other significant costs, are stacking up against these processes. This has created substantial awareness of the need for and commitment to developing less environmentally sensitive processes. For example, Boeing currently uses ammonia (a highly regulated, environmentally sensitive substance) to conduct seal tests at the Wing Responsibility Center (WRC). To broaden the conditions under which the seal test can occur (and thus allow Boeing to Lean the seal test function), Boeing is exploring alternative substances for the seal test (such as helium) that could completely eliminate ammonia from the process. Boeing's drive to eliminate ammonia is solely driven by its desire to Lean the entire manufacturing process. At the same time, although this situation represents an important pollution prevention promotion opportunity, the extent the constraints Boeing faces are unnecessary from an environmental protection and/or overall public policy standpoint, they impose substantial opportunity costs on Boeing and divert resources from its fundamental mission of building competitively priced, high quality airplanes.

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[22]National Advisory Council for Environmental Policy and Technology. Transforming Environmental Permitting and Compliance Policies to Promote pollution Prevention: Removing Barriers and Providing Incentives to Foster Technology Innovation, Economic Productivity, and Environmental Protection. April, 1993, page 23.

IV. Implications

The Boeing case studies provide an interesting window into the dramatic shift in manufacturing paradigms taking place in response to the highly competitive marketplace of the 21st century, where pressure to reduce the time-to-market cycle will continue to intensify for most companies. Such companies will need to conceive and deliver innovative products faster than the competition, while maintaining quality, lowering production costs, and remaining highly responsive to customer needs. At the Boeing Company, Lean Manufacturing is in the forefront of the company's efforts to eliminate continually all non-value added aspects of the enterprise and ensure optimal competitiveness. Lean has provided Boeing with a basis to promote and fundamentally rethink how to produce and deliver goods and services, and meet its production challenges.

Importantly, in addition to enhancing Boeing's competitiveness in its industry, Lean strategies (identifying and retooling the value chain, adopting product-aligned, cross-functional manufacturing, designing for manufacturability, and taking a "whole system view"), have reduced the amount of energy, raw materials, and non-product output associated with its manufacturing processes. In many cases, these reductions translate into important environmental improvements. Boeing's approach to Lean implementation resembles and expands the pollution prevention cultural elements long advocated by public environmental management agencies. Beyond this, the resource productivity improvements associated with Lean can and should also be considered in the context of sustainability, given Lean's relationship to production efficiency, and the increasingly smaller "ecological footprint" made by firms engaging in Lean Manufacturing.

Where Boeing was able to "Lean" its operations, the company now realizes productivity improvements ranging from 30 to 70 percent. For "environmentally sensitive" processes, however, improvements have been limited. Boeing's inability to Lean these operations has resulted from a complex array of technical and regulatory constraints affecting implementation time, predictability, and overall cost of the Lean initiatives. As a result, environmentally sensitive processes create a substantial roadblock to Boeing's complete implementation of Lean principles and the competitive advantages they provide, while remaining, for the most part, isolated from the resource productivity benefits Lean can deliver.

The findings from these case studies hold important implications for environmental (and other public/worker health) management agencies. In particular, Lean's strong association with resource productivity enhancements contrasted with Boeing's almost complete inability to Lean environmentally sensitive processes points to an opportunity for agencies to examine regulatory responsiveness opportunities that could produce significant competitiveness and environmental improvement outcomes. The case studies indicate that, in particular, there are three areas where agency action could make a substantial difference.

First, at Boeing (and presumably other companies implementing Lean), the initial conversion process from a batch and queue function to a product aligned, single piece-flow manufacturing environment is associated with substantial retooling of the entire manufacturing process. This includes moving from large scale, static machines to right sized, mobile equipment, reconfiguring factory operations (requiring moving, modifying, and constructing existing and new equipment), and obtaining all necessary approvals for these changes all under tight time constraints to ensure profitability. To facilitate this conversion process, the case studies point to three critical needs: increased receptivity to innovative process change (in particular, the ability to accommodate small scale, flexible, and potentially mobile processes); enhanced predictability to the likely regulatory constraints such equipment will operate under; and timely (preferably real time) responses to construction and modification actions. Anyone ever involved in federal, state, or local regulatory processes knows that these shifts will represent a substantial challenge for agencies, both because existing regulatory review processes have proven rather effective at ensuring practical enforceability and protecting human health and the environment, and because moving outside of existing legal and regulatory precedent represents substantial risks to both regulatory agencies and permitted sources.

Second, Lean's continual improvement culture combined with customer demands and competitive pressures result in a manufacturing environment subject to constant, on-going change. As a result, after the basic Lean conversion takes place, modifications to material inputs, product outputs, non-product outputs, equipment, equipment configurations, and operating parameters are likely to be the norm. The Boeing case studies indicate that the business case for Lean initiatives is highly sensitive to implementation time frames. In this environment, even minimal regulatory delay holds the potential to erode quickly a process improvement's financial return, which, in turn, could result in foregoing the resource productivity enhancements associated with the change. This type of dynamic manufacturing environment poses a special challenge to regulatory agencies (that often conduct case-by-case review and approval permitting actions) to keep timely pace with these changes, while ensuring enforceability and environmental protectiveness.

Third, Finding 3 focused on the robust waste elimination culture that Lean generates. At Boeing, Lean thinking has produced important and substantial resource productivity financial drivers and imbeds them in a system driven by and dedicated to the elimination of all forms of waste throughout the product value chain, continual improvement (pursuit of perfection), substantial supplier, customer, and employee involvement, and strong, visible performance metrics. Moreover, Lean thinking utilizes the language of business and operations; it is familiar to and readily accepted by those individuals most connected to the fundamental operations (and operational choices and directions) of the company. Lean thus holds the potential to invigorate pollution prevention promotional efforts. As indicated earlier, its systemic approach is highly parallel to existing pollution prevention promotion efforts but appears to reach beyond both from a financial and cultural perspective. And, given that Lean still remains a relatively new concept, environmental agencies' traditional pollution prevention role as technical assistance providers and information clearinghouses could improve the timeliness of diffusing Lean thinking.

Although based on a limited set of examples, the Boeing case studies suggest that, while Lean thinking is redefining the manufacturing landscape and the way production activities take place on the factory floor, the regulatory system – which grew up and evolved regulating a batch and queue, mass production environment -- continues to be structured and operate with batch and queue processes in mind and operate itself as a batch and queue enterprise. To the extent that Boeing's experience provides a window into the larger world of American production activities, these case studies can provide an opportunity for environmental regulatory agencies, through responsiveness to Lean initiatives, to create a substantial competitiveness and environmental “win – win” outcome. Assisting to eliminate the barriers to full implementation of Lean, creating the opportunity for Lean thinking to retool environmentally sensitive processes, and aggressively promoting the adoption of Lean thinking holds the potential to support American industry in its efforts to compete globally, make important advances in pollution prevention, and move us more swiftly along the road to a more sustainable form of capitalism.

Appendix A: Boeing Everett

Introduction

Boeing is implementing Lean projects in various ways throughout its Everett Plant. The Company created an overall Lean Group to assist in the development and implementation of Lean initiatives throughout the plant. Programs invite the Group to participate in specific Lean projects if desired. The different airplane programs and organizations have also created their own Lean offices to focus specifically on Lean efforts within the particular program. For example, the 777 program has developed its own office, Critical Process Reengineering (CPR), to look for opportunities within the 777 line.

Throughout the Everett plant, Lean initiatives have yielded measurable results. Larger efforts, like some of those described below, have resulted in substantial resource productivity gains and savings. Smaller efforts have also produced significant benefits. For example, the development and implementation of an alodine pen to be used prior to primer touch up, has reduced hazardous waste generation by approximately 36, 55-gallon drums per year. As part of a small tool recycling and reconditioning program, the 777 Wing Majors shop is recycling plastic spatulas used to apply sealant, reducing hazardous waste generation by approximately 90 percent (only the scraped sealant residue and velcro pad are disposed of, not the spatula itself).

Lean Efforts

To illustrate in greater detail the affect of Lean Manufacturing efforts at the Everett plant, five Lean projects were selected for closer examination. The initiatives selected and detailed below are the 777 Floor Grid Component Delivery Process, the 747 Line Side Supply and Simplified Ordering System, Chemical Point of Use Stations, 767 & 747 Wing Seal Moving Lines, and the 747 Horizontal Stabilizer project. These efforts are at various stages of implementation and the final effort, the 747 Horizontal Stabilizer Project has been put on hold due to technical and regulatory constraints.

777 Floor Grid Component Delivery Improvements

Boeing, as part of its overall Lean efforts, created a Lean Office to support the Twin Aisle Program (747s, 767s, and 777s). The 777 Line also formed its own group, CPR, to analyze current practices and identify potential Lean opportunities within the 777 program. In identifying potential opportunities, 777 operations were examined in total, providing a broader perspective of the overall program. In taking this more global approach, CPR identified as cost reduction opportunities the shipping processes used for seat tracks and floor beams. Boeing produces the parts in Wichita, Kansas and Tulsa, Oklahoma and then ships them to the Everett plant in Washington State.

CPR held a “Link the Flow” workshop to develop a Lean Vision for the shipping of 777 floor grid components. Workshop participants focused on shortening the overall value chain and developed a vision of the ideal shipping process. The participants also developed an interim vision, which serves as a midpoint target in the process of continually improving the shipping system.

Previously, Boeing delivered 777 seat tracks from Wichita and Tulsa to the Boeing Everett plant by truck. The parts were unloaded at Receiving and Inspection and then delivered to the factory for assembly. Boeing shipped 777 floor beams by truck from Tulsa to Kansas City then loaded them onto a train for shipment to Seattle via rail. From Seattle, a truck transported the floor beams to Receiving and Inspection at the Everett plant. Eventually the parts were brought to the factory for production purposes.

The Workshop resulted in a new delivery method for 777 floor grid components. Trucks now transport seat tracks from Wichita to Tulsa, pick up the floor beams then, carrying complete ship sets, travel directly to Everett and deliver the parts directly to the factory for use. Receiving and inspection processes are conducted at the plant. The redesigned shipping process allows a single truck to deliver a shipset of floor grid components directly to their point of use.

As a result of the new shipping process, Boeing has realized the following resource productivity gains:

- Multiple transfers, rail travel, and truck travel to the rail heads have been completely eliminated. Trucks no longer run empty from Kansas City to Tulsa because shipping by rail has been removed from the process.
- Eight days of travel and three days of receiving and inspection have been eliminated.
- Approximately $7,900 has been saved per shipset or $396,000 in annual transportation costs.
- Floor grid inventory has been reduced by 25 percent. Components are now shipped directly to the factory when they are needed, reducing the number of overall ship sets required in the delivery pipeline.
- Each ship set uses 50 percent less transportation (and associated energy and maintenance). Previously, Boeing trucked half of one airplane's worth of floor grids to Everett and trucked and then shipped by train the other half to Seattle; Boeing now ships one airplane's worth of floor grids in one truck from suppliers in Tulsa and Wichita directly to the Boeing factory in Everett.
- Overall handling of materials has been reduced, yielding a reduction in forklift use. Decreased forklift operation represents savings associated with fuel, maintenance, and driver time.
- Also, in response to Boeing's new shipping process, the floor grid component suppliers have adjusted their manufacturing schedules so that they do not produce and accumulate excess inventory at their production sites.

747 Line Side Supply and Simplified Ordering System

The Wing Responsibility Center, using a specially-chartered team working with the Parts Control Organization, (the organization responsible for material handling and inventory control across the Boeing Commercial Airplane Group), developed the 747 Line Side Supply and Simplified Ordering System. This 747 Lean project focuses on improving the inventory and supply chain systems for fiberglass panels comprising wing trailing edge areas.

Under the previous inventory and supply system, a supplier in Kent delivered bulk shipments of panels to the Everett plant. Boeing temporarily stored the panels in a factory parts control area before delivering them to the factory floor for installation. The fiberglass panels are fragile, requiring each to have cardboard wrapping, with approximately 60 percent having plastic bubble wrap inside the cardboard. Boeing discarded the cardboard when unwrapping the panels in the factory parts control area and the bubble wrap when a mechanic installed the panel on an airplane.

To provide better inventory control and decrease damage, the Wing Responsibility Center is implementing a "kanban" cart system. This system is built around constructing and introducing custom carts which the vendor in Kent will use to transport the panels directly to the 747 Wing Majors area point of installation. To control the amount of inventory shipped, one set of carts is capable of holding only one ship set of panels. The Wing Responsibility Center's return of an empty cart signals the vendor that Boeing requires another ship set.

The transportation carts are also designed to reduce packaging waste. Carts have restraining straps and are segregated into padded compartments so that individual fiberglass panels require no packaging. Carts are also more ergonomically correct to reduce worker injury.

When fully implemented, Boeing anticipates the following resource productivity gains.

- Fiberglass panel inventory will be reduced from 14 ship sets to 4.
- Rework due to handling damage will be virtually eliminated. (Previously shipping and storing handling damage required fiberglass rework of a significant number of the 140 panels in a ship set.)
- Approximately 350 cubic feet of cardboard and bubble wrap packaging will be eliminated per wing ship set.
- Parts and mechanics travel will be reduced because parts will be shipped directly to the point of use in the wing assembly area.

Chemical Point of Use Stations

Boeing's Safety, Health, and Environmental Affairs organization (SHEA) developed the Point of Use system for chemical materials. Generally, point of use efforts enable the storage of materials where the production process utilizes them. Boeing's key objectives for point of use chemical stations are reductions in mechanic travel and better control of the supply, use, and distribution of hazardous materials. Ultimately, reduced mechanic travel time was the primary financial driver for this change. Currently Everett has over 120 point of use stations.

Prior to implementing the point of use stations, several chemical disbursement centers, known as chemical cribs, distributed the paints, sealants, solvents, and other chemical materials required for airplane assembly. Mechanics were required to pick up new materials from, and return unused and waste materials to, cribs. This entailed frequent travel over substantial distances.

The new stations are self-help areas that allow mechanics to pick up materials and return waste at the point of use. A Hazardous Material worker visits the point of use stations at least twice a shift to check supplies, pick up waste, and resupply material for the specific applications occurring within the station area. Boeing controls the amount of chemical inventory and waste on the floor by using minimum/maximum quantities, right-sizing containers, (holding only the necessary amount of material required for a specific application), and limiting each station's quantity of containers.

Boeing tracks the point of use station materials by bar code to determine what types and quantities each factory location uses. Boeing uses the tracking to prepare a 30 day reduction report. The report analyzes the amount and type of chemicals used and helps to determine how much inventory to carry where in the system. If a particular location does not use a specific product regularly, Boeing lowers the product's maximum amount at the station. Boeing expects to track dry goods for chemical applications in the future to assist in overall waste reduction.

Each point of use station also utilizes small, (less than 55 gallons) segregated cans for waste materials. Shops segregate their own waste, and Boeing color codes chemical products and the waste stream to reduce the possibility of mistakes. Each also has a reuse section. If material is leftover after an application, mechanics can place the excess material back at the station for future use.

Implementation of the Point of Use Stations has yielded the following resource productivity gains:

- chemical use per airplane has been reduced by approximately 11.6 percent;
- the amount of chemicals on the shop floor has been reduced by 23 percent;
- overall material waste has been reduced due to the use of right-sized containers and easier mechanic access to materials; and
- mechanic travel has been reduced by 56 percent, representing an average of 567 fewer trips and 95 hours of less travel per day.

767 & 747 Wing Seal Moving Lines

The Everett Wing Responsibility Center has been engaged in efforts to establish several moving production lines. As part of that effort, the Center examined the 767 and 747 wing sealing processes. Operations within those processes include exterior sealing, in-tank sealing, pressure testing, and painting applications. The Center conducts these large scale chemical processes in a separate, dedicated factory building with full environmental controls, including specialized air cleaning and water collection systems. Cranes lift the large wing assemblies to the building from various areas in the factory where assembly takes place.

Previous operations had each 767 and 747 wing craned into one of 12 different positions in the building for internal and external sealing and pressure testing. Subsequently, cranes moved each wing to three additional positions, each corresponding to separate processes: spar (edge) painting, large surface painting in vertical paint booths, and a final job pickup position. As many as three sets of 767 and 747 wings could be in work at any given time. Chemicals were spread among all 12 positions, and varied depending upon the work being done in each position.

As part its Lean efforts, the Wing Responsibility Center has reconfigured these sealing operations into two moving lines, for 767 and 747 wings. This process results in no more than four wings receiving work at a time: one 767 and 747 wing on the moving lines, and one of each in the vertical paint booth.

The moving lines, established in April 2000, have four or five workstations, depending on airplane model, on each side of the wing. At these fixed workstations, mechanics perform exterior sealing and corrosion sealing as the wings move slowly by on two drive units. Each workstation is height-adjustable to improve ergonomics and has a point of use chemical station containing the materials required for each processing step. Waste is deposited and collected at the point of use stations.

The Wing Responsibility Center has short-term plans to add in-tank sealing, exterior masking, and painting to the line activities. Long-range plans include the possibility of adding leak testing, plumbing installation, and the large-scale painting currently done in the special paint booths.

The moving seal lines, as currently configured, have achieved the following benefits.

- Flow days have been reduced from 13 to 6 for the 747 and from 12 to 6 for the 767.
- Crane moves, required to move the assembled wing throughout the factory, have been reduced from 7 to 5. (Limiting crane moves is a priority for Boeing because the complexities of crane moves for large aircraft parts often cause delays in the overall production process.)
- The point of use stations, affixed to work platforms, allow for better chemical material inventory control, reducing the amount of both chemical inventory and waste. Boeing is also exploring the possibility of developing a process that would allow employees to mix seal at the gun itself, so mixed sealant in freezers would no longer be required. This would reduce the waste generated by sealant inventory that is not used within a specified period of time.
- Fixed position sealing requires less sealant, thereby producing less hazardous waste. In addition, because there is less inventory on the floor, (i.e., 4 wings versus 12), there will be less overall chemical inventory spread throughout the building.
- There have also been significant gains in available floor space, which may be used in the future to accommodate additional sealing and mechanical assembly processes.

WRC's initial design efforts indicated that the ideal configuration for the moving lines would have been two parallel lines (one each for the 767 and 747), thus optimizing building space. Although the building currently has full environmental controls, Boeing determined that this ideal configuration (from a production process perspective) would require new building and environmental permitting activities. Because implementation time was critical to the viability of this project, the anticipated delays of conducting these activities, and uncertainties associated with them, convinced WRC to accept a less than ideal configuration; aligning the moving lines to utilize existing ventilation systems and environmental controls.

Technical constraints have also influenced the development of the moving lines. Specifically, the cure time of sealants and paints dictate the flow time of the moving line. The flow cannot be too rapid because paints and sealants require specific curing times. In an effort to address this issue, the Wing Responsibility Center is currently exploring the existence of new technologies such as faster curing sealant and accelerated paint curing.

747 Horizontal Stabilizer Project

The Everett Wing Responsibility Center also has examined the possibility of establishing a moving line for the 747 Horizontal Stabilizer. Like the Wing Seal process, the Horizontal Stabilizer production consists of both chemical and assembly processes. Unlike the Wing Seal line, however, the WRC had interest in locating the entire horizontal stabilizer process line on the main factory floor. The WRC currently joins the 747 horizontal stabilizer in the main factory, then transfers it to an environmentally controlled building, roughly ½ mile away, for sealing, painting, and seal testing. As a fuel cell, the 747 horizontal stabilizer must receive a seal test. The current test entails filling the cell with ammonia to detect any leaks. Additional seal work and paint applications are also conducted in this facility. The WRC then moves the horizontal stabilizer back to the main factory for anti-corrosion applications and final assembly. (The anti-corrosive application is conducted within temporary confinement walls with a ventilator.)

The Wing Responsibility Center has envisioned using small booths or other technologies to replace large scale chemical and painting processes and integrating these processes into a continuous manufacturing cell-based production flow, thus eliminating multiple crane-dependent stabilizer moves in and out of specialized facilities. This would create a one-piece, pull-production system capable of all stabilizer process steps: assembly, sealing, painting, leak testing, and paint and corrosive inhibitor compound (CIC) applications. WRC would depend on
smaller, right-sized, moveable equipment to support this redesigned process.

The Wing Responsibility Center anticipates the following resource productivity gains from implementation of the 747 horizontal stabilizer moving line.

- A reduction from 16 to 4 flow days.
- Elimination of 23 overhead crane moves, reducing the total number from 31 to 8.
- Space requirements reduced from 29,600 to 14,800 square feet.
- Significant energy savings due to the reduction in crane moves and space required for production.
- An approximate 10-20 percent reduction in paint overspray and solvents required for component applications due to the use of small, in-line chemical operations.

Regulatory and technological constraints (and the time required to develop possible solutions) has caused WRC to place the entire 747 Horizontal Stabilizer project on hold. WRC directed manufacturing, engineering, and technical resources toward overcoming some of these obstacles, however the work was expensive and time consuming. Approaches explored to overcome some of these constraints included changing the technology associated with certain processes, eliminating the processes, or substituting another, less hazardous process.

In particular, the seal test and painting applications have presented significant obstacles. WRC currently conducts the seal test (which uses ammonia, a compound strictly regulated by OSHA, fire code, and environmental regulatory requirements) under only highly constrained conditions. These strict requirements dictate the limited conditions under which the seal test can occur. In response, Boeing is exploring alternative substances (such as helium) and methods for conducting the seal test. If helium proves viable, WRC would completely eliminate ammonia from the process.

Spray painting/coating operations also presented various obstacles. To move painting processes onto the main factory floor, the Wing Responsibility Center began developing self-contained, moveable, right-sized painting units. The Center examined smaller units because it viewed the costs of moving "as is" painting operations onto the floor as too great.

As WRC explored various technological approaches to small scale, in-line mobile equipment, the number and variety of requirements associated with moving the spray painting/coating operations onto the factory floor became apparent. Requirements included those associated with the Building and Fire Code, OSHA, and the Clean Air Act. Although no single requirement or regulation proved to be an impediment that could not be overcome, the combination of requirements was overwhelming in light of the time and resources WRC could make available to the project. WRC also perceived significant uncertainty as to whether any self-contained, moveable, right-sized painting unit could receive a permit under the Clean Air Act. Because of the cost, time, and uncertainty associated with the identified regulatory requirements, WRC discontinued further technological development efforts and placed Horizontal Stabilizer moving line development entirely on hold.

Appendix B: Boeing Auburn Machine Fabrication

Introduction

The Boeing Machine Fabrication Manufacturing Business Unit (MBU) in Auburn, Washington produces various components for Boeing aircraft, including wing, landing gear, and fuselage parts. It produces over 1,000 different products and an average of 22,000 parts per month. The MBU employs approximately 700 people, and the factory itself is 550,000 square feet.

The Machine Fabrication factory was previously organized in a job shop layout, supporting "batch and queue" production techniques associated with producing large quantities of goods in a function-driven structure. This meant that all processes were co-located throughout the factory based upon functional commonality (e.g., boring mills were all located in a boring mill area, assembly in the assembly area, etc.) Work traveled throughout the factory from job shop to job shop in order to produce a final product.

This manufacturing structure required substantial space. As work traveled from one area to another, it sat in area "queues" until ready for work. Vast amounts of factory floor space was dedicated to storing Work in Process (WIP). In addition, space was required to store inventory, as bulk purchasing of raw materials and production of new parts continued even as WIP sat in area queues. Space was also needed for storage of finished products because the production schedule was not necessarily based on completing production of a part at the time a customer required it. Overall, the Machine Fabrication shop utilized approximately 650,000 square feet, including rented off site storage space.

Because of the factory's configuration and size, WIP traveled literally miles throughout the production process. A typical job had as many as 30 station moves from raw material to finished product. Cranes, trucks, and forklifts were the primary methods for moving WIP and materials from job shop to job shop.

As the MBU brought new and varied products in, it needed to acquire large complex equipment to support the changing volume of goods. These machines were capable of machining many different types of features, but were costly and required construction of their own foundations to operate. The variety of new products also required a variety of support tools, including measuring and burring equipment, shop supplies, and perishable tools.

The complex flow of these new products additionally required a large staff to support programming, tooling, planning, and engineering. Within Machine Fabrication, employees generally operated only within their particular job shops, developing and applying a single set of skills to specific facets of the production process.

The MBU measured success in terms of machine efficiency and utilization, production backlog, and machine tool setup savings associated with "batching." The MBU consider these factors to be representative of productivity. Although the batch and queue process minimized marginal unit cost at each job shop, it was susceptible to problems such as inflexibility, excessive travel and inventory, a higher number of flow days[23], greater overall costs, and quality issues. For example, operating within this manufacturing environment, generally required 6-10 months of raw material to finished good processing time.

Lean Manufacturing

In January of 1996, the Boeing Company introduced Lean Manufacturing to the Machine Fabrication Shop leadership as an initiative to promote cost reduction. The Machine Shop created a "Lean Team", which analyzed and documented factory data associated with quality, cost, delivery, safety, and morale. Members of the Team represented various entities throughout the production process including management, tooling, quality assurance, Safety, Health, and Environmental Affairs (SHEA), production staff, programming, and more. The Team was empowered to identify waste in the Machine Fabrication Shop's processes, develop actions to minimize that waste, measure the results, develop any additional actions to improve minimization, and to repeat the cycle continually. The Lean Team began by conducting a Lean Manufacturing Assessment, which analyzed where the MBU spent resources, identified what products the MBU produced, and how much it cost to produce those products. The Team also developed a "Lean Vision" to describe and communicate to the Machine Fabrication Shop as a whole the initial production system changes envisioned for the MBU.

The Lean Team's four key "Vision" elements were: product/process focused cells; simplified scheduling; shop floor control; and focused support.

- *Product/process focused cells:* As described in the Vision, product/process focused cells "combine processes and equipment re-located from functional areas, employ multi-skilled personnel, and will be utilized to manufacture and assemble single ship-set quantities." The cell structure addresses problems associated with a batch and queue structure, such as excessive travel and inventory, higher flow time, higher costs, quality problems, and a lack of product ownership.

- *Simplified scheduling systems:* The Lean Vision states that the MBU will utilize simplified scheduling systems where possible to reduce the impact of schedule changes. "Simplification will be achieved by utilizing a repetitive production cycle based on the firing order[24], pull aheads[25] for the level loading of bottlenecks and first in/first out[26] (FIFO) for cellular order completion."

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[23] Flow days comprise the period of time required to produce a finished good from raw materials. The costs associated with a flow day include floor space, managing inventory, heating and lighting, handling time, taxes, engineering changes, and capital tied up in the production process.

[24] The firing order is the sequence in which airplanes are built.

[25] "Pull ahead" is done so that production requirements are met while a manufacturing area is shut down for any of a variety of reasons, including planned maintenance.

[26] Products are completed in the same sequence as started.

- *Improved shop floor control*: The third component of the Vision calls for visual controls to replace information systems to simplify and improve overall shop floor control. Because cellular production greatly decreases product movement, "additional simplicity will be achieved by utilizing visual controls, traveler reduction, and managing post-cell processing via first in/first out."

- *Organizational support structure:* The last element of the vision calls for Manufacturing Engineering to change to "provide focused and dedicated support at the product center and cell levels." This product and cell specific support is designed to improve customer focus, optimize production efficiency, and promote ownership of the products and processes.

To implement the Lean Vision, the Machine Fabrication Shop made fundamental changes, (based upon the four key elements listed above), to its manufacturing structure. Factory operations are no longer co-located throughout the Shop based upon functional commonality; instead, the MBU has designed and implemented product-focused cells. The MBU has moved all the necessary equipment, people, and resources required to produce a product into a specific cell and all operations are performed in that cell, using a first-in/first-out approach to scheduling. The MBU has structured cells so that single ship sets[27] flow through the production process from one operational step to the next. This has required incorporation of component and tool storage, milling, drilling, honing, grinding, turning, deburring, and assembly, as well as shipping, receiving, and quality assurance into each cell.

The MBU also designed a variety of processes to compliment and enhance the performance of the cell manufacturing structure. Tooling and equipment capability are matched with the fit, form, and function of the part being fabricated in the cell. The MBU has scaled manufacturing equipment, where possible, to need and placed it on wheels to increase flexibility. Product teams exist instead of process teams, and employees receive cross-training to perform effectively the different operational functions within the cell. Ergonomic work tables and stations have been installed to help reduce worker injury.

A key component of implementing the Machine Fabrication Shop Lean Vision was, and continues to be, employee inclusion and training. The MBU encourages all shop employees to participate in the effort, including identifying areas of waste and developing process changes to remove waste from production. The MBU utilizes Accelerated Improvement Workshops (AIWs) to maximize employee education, involvement, and support a continual improvement culture. Approximately 5-10 AIWs are scheduled each month. The MBU held the first AIW in May of 1996 and since that time hundreds of Machine Shop employees have participated in AIWs.

To measure the success of Lean initiatives, the Lean Team established performance standards for the MBU. These standards include quality (defects and cost of quality), product cost, delivery performance, flow, inventory turns, safety, WIP, and productivity.

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[27] A ship set is one airplane's worth of parts. If two of one item go on any given plane, the ship set value is two.

High Level Results

According to Boeing, since initiating Lean Manufacturing efforts, the MBU has experienced substantial overall improvements:

- the MBU has reduced total cost by 30 percent;
- productivity has improved by 39 percent;
- the factory has reduced approximately 70 percent of flows by 70 percent;
- production flexibility has increased approximately 40-50 percent;
- defects have been reduced from 1,200/10,000 in 1996 to fewer than 300/10,000 presently; and
- the MBU has reduced by over 51 percent its quality cost performance measure (measured as total cost of dollars lost due to defects).

In addition, Lean strategies have yielded significant gains with respect to specific elements of the manufacturing process, contributing to the MBU's overall improvements. Three specific manufacturing elements (travel, space, and inventory), illustrated below, highlight some of the higher level changes and results produced in the MBU.

Travel

Numerous Lean strategies/tools have had an affect on the amount and mode of people and product travel. Key strategies include the following.

- Production processes have been reconfigured into product cells, which include most manufacturing operations necessary to produce specific products.
- Wheels are attached to much of the equipment within the product cells, reducing the need for trucks and forklifts throughout the production process.
- Point of use stores are incorporated into each product cell and are stocked using a minimum/maximum system.

These strategies have produced significant travel-related resource productivity gains. For example:

- internal factory product travel has decreased anywhere from one to three miles, depending upon the product;
- overall people travel has been reduced by approximately 34,000 feet; and
- energy use and maintenance costs have been reduced due to the decrease in truck and forklift use.

Space

Lean techniques implemented have also significantly affected the amount of space utilized, and the way space is utilized, by the MBU.

- Reductions in bulk purchasing have decreased the amount of inventory on site.
- Manufacturing occurs in ship sets of one resulting in little WIP within the product cells and on the factory floor.
- Products are completed and delivered when needed by the customer, so there is less finished product on site.
- Coordinate Measuring Machines (CMM), used to inspect the quality of products, are programmed

to adjust themselves for temperature differentiations (all CMM testing was previously conducted in an 8,000 square foot temperature controlled space).

These techniques are directly associated with a substantial decrease in the per unit of product manufacturing space requirements and associated energy and building maintenance needs. Specifically:

- Space utilized by the MBU has decreased from 650,000 to 450,000 square feet. Of the 200,000 square feet reduced, 100,000 square feet is storage space that is no longer required and the other 100,000 is now open factory floor.
- Newly open floor space allows for new products to be absorbed into existing space without adding to the MBU's cost structure.
- The need for a temperature controlled atmosphere for CMM inspection has been eliminated, freeing up 8,000 square feet and yielding energy savings associated with eliminating the lighting and cooling of the temperature controlled, enclosed space.
- Use and occupancy fees from off-site storage space have been eliminated.

Inventory

Improved inventory control is an important focus of the Machine Fabrication Shop's Lean efforts. Significant changes made to its inventory practices include the following.

- Existing inventory "burn down" efforts have eliminated the need (in the short-term) to purchase new raw materials.
- Regular bulk ordering of materials has been eliminated.
- Modifications to the supply chain have tied raw material purchasing/delivery to production scheduling. For example, one supplier now produces only 60 days worth of materials at a time. The Machine Fabrication shop stores one 30 day supply on site and the supplier holds the second 30 day supply at its site. When the Shop has used its on hand supply, it requests the remaining stock from the supplier. This request notifies the supplier that it should begin producing the next 60 days worth of materials.

Resource productivity gains associated with these improvements include:

- Short-term raw material spending has been reduced by $22 million.
- The amount of storage space required for inventory has been reduced.
- The total inventory turn rate has increased from three to seven per year.
- Increased inventory turn rates have reduced the chance for engineering design changes to render WIP or finished goods "off specification," and therefore in need of scrapping or rework. (Because there is less material moving faster through the production process, engineering changes affect fewer parts.)
- Holding less inventory reduces the opportunity for damage or spoilage, resulting in better overall utilization of raw materials.

Specific Product Cells

To illustrate additional and more detailed Lean strategies and tools incorporated into the manufacturing process, two specific cells were selected for closer observation; the 777 Stow Bin Arch Cell and the 777

Side of Body Fittings (pickle fork) cell.

High Speed Machining Cell: Stow Bin Arch (777 Overhead Storage Bin Arches)

The Stow Bin Arch was a new product line when the Machine Fabrication Shop brought it into the factory in 1997. This enabled Lean strategies and processes to be implemented at the onset in a cell structure specifically designed to produce the Stow Bin Arch.[28]

The Stow Bin Arch cell capabilities include sheet metal details, three axis high velocity milling, and assembly. The cell incorporates several key Lean tools, most notably small, right-sized equipment for specific production operations, including a table top boring mill and tapping machine. In addition, there is a right-sized hand drill tool, which requires no flooding lubricants and can be turned off when not in use. The right-sized machines are often built on wheels, increasing production flexibility.

The Stow Bin Arch cell also contains a chaku chaku line for production of sheet metal clips, brackets, and angles. The line consists of right-sized table top blanking, holing, and tapping machines. This allows an operator to produce only the parts that are needed at a specific time.

In addition to smaller, right-sized equipment, the Stow Bin Arch cell utilizes more efficient equipment for those operations that cannot (to-date) be completed with the use of right-sized machines. Smaller, moveable high precision milling machines are now being incorporated into the Stow Bin production process instead of the traditional, larger, immoveable milling machines. The larger machines require their own foundations and cannot be easily and inexpensively moved. The newer, smaller machines are moveable and can be installed with less effort. These machines are also less expensive than the larger machines to run and maintain.

The cell also contains its own "store" where required parts and tools are kept. Inventory is maintained through a visual que system. Part containers are designed with cutouts, which hold a specific, maximum number of parts. This provides a visual inventory control system to minimize the amount of inventory in the cell. A similar inventory control system is used as part of a moving line within the cell. Inventory kits are created and stored beneath the line itself, where the parts are needed. The kits consist of the number of parts required for one shift's worth of work.

Visual controls are also used to simplify and improve inspection processes within the cell. "Go/no go" inspection boards are used to determine if a part has been properly holed. Employees simply place the specified part on an inspection board, which is appropriately configured with rivets. If the part fits over the rivets properly, the part has been produced correctly.

These Lean initiatives have produced important resource productivity and cost per unit gains for the MBU. For example:

- The number of components in the arch has gone from 40 to 26 as a result of a design for

[28]The previous manufacturer produced the stow bin arch in a batch and queue environment.

manufacturability effort. The arch is now produced from a monolithic plate instead of numerous sheet metal parts.
- Production cycle time has gone from 31 to 11 days.
- Overall cost per ship set has decreased from $350,000 to $155,000.
- Right-sized machines have resulted in less energy used, fewer chemicals/flooding lubricants required, scrapped material reductions, and less space required for equipment.
- Conversion to smaller milling machines has resulted in less energy used, easier maintenance, and cost savings of $1.5 million a month.
- Point of use stores have reduced employee travel and improved inventory control.

Large Aluminum Parts Cell: 777 Side of Body Fittings (pickle fork)

The pickle fork cell produces the body fittings that attach the wing to the body of the plane. The MBU previously produced the pickle fork using batch and queue techniques. When implementing Lean, the primary initiatives for pickle fork production were to create a product-focused cell, increase material efficiencies, and more effectively manage quality within the cell.

The pickle fork cell's capabilities include large part machining, close tolerance boring, hand drilling and finishing, assembly, and coordinate measuring machine inspection. In addition, like the Stow Bin Arch cell, the pickle fork cell maintains its own "store." The store contains the maximum number of parts required on the floor and uses cutouts as a visual control to maintain the proper inventory levels within the cell. Visual controls are also used to standardize and improve work quality. Color coded systems are used to ensure that the proper drills are being used to perform the right task at the right time in production.

To increase materials efficiency, the main component of the pickle fork is now produced out of forged, restrike aluminum. Previously the part was produced from block aluminum, which generated a significant amount of scrap because the pickle fork component was cut and shaped from the block. The pickle fork forgings now arrive in the approximate shape of the component so less aluminum is scrapped. In addition, the type of aluminum previously used for the pickle fork required shipping to California for stress relieving and return back to Auburn for continued production.   The current aluminum forgings do not require stress treatment.

Resource productivity gains:
- Part assemblies are now produced in less than 25 days vs. 180 days previously.
- Rejection rate for pickle forks has been reduced from 100 percent to zero, with zero scrap.
- Visual controls have supported less defects and scrap and more standardized work quality.
- Use of forged aluminum has produced less scrap.
- Use of restrike aluminum has reduced transportation requirements (and associated energy and costs) and flow days required for production.

Obstacles

Despite significant gains in production, the MBU's conversion to cell manufacturing is not ideally configured. Several key operations remain batch and queue processes; specifically, painting, chemical treatment, shotpeening, and oven processes. For example, the pickle fork cell process flow is interrupted for chemical processing and painting operations. These processes cannot be contained within the cell because of technological and regulatory issues. The Machine Fabrication Shop has explored moving these processes into product cells, but has encountered obstacles that make it difficult and/or cost prohibitive to do so. Among the key obstacles encountered are environmental regulations, safety regulations, and lack of necessary technology.

Painting

Cell process flows are currently interrupted for painting operations. Ideally, the Machine Fabrication shop would like to use small, flexible, right-sized equipment for painting applications. Painting booths would be designed for specific applications, and to increase production flexibility, would be moveable.

The Machine Fabrication Shop considered various paths in its effort to incorporate painting applications into the product cells. In exploring options to the current painting process, the MBU examined the feasibility of developing smaller, right-sized booths, located appropriately throughout the production process. As this examination progressed, however, several obstacles became apparent.

Ventilation systems for the booths presented a series of impediments. Under OSHA, the smaller painting booths require proper venting. The MBU considered a variety of outside venting options, including venting through the roof of the building and through its walls. Overhead obstructions eliminated roof venting as a possibility so the MBU focused on venting the smaller booths through the walls of the building, noting that outside venting would tend to lock equipment into a given configuration, thereby reducing some of the desired flexibility.

The need for outside ventilation through the walls of the building reduced the number of possible painting locations. Further analysis indicated that both the lack of appropriate and available locations for the booths as well as the cost of materials required to properly construct multiple booth sites presented significant costs.

In addition, because the booths required outside venting, federal and local air permitting would apply. Although the MBU did not pursue development of the smaller, flexible booths to the permitting stage, air permitting issues were considered in its decision to discontinue the effort. The MBU weighed the uncertainty associated with permitting an unconventional painting application process. Uncertainties such as whether the smaller, more flexible booths could get permitted, in what time frame, at what cost, and with what limitations were taken into account.

The combination of total construction cost, lack of appropriate booth locations, and the uncertainties associated with permitting, resulted in the MBU abandoning the effort. In light of the obstacles encountered, the MBU opted instead to purchase new painting equipment to upgrade the current process.

The Machine Fabrication Shop anticipated that using smaller, right-sized booths would produce significant results if the current obstacles could be surmounted. The anticipated resource productivity gains are listed below.

- Reduction in energy use as smaller, right-sized painting booths could be turned off when not in use. The current, larger booths remain on all day, whether in use or not.
- The existing paint shop would be eliminated, opening up approximately 10,000 square feet of floor space and reducing maintenance activity.
- Reduction in overall waste associated with painting operations. Currently, if paint mixtures are not used within a specified period of time, the paint must be thrown out. In a cell structure, with a right-sized machine, only the amount of paint currently required for a part would be mixed. Paint supplies and inventory would also be more easily and effectively managed within the cell.
- Production flow days would be decreased by two to four days.

As a result of the MBU's effort to move painting processes into the product cells, and the regulatory obstacles associated with doing so, the MBU has been supporting the company's reserach into development of non-chromate paints. The MBU has explored using alternative paint products that are less hazardous and has conducted experiments using various alternative materials. The MBU has tested water based paints and is currently exploring the use of powder coating. The MBU continues to explore alternatives to chromate paints to gain the ability to have greater flexibility for applying Lean concepts to paint processes.

Chemical Processing (Dye penetrant inspection and tank lines)

Like the painting processes, the Machine Fabrication Shop would like to incorporate chemical processing into the cell structure. The ideal equipment would be small, flexible, scaleable resources that could be right-sized and placed in multiple areas. However, regulatory requirements and technical complexities have constrained Boeing's ability to convert from a batch to a cell-based process.

The MBU encountered a variety of obstacles to implementing a non-batch chemical processing system. In particular, it was unable to resolve, in a cost-effective manner, issues raised by the building and fire code. Under the Code, the design and size of the Machine Fabrication Shop's building did not allow for targeted distribution of smaller scaled chemical processes throughout the product cells. However, the MBU did resolve technological issues associated with small, chemical processing. A right-sized chemical processing line prototype was developed and tested with water. Initial testing proved successful, however it was cost prohibitive to move the smaller processing lines onto the factory floor and comply with the building and fire code.

Additional obstacles were also identified, however the MBU did not attempt to address them in light of the obstacles presented by the building and fire code. These issues included difficulties in locating the chemical processing lines where they could be easily hard plumbed and employee safety issues related to exposure.

The Machine Fabrication Shop anticipated that smaller, right-sized chemical processing would produce important results. The anticipated resource productivity gains are listed below.

- Reduction in overall chemical usage.
- Reduction in the amount of rinse water required. Currently large tanks are filled for each run, regardless of the number of parts being processed. This represents a major incompatibility between the batch and queue environment and Lean Manufacturing. Because of Lean practices, fewer parts are processed at a time. The same environmental load exists however, because the tanks are filled whether three or 50 parts are being processed.
- Production flow days would be reduced by two to four days.

As with paints, the MBU continues to explore the use of less hazardous materials in its chemical processes. This exploration is driven by the regulatory obstacles encountered by the MBU in the course of its Lean efforts.

Appendix C: Lean Terms and Definitions

Batch-and-queue	The mass production process of making large lots of a part and then sending the batch to wait in the queue before the net operation in the production process. Contrast with single-piece-flow.
Cellular Manufacturing	An approach in which manufacturing work centers (cells) have the total capabilities needed to produce an item or group of similar items; contrasts to setting up work centers on the basis of similar equipment or capabilities, in which case items must move among multiple work centers before they are completed.
Chaku-Chaku	A method of conducting single-piece flow, where the operator proceeds from machine to machine, taking the part from one machine and loading it into the next.
Constraint	Anything that limits a system from achieving higher performance, or throughput.
Cycle Time	The amount of time to accomplish the standard work sequence for one product, excluding queue (wait) time. If the cycle time for every operation in a complete process can be reduced to equal takt time, products can be made in single-piece flow.
Inventory	The money the system has invested in purchasing things it intends to sell.
Just-in-Time	A production scheduling concept that calls for any item needed at a production operation – whether raw material, finished item, or anything in between, to be produced and available precisely when needed.
Kanban	A card or sheet used to authorize production or movement of an item.
Muda (waste)	Any human activity which absorbs resources, but creates no real value; Activities and results to be eliminated; within manufacturing, categories of waste include: excess and early production; delays, movement and transport; poor process design; inventory; inefficient performance of a process; and defective items.
Non-Value-Added	Activities or actions taken that add no real value to the product or service, making such activities or actions a form of waste.
Pull System	A manufacturing planning system based on communication of actual real-time needs from downstream operations ultimately final assembly or the equivalent.

Right-size	Matching tooling and equipment to the job and space requirements of lead production.
Single Piece Flow	A situation in which products proceed, one complete product at a time, through various operations in design, order-taking, and production, without interruptions, backflows, or scrap.
Takt Time	The available production time divided by the rate of customer demand. Takt time sets the pace of production to match the rate of customer demand and becomes the heartbeat of any Lean system.
Value Stream	The set of specific actions required to bring a specific product through three critical management tasks of any business: problem solving, information management, and physical transformation.
Visual Controls	Displaying the status of an activity so every employee can see it and take appropriate action.