Massachusetts Institute of Technology

Lean Aerospace Initiative

Summary of Research Conducted by the Manufacturing Systems Team
1994-2002

Research conducted by the Manufacturing Systems Team
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Introduction

The Manufacturing Systems team was one of the research teams within the Lean Aerospace Initiative (LAI) whose goal was to document, analyze and communicate the design attributes and relationships that lead to significant performance improvements in manufacturing systems in the defense aerospace industry. This report will provide an integrated record of this research using the Production Operations Transition to Lean Roadmap as its organizing framework.

The Production Operations Transition to Lean (POTTL) Roadmap was prepared by industry, government and academic members of the LAI. It reflects a roadmap to transition to lean production operations. It is a roadmap consisting of eight phases that progressively develop the production operation to a lean manufacturing system. Research results are presented briefly within this framework and each phase of the paper ends with an extensive list of resources for further reference. Each of these references can be obtained from the LAI web site at http://web.mit.edu/lean under the Publications tab.

Phase I Research (1993-1996)

Since LAI is based on findings from the International Motor Vehicle Program (IMVP), the first research effort targeted an area highlighted in IMVP research. This resulted in a Phase I start-up Focus Team known as "Fabrication and Assembly Focus Team."

As noted in IMVP research, the level of inventory serves as an important barometer to the "lean" health of the industry. Consequently, the first major effort of the team was to develop an inventory survey intended for wide distribution within the defense aircraft industry. The survey yielded significant findings and revealed additional areas that warranted investigation. Shortly after completing and reporting on the inventory survey, the Focus Team opted to update its perceived restrictive name and became known as the "Factory Operations Focus Team."

Although this team recognized that there was no "Toyota" in the defense aircraft industry, it did recognize pockets of "lean" activity. In an effort to highlight the enablers, barriers and results from these pockets, the team embarked on a course of case studies. This resulted in a set of five case studies documenting some lean changes, a very detailed case study on precision fabrication, and a case study on operator certification.

In conjunction with the MIT research, the Factory Operations Focus Team, under the leadership of an LAI industry member, organized and led several non-member benchmarking trips to sites that had accomplished a lean transition. The benchmarking team collected information about the transformation process, the results of the transformation, and the applicability to the defense aircraft industry. A report on each visit was completed and disseminated within LAI.

Research results from the case studies indicated that flow optimization of the product was an important factor in achieving lean results. Research in this topic area was subsequently expanded. The team identified products representative of each sector (airframes, engines, and electronics) yet manageable for research and benchmarking. A questionnaire was developed and a thorough validation of this questionnaire was conducted to assure consistency of results. This effort resulted in a major report.

In the last year of Phase I, the Focus Team was interested in obtaining research that would facilitate an understanding of implementation. Tapping existing resources, the team was able to develop a hypothesized model of lean implementation and test this model with case studies that had already been completed, new case studies specifically started to test the model, and a literature review.

Phase II Research

During Phase I research, it was learned that organizations differ widely and companies have vastly different data collection systems. It was also found that there were few common operation definitions and operation characteristics varied drastically. There were few metrics that were common and the control methodologies employed varied. These types of differences make detailed findings from surveys and case studies problematic. Therefore, in Phase II the team wanted to conduct research that was mindful of the breadth in the industry but focused on more depth of understanding in each sector.

With the concurrence of the focus team, a strategic research approach was developed that was founded on the Lean Enterprise Model and focused on the first overarching practice, "Identify and Optimize Enterprise Flow.” To accomplish a more detailed understanding of operations in the industry, it was decided to conduct on-site field research and to drill down on those practices that enable reduction in the metric, "order to point of use delivery cycle time.” This approach would allow careful observation and data collection in a field environment.

The theme that was chosen by the team was to identify features that minimize cost, optimize flow, improve quality and enhance flexibility while considering labor and worker empowerment as operation issues. In conducting our research three main thrusts were considered: (1) design and management of complex manufacturing systems, (2) production control in factories and supply chains and (3) transition to production (which manifested itself into improving cross-functional communication). The first two thrusts produced products in Phase II and the third thrust continued into Phase III. In the first thrust there were three sub-thrusts: (1) a study of each sector’s manufacturing system design, (2) a study of the elements of "lean" system design and (3) a study of "lean" system implementation in the space sector. Of these sub-thrusts, the first two sub-thrusts produced products in the phase and the third sub-thrust continued into Phase III.

In the first sub-thrust the objective was to understand the manufacturing system. Manufacturing system elements that enabled reduced cycle time were identified and research was conducted in separate LAI manufacturing sectors focusing on assembly operations. This research first focused on the engine sector followed by the airframe and electronic sectors. In each sector exploratory research was necessary to understand the sector operational characteristics, however, with each sector study more knowledge was gained of the manufacturing system characteristics.

In the second sub-thrust the objective was to characterize what was meant by a "lean" manufacturing system design. There is a plethora of literature on lean but very little system level analysis of the design of a "lean" manufacturing system. This research focused on creating this framework. Initial studies were in the automotive industry but additional industries including the defense aerospace industry were also studied. The result was the development of a production system decomposition to understand a "lean" system from a systems level.

The final sub-thrust was started in LAI's Phase II but was completed in Phase III.

Phase III Research

The research goal for the Lean Aerospace Initiative in this phase was to study the concept of "Best Life Cycle Value" for aerospace systems. This entailed work to develop a fundamental understanding of value added practices offering best life-cycle value. Doing this entailed addressing the barriers that prohibit a lean implementation.

The concept of providing best life-cycle value led to the identification of five key research themes:

1. Measuring Value to the Enterprise
2. Time
3. Organizations and People
4. Knowledge and Information Infrastructure
5. Government as a Lean Customer and Operator

Having learned many things about the defense aerospace industry and other industries over the last few years the team felt positioned to assist in providing guidance on manufacturing system design. The research for Phase III developed guidelines for the design of manufacturing systems particularly related to the complex industry environment faced by defense aerospace companies. To reflect this increased scope of focus beyond the factory floor to include the overall manufacturing system, the team changed its name to the Manufacturing Systems Team.

Specific details of each of these major research areas are presented in the appropriate phases of the Transition-to-Lean Roadmap. For convenience, the specific Transition-to-Lean Roadmap phase sections capture all relevant research related to Factory Operations in one place while providing links to referenced information after each Transition-to-Lean Roadmap phase.

The Transition-To-Lean Roadmap

The Production Operations Transition-To-Lean (TTL) Roadmap (Figure 1) provides a guide for transitioning an exiting production operation to one that fully implements a lean manufacturing philosophy and lean best practices. The roadmap defines a systematic implementation process, specific actions in order of precedence that are milestones in the journey from mass to lean production. The model is organized into major phases with the points of interface defined with other systems that are both internal to production operations and external to the business enterprise.[1]

The Production Operations Level Roadmap (see Figure 1) consists of eight phases of implementation overlaying two broad interfaces shown as backdrops. The first backdrop represents the interface of the Production System to the remainder of the business enterprise. Those business systems and processes that will require changes and/or new interfaces to be developed are noted in this area of the Roadmap. The second backdrop represents the overall supply chain to the ultimate customer that lies outside of the immediate business enterprise and the regulatory and legal requirements of the environment in which the business enterprise operates. Each of the eight phases of implementation shows a number of specific actions in a recommended order of precedence. Phase 7 is unique in that the actions shown may take place at any and at numerous times concurrently with Phases 2 through 6. Phase 7 is indicative of the fact that transitioning an organization to lean is a learning journey. Each organization is unique and a common path for all will not always work. Internal progress review or feedback should be taken often and the path to lean may need some alteration or enhancement once underway to get the performance results desired.[2]

The TTL Roadmap lays a framework from which the interpretation and adaptation to each manufacturing system can be achieved. But a formal understanding of the full process is needed before any tailoring can take place.

References for Introduction

Crabill, John, et al on the Production Operations Transition-To-Lean Team, Production Operations Level Transition-To-Lean Roadmap Description Manual, Version 1.0, Cambridge, MA, MIT, 5 June 2000.

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[1] Crabill, John et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

[2] Crabill, John et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

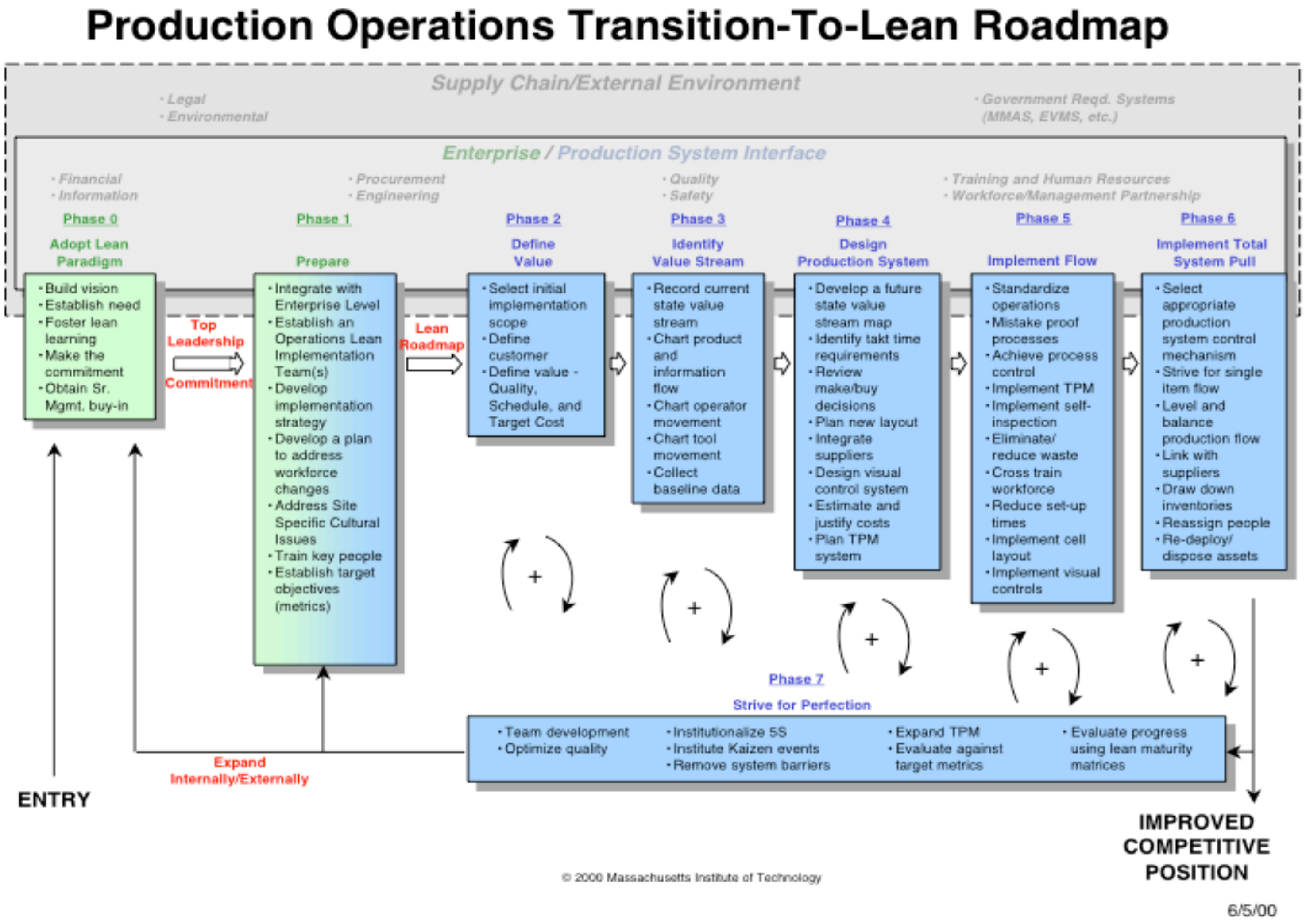

Figure 1: Transition-to-Lean Roadmap

Phase 0: Adopt Lean Paradigm

Phase 0 of the Production Operations Roadmap is identical to Phase 1 of the Enterprise Level Roadmap [3]. This duplication at the beginning phase was done so as to ensure a common point of integration. This allows the transformation to be viewed in the context of either production operations or as part of the total enterprise lean transformation. The details of the process steps outlined here should be made more specific to production operations if this is where the transformation begins.[4]

0.1 Build Vision

Considerable effort is required to understand the lean paradigm and then to interpret the underlying principles and practices as they would apply to your company. It will likely be necessary for several senior managers to acquire the in-depth knowledge and insights associated with lean, and to begin building a shared vision within the company of how it would look and behave if it became lean. Attending seminars, conferences, workshops and leadership exchanges can be helpful, in addition to appropriate readings.[5]

0.2 Establish Need

Experience has shown that few companies are willing to make the dramatic, pervasive changes required unless they are experiencing a major challenge or even a threat of survival. It is very unfortunate that this seems to be the case, because the transformation could be accommodated with less trauma if attempted when the company is stable and healthy. Nevertheless, it is useful to define a particular forcing function as a stimulus to begin the lean transformation. This can best be done as an outgrowth of the strategic planning process. Through assessment of alternative approaches, determine that lean is the best choice to address the major threat and to position the enterprise for its future competitive environment.[6]

Factory Flow Benchmarking

One way to establish the need to change is to benchmark other companies that are performing similar processes. The lessons learned from these benchmarking activities can both sharpen the strategic planning process as well as provide assurance to managers who are not convinced that changes are needed.

The manufacturing systems team conducted research on specific parts in the airframe, electronic and engine sectors to determine the flow characteristics of that sector. These studies fall in the "establish need" portion of Phase 0 since the results showed the amount of waste in the industry. Through these studies, flow

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[3] Nightingale, D., and Milauskas, R., Transition-To-Lean Roadmap Enterprise Level, Progress Report
[4] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[5] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[6] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

efficiency and wait times were the metrics used to compare the different companies. The results from these visits are summarized in the table below.

Table 1: Factory Flow Benchmarking Results

Sector	Flow Efficiency	Wait Fraction
Airframe	0.02% to 0.8%	96%
Electronic	0.02% to 18.7%	Max 25% to 98%
Engine	0.7% to 13.0%	87%

These results show that most of the cycle time in the defense aerospace industry is wait time and most of this wait time was attributable to storage delay. This incredibly high percentage of time spent waiting demonstrates the need for change in the aerospace industry.[7]

0.3 Foster Lean Learning

Essentially all key leaders need to be brought up to speed on the lean paradigm. Regular, frequent meetings need to be organized. Outside consultants can be utilized. The enterprise leader needs to develop insights into which senior managers may be unable or unwilling to effectively lead this change. This applies not only to managers at all levels, but also to supervisors and shop stewards if the company is unionized. Lean thinking must be learned; mass production thinking must be unlearned. An overall framework must be developed to foster lean learning. Visits to other organizations that have successfully transitioned to lean are particularly helpful.[8]

Non-Member Benchmarking

Many companies used benchmarking trips to develop lean awareness in key members of the organization. Information that supports significant achievements can be particularly powerful learning tools.

Early in Phase I, the manufacturing systems team conducted benchmarking survey trips to non-member companies to expose leaders in the aerospace industry to new ideas. The results of these different trips to John Deere, GE Diesel and Ford Electronics are outlined in individual case study reports.

The John Deere visit was enlightening to see the incredible results that were achieved in a two-year time period. The customer would pull product from an assembly line fed by self-contained modules and just-in-time material delivery. The products were divided up into modules and each of these modules were fabricated and assembled in a unique line in close proximity to the final assembly line. This tight coupling between operations is intended to place internal producers and suppliers in close proximity to facilitate communications, minimize inventory and transportation times, and make the production process visible. The

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[7] Shields, J. Thomas, Factory Flow Benchmarking Report
[8] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

coupling in the planter factory is tightened further by the absence of final assembly line workers. The module workers not only build the sub-assembly but also install their sub-assembly product onto the planter. Consequently, if there is a problem in final assembly, there is immediate corrective feedback to the builders of the sub-assembly. Here were some typical results in 1994:

- 30% less inventory
- Cycle time reduced 46% in parts manufactured from raw material and 42% in materials purchased complete
- Salaried work force down 20%
- Material handlers down 60% over the last five years
- Warranty costs down 22% over 4 years
- Warranty claims per planter down 30% over four years
- Sales per employee per year up 55% in two years
- Combine manufacturing floor space down 20% due to focused operations
- Planter floor space down 55% due to focusing
- Flow times for combine components experienced improvement factors from 6 to 15
- Levels of management reduced from 7 to 4[9]

The GE visit showed similar improvements to production as well as outlining how GE won back customers and created jobs by significantly improving quality and costs. A number of small continuous improvement teams were set up within each of the business teams. Over an eighteen-month period 89 Continuous Process Improvement (CPI) teams were formed and 520 CPI projects were undertaken. Key areas for improvement were excessive inventory, throughput time, defect levels, and inefficient processes. Improvements were also pursued in energy consumption, ergonomics, health and safety. GE Diesel achieved striking improvements in key metrics. Productivity improved by 53 percent, defects were reduced by 84 percent, and investment in inventory was reduced from $40 to $15 million. The resulting quality, delivery and cost improvements are key factors in the winning of new customers and the doubling of unit production at GE Diesel since the early 1990s.[10]

The third visit to Ford Electronics was equally as educational and showed how Ford achieved "customer delight" with a total quality and productivity management culture and infrastructure. The benchmarking team found evidence

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[9] Stahl, Fred, Manufacturing Change at the John Deere Harvester Works: Report on the Visit of the Ad Hoc Lean Aircraft Initiative Team

[10] Hodnett, Sam, Worker Empowerment at GE Diesel Engine: Report on the Visit of the Lean Aircraft Initiative Factory Operations Team

of every overarching practice of the Lean Enterprise Model (LEM) in use on the floor as part of the everyday operation.[11]

0.4 Make the Commitment

The top manager in the business unit, with the understanding and support of senior managers, is responsible for making the go/no-go decision regarding lean. If the business unit operates under a broader corporate structure, the next higher level needs to understand and hopefully support this decision. There should be no ambiguity regarding decision authority or resource control relative to the decision to pursue a lean transformation. There is a compelling argument that conversion to lean requires a comprehensive approach; i.e., the various lean principles and practices should not be implemented selectively but as a total “enterprise thought system.” The enterprise leader and senior managers should recognize that significant resources (particularly the time of the workforce) may be required. Although there may be barriers to implementation external to the organization’s ability to control, the commitment made implies a decision to support with resources and attention those items that can be changed and to work with others to reduce those barriers not controlled internally.[12]

0.5 Obtain Senior Management Buy-In

The decision to pursue lean, once made, must be viewed as non-negotiable and irrevocable. Full buy-in of all senior managers is mandatory. Expectations of each manager must be made clear. They all must realize that the company is embarking on a great voyage, into only partially charted waters. Doubts must be put aside and replaced with creative solutions to the inevitable challenges that will arise. The considerable risks are balanced by the potential of tremendous advancement in competitiveness. Senior managers are the key link between the enterprise leadership and the workforce. The success of the lean transition depends critically upon full buy-in of senior managers. Senior managers who prove to be unable or unwilling to change must be replaced. It is frequently to a company’s advantage to aggressively recruit leaders from the outside who have been successful in guiding lean transformations.[13]

Non-Member Benchmarking

Throughout the research efforts maintained by the manufacturing systems team, it has been seen repeatedly that the support of senior management is a critical step to begin a manufacturing system improvement. In the benchmarking studies conducted through Phase I, this senior management support was vital.

The general manager of factory operations at John Deere where an ad hoc team visited was the prime supporter and visionary of the transition that the site had to

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[11] Everett, Jim, Customer Delight at Ford Electronics (North Penn Electronics Facility)

[12] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

[13] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

undergo. The general manager was noted to never be in his office on Fridays. That was his reserved day to be out on the floor talking to the workers. This habit is a powerful expression of the value of the workers to the management.[14]

Senior management provided the impetus for change at GE Diesel in the early 1990s by cutting down the layers of management from four to two. The new culture at GE Diesel is visible because no one wears ties or white shirts, there is no time clock, there are no reserved parking spaces and the workers are motivated, empowered and involved.[15]

At the Ford Electronics plant visited by the team, it was obvious that the vision had originated with the highest levels of management and they were responsible for communicating it throughout the organization. It was quite evident that management leadership, enthusiasm and drive to achieve the common objective had created a vision which flowed through the plant with an infectious fervor.[16]

Success and Failure of the Implementation of Lean Manufacturing

The power of the support of the senior management was also illustrated in two comparative case studies. These two case studies compared lean implementation efforts and outlined why one was a success and the other was not.

At the first site, the main reason for the failed modernization effort is attributable to a lack in continuity of senior level leadership. After the modernization began, there were two changes in the senior leadership levels. Each new plant director came from the corporate level above the existing leadership ranks at Site A and had his own version of the plan, and his own ideals that didn’t mesh with the existing culture. Some of the differences of opinion were so great that they caused many people, including the original change agent and lean thinker, to leave the plant. Also, each successive plant manager failed to support or foster lean thinking in the organization. The combination of the changes in company culture with the multiple leadership changes, as well as the failure of the leaders to optimize their investments while becoming enamored with buying new machines derailed the modernization effort.

Consistent leadership from the top plant level, which opposed the corporate skepticism, along with a focus on lean thinking, was the main driver and element of success at Site B. The plant manager made it known that everyone in a leadership position must become a lean thinker. The site succeeded in creating a

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[14] Stahl, Fred, Manufacturing Change at the John Deere Harvester Works: Report on the Visit of the Ad Hoc Lean Aircraft Initiative Team

[15] Hodnett, Sam, Worker Empowerment at GE Diesel Engine: Report on the Visit of the Lean Aircraft Inititiative Factory Operations Team

[16] Everett, Jim, Customer Delight at Ford Electronics (North Penn Electronics Facility)

> leadership structure where people understood the plant's commitment to making lean work.[17]

References for Phase 0

Crabill, John, et al on the Production Operations Transition-To-Lean Team, Production Operations Level Transition-To-Lean Roadmap Description Manual, Version 1.0, Cambridge, MA, MIT, 5 June 2000.

Everett, Jim, Customer Delight at Ford Electronics (North Penn Electronics Facility), Report, RP97-03-24, Cambridge, MA, MIT, 1997.

Hodnett, Sam, Worker Empowerment at GE Diesel Engine: Report on the Visit of the Lean Aircraft Initiative Factory Operations Team, July 26, 1995, Report, Lean 96-01, Cambridge, MA, MIT, 1996.

Nightingale, D., and Milauskas, R., Transition-To-Lean Roadmap Enterprise Level, Progress Report, Lean Aerospace Initiative, Cambridge, MA, July 12-13 1999.

Shields, J. Thomas, Factory Flow Benchmarking Report, Report, RP96-06-61, Cambridge, MA, MIT, 1996.

Stahl, Fred, Manufacturing Change at the John Deere Harvester Works: Report on the Visit of the Ad Hoc Lean Aircraft Initiative Team, June 7, 1994, Report, Lean 94-04, Cambridge, MA, MIT, 1994.

Vaughn, Amanda, Success and Failure of the Implementation of Lean Manufacturing in the Aerospace Industry, Thesis, Cambridge, MA, MIT, 2000.

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[17] Vaughn, Amanda, Success and Failure of the Implementation of Lean Manufacturing in the Aerospace Industry

Phase 1: Prepare

The preparation phase is where the strategy is defined and the support structure is put into place for the transformation to lean. This phase also marks the point on the Roadmap where a production operation focused lean transformation starts to take a different but complimentary path from a transformation from an entire enterprise focus. During this phase a cross-functional group is established and given the authority, responsibility, and accountability for the transformation. Interfaces with other parts of the enterprise and key business systems are recognized and defined. Major issues such as workforce changes and culture attributes are surfaced and addressed. Knowledge of lean principles and practices begin to be learned by key parts of the organization. Policies and guidelines are set into place as well as the metrics to measure implementation progress.[18]

1.1 Integrate with Enterprise Level

Transitioning production operations to a lean operating philosophy cannot be done to its maximum potential without integration with the other business functions. A major shift towards lean practices implemented in the shop areas alone will directly impact the operations in procurement, materiel management (stockrooms and production control), product definition, facilities, human resources, and financial management. These areas not only need to be aware of what is being done but also must become part of the process so that their internal operations can be modified to facilitate the change. A good way to coordinate and ensure good integration of activities is by setting up an Enterprise Lean Council or Enterprise Lean Integration Team.[19]

1.2 Establish an Operations Lean Implementation Team

Form a team consisting of at least one senior level leader from each of the principle production operations areas and points of contact from key areas such as: human resources, public relations, procurement, marketing, business management, engineering, information services and program offices.[20]

1.3 Develop Implementation Strategy

Strategically determine where to concentrate your efforts to maximize the total benefit while achieving the overall objectives of the enterprise's long-range strategic plan. The key question here is: "Where should we spend our time?" To answer this you must ask: "Where are the opportunities for improvement?"; "Which improvements would create the most value for our customers?"; "Which improvements can be defended from competition?"; "What can we do that no one else can do?"; and "How can we differentiate ourselves from the competition?" The premise here is that a strategically

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[18] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[19] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[20] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

focused lean implementation will produce a quicker and a much more lasting benefit to the company.[21]

Hypothesized Lean Implementation Model

The Manufacturing Systems team created a possible implementation strategy. It is a tool to help focus the improvement efforts into the most effective order and helps an organization see that certain steps must be followed in order to achieve the highest degree of utilization from those efforts.

The Manufacturing Systems team developed the Hypothesized Lean Implementation Model (figure 2) as part of the Phase I research thrust to outline lean implementation considerations in factory operations of low volume/high complexity production systems. The research involved in this model developed and tested it with a series of case studies.

The Hypothesized Lean Implementation Model contains four levels:

1. Building a lean infrastructure to support lean behavior
2. Redesigning the flow of products in the factory
3. Revamping the operations management
4. Fostering process improvement[22]

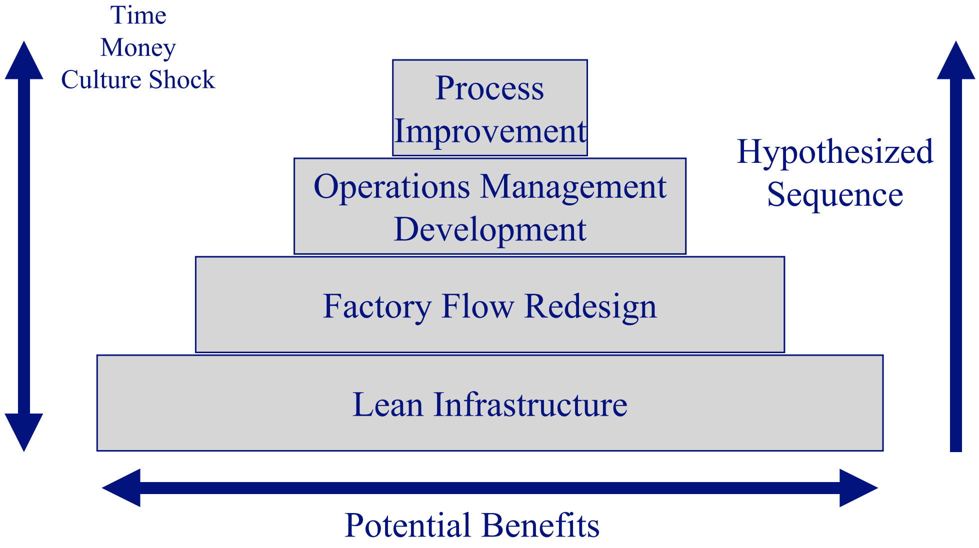

Figure 2: Hypothesized Lean Implementation Model

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[21] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

[22] Shields, J. Thomas, Lean Implementation Considerations in Factory Operations of Low Volume/High Complexity Production Systems

Another view of this model better illustrates the need for the model to be followed in the defined order to fully realize all of the potential lean benefits. Figure 3 illustrates the relationship between the transition phases. The degree of implementation of any lean transition phase restricts the potential benefits that may be achieved in any later phase by the degree of implementation of the preceding phases. This idea of total lean utilization is the key to the hypothetical lean implementation model. By using this idea, the impact of the degree of success of one level will determine the possible degree of success of the subsequent levels.

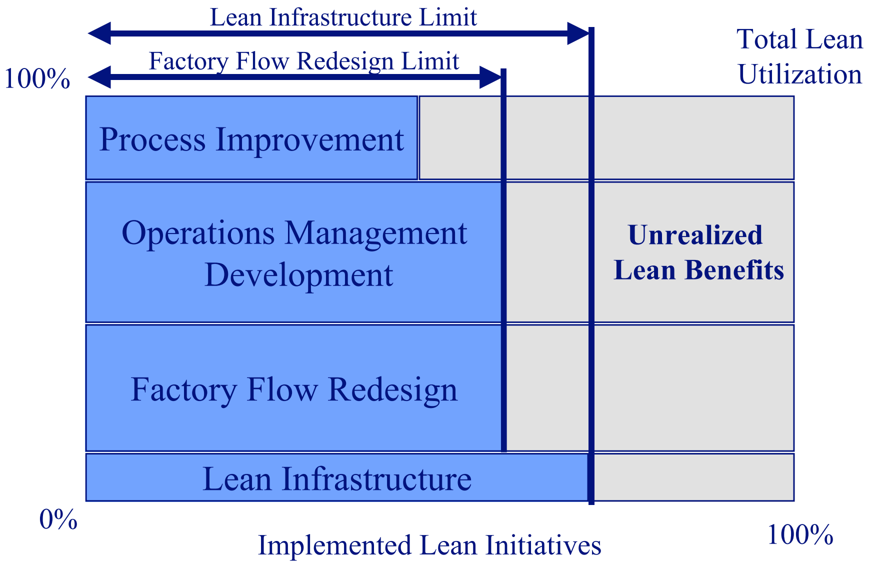

Figure 3: Foundational Effects and Company Circumstances

The sequence proposed by the model is supported by a series of case studies conducted by Pozsar.[23]

1.4 Develop a Plan to Address Workforce Changes

Experience has shown that people more than anything else are what make an organization either excel or fail in performance. During the course of becoming lean, people will be transitioning in their work roles. There will be skepticism as to the real motives for this initiative. Layoffs during implementation should be avoided if at all possible. Any foreseen layoffs should take place before the start of implementation. However, it is critical that a clear and fair policy be established at the beginning to address workforce changes during the process of becoming lean, including changes in job content, transfers/reassignments, and the possibility of reduced staffing levels. Communicating the need to change in order to sustain and grow the business by cutting costs and

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[23] Pozsar, Michael John, Application of the Lean Aircraft Initiative Factory Operations Model to Case Studies in the Defense Aircraft Industry

becoming more responsive to customer needs is often the case and should become part of the message. It also helps to develop trust by having high-level leaders make a strong visible commitment by directly participating in the implementation. Any workforce reductions perceived to be connected with lean could stall implementation. [24]

1.5 Address Site Specific Cultural Issues

Design the lean implementation program to suit the nature and needs of the organization. Every organization has its own personality and uniqueness. Strictly following another company or division's success story may be your failing. Strive to develop buy-in by the workforce early and maintain the momentum of the value they see in the changes taking place. Teaming is another essential. Employee teams need to be structured so employees are able to contribute ideas and suggestions to the changes being made. They need to take some ownership of the change, view the new process as theirs and feel that they have control of the outcome of the process. To obtain this wide buy-in it is often useful to establish appropriate stakeholder partnerships. Orchestrating some early successes (wins) to demonstrate the benefits helps to build buy-in. [25]

1.6 Train Key People

Training should start with the senior leadership with the objective of obtaining a correct understanding of lean principles and what their role will be as the organization moves toward becoming leaner. The next training group will include those individuals that will be leading lean projects. Their training will be much more intense and consist of both theory and hands on application under an experienced teacher and practitioner of lean practices. The third training group is the balance of the organization; they should receive a short course on lean philosophy as well as the organization's plan for implementation. A lean library, resource center, or on-line tool-kit may be established for anyone who would like to learn more.[26]

1.7 Establish Target Objectives

A few high-level target objectives that everyone in the organization can both visualize and contribute to attaining needs to be established and communicated. This can take the form of a balanced set of metrics such as product throughput time reduction, total product cost, customer satisfaction scores, and overall product quality are some examples. Often the metrics will drive behavior, therefore, it is important to ensure that the metrics chosen will influence the lean behavior planned. It is essential that the metrics chosen be aligned with the enterprise metrics. This is another important linkage with the enterprise efforts. This action can also be enhanced by using a catchy motto such as "222 Aircraft for the Price of 200", or "Lean Today Here Tomorrow". [27]

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[24] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

[25] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

[26] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

[27] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

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Crabill, John, et al on the Production Operations Transition-To-Lean Team, Production Operations Level Transition-To-Lean Roadmap Description Manual, Version 1.0, Cambridge, MA, MIT, 5 June 2000.

Pozsar, Michael John, Application of the Lean Aircraft Initiative Factory Operations Model to Case Studies, Thesis, Cambridge, MA, MIT.

Shields, J. Thomas, Lean Implementation Considerations in Factory Operations of Low Volume/High Complexity Production Systems, Report, RP97-04-152, Cambridge, MA, MIT, 1997.

Phase 2: Define Value

At this phase of implementation the focus is placed upon understanding value in the eyes of the customer and those processes most directly related to providing this value. The area of initial implementation may initially be very narrow such as a specific family of parts, sub-assemblies, or a particular manufacturing process. A more ambitious and risky approach for an initial implementation may be for a large or complex assembly or for an entire manufacturing facility or site.[28]

2.1 Select Initial Implementation Scope

The boundaries of the products/processes to be transitioned to lean need to be defined as to the point upstream where the physical transformation of material into a product begins and downstream where the product is received by the customer. The order to delivery information loop that controls the production process from order receipt to delivery also needs to be defined. Too broad of an initial project area will complicate and stretch out the transition process. Best results are obtained by breaking up the areas for transition into practical and manageable steps while still retaining the overall systematic approach and plan.[29]

2.2 Define Customer

Lean focuses upon meeting the needs of the ultimate user of the product. Waste enters into the production system when requirements of internal or intermediate customers are mistakenly taken for that of the ultimate user of the product. A prerequisite to correctly defining which operations are value-added and which are non-value-added is a clear definition of who this ultimate customer is.[30]

2.3 Define Value – Quality, Schedule and Target Cost

Care must be taken to separate the ultimate customer's definition of value from that of other functional areas of the business as well as other business organizations in the overall product flow. Value needs to be defined in terms of their expectations of the product. This definition can be broken down in different ways, but almost always includes as minimum elements: product quality, delivery schedule, performance and meeting target cost.[31]

References for Phase 2

Crabill, John, et al on the Production Operations Transition-To-Lean Team, Production Operations Level Transition-To-Lean Roadmap Description Manual, Version 1.0, Cambridge, MA, MIT, 5 June 2000.

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[28] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[29] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[30] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[31] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

Phase 3: Identify Value Stream

The value stream map or chart serves to identify when and where value is being added and where waste is occurring along the entire path of the product. Value stream mapping provides a means to easily recognize and communicate what is taking place thus allowing team members to more readily target waste elimination. Value stream mapping is an iterative step in the transition to lean process and is an important part of the continuous improvement process. There are many simple and effective ways for recording the value stream; sophisticated computer simulations or mathematical models are not required.[32]

3.1 Record Current Value Stream

The purpose for constructing a current state value stream map is to allow the entire production system to be documented in a simple manner that shows where the waste in the production process is. The map is usually one page that shows the entire flow from order receipt to final delivery. Information from both metric data and observation is collected and added to the map that will help to show where there is waste in the production process that can be eliminated. Maps are often developed at different levels of detail to help further meet this objective. The map is used in the transition planning to prioritize projects based upon potential savings.[33]

Testing in the Electronics Sector

The purpose of recording the current value stream is to gain a thorough understanding of what is happening in the production system and why. This understanding of all the steps can help gauge an initial improvement effort by showing where and when value is added to a part. Part of Marco Roman's work in the electronics sector demonstrated the need to understand the current value stream and what potential savings in cycle time could be realized by streamlining it.

Electronic components in all programs studied included numerous stages of testing. But each program also included a final acceptance testing procedure which varied widely from site to site. This extensive final acceptance testing was a defining characteristic of manufacturing in this sector. This final testing may ensure that only good working products are shipped to the customer, but a more thorough understanding of the value stream and where certain problems may occur could prevent defects in early stages from continuing through the manufacturing process.

In the commercial programs studied in this research, 47% of the delays in shipping were attributed to production problems as opposed to forecast errors, shipping delays, documentation errors or part shortages. The production

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[32] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

[33] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

problems were further broken down to find that 35% of the production problems were circuit board failures and another 29% were failure of the testing equipment. Yet another breakdown of the circuit board failure shows the lack of an adequate screening method of the circuit boards throughout the production process. Seventy four percent (74%) of the defective boards were found in the final test area as opposed to only 16% of the defects found in the assembly stages and 10% of the defects found in the pre-screening when the parts arrive from a supplier.

This issue of defects being identified late in the production operation causes the production system to become overwhelmed with work. Not only is a manufacturing system having to process new orders, but there is a large number of jobs being processed multiple times for rework before they are sent through the testing phase again. With an incremental improvement in test yields the system experiences a larger gain in throughput performance (reduction in delays). This improvement in test yield was tracked for one year in one of the case study programs. For a 5% increase in yield in the testing area, a 30% improvement in cycle time was realized.

Some other testing practices which could improve testing yield, quality and the flow of the manufacturing processes would be to test further upstream. In the projects studied, many had visual inspections in the upstream processes, but only one had functional tests of electrical connections that were added in a certain process step. Robust assembly processes and the appropriate care when parts are transported from one station to another can have significant impact on test yields. Testing equipment reliability must also be addressed. Many of the final tests are intricate and require specially trained personnel. The delicate testing equipment should undergo preventative maintenance to ensure reliability and increase the uptime of the equipment. This will also improve the flow of the overall processes since the testing operations were frequently observed to be the bottlenecks of the operations.[34]

Value Stream Mapping

Value stream mapping (VSM) is an improvement tool that has been used as an integral part of lean transformations. It has been shown to yield vast improvements in lead-time throughout manufacturing, including the aerospace industry, and beyond the factory floor. A value stream mapping exercise was performed at Heidelberg. The activity outlined possible improvement opportunities and helped identify the impact of the system being studied on both the upstream and downstream operations. It has also been seen that in some cases VSM is being used in what were not considered its initial appropriate environments. It was, therefore, the goal of this study to explore under what conditions (environmental) is it most appropriate to be performed and determine what insights could be given about VSM to aid in its success for the user.

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[34] Roman, Marco, Lean Aerospace Initiative Electronic Sector Study

In order to determine the appropriate conditions under which VSM should be performed, multiple case studies were completed. From these cases, a theory was developed about VSM. This theory was converted to a survey, which was used to capture the experiences of those doing VSM in the manufacturing sector of the aerospace industry.

It was seen that the five environmental characteristics (Table 2): ability to pick a representative part, capability, complexity, type of organization, and investment, could be used to explain the appropriateness of value stream mapping. These characteristics are organized in Figure 4 showing how they affect VSM. Three of the factors affect the success of the event itself, while two others affect the implementation of the new map.

Representative	Product that has similar process steps to the majority of the products that go through the system. The category also includes the time to obsolescence of the map due to product or process changes.
Capability	Level of difficulty associated with the production of a part.
Complexity	Technological ability to repeatedly assemble something with minimal intervention and minimal disruptions (scrap, rework, shortages).
Organization	Level of innovativeness (change) supported on the factory floor.
Investment	Availability of money and labor to make change.

Table 2: Five Environmental Characteristic Definitions

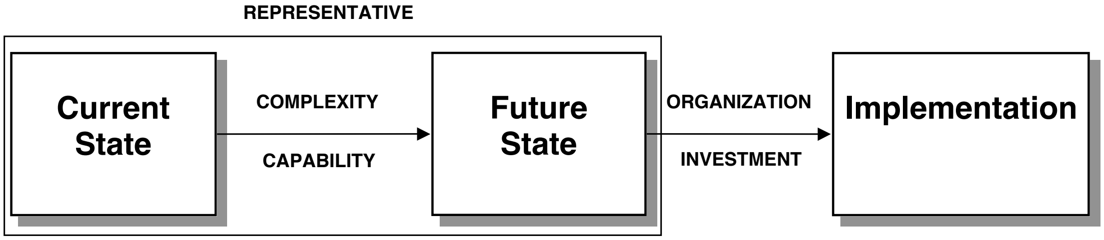
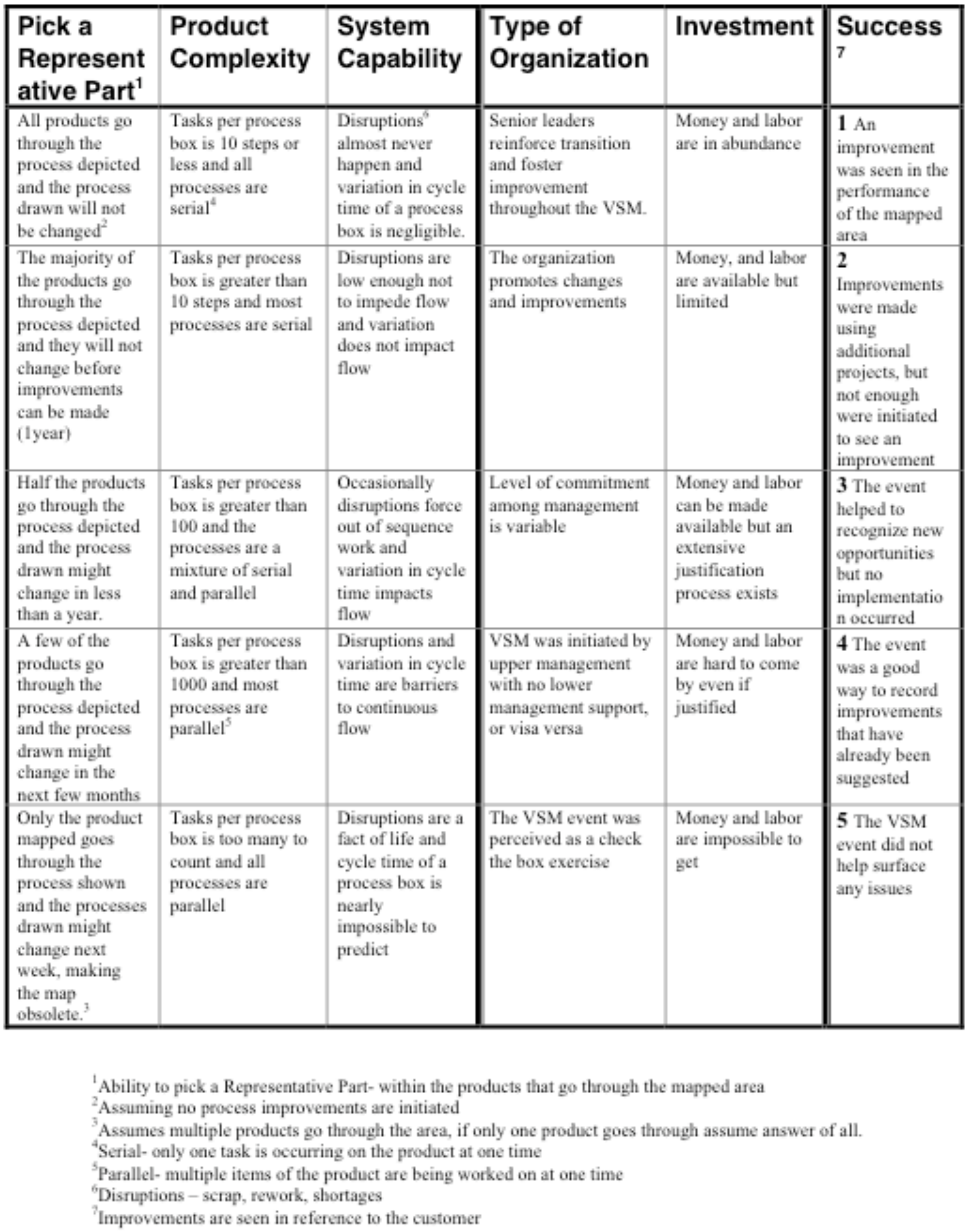


Figure 4: The Effect of Environmental Characteristics on Implementation

Using this organization of the five characteristics, a VSM Matrix has been created which is structured similar to Figure 4. The VSM Matrix, shown in Table 3, can be used to determine how a company, or VSM area, fits into each category. By determining where the company fits in, from most appropriate for value stream mapping to inappropriate, leadership can see how effective VSM will be by studying the tradeoffs of different categories.



Pick a Representative Part[1]	**Product Complexity**	**System Capability**	**Type of Organization**	**Investment**	**Success**[7]
All products go through the process depicted and the process drawn will not be changed[2]	Tasks per process box is 10 steps or less and all processes are serial[4]	Disruptions[6] almost never happen and variation in cycle time of a process box is negligible.	Senior leaders reinforce transition and foster improvement throughout the VSM.	Money and labor are in abundance	**1** An improvement was seen in the performance of the mapped area
The majority of the products go through the process depicted and they will not change before improvements can be made (1year)	Tasks per process box is greater than 10 steps and most processes are serial	Disruptions are low enough not to impede flow and variation does not impact flow	The organization promotes changes and improvements	Money, and labor are available but limited	**2** Improvements were made using additional projects, but not enough were initiated to see an improvement
Half the products go through the process depicted and the process drawn might change in less than a year.	Tasks per process box is greater than 100 and the processes are a mixture of serial and parallel	Occasionally disruptions force out of sequence work and variation in cycle time impacts flow	Level of commitment among management is variable	Money and labor can be made available but an extensive justification process exists	**3** The event helped to recognize new opportunities but no implementation occurred
A few of the products go through the process depicted and the process drawn might change in the next few months	Tasks per process box is greater than 1000 and most processes are parallel[5]	Disruptions and variation in cycle time are barriers to continuous flow	VSM was initiated by upper management with no lower management support, or visa versa	Money and labor are hard to come by even if justified	**4** The event was a good way to record improvements that have already been suggested
Only the product mapped goes through the process shown and the processes drawn might change next week, making the map obsolete.[3]	Tasks per process box is too many to count and all processes are parallel	Disruptions are a fact of life and cycle time of a process box is nearly impossible to predict	The VSM event was perceived as a check the box exercise	Money and labor are impossible to get	**5** The VSM event did not help surface any issues

[1] Ability to pick a Representative Part- within the products that go through the mapped area
[2] Assuming no process improvements are initiated
[3] Assumes multiple products go through the area, if only one product goes through assume answer of all.
[4] Serial- only one task is occurring on the product at one time
[5] Parallel- multiple items of the product are being worked on at one time
[6] Disruptions – scrap, rework, shortages
[7] Improvements are seen in reference to the customer

Table 3: VSM Matrix

The validity of the matrix was tested using a survey. Each environmental factor was scored on a one to five scale, with five being most appropriate. Figure 5 shows that the total of these scores correlates to the success of the VSM event.

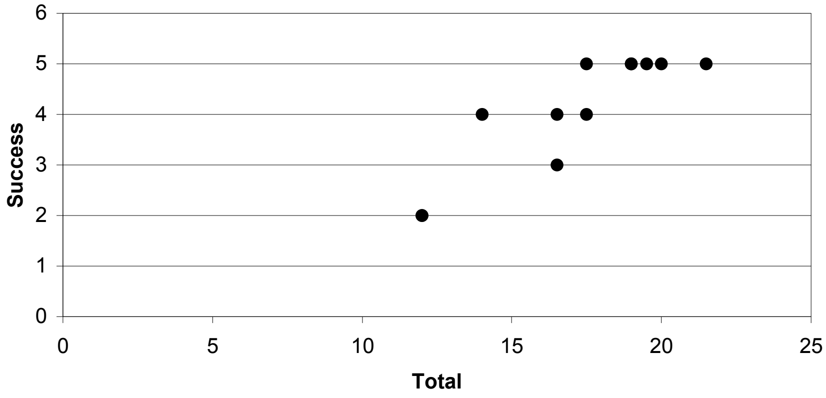


Figure 5: Comparison of Environmental Characteristics to Success

It has been shown that the five identified environmental characteristics do correlate with the success of the value stream mapping event. It is, therefore, recommended that future studies be performed to isolate the affect of each factor, and verify that additional factors are not needed. This theory could also be taken beyond value stream mapping to include other improvement tools.[35]

3.2 Chart Product and Information Flow

Following the product as it moves through the production system and seeing what happens to it is very revealing. The amount of time a product is sitting idle should be recorded as well as the distance it travels when in motion, the times it is moved or positioned, and the amount of rework should all be recorded. The amount of time spent collecting and submitting data on the product's location, time charging, and other information recorded should be measured. This information may be added to the current state value stream map for analysis during the design phase.[36]

3.3 Chart Operator Movement

The operator's actual movements in the shop are traced over a layout of the facility to create a spaghetti chart. Analysis of the chart will show wasted actions and movement that can be usually removed from the process by standardizing operations and/or simple rearrangement of the work area. A mechanic in an assembly operation is generally the one who adds value to the product and therefore his movement around the shop should be minimized. However, in fabrication operations it is the machine that usually adds value

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[35] Salzman, Rhonda A., Manufacturing System Design: Flexible Manufacturing Systems and Value Stream Mapping.

[36] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

to the product and the mechanic should not be linked to it. In either role the mechanic's activity should be focused on facilitating what ever will aid in getting value added to the product faster.[37]

3.4 Chart Tool Movement

A similar spaghetti chart outlining the movement of tools in the shop with a subsequent analysis will show additional opportunities for the removal of wasted motion from the operation.[38]

3.5 Collect Baseline Data

Performance of the current production system provides a baseline to measure progress and develop a business case justification for any improvement expenditures. Data on direct and indirect costs, production cycle and throughput time, and quality and schedule performance should be documented.[39]

References for Phase 3

Crabill, John, et al on the Production Operations Transition-To-Lean Team, Production Operations Level Transition-To-Lean Roadmap Description Manual, Version 1.0, Cambridge, MA, MIT, 5 June 2000.

Roman, Marco, Lean Aerospace Initiative Electronic Sector Study, Thesis, Cambridge, MA, MIT, June 2000.

Salzman, Rhonda A., Manufacturing System Design: Flexible Manufacturing Systems and Value Stream Mapping, Thesis, Cambridge, MA, MIT, June 2002.

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[37] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[38] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[39] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

Phase 4: Design Production System

The concept behind this phase is to do the high level design of the production system. This design must recognize that the implementation will take several stages (Phases 5 and 6). Therefore, the key point in this phase is to consider the system design in total and not to get mired in the details of the implementation. This phase involves less implementation and more planning. It is important to understand where and how the production system will evolve.[40]

The idea with this phase was to ensure that a production system was designed to meet production requirements rather than evolved over time. This requires systemic thinking. There were two methods developed to assist in this design process: Manufacturing System Design and Axiomatic Design of Manufacturing Systems. In the first, a framework was developed to illustrate the process of manufacturing system design about which a number of tools that assist this process could be used. In the latter, a specific approach was used to force the linkage of manufacturing design to functional requirements needed in the manufacturing system design.

Manufacturing System Design

Manufacturing systems are expensive, complex and system performance is difficult to predict. Many times manufacturing systems evolve over time as new products or machinery is added to an existing system. Designing a manufacturing system from scratch or for an upgrade is not easy. Often this process is a trial and error process. In this context, a structured framework was developed to assist in the manufacturing system design process.

The scope of manufacturing system design is presented as a design process in the form of a framework. The framework is an excellent visual tool to understand the extent of the manufacturing system and its importance to the corporation in achieving corporate objectives. Because of the impact the manufacturing capability has on the success of the corporation, it is important to recognize that the manufacturing system is larger than a factory and the system design process extends beyond the factory floor. The framework clearly shows this view by representing the stakeholders, executive management, and middle management, product designers, suppliers, marketing and factory floor as part of the design environment. The framework emphasizes holistic thinking by supporting system level design and system level improvements as opposed to local improvements.

The system design is explored in terms of infrastructural design (decision and strategy components) and structural design (detailed factory floor design). The structural design begins only after a product strategy has been formulated, which indicates completion of the infrastructural design. A product strategy is a plan where all of the core competencies of a company work collaboratively to offer the

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[40] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

best solution possible. The major components of this strategy are product design, manufacturing, suppliers, and marketing. The strategy also reflects the needs of the corporation and provides a long-term plan for the manufacturing organization. The emphasis is for a manufacturing system to be designed based on an overall strategy and not just on a product design strategy since the product is just one part of the strategy. The product strategy should take into account the dynamics of product lifecycle and industry life cycle such that the manufacturing system can be designed to adapt to these dynamics. This continuous adaptation in the form of continuous improvements to build manufacturing capability for the future is also emphasized in the framework. The framework is a tool of many tools. It recommends use of existing strategy concepts and manufacturing system design tools where they can make a meaningful contribution. A manufacturing system design process is recommended based on the insights gained during the framework development exercise. The process not only provides a way to think about manufacturing system design but also serves as a quick guide to understand the scope of the design. The framework is shown in Figure 6. This framework was developed through experience, other available tools and the application of systems engineering ideals.[41]

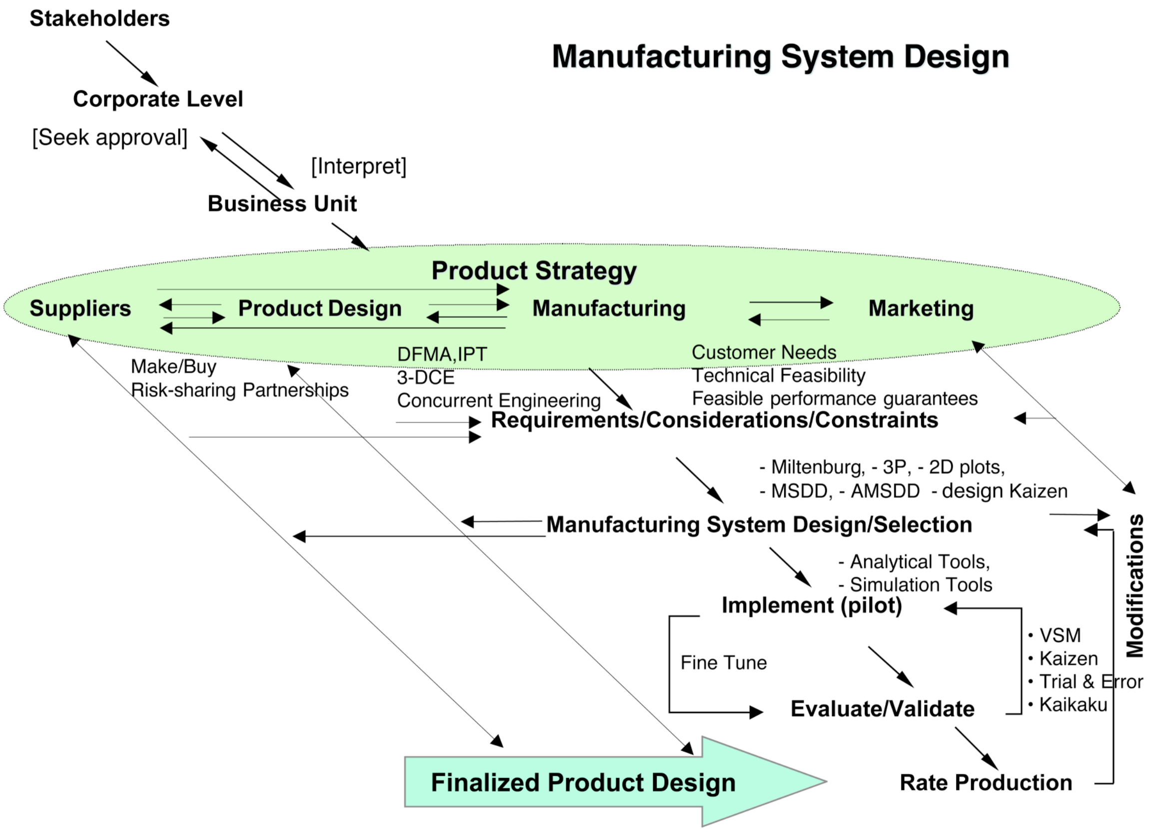

Figure 6: The Manufacturing System Design Framework

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[41] Fernandes, Pradeep, A Framework for a Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond Factory Floor

Further research by Amanda Vaughn provided validation of this framework. Fourteen case studies spanning assembly operations from major aerostructures, electronics, launch vehicles and spacecraft were used to test the hypothesis that a firm that followed the process outlined by the framework would design a more effective manufacturing system as measured by actual performance compared to the planned performance. In each case study, the actual manufacturing system design process used by the site was either captured in real-time as the manufacturing system was being designed or retrospectively and a framework congruence value was determined. This value, obtained through a structured survey/interview process, is a measure of how closely the manufacturing system design process proposed by the framework matches the processes actually followed by the case studies.

This framework congruence value was compared to a performance metric of the resulting manufacturing system. The performance measure used in this study was the actual/planned performance of the manufacturing system. An actual/planned performance measure of 1 means that the system was able to assemble the product in the number of days planned, while a performance measure of 3 would mean that it actually took 3 times longer to assemble the product than planned. This performance measure was appropriate for all the assembly operations contained in this data set and allowed the figures to be normalized for comparison.

The results of the framework validation are shown in Figure 7. This graph shows that the cases that were able to meet their planned performance corresponded to higher framework congruence scores, supporting the hypothesis that following the process proposed by the framework could result in a better performing manufacturing system design.

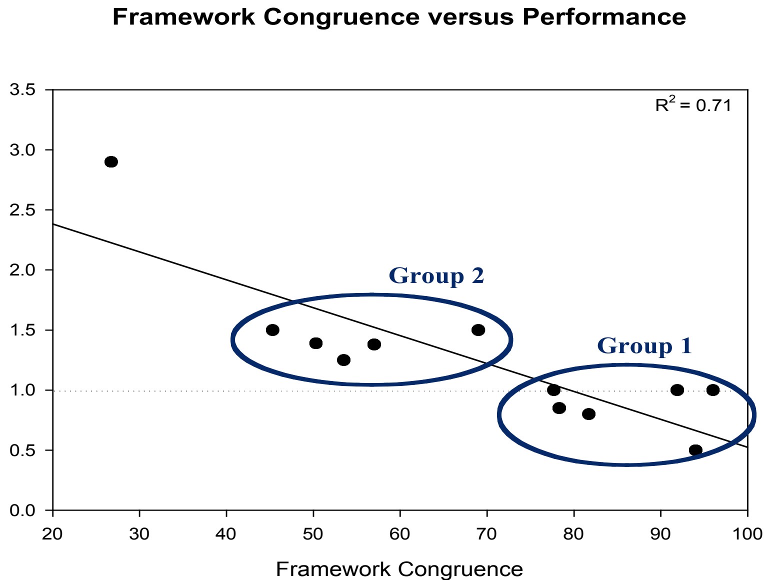

Figure 7: Framework Validation Results

The two groups marked on the graph emerged in the data set. Looking at these two groups allowed the similarities and differences between the cases that were able to meet their planned performance and those that were not to become clear. Looking for common traits between the cases in group 1 led to a collection of determinants of performance. These are:

- Breadth of functional interaction in each design phase
- Strategy presence
- Status of manufacturing
- Co-location of engineering and production
- Customer involvement
- Enterprise perspective
- Production volume independence

The first determinant of performance, breadth in each design phase, emerged both through numerical analysis and in observations from the case studies. Differences in the inclusion of the product design function for a manufacturing system redesign or the inclusion of manufacturing in a new product design impacted the result of the manufacturing system design process. The difference in breadth portion of the total framework congruence scores was statistically significant and was the main difference between the two groups.

The next two determinants of performance that differentiate groups 1 and 2 are the presence, and role, of a manufacturing strategy. The results show that the cases in group 1 had a manufacturing system that at least met the planned performance and all had a manufacturing strategy. Examples of the manufacturing strategies include capitalizing on similarities in product variations or the reduction of craft type work that occurred on early models of a product. In these cases, the manufacturing function was just as important to the realization of their products as the product design function.

Another determinant of performance is a trait of the organizational structure. Every case in group 1 had manufacturing and a large portion of product design co-located in the same building or complex. But there were also a few cases that were not in group 1 that were also co-located. This implies that co-location of manufacturing and engineering is an enabler but alone is not sufficient to design a manufacturing system that meets the performance targets. Just because these functions are located in the same vicinity does not mean that they will interact, as is the case for the sites in group 2 that were co-located and did not meet the planned performance standards. What is important about this result is that all the cases in group 1 that met their performance were co-located.

Customer involvement had a profound effect on the manufacturing system design process and the amount of interaction between manufacturing and the other functions. Where affordability was an explicit customer requirement, the companies were able to meet the challenge. The focus on affordability is prevalent in the newer programs that were studied in this research. In these programs where the customer is concerned about manufacturing and acquisition costs, manufacturing has become an integral part of the program development in the early stages.

A few of the cases in group 1 exhibited a unique, and powerful trait. A handful of the cases in group 1 designed their manufacturing systems with an overall enterprise-level perspective, rather than a single program, or product, perspective. In these cases, the product strategy in the framework was interpreted to become the product strategy for a complete line, or family of products instead of a single product. This is not a determinant of performance in the same sense that the others mentioned here are since not all of the cases in group 1 maintained an enterprise perspective. In these cases where the firms had an enterprise perspective of the manufacturing system, the system was designed to be an integral part of the competitive strategy for the future. The integration of the manufacturing aspect into the enterprise perspective created a completely different level of effectiveness to the manufacturing system design and product design processes.

An interesting finding was that the performance of the manufacturing system was not dependent on the production volume. In fact, it was the quality of the manufacturing system design process that had the most impact on system performance. The performance of the manufacturing systems of the cases detailed in this research was independent of the production volume.[42]

Axiomatic Design of Manufacturing Systems

One methodology that exists to assist a company in the design of a manufacturing system is the Manufacturing System Design Decomposition (MSDD) which is a product of the Production System Design Lab (PSD) at MIT. The MSDD is a methodology that can be used to systematically relate the desired design outcomes (known as functional requirements in axiomatic design terminology) to the design principles and the design parameters that are used to achieve the desired result. The methodology also encapsulates the hierarchical nature of a manufacturing system as well as the linkage nature of a manufacturing system. The purpose of this particular report is to introduce the concepts of axiomatic design and introduces the two fundamental functional requirements.

Axiomatic design defines design as the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through the mapping between Functional Requirements (FRs) and Design Parameters (DPs).[43] The FRs represent the goals of the design, or what we want to achieve. The DPs express how to satisfy the FRs. In most design tasks, it is necessary to decompose the problem.

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[42] Vaughn, Amanda F., A Holistic Approach to Manufacturing System Design in the Defense Aerospace Industry.

[43] Suh, Nam P., The Principles of Design

The development of the hierarchy is done by zigzagging between the functional domain of the FRs and the physical domain of the DPs. In order for the mapping between the two domains to be satisfied, two axioms must be followed:

1. The Independence Axiom: Maintain the independence of the FRs.
2. The Information Axiom: Minimize the information content of the design.[44]

The first functional requirement (FR1) of a manufacturing system, according to the methodology, is to synchronize the cycle time of each element in a manufacturing system with the demand for the element. This gives synchronous and predictable output that is the corresponding design parameter (DP1) of standardized work. Zigzagging between the domains will give subordinate functional requirements to FR1.

These FRs and DPs and the principles of axiomatic design are then discussed for a variety of different manufacturing systems, a transfer line, Toyota cell, flexible manufacturing system and high volume batch production.

The paper introduces a new approach to manufacturing system design which addresses several of the fundamental issues relevant to the design and implementation of a new manufacturing system. The axiomatic design approach is used as the basis for a systematic design structure.[45]

Understanding Lean Manufacturing According to Axiomatic Design Principles

This report is a follow-on to the previous publication entitled *Axiomatic Design of Manufacturing Systems*, which served as an introduction to the principles of axiomatic design and how they could be applied to manufacturing system design.[46] This report takes those principles and outlines how they were used to design the manufacturing system of a Boston area manufacturing company. Then the methodology is applied to a different company to help improve their cell design.

First, the key concepts of axiomatic design are outlined. The definitions of Functional Requirements (FRs) and their corresponding Design Parameters (DPs) and how they can be applied through the independence and information axioms to manufacturing system design are discussed.

One of the case studies in the paper was of a Boston area company that manufactures power tools. For one of their newest products, there was such an increase in demand that the company simply couldn't produce the product fast enough to keep up with the demand. They were not meeting deliveries in a timely matter and subsequently losing customers. The existing machining cell for this product was studied and improved in

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[44] Suh, Nam P., The Principles of Design
[45] Cochran, David S., Vicente Reynal, Axiomatic Design of Manufacturing Systems
[46] Cochran, David S., Vicente Reynal, Axiomatic Design of Manufacturing Systems

order to meet customer demand. The main goals for the improvement effort for changing the machining cell so it could meet customer demands were:

1. Decrease work in process and finished goods inventory.
2. Reduce customer order lead-time.
3. Produce only what is needed when it is needed.

These goals were then translated into the high level functional requirements:

FR1: Create a predictable output
FR2: Create continuous flow
FR3: Produce what is needed only when it is needed (Just-in-Time)

The functional requirements were then mapped into the physical domain to determine the main design parameters:

DP1: Standardize work
DP2: Connect processes with same volume requirements
DP3: Create a pull system

After these design parameters were determined, the design equation was used to determine the best implementation order for these design parameters. Using the independence theorem of axiomatic design to decouple the functional requirements from design parameters, the implementation sequence can be found. In this case, the best implementation sequence is

1. Connect processes with same volume requirements
2. Standardize work with a consistent cycle time
3. Create a pull system

In order to implement these DPs, they are decomposed into supporting functional requirements and design parameters. This method of continuously decomposing DPs into supporting FRs is called *zigzagging*.

After decomposing the high level FRs into DPs and decomposing to the lowest possible level, the root cause was determined and the operations were improved. The resulting machining cell was able to meet the customer demand.[47]

Design of Production Systems in Aircraft Assembly

In order to have the ability to design a complete production system and ensure that the plan is staying true to the original lean ideals, some sort of strategy or methodology must be followed. In complex manufacturing systems such as aircraft assembly, it is difficult to coordinate the design of all the elements that comprise the

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[47] Reynal, Vicente, David S. Cochran, Understanding Lean Manufacturing According to Axiomatic Design Principles

system to work together effectively in achieving the overall goals. Andrew Wang's research provides a methodology for analyzing a current production system to understand how the design attributes interrelate and the method to redefine those attributes based on the principles of lean manufacturing.

Aircraft assembly is a particularly attractive sector within the aerospace industry to implement lean manufacturing since it is estimated that major innovations in airframe conventions occur once every 10 years as compared to every 3 years in electronic controls. In addition, commercial aircraft have had the same configuration for many years and no significant change is foreseeable in the near future. With airframe designs that have such long life cycles improvements made in the assembly processes will have a long return period and are therefore, quite valuable.

After conducting numerous case studies and site visits, the researcher found that there was no clear outstanding performer in the airframe sector of the aerospace industry. All the scheduling systems were similar – forecast and MRP was used, but informal scheduling and expediting late parts really drove production. The results were either that work had to travel with the wings when the wings were delivered to the assembly line, or that the wings would be delivered completed, but late.

The ratio of actual/planned throughput times was collected to determine how well the wing assembly areas were conforming to schedule and the result was that every manufacturer took longer to build their wings than was planned – some up to 60% longer. Unfortunately, these measurements do not take into account traveled work – where people will continue to work on the wing even after it has been delivered to the assembly area to be mated with the fuselage. This makes the normalized throughput times overly optimistic. In addition to this, every site was comparable in the amount of overtime put in by the workforce.

The results show that there was no outstanding performer in the airframe sector. This is attributed to the fact that all the sites studied had similar manufacturing systems and none was operating in a unique environment where the system had been designed with lean principles in mind.

Wang's research then analyzes the problems seen in the airframe sector with the use of the Production System Design Laboratory's Production System Design Decomposition (PSDD). This decomposition uses the principles of axiomatic design to describe the hierarchical relationships between different functional requirements in a production system. The thesis traces the different attributes seen in the airframe sector with their corresponding portions of the PSDD. The analysis is useful to highlight potential improvements in the production system design and the different implications that lean principles have in the airframe sector.

Finally, Wang attempts to create a version of the PSDD that is tailored to the manufacture of military aircraft using the axiomatic design approach and principles. The new decomposition is made by tracing through the different paths of the existing

PSDD and changing the functional requirements and design parameters to tailor them to the aerospace industry. Through this process, Wang found that many existing procurement policies hinder an aircraft manufacturer from implementing lean principles. Some of these existing policies had tremendous impact to maintain the strength of the aircraft industry throughout history, but they are now hindering effective production system design. In light of this, Wang develops a tool to assess the current state of a manufacturing system to help guide a system design effort.[48]

Production System Design and its Implementation in the Automotive and Aircraft Industry

Continuing research from the Production System Design (PSD) Laboratory at MIT is presented in Vicente Reynal's thesis. The purpose of the research is to define the design attributes necessary to design new or convert existing production systems to ones that support and use the principles of lean manufacturing, and to develop a methodology for implementing the design principles developed. The hypothesis is that a set of lean production design attributes applies to both the automotive and other lower volume industries like aircraft. The lean production system design attributes are obtained by understanding the relationships that exist and what a lean production system must achieve functionally and how these are achieved physically. This relationship is represented by the Manufacturing System Design Decomposition (MSDD) which is a product of Prof. David S. Cochran and the PSD Lab at MIT.

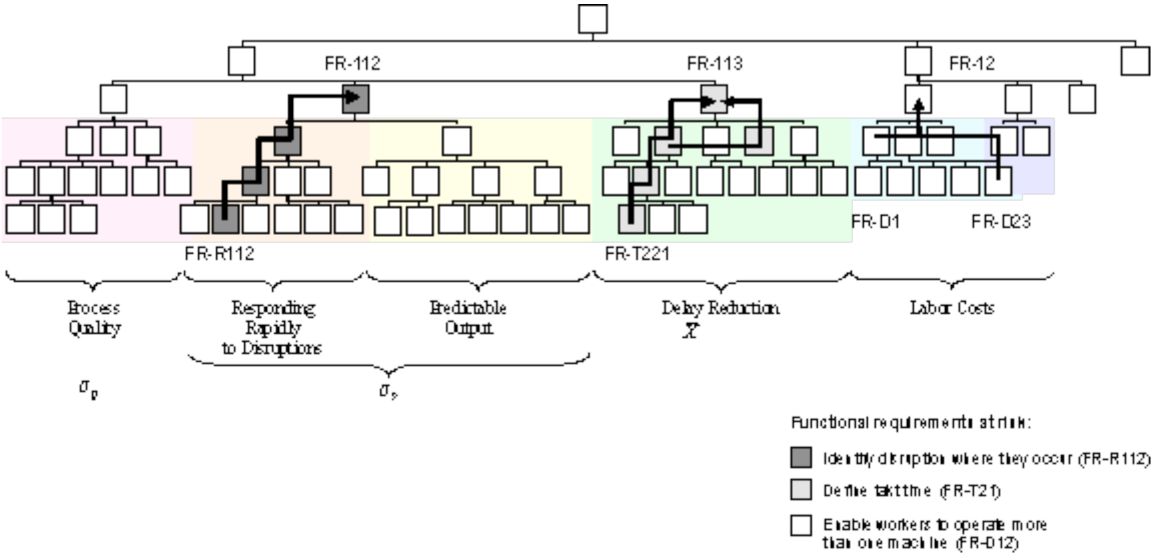

Figure 8: Manufacturing System Design Decomposition (MSDD)

Reynal's thesis is based on six case studies: two automotive (one lean and one mass producer), three aircraft engine companies and one OEM company. From the lessons learned in the case comparisons, a methodology for designing new

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[48] Wang, Andrew, Design and Analysis of Production Systems in Aircraft Assembly

production systems or converting existing ones to a production system that utilizes the lean production system design attributes is developed.

The assembly areas of two automotive companies, one lean and one mass producer, were compared. Then three aircraft engine assemblers were studied to determine if the same methodology would apply to a producer functioning at a lower volume than that of the automotive industry.[49] The three companies were compared against the design parameters laid out in the MSDD. It was found that the only company with a very predictable output (company C) applied many of the lean design attributes. Company C which designed its production system to be balanced to the customer takt time, implemented a pull system and designed the assembly operations and stations to be able to perform equally well to a range of operating conditions. Even though Company C had the highest total number of parts (for a similar engine size), its output is very predictable and stable. In addition to the predictable output, Company C achieves 100% on-time delivery while Company A and B performed at 67% and 25%, respectively.

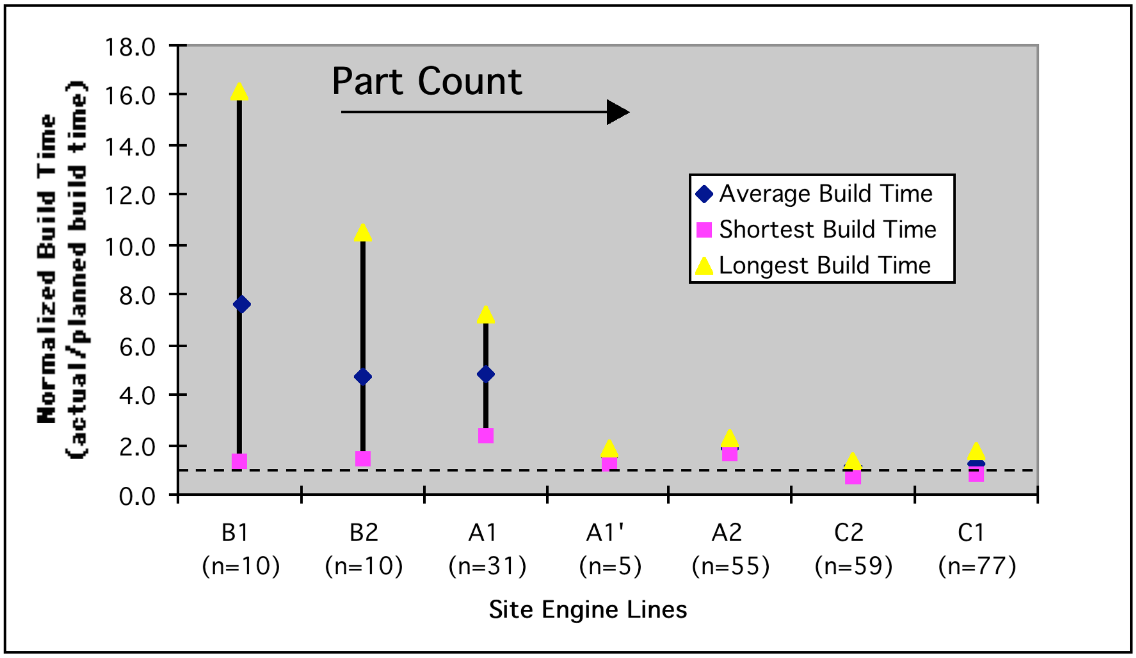

Figure 9: Normalized Build Times for Engine Assemblers

The data for the A1' line was obtained subsequently and the changes that were implemented on that line are outlined in the Engine Sector Research Summary.

In the last portion of Reynal's thesis, a methodology for implementing lean production systems was developed based on the benefits and design attributes presented in the Manufacturing System Design Decomposition (MSDD). The

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[49] For more information on the engine sector case studies, please refer to the Summary of Research Conducted in the Engine Sector, LAI Report RP00-01.

implementation methodology demonstrates that the production system conversion must be supported by the integration of the supply chain and product development.

From the findings presented in the thesis and from the lean implementation methodology, it needs to be reemphasized that the economies of time are the new focus of manufacturing rather than just economies of scale. This means that the customer demand cycle time or takt time drives the design of machines or operations that support the requirements of the system or its users.[50]

A Decomposition Approach for Manufacturing System Design

The latest work from the Production System Design (PSD) Laboratory is an article submitted for the Journal of Manufacturing Systems. This paper goes beyond the previous by exploring the other uses of the Manufacturing System Design Decomposition (MSDD) and how it is useful as a communication tool within an organization and how it can fit into the larger picture of striving to create a manufacturing system that supports the overall business objectives and strategies of the company.

Designing a manufacturing system to achieve a set of strategic objectives involves making a series of complex decisions over time. Making these decisions in a way that supports a firm's high-level objectives requires an understanding of how detailed design issues affect the interactions among various components of a manufacturing system. This paper presents an axiomatic design-based decomposition of a general set of functional requirements and design parameters for a manufacturing system and explains how this decomposition can be used as an approach to aid engineers and managers in the design and operation of manufacturing systems.

In practice, designing the details of manufacturing systems (equipment design and specification, layout, manual and automatic work content, material and information flow, etc.) in a way that is supportive of a firm's business strategy has proven to be a difficult challenge. Because manufacturing systems are complex entities involving many interacting elements, it can be difficult to understand the impact of detailed, low-level deficiencies and change the performance of a manufacturing system as a whole.

The MSDD has four main objectives:

1. Clearly separate objectives from the means of achievement
2. Relate low-level activities and decisions to high-level goals and requirements
3. Understand the interrelationships among the different elements of a system design
4. Effectively communicate this information across the organization.

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[50] Reynal, Vicente, Production System Design and its Implementation in the Automotive and Aircraft Industry

The paper goes on to describe each of these in detail as well as review the concepts of axiomatic design as applied to manufacturing systems. It does this through two examples of the MSDD in use to address design issues in manufacturing. The MSDD provides an excellent platform to integrate the various disciplines of manufacturing system design.[51]

4.1 Develop a Future State Value Stream Map

Using a system view of the operation determine how you want the system to function. Some key questions are: what type of production system do you want, how do you want to synchronize with your suppliers, how are deliveries going to be made to your customer, and how are you going to coordinate and control your production operation? Each of these questions leads to system decisions that will define the future state value stream. Since our objective is to transition to lean production operations the future state value stream should incorporate lean concepts that ensure close coordination with suppliers, smooth flow of parts and assemblies through the operation, and all linked by the customer demand rate.[52]

4.2 Identify Takt Time Requirements

Although the formula for determining takt time is relatively simple (see the formula below) there are other factors that must be considered.

$$\text{Takt Time} = \text{Available Time} / \text{Average Daily Demand}$$

The first step is to determine the maximum output that the production system should be designed to handle (i.e. its highest capacity). It is often useful to consider the demand in some period in the past and to forecast the future demand anticipated. Then a minimum takt time can be determined that addresses the highest demand that is anticipated. The demand is often variable; therefore, the idea is to create a system that will work well with many different customer demand rates. The production system must be capable of addressing this variable demand. Therefore, a range of takt times must be designed into the production system that will meet the expected demand. The minimum takt time will establish the maximum capacity of the system and the maximum takt time will establish the minimum capacity of the system. At any point in time the average customer demand will define the takt time needed throughout the facility. This takt time determination must be done for the major components and the final product. If the components of the product are common among several product lines, the demand for each product must be considered in the takt time calculation.[53]

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[51] Cochran, David S., et. al., A Decomposition Approach to Manufacturing System Design

[52] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

[53] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

Production System Design and its Implementation in the Automotive and Aircraft Industry

In this thesis, Vicente Reynal defines the design attributes necessary to design new or convert existing production systems to ones that support and use the principles of lean manufacturing, and develops a methodology for implementing the design principles developed. The hypothesis is that a set of lean production design attributes applies to both the automotive and other lower volume industries like aircraft. The lean production system design attributes are obtained by understanding the relationships that exist and what a lean production system must achieve functionally and how these are achieved physically. This relationship is represented by the Manufacturing System Design Decomposition (MSDD) which is a product of Prof. David S. Cochran and the PSD Lab at MIT.

Through the six different cases studied in this research, the need to produce to the customer demand cycle time, or takt time, is mentioned as necessary to be able to achieve a predictable output.

Also, this thesis reemphasizes that the economies of time are the new focus of manufacturing rather than just economies of scale. This means that the customer demand cycle time or takt time drives the design of machines or operations that support the requirements of the system or its users.[54]

4.3 Review Make/Buy Decisions

After designing the future value stream and determining the production system takt time, it is often necessary to review previous make/buy decisions. Often certain types of parts or assemblies naturally fit the new value stream or a new layout. Therefore, it makes sense to group all like parts or assemblies that can be processed within the production system takt time. This requires the review of previous make/buy decisions to pull in those parts/assemblies that fit the internal value stream and to outsource those parts that do not conform to internal processes or value activities planned.[55]

4.4 Plan New Layout

The key in a new layout design is to ensure that each of the operations can be completed within the takt time. The first step is to review the future value stream to see if present operations have the potential to be improved so that they may be completed in less time. Each operation should be evaluated relative to the takt time to determine if it can be completed within the minimum takt time or not. Those operations that are less than the minimum takt time may be combined with other operations as long as the combined operations minimum takt time is not exceeded. For those operations that are longer than the takt time, some means must be devised to subdivide the operations to ensure that the minimum takt time is not exceeded or parallel processing must be done. The least

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[54] Reynal, Vicente, Production System Design and its Implementation in the Automotive and Aircraft Industry

[55] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

desirable solution is to plan work-in-process inventory and lot size production to de-couple operation steps that exceed the minimum takt time. To improve the chances for success in the next phase, the new layout should be situated as much as possible to allow contiguous one-direction flow through the production system. [56]

Cellular Manufacturing in Engine Fabrication

One way to achieve continuous flow throughout the production system is to incorporate a cellular manufacturing system. In Hoppes' case study based research, he documented the changes that one engine manufacturer underwent to implement a cellular manufacturing system.

This site had made a commitment to become a world-class machining center and was ready to make changes to reach that goal. Part of this new strategy required the products to be divided up into families so the cells could more easily be grouped. This was accomplished by assigning a color to each production process and mapping the complete production sequence for a part number on the wall. This made it easier to locate common flow by combining common colors to place parts with the same processes into cells.

Following this cell assignment, kaizen events occurred for each cell to determine the optimal layout. The teams would use cardboard cutouts to represent the machines so they were free to experiment. And when the space on the floor was too crowded to freely experiment, the teams would take their cardboard out to the parking lot to work.

Once the layouts of the individual cells were determined, tiger teams were assigned the full-time job of moving machines. This cut the relocation time down from a predicted 12 weeks to just 3 days.

After the relocation, production was launched in the new cellular layout. The following table contains the changes in performance in one of the 36 cells created in this major manufacturing system redesign.

Table 4: Improvements at case study site before and after cell implementation

	Before	After
Employees	1,224	690
Materials Employees	126	21
Quality Employees	463	71
Plant space (square feet)	1,600,000	656,000
Stocking locations	21	1
Average lead time (weeks)	20	4
Sales per employee	-	137% increase
Defects per million	-	38% reduction
Customer complaints	-	29% reduction
Cost per standard labor hour	-	24% reduction

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[56] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

These changes have created an empowered workforce that gives the customer a high quality product fast. The cellular manufacturing environment coupled with continuous improvement efforts has helped to make this site the world-class machining center that they had hoped for.[57]

The Monument of Monuments

A well-known example of the dramatic changes of implementing a lean linked cell manufacturing system is found in James Womack's book Lean Thinking. In it, Womack outlines five different case studies of companies that came back from the brink, embraced lean manufacturing ideals and flourished. One of these case studies is the American aircraft engine manufacturer Pratt and Whitney.

In this portion of the P&W case study, a new layout was created to replace a "monument" which is a machine too big to be moved and whose scale requires operating in a batch mode. The monument contained in the original layout was a massive, expensive complex of twelve blade grinding centers. The idea behind this system was to be able to totally automate the grinding of the blade roots for turbine blades using the world's fastest and most sophisticated equipment. This system replaced nine manual grinding centers and the required touch labor associated with them.

But this system had many problems. First of all, since the grinding processes were all automated, it had to be guaranteed that the blades were held in the fixtures properly or the blades would be destroyed. This made a non-value added and hazardous encapsulation process necessary as well as then needing expensive molds, long changeover times and the use of a complicated material retrieval system. In addition to the complications in the grinding process, the encapsulation then needed to be removed which then required numerous detailed inspection steps to ensure that the blades were clean. And even though this system replaced the touch labor hours, the laborers were simply replaced by skilled technicians who were required to keep this system running.

When the manufacturing system started to change and implement lean manufacturing, it became obvious that this grinding center had to be replaced. It was replaced with a series of eight smaller three-axis grinding machines that used ingenious fixtures to hold the blades eliminating the need for the problematic encapsulation process. This cellular layout allowed one worker to move parts from one machine to the next by hand, standardize his or her own work, gauge parts to check quality, change over each machine for the next part type in less than two minutes and make only what was needed when it was needed. Throughput time for the blades was reduced from 10 days to only 75 minutes.

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[57] Hoppes, John, Lean Manufacturing Practices in the Defense Aircraft Industry

The following table highlights the improvements from the implementation of the "chaku-chaku" (meaning "load-load" in Japanese) cell at P&W.

Table 5: Lean versus Monumental Machining

	Monument	Chaku-Chaku Cell
Space/Product cell (square feet)	6430	2480
Part travel (feet)	2500	80
Inventory (avg. per cell)	1640	15
Batch size (number of blades)	250	1
Throughput Time	10 days	75 minutes
Environmental	Acid cleaning and X-ray	No acid, No X-ray
Changeover downtime	480 minutes	100 seconds
Grinding cost per blade	-	51% decrease
New blade type tooling cost	-	70% decrease

This example of eliminating a monument and incorporating a cellular layout was one of the earliest in the P&W manufacturing system redesign. P&W has made tremendous progress on their journey to lean and their new physical layout is a tremendous part of it. This new layout has allowed P&W to dramatically reduce its costs while pleasing its customers.[58]

4.5 Integrate Suppliers

Suppliers should be a major consideration in the future value stream. With the production system takt time and the layout defined, the suppliers need to be synchronized with the production system. Therefore, each of the suppliers should be integrated into the production system with the guiding principle that they be able to deliver their products to support the production system's capability to meet the minimum takt time. There are multiple ways to do this integration but the production system design should consider the systems that will provide the necessary information to the suppliers to make it possible for them to conform to this new system design. This integration requires two-way communication between the supplier and the customer. [59]

Supplier Relations in the Engine Sector

The engine sector provides examples of how suppliers can be integrated into the manufacturing system so the engine manufacturer can produce engines to take time without having large amounts of inventory around the factory floor. Three different sites were studied and one was re-visited after they changed their manufacturing system and completely altered their relationship with their suppliers.

At site B, the manufacturing system was a push type system based on a forecast with monthly batches of finished product due by the end of the month. Suppliers were responsible for ensuring that all parts arrived on-site by the end of the month

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[58] Womack, James P., Lean Thinking

[59] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

prior to need. This system did not perform well on the on-time delivery metric. At site A, the manufacturing system was a push type system based on actual demand controlled by a Manufacturing Resource Planning (MRP) system. Suppliers were responsible for producing parts as ordered by the MRP system and delivering them to a central warehouse. Parts were then delivered to the final assembly plant three days prior to need on the assembly line according to the MRP schedule. At both of these sites, an informal system was in place to manage part shortages. Resource planners and managers spent a large portion of their time finding short parts and coping with the disruptions caused by these part shortages.

At site C, the manufacturing system was quite different as is shown in the following figure. This was a hybrid system characterized by 80% of the total value-worth of parts being pulled into the final assembly process. MRP was used for long range planning and the scheduling of the 20% lower value-worth of parts but the major parts were pulled from the suppliers using a *kanban* system based on a production process whose takt time was adjusted to meet customer demand. A warehouse was used but 100% of the communication between the warehouse and the assembly area was done with a *kanban* system. For those 80 percent value-worth parts, the *kanban* system signaled the actual demand for fulfillment of parts; however, production requirements were frozen to the suppliers six weeks prior to the actual date parts were estimated to be needed. At the assembly plant, engines were built in dedicated production lines. In addition to the reduced floor space in the assembly area and the ease of spotting perturbations in the flow, the layout at site C was subdivided by module so that each met takt time. The pace of the final assembly area at site C was dictated by the amount of engines or various spare modules that must be delivered to the customer. Since engine manufacturers were making spare parts in addition to new engines, site C designed lower module work content at some stations so that modules could be built to meet the new engine takt time as well as needed spares. Material handling at this site was the most advanced witnessed. As depicted in Figure 4, the parts were supplied to the production floor by means of a *kanban* system. A limited number of part containers for each engine line were moved between the material staging area and the production floor signaled by downstream demand. There was also a small item replenishment system that ensured no stock-out of small, inexpensive parts. This system was able to consistently supply parts to the engine assembly area in a manner to ensure that 100% of the engines were completed on time.

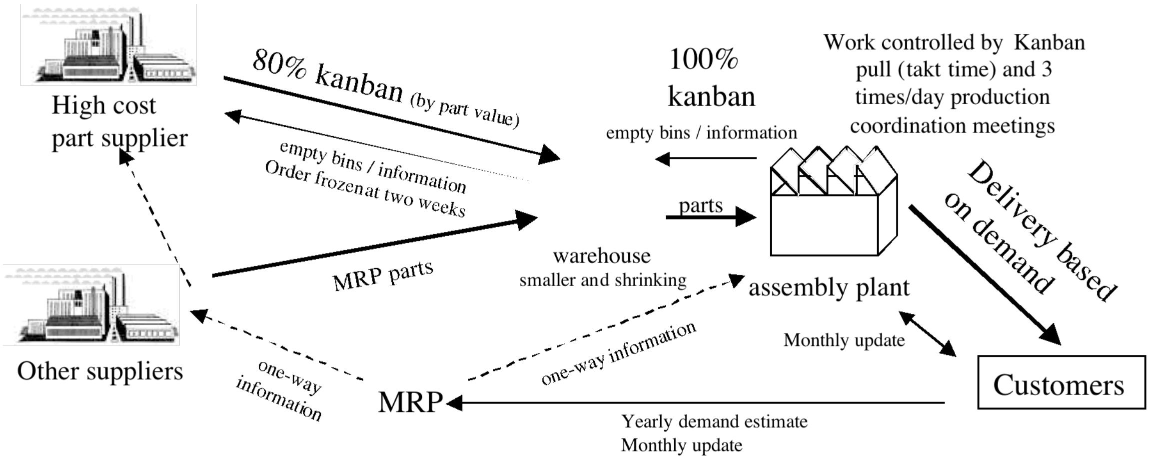

Figure 10: Site C 80% pull Hybrid Manufacturing System

Site A' changed from a departmental layout to a flowline layout and improved the way parts were provided to the final assembly plant. This new system design shown below, still used MRP to schedule all the constituent parts and assemblies, however, parts no longer went to a warehouse. Parts came directly to the assembly plant from the component centers (who were responsible for both internal and externally sourced parts). A daily milk run connected all component centers to the assembly plant. To ensure a steady stream of parts, an *andon* system was added to the part control mechanism. An *andon* system is some means that allows the status of assembly to be seen from around the entire assembly area. Normal *andon* systems will alert the assembly area when something has happened that will stop the assembly process. This *andon* system was unique. When a part shortage was anticipated to stop the assembly line the line status *andon* light was turned on at the assembly plant as you might expect, however the light also illuminated in the General Manager's office of the internal supplier. Since the Site A' internal supplier also had oversight on outsourced parts of this type there was immediate attention to part shortages in the system. Because the *andon* system had visibility at the group Vice President's level, the possible stoppage was bound to get immediate attention. Within the assembly plant, a cellular design was implemented to allow single piece flow. The cell footprint area was reduced and the output of the cell was contiguous to the next assembly station. The material handling system at Site A' also changed. Concurrently with the change to cells for the production of engine modules, the material center changed to providing kits for each engine module on specially designed carts. These carts acted like *kanban* containers being rotated between the module build area and the material handling area. Small parts were maintained at the cell and replenished on a regular basis.

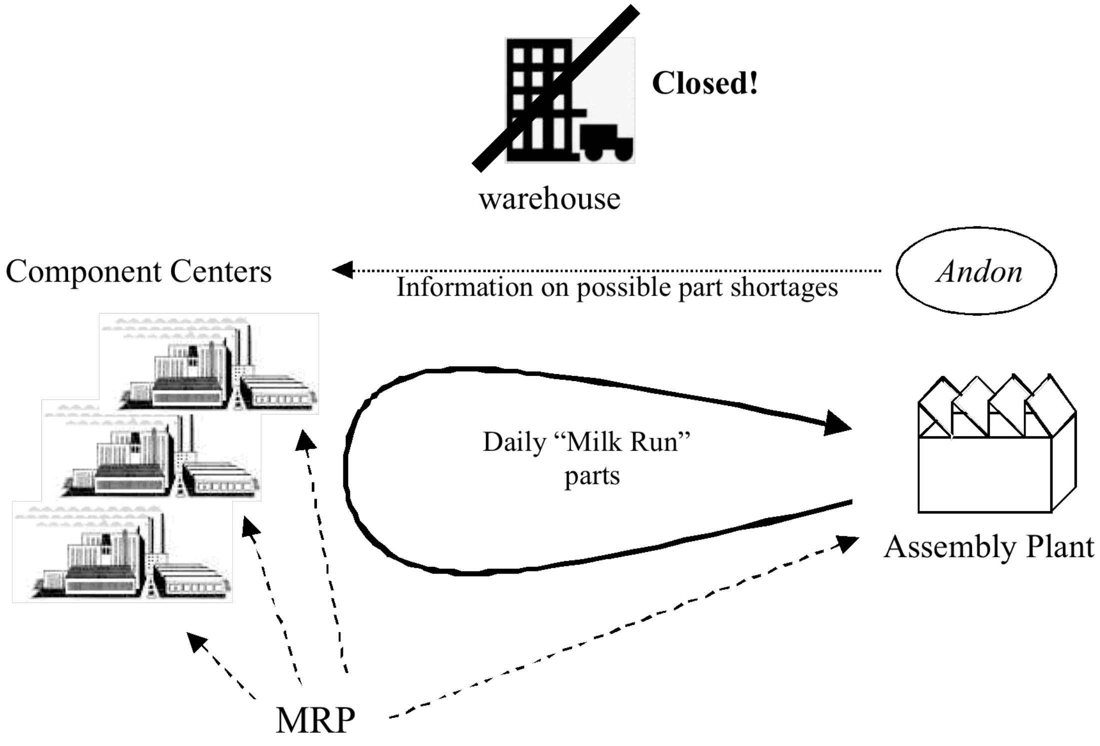

Figure 11: Manufacturing System at Site A'

These changes in the manufacturing system from Site A to A' resulted in a significant improvement to their variation in cycle time and on-time deliveries. The following table summarizes the on-time delivery history for all the sites. It is obvious that the more flexible and responsive supplier relationships at Site A' and Site C resulted in a smoother running system where part shortages was no longer a problem.[60]

Table 6: On-Time Deliveries at Engine Sector Sites

Site	Late	On-Time
A	35%	65%
A'	7%	93%
B	70%	30%
C	0%	100%

Supplier Relations in the Electronics Sector

The electronics sector study conducted by Marco Roman contains some good examples of how the suppliers were linked into a company's manufacturing system to limit the disruptions to the flow.

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[60] Ramirez-de-Arellano, Luis, et al, Summary of Research Conducted in the Engine Sector

The electronics sector study contained detailed analysis of both commercial and military contracts and outlined the different problems experienced in each. On the defense side, the main source of delay was the shortage of purchased parts from suppliers. This part shortage problem was attributed to 30% of the delays. Further investigation into these part shortages showed that the delays were caused by the suppliers having to restock faulty circuit boards which were either discovered in receiving or at other times in the manufacturing process. Interviews revealed that suppliers were not being held accountable for their performance. Material managers were often asked why their suppliers were late with components and no one seemed to have a confident answer to the question.

One way to achieve this accountability on the part of the suppliers is to use a certification system. In this study the commercial programs had a 100% certified supplier network and the military programs dealt with 43% of the suppliers being certified. Certification of suppliers not only increases the accountability for quality but also decreases the cost for ownership of purchased parts, reduces the need for incoming inspection resources and reduces total cycle time. In addition, there was a correlation found between the percentage of certified suppliers and the percentage of supplied components causing production delays – the more certified suppliers fed the program, the fewer delays experienced in the system due to supplied part shortages.

One program had a unique relationship with their certified suppliers. When parts were received from a certified supplier they were not inspected, but sent directly to the production area and did not have to go through the receiving inspections that all non-certified parts had to go through. By eliminating the need for all received parts to go through a receiving inspection, the site had freed up 25,000 square feet over numerous programs. In addition, this practice reduces costs of packaging, transportation and cycle time. This is a prime example of string to have the right thing, at the right place, at the right time.[61]

4.6 Design Visual Control System

To enable a lean production system, it must be as simple an operation as possible. One method to do this is to design easily understood visual control systems that communicate production system control. In fact, the best production system is one that controls itself. By designing visual means of control, everyone within the system may take actions to keep the production system in control. Therefore, this step requires not only the physical design of visual devices to control the operation but also the education of the workforce (and management) in how the system can be controlled from within.[62]

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[61] Roman, Marco, Lean Aerospace Initiative Electronic Sector Study

[62] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

Cellular and Continuous Flow Manufacturing

Part of a major manufacturing restructuring effort could contain the development and deployment of a visual control system. Such a control system is one of the key characteristics of a system that is fully prepared to support a flow and a pull manufacturing system.

One case study in Hoppes' research implemented a visual control system as a part of their manufacturing system restructuring effort. The flow throughout the system once a kit has been delivered to the floor completely relied on operator input and a visual control system. First of all, a cell operator will raise a flag that can be seen throughout the area when the cell needs another kit from the prep area. When the product leaves the first cell, it is taken to a solder station. The kit is taken in a colored bin, which is color-coded based upon which day of the week the job was released onto the floor. Since the system operates on a first in first out basis, this instantly alerts the operator on which kit to process first.

In the rare event of a rush job, the kit is noted with a red tag. Policy states that there can be no more than 6% of the jobs possessing a red tag at any one time. The number of red tags is reviewed daily to ensure that this policy is being followed.

Another form of visual control in this system is the kanban system that controls the flow of the kits into the bottleneck areas. These kanban boards have a maximum WIP level and the operators change the WIP level when they deliver or remove a product.

This visual control system ensures that the cell operators knew which set of work was their next priority and that the bottlenecks were not being starved for work.[63]

4.7 Estimate and Justify Costs

This new future state value stream and its production system design will most likely involve investment. This investment must be estimated and justified. Although this sounds straightforward it seldom is. Many of the cost savings are not easily quantified and present accounting systems and their metrics often penalize lean activities. Therefore, the senior level management buy-in that was obtained earlier is useful to help guide and shape this justification process. It is helpful to address the system effects and to characterize the system improvements as the measure of effectiveness that will be most meaningful. [64]

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[63] Hoppes, John, Lean Manufacturing Practices in the Defense Aircraft Industry

[64] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

4.8 Plan TPM System

Since the production system is being designed to improve flow and minimize waste, it is important those production resources are available when they are needed. In this new production system design, there is no (or little) safety buffer to alleviate system perturbations. The way to ensure that unplanned perturbations are avoided is to implement a Total Productive Maintenance (TPM) System. This system will ensure that production resources are monitored and systematically maintained so that there are no or a minimum number of unplanned production disruptions. The system design phase is perhaps the best time to plan for the implementation of a TPM system.[65]

Test Equipment in the Electronics Sector

Preventative maintenance should also be considered for testing equipment in addition to production equipment. In the electronics sector final testing is an intricate and involved process that may require delicate equipment and expert technicians. Marco Roman's research into the electronics sector revealed that the failure of testing equipment was a sizeable cause of delay.

A TPM program for test equipment will ensure more uptime for testing equipment. The study found a correlation between the percentage of time that testing equipment was functional was directly proportional to the throughput yield percentage and also decreased overall cycle time.

One unique aspect of testing equipment, which is suitable for a TPM program, is calibration. One site studied in this research had a strict maintenance schedule that was followed and understood to be important by all factory personnel. As a result, the site had not had testing equipment that was out of calibration for several years.[66]

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Phase 5: Implement Flow

This phase marks the conversion from a batch and queue type of operation to cellular type of operation. In this phase individual cells are established in the production system to implement flow within those cells. The principles of this phase are applicable to both fabrication and assembly.[67]

5.1 Standardize Operations

Standardized operations mean everyone in a work team performs a given task in the same "best" way to optimize the process flow. Personal, unilateral innovation is not allowed. Continuous improvement (kaizen) is encouraged and if a better way to do the work is discovered, it is presented to the work team and leader for evaluation and if judged to be an even better way to do the task it may then become the new standard. Standardized operations lead to standard times, which allows work to be synchronized and also provides metrics by which work can be continuously monitored and improved.[68]

5.2 Mistake Proof Processes

Product defects are wasteful and if not discovered early in the manufacturing process they can lead to unneeded cost and customer dissatisfaction. One of the principles of lean is that it is not acceptable to produce even a small number of defective goods. Mistake proofing methods are simple in nature and avoid inadvertent errors by using such things as locating guides on the part or the tool, limit switches to detect errors, counters, and checklists. These devices function to shut down, control, or provide a warning to the manufacturing process.[69]

5.3 Achieve Process Control

A process that is under control is statistically predictable as to its outcome. Process variations result from one of two types of errors: special causes or common causes. If the process has no special cause present, the process is said to be in statistical control, or stable. The average and limits of variation are predictable with a high degree of confidence over the immediate future. In the absence of statistical control, no prediction is possible. "Process capability" is often what we mean when we say process control. Process capability is a way of measuring product or process variation against a set of design or customer specifications. Two common capability indices are Cp and Cpk. Cpk is a preferred capability that takes into account all three factors of process centering, process variation, and the tolerance of a specification. "Achieving Process Control" can also mean consistency about the production system performance measures such as throughput time, on-time delivery, quality, equipment reliability, etc.[70]

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[67] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[68] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[69] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[70] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

Process Variability Reduction

Customers in the defense aircraft industry keep demanding better fit of the completed product. Manufacturers that can *consistently* provide superior component fit have more control of their processes (smaller process variability) and therefore can produce products that better fit the customer's needs. Through variability reduction, firms can also realize a reduction in production tooling, rework costs, assembly complexity, and parts expediting, among other benefits.

One of the case studies in Hoppes' thesis was how a site was able to reduce their process variability and reach an entirely new level of component fit and quality through the precision assembly concept. The goal of precision assembly is to eliminate the need for hard tools, and instead use locators on the part as an index for a mating part. The extensive use of SPC data to gain control of a process allowed the site to be able to avoid tolerance stack ups and ship products with full size mating holes in them that did not require any subsequent machining or deburring. Precision assembly has ensured that full size holes meet consistently. This elimination of machining on the assembly line resulted in 60% fewer hours for assembly of the product studied in this case.

Table 7: Comparative Assembly Data for Floor Bean in a Precision vs. Non-Precision Assembly

	No Precision Assembly	Precision Assembly
Beam Components		
Unique component part numbers	51	37
Total number of components	426	387
Total number of fasteners	180	158
Actual Assembly Time	100%	46.5%

Another benefit to precision tooling is the extensive use of "soft" tooling which allows engineering changes to be easy and inexpensive when compared to assembly that uses "hard" tooling. A controlled, repeatable process is necessary for implementing precision and tooless assembly. Incorporating SPC into the manufacturing system with capable measuring tools will help start to trace, and therefore focus efforts to help reduce, process variability[71]

5.4 Implement TPM

TPM stands for Total Productive Maintenance. The focus of TPM is on five major elements: maintenance prevention (avoidance of breakdowns), predictive maintenance (being able to predict impending breakdowns i.e. using sensors, etc.), improvement maintenance (fix the problem so it doesn't recur), preventive maintenance (routine maintenance to avoid breakdown), and 5 S maintenance by equipment operators (e.g. cleaning so that oil leaks show, replacing filters, daily inspection of equipment,

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[71] Hoppes, John, Lean Manufacturing Practices in the Defense Aircraft Industry

recognizing early signs of trouble). TPM is essential for the successful implementation of machine intensive, just-in-time production systems.[72]

5.5 Implement Self Inspection

Self-inspection is based on the fundamental principle of self-discipline. Self-inspection implies that the operator has been properly trained, has the proper tools to inspect his work, is conscientious in his work, and has the integrity to refuse to let discrepancies propagate downstream from his workstation. Not only is worker discipline necessary but worker-management interactions must be designed in a way to ensure integrity of the self-inspection program.[73]

Operator Certification Case Study

Operator certification is one way to implement self-inspection procedures and is a lean practice with high potential payoffs. It is the process where production workers are taught, authorized and given the resources necessary to inspect their own work. The operator certification case study was conducted by the Manufacturing Systems Team in order to provide the entire aerospace industry with the experiences of one sector with operator certification.

The goals of an operator self-inspection program are to provide immediate detection of man, machine and process errors, provide an alternative to 100% in-line inspection by quality control personnel, provide greater incentive to manufacturing personnel to identify part status accurately and provide positive feedback to operators who prevent errors from re-occurring.

One program studied illustrates the level of empowerment of the operators as well as the strict roles that the workers and management were to uphold to maintain the integrity of the system. In this system, every operator had an “escape code” in addition to his or her normal certification code. If the operator was under pressure (real or perceived) by management to pass a part, the operator could enter in their “escape code” which would make it appear on the screen as if the part had been certified, but it internally makes a note that the operator did not certify it and orders an inspection on the part. The table below highlights the improvements credited to the operator certification program at this site.

Table 8: Case study site benefits from Operator Certification

Type of Action	Benefits
Mechanical inspection manpower	Decreased 44%
MRB actions for all products	Decreased 66%
MRB actions for military products	Decreased 90%
Manufacturing lead times	Decreased from 12.1 to 7.3 weeks

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[72] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[73] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

The study found that the necessary enablers for a successful implementation of an operator certification program are corporate commitment, management of the human interface, data management and labor buy-in.[74]

5.6 Eliminate/Reduce Waste

All the principles of lean are designed to eliminate or reduce waste. Taiichi Ohno classified waste into 7 categories: overproduction ahead of demand, waiting, transport of materials, over processing, inventories more than absolutely required, unnecessary movement by employees, and production of defective parts. Inherent in this concept is continuous process improvement where processes are continually reviewed to systematically reduce waste.[75]

Factory Flow Benchmarking

One premise of a lean system is the constant pursuit to eliminate wasted time, movement and operations. Benchmarking efforts can be used to look for waste in different systems to help focus an improvement activity.

The Manufacturing Systems team conducted research on specific parts in the airframe, electronic and engine sectors to determine the flow characteristics of that sector. These studies fall in the "establish need" portion of Phase 0 as well as this phase of eliminate and reduce waste since the results showed the amount of waste in the industry. Through these studies, flow efficiency and wait times were the metrics used to compare the different companies. The results from these visits are summarized in the table below.

Table 9: Factory Flow Benchmarking Results

Sector	Flow Efficiency	Wait Fraction
AIRFRAME	0.02% to 0.8%	96%
Electronic	0.02% to 18.7%	Max 25% to 98%
Engine	0.7% to 13.0%	87%

These results show the most of the cycle time in the defense aerospace industry is wait time and most of this wait time was attributable to storage delay. In a lean system waiting is defined as waste so in the defense aerospace industry cycle times could be reduced if the waiting time was simply reduced or eliminated.[76]

Optimizing Process Flow – Key to Waste Minimization

Process improvements reduce waste by identifying non-value added steps within a process (or groups of processes). One of the case studies in Hoppes' research

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[74] Cowap, Stacey, et al., Operator Certification: A Case Study in Operator Self-Inspection

[75] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

[76] Shields, J, Thomas, Factory Flow Benchmarking Report

traced process improvements to show the impact the improvements had on waste minimization as well as the impact in another case study of a restructuring effort. This restructuring focused on the flow of a group of processes rather than on an individual process and this type of improvement effort quite frequently results in a radically different, more efficient process flow.

One of the case studies outlined in Hoppes' thesis depicts the results of a process improvement for a product that was put back into production after a four-year break, but now utilized work and quality improvement teams. As the figure below shows, the product was fabricated with 17% fewer hours after one year in production than when it was in production for 7 continuous years in the original run.

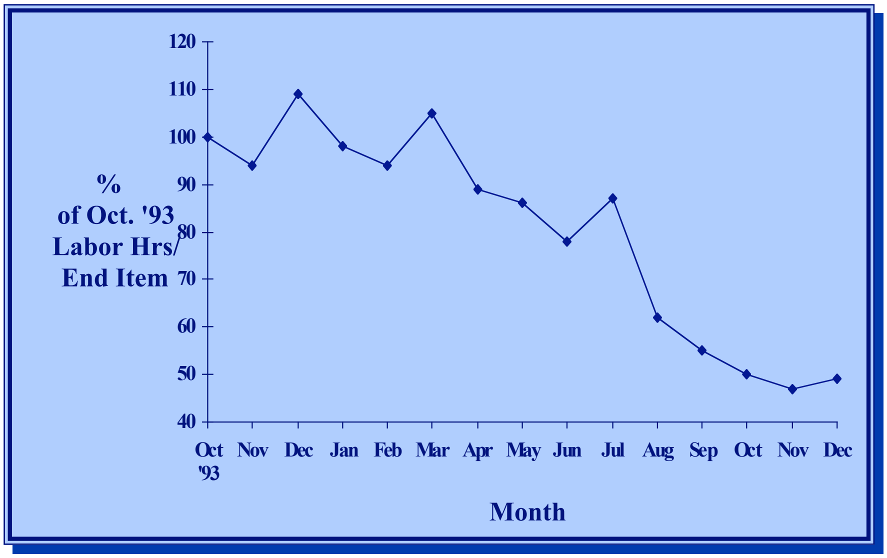

Figure 12: Comparative case studies - Process Improvement Results

Therefore within a year and a half span, the site had been able to restart manufacturing of the product *and* dramatically reduce the number of production labor hours below the level that existed after seven years of the original program's production. The enabling practices in this case study were employee empowerment and the formation of structured work teams as well as the increased operator involvement in cost issues.

Hoppes' research also explored the benefits of flow optimization. Flow optimization is the reduction of unnecessary processing steps and elimination of other sources of waste during production. Unlike the process improvement outlined above, flow optimization often requires complete restructuring of the production processes to reduce waste and move toward continuous flow production.

The graph below shows the results from one case site's effort to optimize the flow of the product through the manufacturing processes. It shows the trend that the average cycle time and deviation in cycle times decreases over the nearly two-year period.

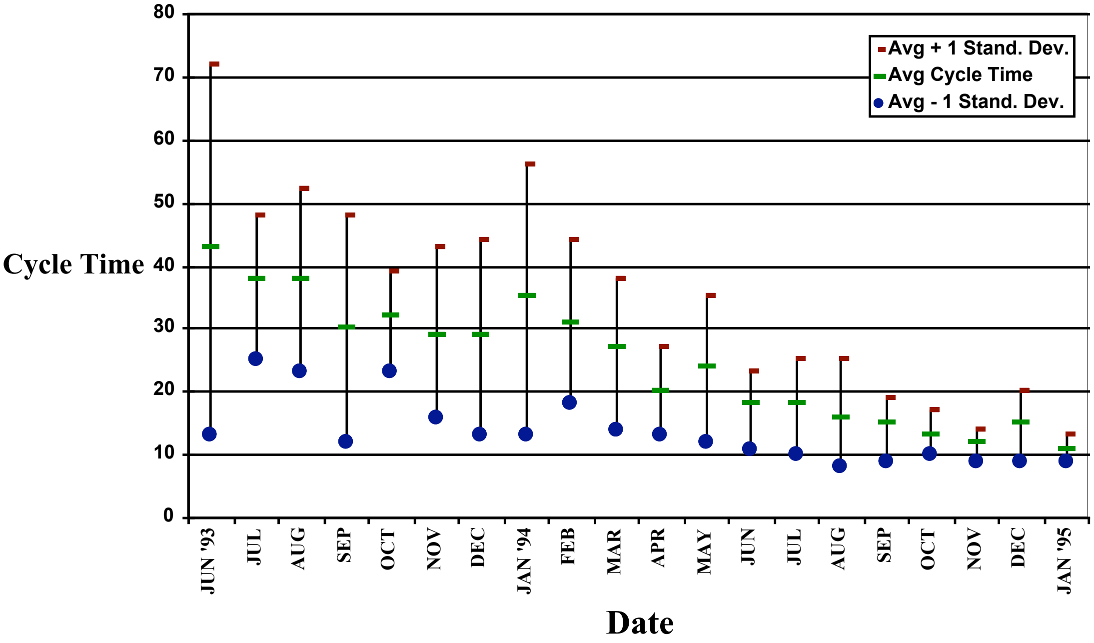

Figure 13: Case Study Results of Flow Optimization

These comparative case studies together allowed Hoppes to explore the varying degrees of success between firms that practiced process improvements and others that restructured their entire manufacturing operation. Restructuring moved production from process-focused departments to product focused cells or focused factories which reduced the amount of waste in the system and improved the cycle time for the product moving through the system.[77]

Precision Fabrication Case Study

This case study is a specific and in depth example of a process improvement which was aimed at reducing the variability and the waste involved with a stretch forming process. Such a detailed study of a process improvement in the airframe sector allowed all the contributions to variability of the process to be addressed and was conducted with actual experiments in the field. It entailed detailed study to determine all the possible sources of variation that caused the waste before actions were taken to improve/reduce them.

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[77] Hoppes, John, Lean Manufacturing Practices in the Defense Aircraft Industry

The process that was studied in detail was the stretch forming of a sheet metal leading edge in the airframe sector and the difference between the bent configuration, and the configuration after the metal would spring back from the elastic deformation. The following graph shows the reduction in the standard deviation from this stretch forming process. The variation was substantially reduced from the use of a better control method. This allowed the process to repeatably perform at the optimal settings.

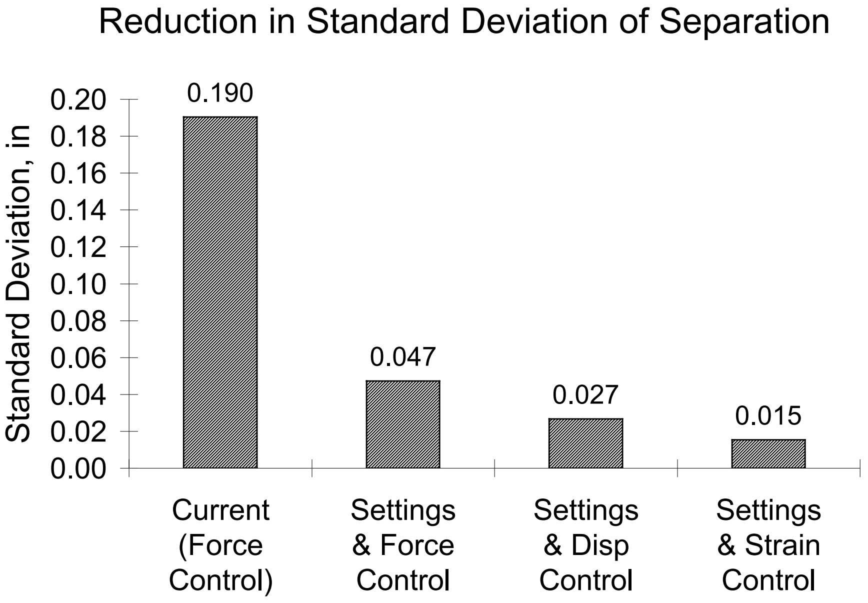

Figure 14: Reduction in standard deviation in the sheet metal forming process

The conclusions from the precision fabrication case study include that major fabrication improvements are possible, and the existence of precision fabrication fosters other lean objectives within a manufacturing system.

This process improvement in fabrication led to some insight regarding the necessary enablers for a firm to achieve precision, and possibly toolless, assembly. Parris' work discovered the enablers of precision assembly to include fundamental understanding of the involved processes, a good design, the use of precision fabrication, the use of common CAD definitions, adequate measurement technology and the existence of a lean production system.[78]

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[78] Parris, Andrew, Precision Stretch Forming of Metal for Precision Assembly

5.7 Cross-Train the Workforce

Smooth and continuous flow of work often depends on how well the workforce is cross-trained to support the total process flow. Adjacent workers picking up some of the work content of the more heavily loaded workstation can usually smooth slight variations in workstation work content. Cross training brings the ability to switch from one task to another, thereby relieving stress, boredom or tiredness of the worker. Cross training provides appreciation of the contribution of others and builds team spirit. Consolidation of job classifications may be a necessary prerequisite to cross training.[79]

5.8 Reduce Set-Up Times

Set-up time is categorized as internal set-up time or external set-up time. The internal setup time is that setup time which requires the machine to be stopped; external setup time is that setup time that can take place while the machine is running. The most important concept of setup time is to convert as much of internal setup to external setup. Until set-up time, transport time, work order processing and other batch related items of time waste are reduced, lot size reduction usually only adds to total cost. However, as set-up time is reduced, lot size can then be appropriately reduced with its corresponding reduction of finished and intermediate product inventory.[80]

5.9 Implement Cell Layout

A proper cell layout is critical in attaining flexibility in the number of workers within a workshop to adapt to demand changes. The recommended layout for a cell is the counter-clockwise flow direction “U-turn” layout. In this configuration the entrance and exit of a line are near the same position. This layout structure allows workers to easily see unbalanced operations and to take action to provide the necessary support for keeping the flow of work uninterrupted; it also allows regions or areas to be developed for specific worker operations and walk patterns.[81]

5.10 Implement Visual Controls

The concept of visual control is based on the 5S principles with the intent of being able to determine the state of the shop “at a glance”. A clean, orderly shop, in the sense of lean production, allows this to happen. The first two 5S principles divide items in the shop into “necessary” and “unnecessary” classifications. Anything unnecessary is removed from the area (disposed of, surplussed, put in red-tagged storage, etc) and the necessary is made orderly, easy to find, easy to reach, and easy to use and maintain (e.g. shadowing of tools). Shop cleanliness, the third S, is essential to spot problem machines at a glance (e.g. leaking oil), and out of place items. The fourth S, provides for standardizing ways of doing work, cleaning, organizing parts and tools, and provides the way to spot “out of the ordinary” problems and inefficient ways of doing things. In addition to the 5Ss, visual controls also rely on up-to-date, simple posters or signs within the shop to indicate the status of today’s production, quality metrics, and progress on continuous

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[79] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

[80] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

[81] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

improvement. Successful visual controls rely on the fifth S of self-discipline for sustaining the overall effort of the 5Ss and keeping current the shop statistics using charts. Another aspect of visual control is the ability to bring resources to bear quickly whenever there is a production problem. This often entails a way to signal that there is a problem and an easy way for all resources to know where the problem is located. (Note that many organizations have added a sixth S for safety.)[82]

References for Phase 5

Cowap, Stacey, and James Schoonmaker, Operator Certification: A Case Study in Operator Self-Inspection, Case Study – Lean 95-04, Cambridge, MA, MIT, 1996.

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Parris, Andrew, Precision Stretch Forming of Metal for Precision Assembly, Thesis, Cambridge, MA, MIT, 1996.

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[82] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

Phase 6: Implement Total System Pull

In this phase the intent is to link the various flow operations that have been established in miniature throughout the production system and to establish pull operations across all the processes/operations /cells within the entire production system. This often equates to linking individual cells within the production system and suppliers with a pull type system. Successful completion of this phase results in a just-in-time type of pull production system that starts with suppliers and ends with the final customer.[83]

6.1 Select Appropriate Production System Control Mechanism

A production system plan was developed in Phase 4, and in Phase 5 efforts were made to remove waste from the system to achieve predictable output. With the help of the workforce, as simple a system as possible should be implemented to control the flow of parts and assemblies in the production system. We use the word 'control' instead of 'plan' to emphasize that the system should be as self-regulating as possible thereby reducing the time constant of reaction, and conveying information upstream and downstream. More sophisticated systems may be necessary in certain circumstances but often a simple card, cart, or bin visual system is very effective. One method that is both visual and effective is a kanban system. The prerequisites for a kanban type system are: (1) a pull system mentality, (2) a system with a predictable output, and (3) standard work-in-process inventories. Other possible control mechanisms could be Constant Work in Process (CONWIP), scheduling policy systems, MRP/ERP systems or hybrids of several different mechanisms.[84]

Control Point Policy

Control Point Policy (CPP) is a control system for a factory floor developed by Dr. Stanley Gershwin at MIT. It is a control system that is geared toward multiple stages and multiple part-type systems. Sawan Deshpande describes CPP and compares it to MRP II, which is the most common control system. Deshpande's thesis also consists of a case study when CPP was implemented at a site in the aerospace industry.

The overall goal of any scheduling system to try to achieve a profitable balance between inventory, work-in-process, lead times and machine utilization. But different types of scheduling systems, whether they are token, time or surplus based, are suitable for different types of manufacturing environments. For example, a token-based scheduling system, like a kanban system, is not suitable for a pure make-to-order or engineer-to-order type of manufacturing system. Unfortunately, the aerospace industry fits into this category and not the make-to-stock or assemble-to-order categories in which a kanban system flourishes. Unlike token based policies, like kanban, time based scheduling policies can be used in any type of manufacturing system from the most basic make-to-stock to

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[83] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

[84] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

the more complicated environments that exist in the aerospace industry since it comes in three different varieties – token, time or surplus based.

Control Point Policy follows a two-step process: establishing a fixed, prior set of rules; and executing a real-time algorithm. In advance, it gives a fixed ranking to all the part-types that flow through the work centers. Then in real-time, at each work-center, the policy checks the following three conditions:

i. If a part is present in the upstream buffer
ii. If there is space in the downstream buffer
iii. If the part is ready according to a conservative schedule

If and only if the answer is "yes" to all of the above conditions, the policy assigns a green flag to the part (now called a green part). If the answer is "no" to any of the three conditions, the policy puts a red flag against the part (now a red part). This is done for each part, from the top to the bottom of the ranking list, and list of green parts and red parts is produced. The highest-ranking green part is processed through the work-center first. The next highest-ranking green part is processed next and so on.

All three conditions are essential. The first must be satisfied because a part that is not present cannot be worked on. The second prevents excess inventory from collecting on the floor. The third prevents the factory from working on parts that are early while others are late, and also limits inventory. The product ranking ensures that if more than one part survives the three filters, the highest-ranking product gets the first priority.

In the case study, every step of the implementation of CPP in a real factory is outlined. The case study emphasizes the decisions of the control points and such prior to the actual system implementation as the key to achieving the optimal system performance. It is important to have an in-depth understanding of the flow throughout the factory in order to make the best decisions. A sup-optimal result of the Control Point Policy does not result from the policy, but rather from the decisions made prior to the introduction of the policy. The steps to implement CPP include: selecting the number and location of the control points, ranking the products, incorporating any existing batching policy if there are any batch-based work centers in the system, decide the policy at non-control points and select the buffer sizes. The following table summarizes the improvements achieved through the CPP implementation experiment.

Table 10: Improvements after the implementation of Control Point Policy

Situation	Problem before (out of 7)	Scope for Improvements After (out of 6)
Excess WIP	5	4
Knowledge on the location of WIP	3	6
Due date performance	7	4
Need for manual scheduling	7	3
Part availability when needed	6	6
Sensitivity to crisis	4	4
Work schedule accuracy	7	4
Need for manual expediting	7	4

Deshpande's work concludes with the modeling of CPP alongside kanban, CONWIP and other scheduling policies for a variety of different situations. On all metrics, WIP, inventory, lateness and lead-time, CPP outperformed all the others.[85]

Just-in-Time Engine Assembly

The Engine Sector study provided the researchers with the opportunity to study a vast selection of manufacturing systems. The three sites (A, B and C) ranged from a pure "push" system to a unique hybrid combination of long-term planning with MRP to a kanban triggered "pull".

The manufacturing system at site B was mainly a push system. That is, material keeps flowing whether there was capacity to process it or not. A push system is relatively inflexible to customer demand. At site C, however, the manufacturing system in use was different. Site C used a hybrid manufacturing system that had characteristics of both push and pull.

While some parts were scheduled under an MRP system from the suppliers, 80% of the total value-worth of parts were supplied under a pull system. It was reported that the warehouse size decreased as more parts were added to the pull system. *Kanban* systems generally have a specific number of bins or trays in which a specified number of parts for each part type reside. A *kanban* system often works by having bins sent to the supplier once they have been depleted. This system helps keep inventory to a minimum and also eliminates the need of independent signals to suppliers for production of parts, since the mere arrival of an empty bin signals that more parts of a specific number have to be produced. This production sequence is a pull system, which is based on the authority to produce or supply, coming from downstream processes. Typically these systems are set up to produce products at the rate the customer demands, called the takt time. Elements of this type of system were witnessed at site C. Figure 15 shows a diagram of the hybrid manufacturing system used at site C.

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[85] Deshpande, Sawan, A Scheduling Policy Experiment for Lean

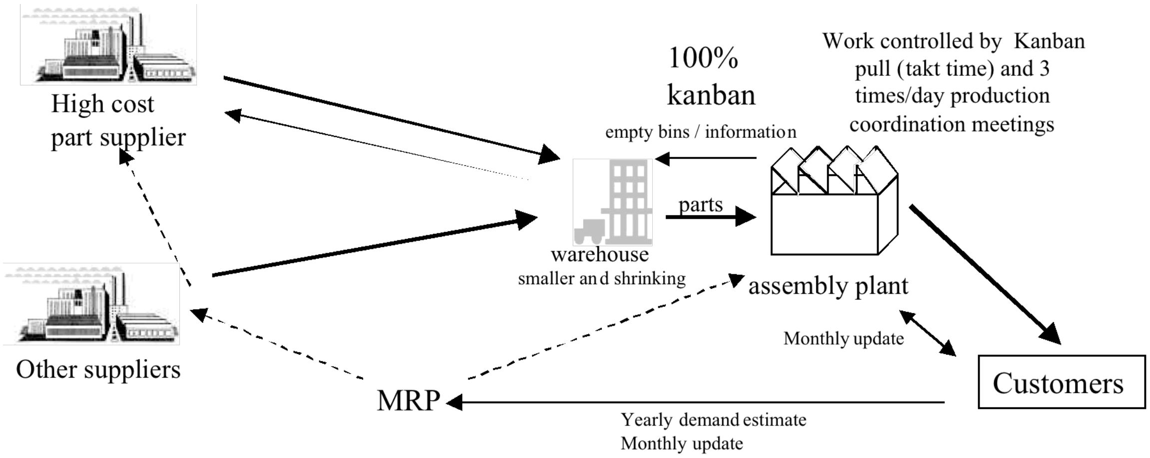

Figure 15: Site C Hybrid Manufacturing System

One month prior to the beginning of the scheduled production month, customers were called and the exact number of engines they'll require was checked, two weeks prior to the beginning of production the number was frozen and the engines were scheduled for the next month. This had the advantage that production for that month was now fixed and accurate scheduling and planning could be done, which allowed for smooth operations at the plant. This was crucial because it added stability to the suppliers. This kept the production output level over a relatively long period. Every year communications were made with customers to try to determine what the engine demand of that customer would be for that year. Based on this information, a preliminary schedule was made with monthly production requirements for each customer. These requirements helped determine the takt time (drum beat of the manufacturing system if you will). Generally, actual production was within 10% of the yearly prediction.

Every day at 7am, 3pm and 11pm there was a meeting of each line team, which was attended by the Line Leader, who was in charge of the entire line, the supervisors, and the lead men. At these meetings, they discussed the work distribution for the next shift for each product line. These meetings lasted about 15 minutes. Usually the Line Leader would prompt each attendant to voice his or her concerns about production. At 7 a.m. there was a meeting attended by the assembly leader and the material managers. Issues of overall importance to the assembly were brought up at these meetings.

The manufacturing system observed at site C was a combination of a batch and queue/MRP controlled push system and a system designed with lean manufacturing principles using *kanban* inventory control and pull. The batch and queue manufacturing system was used on the 20 percent value-worth of parts (largest number of parts) while the highest value-worth of parts (the other 80 percent) were processed in the pull system. However, the final assembly of the engine and the overall system control mechanism was based on lean manufacturing practices. The manufacturing system was designed to produce the mix of products demanded by the customer at the rate or takt time demanded by the customer.[86]

6.2 Strive for Single Item Flow

In order to achieve a pull system, product components, subassemblies and final products must flow through the production system as if they were a single item and linked to the demand rate specified by the customer. This single item can be a kanban container, a small lot or a single piece. The objective is to reduce the lot size as much as possible with the ultimate goal of single piece flow. The delay time built into large lot size processing is incompatible with a pull system. To reduce the lot sizes, setup times must be reduced to allow single product items to flow through the production system. Where single item flow can be achieved, the throughput time is drastically improved, quality is usually improved because defects are recognized earlier in the process, and inventory is reduced because there is a lower work-in-process level and finished products are rapidly accepted by the customer. Single item flow implies that products are not worked on until the downstream process demands those products.[87]

6.3 Level and Balance Production Flow

Key to implementing a pull system is the leveling of the production to match the mix of products demanded by the customer over a specific time interval. In many cases, this process of leveling production must be a specific objective of the senior managers in the production system. It is often useful to implement level production first in the assembly operations to ensure that the right mix of products is made at each customer demand interval. With the mix of products matching the customer demand, the next step is to ensure all the preceding production operations have a consistent cycle time and that this cycle time is less than or equal to the takt time determined in the production system design phase. This often entails linking the various cells ultimately to the final assembly operations. Instead of planning production, the level and balance concept allows control of the production system. One way that is useful in leveling the production on a daily basis is the use of *Heijunka*. In this system the daily demand is ordered in a box to pull products of the right mix through the system. In essence, this *Heijunka* box performs the sequential planning and control function for the production system. It plans the sequencing needed to satisfy the customer mix demand and it controls the introduction of work to the production floor. Therefore, at the conclusion of this step, each operation would be done at or less than the takt time and the mix of products desired by the customer would be completed within the interval that the customer demands. One should note that customer requirements are not being satisfied from finished goods inventories in this system.[88]

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[86] Ramirez-de-Arellano, Luis, et al, Summary of Research Conducted in the Engine Sector
[87] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[88] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

6.4 Link with Suppliers

Although these steps imply an order, the linkage with suppliers should be an ongoing activity. Suppliers should be encouraged to develop a system that links to the prime just as the prime is developing a system to link to their customer. Therefore, suppliers should determine their takt time requirements and ensure they can provide parts or subassemblies to the prime, as the prime needs them in their operations. Timing is not the only consideration, however. This linkage should include part/assembly configuration and information. The production systems between the supplier and the prime should be synchronized to ensure that each system produces exactly the same sequence of parts/assemblies that are demanded downstream. Often this linkage requires a method of sharing information about the production long-term requirements, production requirement changes and short term production scheduling. With the information available the production systems of suppliers and primes may be coordinated to control production.[89]

Certified Suppliers in the Engine Sector

The Engine Sector Study provided an example of the possibility of having long-term, open relationships with suppliers. Site C, which had the best performance of the three sites studied, had the largest percentage of parts coming from suppliers with long-term contracts.

After data were collected at most sites and the impact of part shortages on the manufacturing systems was understood, we asked our research sites several questions about how they interacted with their suppliers. We were able to get responses from two of our three sites, Site A and C.

Suppliers at site C were kept informed of the status of builds and the actual requirements of the assembly floor. At site C, the suppliers knew when they had to deliver exactly which parts to the factory. Two weeks prior to the beginning of the month, customers were called and the exact number of engines they required was checked. The number was frozen and the engines were scheduled for the next month. This made it much easier to level production loading and foster good relationships with suppliers. Every year communications were made with customers to try to determine what the engine demand of that customer would be for that year. Based on this information, a preliminary schedule was made with monthly production requirements for each customer. No more than 10% of the yearly predictions changed compared to actual production.

Site A had a traditional relationship with its suppliers (both internal and external). The MRP system was used to communicate all formal information between the prime and the suppliers. However, as parts were needed for final assembly and shortages were detected, there was an informal system for communicating information to suppliers. Material managers would call suppliers to determine part status, request priority, or even send a special truck to pick up the material.

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[89] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

Table 11 compares the supplier interactions at sites A and C. From this, it can be seen that site C tended to have a higher percentage of parts obtained from certified suppliers and provided more schedule information to its suppliers. Site C also utilized long term relationships with suppliers more extensively.[90]

Table 11: Comparison of Supplier Relations between Sites A and C

	Site A	Site C
Percentage of all shipments from suppliers, by part number, obtained from certified, qualified or preferred suppliers	85% of 70%	95-97%
Percentage of the dollar value of materials, parts and components provided by suppliers obtained from under long term (3+ years) purchase agreements	50%	85-90%
Percentage of shipments from all suppliers, by part number, subjected to incoming or source inspection	Less than 10%	Less than 10%
Percentage of the suppliers that are provided, on a regular basis, with production schedules and forecasted requirements	50% (yearly orders) 50% (monthly MRP)	Approx. 80%

6.5 Draw Down Inventories

As both the internal and supplier systems implement lean practices, inventory stocks may be slowly depleted. If inventory is drawn down too quickly the production operation may be disrupted because demand is reduced. However, if the excess inventory is slowly drawn down over time, the new production system can transition more easily. In fact, the transition period may be assisted by using this excess inventory to compensate for reduced productivity while systems are being changed.[91]

Inventory Pilot Project

A detailed study of the inventory within a system can alert a designer where the first improvement efforts should be focused. Also, knowing where inventory tends to accumulate is a powerful tool to know which processes need to be redesigned. The inventory survey conducted by the Manufacturing Systems team reviewed the role and amount of inventory maintained in the various systems. The project's approach entailed a survey of 36 different aerospace firms to look at inventory practices as examples of management philosophy and approach to manufacturing, government attitudes and practices relating to inventory and to

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[90] Ramirez-de-Arellano, Luis, et al, Summary of Research Conducted in the Engine Sector

[91] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

identify best practices and opportunities for improvement throughout the industry.[92]

Some of the conclusions from this research include that military contracts carry 10% more inventory than commercial contracts and that a third of the inventory is located in receiving and storage.[93] Another finding from the inventory survey was that military contracts carry far more "front loaded" inventory than commercial contracts, which is illustrated in the figure below.

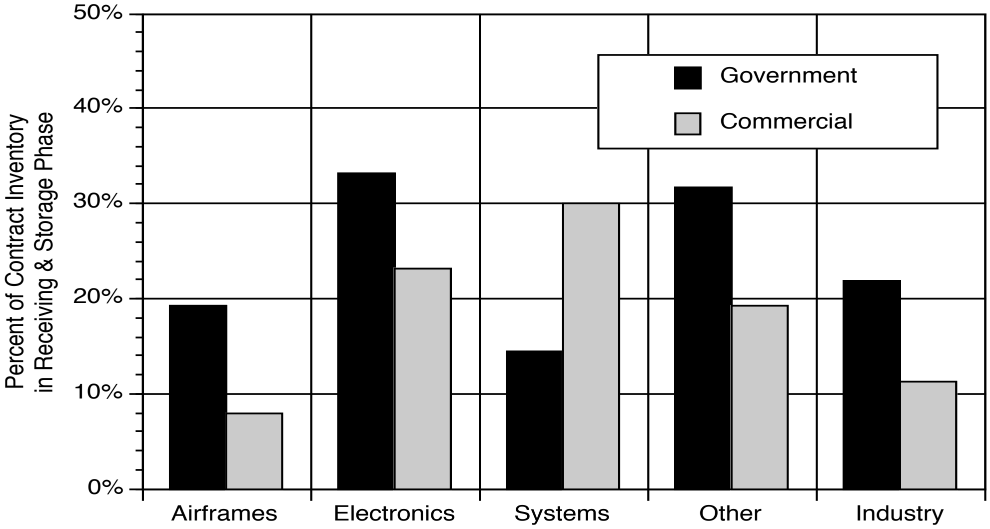

Figure 16: "Front Loading" of Government vs. Commercial contracts

This front end loading is caused by a variety of government and company policies and attitudes and can easily be combated with modern manufacturing advances which are not commonly used in the industry today.[94] The results of the implementation of MRP II revealed substantial decreases in inventory throughout the system, decrease in needed stockroom staff, quicker responses to delivering kits, and decrease in occupied floor space.[95]

The inventory survey concludes with some recommendations to the industry which include speeding up the process for disposing of excess material at the end of a contract and to allow commingling of similar inventory items for different contracts as long as the company has an accurate materials management and handling system. Another recommendation to the industry was to not simply try and draw down inventory for the sake of lowering inventory but to allow the inventory level to drop as a result of an improvement in product flow or yield.[96]

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[92] Ling, James G., et al., Summary of Inventory Pilot Project

[93] Ling, James G., et al., Summary of Inventory Pilot Project

[94] Houlahan, Christina, Reduction of Front End Loading of Inventory: Making the Airframe Industry Lean Through Better Inventory Management

[95] Pomponi, Renata, Control of Manufacturing Processes with MRP II: Benefits and Barriers in the Defense Aerospace Industry

[96] Ling, James G., Summary of Inventory Pilot Project

This goes along with the idea expressed in the Transition to Lean roadmap since it outlines the possibility if a disruption to the manufacturing system if inventories are drawn down too quickly.

6.6 Reassign People

As the production system is implemented, there will be changes that will impact the workforce. It is important to deploy these trained and experienced people to other areas so that they can teach others about this new system. It is here that the foundational preparatory work done in Phase 1 to addresses workforce changes will be most beneficial. To the maximum extent possible people should be reassigned to other areas in the company.[97]

6.7 Re-deploy/Dispose Assets

Just as people will need to be re-deployed, so too will excess assets. Often even simple, less complex resources can be re-deployed for use in special circumstances. Only those assets necessary should be retained in areas that have accomplished the lean transition. All excess assets therefore should be re-deployed or disposed. When excess assets are disposed of, additional floor space can be identified for new business opportunities.[98]

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[97] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

[98] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

Phase 7: Strive for Perfection

This phase provides for continuous improvement and feedback of lessons learned along the lean journey. The various lean techniques and tools implemented in earlier phases are repeated and refined taking the improvements to the next level. The organization matures from directive to collaborative to empowered. Metrics are reassessed and revised or replaced as necessary to ensure that they are meaningful indicators of the production processes and the overall health of the lean implementation. The outputs from this phase may feed back into any and all other phases as the lean transition improves the competitive position of the production operation and the enterprise.[99]

7.1 Team Development

Team development includes technical development to keep pace with new product and process features, organizational development to empower the work force to contribute at all levels, and lean process development to expand upon the tools and techniques being applied. Classroom, workshops, and on-the-job training events conducted with natural workgroups help foster team spirit and can be tailored to the specific production processes being utilized by the team. The role of the team leader, manager, or supervisor expands to include teaching, coaching, and facilitating.[100]

7.2 Optimize Quality

Quality is a perquisite to overall world-class status and tightly correlated with customer satisfaction, market share, and cost. Capturing and reporting DPMO (Defects Per Million Opportunities), PPM (Parts Per Million), first pass yield, or process robustness (sigma) is the first step to continuous improvement. Measuring processes with any of the aforementioned metrics allows for base-lining current process capability, analyzing improvement opportunities, establishing stretch improvement goals, quantifying improvements realized, and controlling process variability. Attainment of increasing quality levels also fosters pride in workmanship. Phase 6 (Implement Pull) mandates quality or production will stop. Six sigma is a statistical measurement tool and also a trademark program developed by Motorola and applied more generally by GE. Emphasis is on processes which yield sustained results.[101]

7.3 Institutionalize 5S

The 5Ss are the foundation for Kaizen and implementing visual production controls. The 5Ss are defined as follows:

Simplify or Sort - Remove unnecessary items from the work area
Straighten or Simplify - Organize tools, accessories, and paperwork
Scrub or Shine - Clean, Repair, and keep it clean
Stabilize or Standardize - Establish and maintain controls and standards
Sustain or Self-Discipline - Strive for continuous improvement

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[99] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[100] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[101] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

Institutionalizing the 5Ss will allow for higher productivity and a safer and more pleasant workplace. (Note that many organizations have added a sixth S for safety.) [102]

7.4 Institute Kaizen Events

Continuous incremental improvement, Kaizen, is a fundamental tool for lean implementation. A Kaizen event starts with mapping (flow chart & spaghetti diagram) the current "As-Is" process and quantifying the processing times and distances traveled by people and parts. Next, non-value added activities are identified by assessing the current process with tools such as Brainstorming and "The 5 Whys". This assessment, along with applying 5Ss and visual control principles, defines the improved "To-Be" process. These improvements are implemented and the new improved process becomes the baseline for future Kaizen events.[103]

7.5 Remove System Barriers

Legacy policies, procedures, and computer systems often create barriers to lean implementation. When these barriers are encountered, the origins of the legacy process should be determined. Unless the legacy process can be traced back to federal, state, local, or corporate requirements, the need for the policy, procedure, or computer system should be questioned and changed, if necessary, to allow for lean implementation. Enterprise level resources should address the federal, state, local or corporate barriers.[104]

7.6 Expand TPM

Total Productive Maintenance (a LEM best practice) provides a comprehensive, life cycle approach to equipment management that minimizes equipment failures, production defects, and accidents. Planned in Phase 4 and initially implemented in Phase 5, TPM enables manufacturing costs associated with variability in both product quality and production schedules to be reduced. Phase 7 tracks the incremental implementation of TPM to achieve a level of equipment reliability that allows for pull and single piece flow (Phase 6).[105]

7.7 Evaluate Against Target Metrics

Target objectives (metrics) were established in Phase 1 to challenge continuous improvement and steer the lean implementation. Tracking and periodic review of these metrics provides assessment of the implementation. The evaluation will determine if mid-course corrections are required or if the metric is no longer adequate.[106]

7.8 Evaluate Progress Using Lean Maturity Matrices

Becoming lean is a considerable and truly never ending journey. Along the way, periodic self-evaluation and/or benchmarking of the organization's degree of leanness against a standard or others further along will help to keep the implementation on course. The

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[102] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[103] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[104] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[105] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual
[106] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

Lean Maturity Matrix is a tool that is increasingly being used by organizations to both evaluate where they are at today and to provide a vision of where they want to be at some point in the future. The typical matrix utilizes a grading scale according to the degree of implementation of several different major lean practices.[107]

References for Phase 7

Crabill, John, et al on the Production Operations Transition-To-Lean Team, Production Operations Level Transition-To-Lean Roadmap Description Manual, Version 1.0, Cambridge, MA, MIT, 5 June 2000.

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[107] Crabill, John, et al., Production Operations Level Transition-To-Lean Roadmap Description Manual

Conclusion

With the conclusion of Phase III of the Lean Aerospace Initiative, the Manufacturing Systems Team no longer is conducting research specifically on manufacturing. Instead the Lean Aerospace Initiative is focusing on the total enterprise. As was indicated by the manufacturing system research, the largest returns come from systems thinking and integrating all functions in the enterprise to achieve the goals of the enterprise. The Production Operations Transition-to-Lean Roadmap has served as a good framework to place relevant manufacturing research that was accomplished during the first three phases of LAI. As such, this product provides both implementation guidance and reference information in one package.