A Holistic Approach to Manufacturing System Design in the Defense Aerospace Industry

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Abstract

Manufacturing has evolved to become a critical element of the competitive skill set of defense aerospace firms. Given the changes in the acquisition environment and culture; traditional "thrown over the wall" means of developing and manufacturing products are insufficient. Instead, the development and manufacture of air and spacecraft require much more interaction between the various functions. Also, manufacturing systems are complex systems that need to be carefully designed in a holistic manner and there are shortcomings with available tools and methods to assist in the design of these systems. This thesis proposes and validates a framework to guide the manufacturing system design process. The exploration and validation acitivities used 14 case studies from major aerostructures, electronics, launch vehicles and spacecraft. Actual manufacturing system design processes were observed real-time or captured retrospectively. An evalution tool was used to compare the actual manufacturing system design processes with the process proposed by the framework. This degree of congruence with the framework was then compared to a metric of actual/planned performance of the manufacturing system. The results of the framework congruence versus the actual/planned performance metric showed that the case studies that were able to meet their planned performance also had manufacturing system design processes that resembled the process proposed in the framework. But the results also illustrated the different traits between the cases that were able to meet their planned performance and those that were not. Looking at the commonalities between the cases in the groups led to the discovery of the determinants of superior performance: breadth of functional interaction through the design process, use of a manufacturing strategy, the status of the manufacturing function, customer involvement, co-location and an enterprise perspective. The combination of the proposed framework and the case studies substantiated and validated the Manufacturing System Design Framework as well as illuminating the set of determinants of performance.

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Executive Summary

Manufacturing systems are expensive, complex and difficult to predict. Couple these characteristics with the current environment faced by many aerospace firms that are still using manufacturing systems designed during the Cold War while functioning in a world where affordability is becoming a customer requirement. Not only this, but the aerospace industry is also possibly entering a phase in its lifecycle where rates of innovation may shift from product innovation to process innovation. Given these challenges, manufacturing has become an element of the competitive skill set of an enterprise and the need exists to be able to design manufacturing systems to meet the required business needs.

In this context, this research was structured to meet four objectives:

- Understand the current manufacturing system design process in the defense aerospace industry
- Propose a model to use for the manufacturing system design process
- Test the model in industry
- Establish key characteristics of the manufacturing system design process

The Manufacturing System Design Framework was a product of P. Fernandes in 2001. Shown in Figure 1, this framework was developed through experience, other available tools and the application of systems engineering ideals.

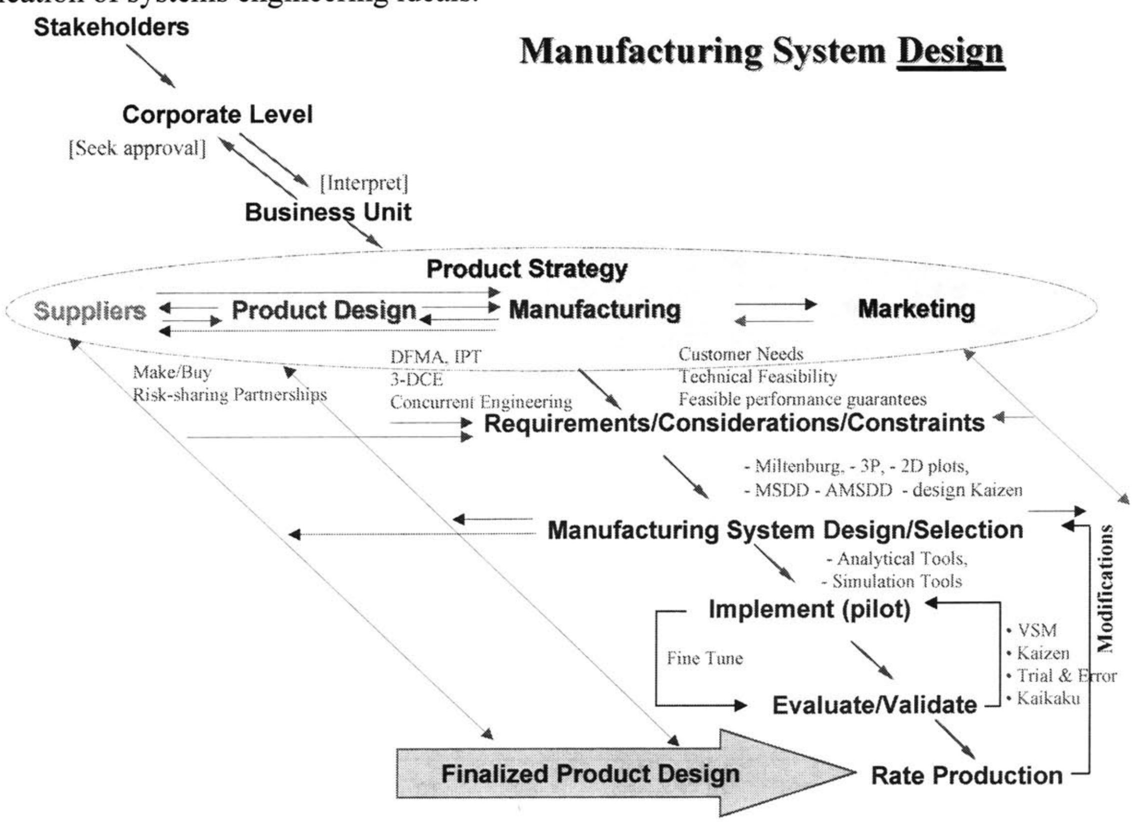

Figure 1: The Manufacturing System Design Framework

This thesis presents the first validation activity 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 2. 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.

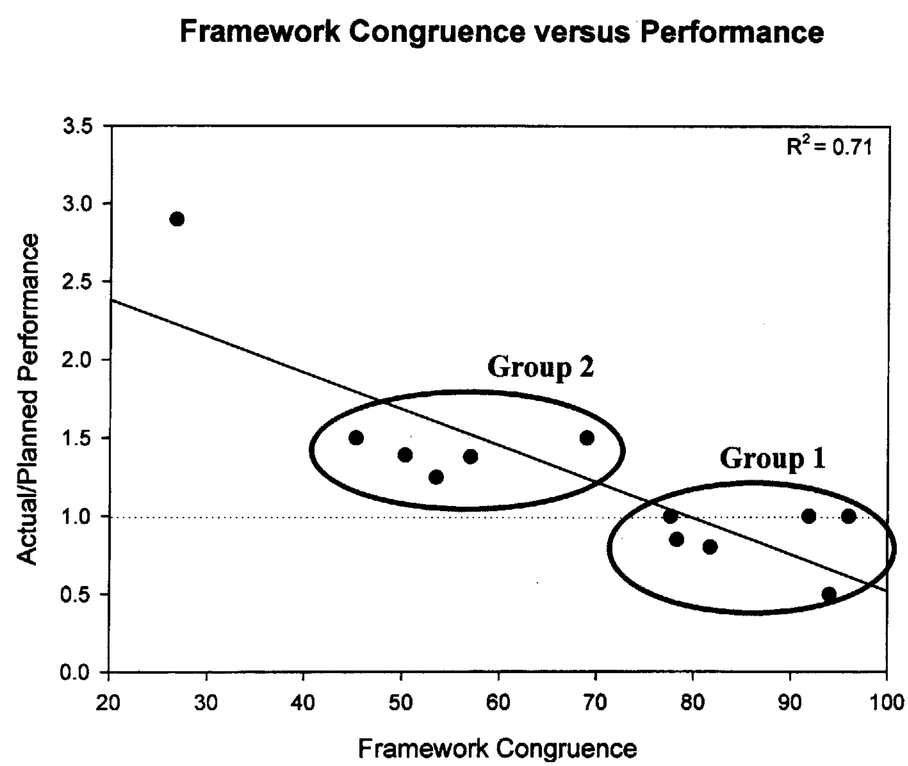

Figure 2: Framework Validation Results

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.

One lack of commonality is the role of production volume in the performance of the manufacturing systems seen in the cases. The performance of the manufacturing systems of the cases detailed in this research was independent of the production volume. This is surprising since in cases like the Joint Strike Fighter (JSF) where there is the potential to product 3,000 aircraft the manufacturing function has tremendous leverage. But some of the cases were able to aggregate across different products or programs to create greater production volume when individual product production volumes were low. The allowed the new manufacturing concepts used in some of the cases to be successful.

The main goal of this research was to test the Manufacturing System Design Framework to see if it was an adequate model of the manufacturing system design process. But it was found that the collection of determinants of performance separated the case studies that could produce their products in the allotted resources from those that could not. The research attempted to see if the framework was valid and ended up with a set of determinants of performance that could help a future manufacturing system design process in an aerospace firm.

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This thesis is the culmination of an experience of a lifetime. But the efforts herein are not my own. It was accomplished through the help and assistance of many people.

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Finally, a heartfelt thank you to my family – this is the second MIT degree that is much yours as it is mine. And to my husband, Chris, thank you for helping me through these two years – you are my best friend and I am thankful for you everyday.

Table of Contents

List of Figures

List of Tables

1.0 Introduction

The Manufacturing System Design Framework was developed and introduced in P. Fernandes' *A Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor*. This framework was based upon research, experience and application of general systems engineering practices and not based on scientific study.

This thesis is the beginning of rigorous validation of the Manufacturing System Design Framework. Through a set of case studies, the manufacturing system design process was compared to actual manufacturing system design processes observed or captured in these case studies.

1.1 Research Motivation

There is no doubt that since the end of the Cold War the defense aerospace industry has seen major changes. These changes have led to some hard times while defense aerospace firms try to regroup and change business models, meet changing customer needs and produce more affordable products. One possible explanation of how the aerospace industry finds itself in this situation is to look at the industry using a model proposed by Utterback.[1] This model shows the shifts in innovation as an industry matures. The aerospace industry can be characterized by innovation, which is arguably entering a more mature phase.

The Dynamics of Innovation in the Aerospace Industry

Utterback's model proposed that sources of innovation and improvement in a mature industry will be different than in the early days of a particular industry. Innovation will effectively shift from product innovation in the formative years to process innovation in later times.

[1] Utterback, J.M., Mastering the Dynamics of Innovation

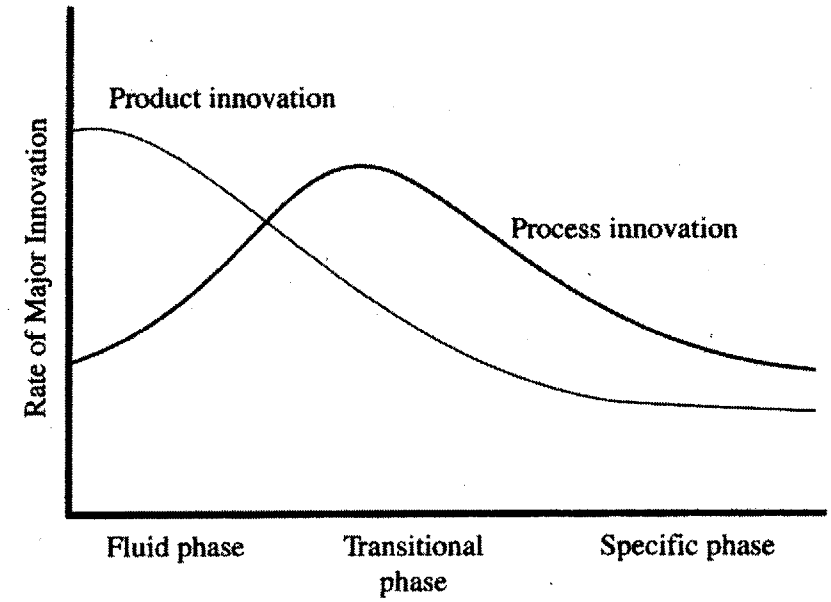

Figure 3: The dynamics of innovation from product to process innovation[2]

These two curves show that in the early phases, the rate of major innovation is higher in the product and this gradually shifts into the processes. So an industry at a later phase will be more dependent on the ability to innovate in processes and manufacturing to remain competitive.[3]

Utterback goes on to outline three characteristic phases that make up these curves: the fluid phase, transition phase and specific phase. The existence of these phases can be seen in the number of firms that populate an industry as shown in Figure 4.

[2] Utterback, J.M., Mastering the Dynamics of Innovation
[3] Utterback, J.M., Mastering the Dynamics of Innovation

Utterback's Dynamics of Innovation

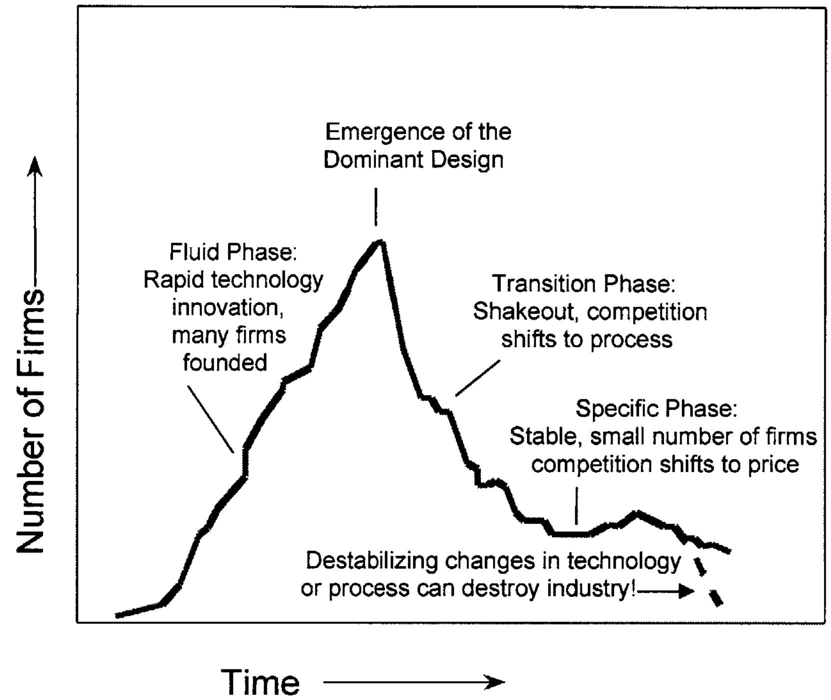

Figure 4: The number of firms as an indication of phases[4]

The fluid phase is dominated by product innovation. Companies focus on design flexibility and product performance. There are multiple competitors in a given field and there are rapid changes occurring to the product. Through all of this rapid innovation and change to the product, eventually a dominant design emerges. The dominant design is the one that wins the allegiance of the market. Many of the previous design requirements become implicit to the design itself. In other words, when a customer thinks of a certain product, the minimum level of features is what is possessed by the dominant design. For example, the QWERTY keyboard is still the industry standard even though more comfortable and efficient designs were subsequently introduced. The QWERTY keyboard was the design that the dominant design article possessed. The typewriter with the carriage return and two cases won the market and made the QWERTY keyboard the norm.

The appearance of a dominant design ushers in a period where the rate of product innovation slows and the competition shifts into process innovation leading to the transition phase. The transition phase is where the focus of firms begins to shift to the factory floor where the large-scale production of innovative products must be worked out. In this phase, product and process innovations become more tightly linked and the industry focus begins to switch to process improvements. The final phase is the specific phase where the competition turns to cost. Product innovations in this phase are mainly evolutionary in nature instead of revolutionary and most innovation occurs in the processes.

[4] Utterback, J.M., Mastering the Dynamics of Innovation, as adopted by Hugh McManus, 2001.

Given this model, Figure 5, below, shows the number of firms over time for three industries: typewriters, cars and aircraft.

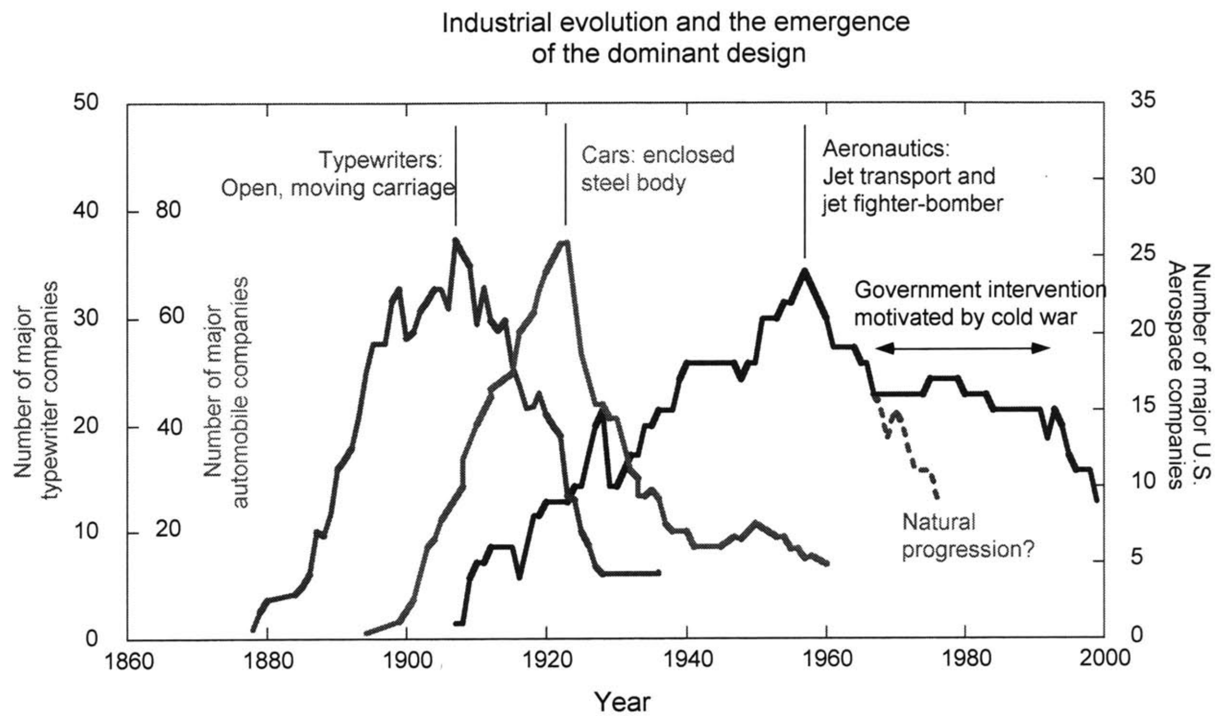

Figure 5: Dynamics of Innovation curves for three industries

This shows the similarity in the number of aerospace firms compared to these other industries, which match the model proposed by Utterback. The difference in the aerospace curve where the natural progression may have been altered could be explained by the fact that the government kept some consolidations or exits from occurring by investing in aerospace technology and its industrial base during the Cold War.

All of this must be presented with a few caveats. It is important to remember that the aerospace industry involves many different technologies which may themselves be in different technological phases and are still showing signs of rapid product innovation. Things like stealth technology, GPS, business jets and composite materials are having a tremendous impact on aerospace products. The innovation in these, and other, designs and technologies will certainly continue.

But the implications of the fact that the aerospace industry may follow this model proposed by Utterback are important. This shows that innovation in the aerospace industry is likely to occur in other areas than it has previously. Since the role of process innovation will likely become more important, it becomes imperative that product innovations are interlinked with process and supply chain innovations. The focus of just innovation of the product has to shift to account for the processes and the role of manufacturing in the realization of these products.

1.2 Research Objectives

This thesis attempts to answer a few key questions. They are:

- How are manufacturing systems designed in the aerospace industry? What processes are currently used?
- What are the emergent key characteristics for manufacturing system design?

Answering these questions will help determine guidelines and a process for manufacturing system design. Since the previous argument about the dynamics of innovation shows the aerospace industry may be in the transition phase, aerospace firms should be focusing on process innovation and manufacturing capabilities.

The research presented in this thesis is conducted in the aerospace industry of today. The case studies used in the framework validation are 14 real aerospace programs that are either designing their manufacturing systems or have recently completed their manufacturing system designs. The real world is the laboratory for this research. Even though this research focuses on the aerospace industry and some of the characteristics that make aerospace production unique, the manufacturing system design framework and proposed process is applicable to all manufacturing environments. This research simply aims to expand on the previous body of manufacturing system design research by incorporating some unique, and difficult, aspects of the aerospace industry.

This research also proposes to further the development of a manufacturing science by trying to determine the key characteristics of the manufacturing system design process. This will create a foundation to aide in the manufacturing system design process by abstracting these essential features. With these relationships, more complete knowledge of how the product design, enterprise strategy and environment impact the final manufacturing system design can be gained.

Given this context, this research was structured to meet four objectives:

- Understand the current manufacturing system design process in the defense aerospace industry
- Propose a model to use for the manufacturing system design process
- Test the model in industry
- Establish key characteristics of the manufacturing system design process

Current manufacturing system design processes were studied in the various case studies and through a literature review of currently available tools and methods to assist in the design process. The results from the case studies are presented in Chapter 6 and the literature review results are in Chapter 2 and also discussed extensively in the work done by P. Fernandes. The impacts of these results on the aerospace industry are outlined in Chapter 3. The proposed model of the manufacturing system design process is presented in Chapter 4. The model validation research design is outlined in Chapter 5 with the results of the case studies where the model was tested in Chapter 6. Finally, the key characteristics of this design process are determined in Chapter 7 and summarized in Chapter 8.

2.0 A Strategic and Systems Perspective of Manufacturing

Chapter Overview

An enterprise contains many operations that combine to form the competitive skill set for that business. These different functions have specific means of achieving corporate goals and the design of these individual functions must match the corporate goals.[5] Whatever the function, there is a structure that links the priorities for separate functions to support and uphold the goals and ambitions of the company. These different areas of marketing, product development, research and development and others comprise the portions of an enterprise strategy. And it is the strategies at these lower levels of the enterprise hierarchy that allow the overall goals and objectives of the enterprise to be operationalized and realized.[6] What is frequently not addressed or acknowledged is how manufacturing operations can fit into this overall concept of supporting the enterprise strategies and add to the competitive qualities of the enterprise.

This chapter explores the role of manufacturing as an addition to the competitive skill set of a company or an enterprise. The chapter then addresses what a manufacturing system is, what it encompasses and some of the elements involved in the design of these complex systems. This chapter concludes with a brief discussion of the difficulties of manufacturing system design.

2.1 Strategy Driven Manufacturing

This hierarchy of enterprise goals comprise the levels of strategies is conceptualized by Hayes and Wheelwright[7], and Miltenburg in separate research[8]. They outline the overall enterprise strategy to be composed of the business strategy which itself is made up of the functional strategies of the different portions of the firm. The hierarchical approach ensures that functional strategies support and uphold the overall business strategy; they cannot be developed in isolation.[9] Strategic fit must be sought out among the different functional areas of the business – and this includes manufacturing. The following figure depicts a generic form of the hierarchy of strategies from the uppermost enterprise goals, down to the individual functional elements.

[5] Robb, R., *Lectures on Organization*
[6] Hax and Majluf, The Strategy Concept and Process
[7] Hayes, R.H. and S.C. Wheelwright, Restoring our competitive edge, Competing Through Manufacturing
[8] Miltenburg, J., Manufacturing Strategy
[9] Hayes, R.H. and S.C. Wheelwright, Restoring our competitive edge, Competing Through Manufacturing

Figure 6: Enterprise system and hierarchy of strategies[10]

Many of these functions, like investment strategies, product development or marketing, have structured ways of determining and refining their individual strategies. A wealth of material has been published on manufacturing operations and manufacturing strategies, but very little of it has been tested, and even less is based on scientific study. Black comments in his research that manufacturing systems are difficult to model because the objectives are difficult to define and may conflict with the overall enterprise goals.[11] This is exactly why this research emphasizes the need to align the manufacturing goals within the hierarchy of enterprise goals. The key to achieve this is for the manufacturing operations to be viewed as just as important to a skill set of a corporation as any of the other functions. Only then will initial manufacturing endeavors and continuous improvement efforts be the most effective.[12]

Manufacturing Strategy

A manufacturing strategy focuses on creating a consistent pattern of decision making within the manufacturing function that supports the corporate strategy and helps achieve the corporate goals.[13] Manufacturing is a unique element within the overall enterprise. And there is growing awareness that the key to a competitive manufacturing advantage lies in the development of a manufacturing strategy that satisfies those business needs.[14]

Manufacturing systems can be designed to provide the corporation with different possible manufacturing capabilities such as cost, quality, performance, delivery time and delivery time

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[10] Fernandes, P., *A Framework for A Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor*

[11] Black. J T., The Design of the Factory with a Future

[12] Pilkington, A., *Manufacturing Strategy Regained: Evidence for the demise of best-practice*

[13] Muhamad, M.R., *The deployment of strategic requirements in manufacturing system design*

[14] Muhamad, M.R., *The deployment of strategic requirements in manufacturing system design*

reliability, flexibility and innovativeness.[15] [16] But superior levels of performance cannot be reached in each of these categories simultaneously.[17] The manufacturing strategy will determine which of the possible manufacturing outputs will more closely match the goals and strategy determined at the corporate, or enterprise, level.[18] This will result in a manufacturing system that reflects the competitive position and strategy of the company.[19]

There are many different strategies that can be applied to the manufacturing operation. For example, a company can actually build a factory to produce goods or perhaps utilize a network of suppliers and just do final assembly and integration, but the basic identification of a need to manufacture a product originates from the corporate strategy.[20] Once there is a need to develop a manufacturing operation, there is a need to have a structured manufacturing system design process. Having some sort of process will allow a firm to design their manufacturing system to support the enterprise goals and to understand how a change in the corporate strategy or manufacturing strategy may require changes to a manufacturing system.[21]

When a company or enterprise fails to recognize the relationship between manufacturing decisions and corporate strategy, it runs the risk of being burdened with a noncompetitive manufacturing system which could be expensive and time-consuming to change.[22] The existence of a manufacturing strategy will help guide the daily decisions and activities with clear understanding of how those daily decisions relate to the overall goals of the corporation.[23]

Benefits of having a Manufacturing Strategy[24]

A strategically managed corporation can have a better chance of growing profitably over the long-term than a corporation managed just by intuition and experience. A manufacturing strategy provides a vision for the manufacturing organization to keep itself aligned with the overall business strategy of the corporation. It consists of long term objectives, programs, and initiatives. These help the business gain and maintain a competitive advantage.[25] The key idea is to prepare a company to compete in the future. The current state is important and the fact that the company has survived thus far is an indication that something was done correctly in the past. Considering manufacturing operation as a strategic weapon rather than just a "widget producer" has enormous effects on manufacturing system design, manufacturing operation and improvement activities. Moreover, a manufacturing system that is designed strategically and integrated properly with the rest of the enterprise functions plays an important role in helping the

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[15] Miltenburg, J., Manufacturing Strategy
[16] Muhamad, M.R., *The deployment of strategic requirements in manufacturing system design*
[17] Rosenfield, D., *Manufacturing Strategy*
[18] Miltenburg, J., Manufacturing Strategy
[19] Hayes, R.H. and G.P. Pisano, *Beyond World-Class: The New Manufacturing Strategy*
[20] Duda, J.W., *A Decomposition Based Approach to Linking Strategy, Performance Measurement and Manufacturing System Design*
[21] Duda, J.W., *A Decomposition Based Approach to Linking Strategy, Performance Measurement and Manufacturing System Design*
[22] Skinner, W., *Manufacturing – missing link in corporate strategy*
[23] Kaplan, R.S. and D.P. Norton, *The Balanced Scorecard – Measures That Drive Performance*
[24] This section is adapted from P. Fernandes, *A Framework for A Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor.*
[25] Schroeder, R.G., *Development of Manufacturing Strategy: A Proven Process*

enterprise achieve its goals.[26] Hayes and Pisano point out that manufacturing strategy is a long-term plan focused on creating operating capabilities a company will need in the future. The key to long-term success is being able to do certain things better than your competitor.[27]

This is especially true for the current status of aerospace industry. As argued by Utterback, the aerospace industry has possibly reached a phase where manufacturing capabilities have the highest leverage. A well-formulated manufacturing strategy can benefit the corporation by enhancing the existing product sales purely through manufacturing abilities. One visible consequence of this phase is the customer demand for low acquisition cost. This is already apparent in the commercial aircraft sector. Airbus is winning more orders since it is offering aircraft at a lower cost. It is not to say that Airbus has a better manufacturing strategy than other manufacturers but, the point being made is that sales are determined by cost and not by product performance. Manufacturing organization plays a major role in acquisition cost of a mature product.

To use manufacturing as a competitive weapon, the corporation needs to be well aware of the market environment and its competitors' position in the market. The value of the strategy is in selecting those elements that the customer values and are difficult for the competitor to duplicate.[28] This information can be used to design manufacturing systems to give the desired output to differentiate products in the market. Once implemented, having a strategy will help the managers set priorities among daily activities by establishing long-term objectives. As Miltenburg says when a formal strategy exists, decisions follow in a neat, logical pattern and in the absence of a strategy the decisions are erratic and often are based on intuition.[29] Likewise, the process improvement activities can also be based on strategic long-term needs rather than on management shock-responses to the latest 'hot system' of the month. The strategy development process also alerts the corporation on a competitor's position and any need to further develop existing core competencies. Manufacturing management without a strategy will only lead to the wrong systems and decisions. A strategy is also a strong communication tool between different levels of management to bring all operations in line with corporate objectives.

A well-formulated manufacturing strategy provides the following benefits:

- Aligns manufacturing with business and corporate strategy
- Decisions based on long-term objectives of the enterprise,
- Assures long-term product, capability and process differentiation from competitors.
- Makes manufacturing an integral part of the enterprise strategy,
- Provides for clear communication between management levels,
- Helps select improvement/capability building activities that will contribute to long-term enterprise success,
- Creates an awareness of competition.

Since the manufacturing function is an element of the enterprise in the same manner as the product design is, manufacturing, manufacturing systems and how they are designed need to be

[26] Buffa, E.S., Meeting the Competitive Challenge, Manufacturing Strategy for U.S. Companies
[27] Hayes, R.H. and G.P. Pisano, *Beyond World-Class: The New Manufacturing Strategy*
[28] Hayes, R.H. and G.P. Pisano, *Beyond World-Class: The New Manufacturing Strategy*
[29] Miltenburg, J., Manufacturing Strategy

understood. A developed process of designing a manufacturing system will allow for the system to be more easily controlled to support the corporate strategy and achieve the corporate goals.

2.2 Definition of Manufacturing System

Even a quick review of the many different books and articles about manufacturing systems yields one important fact. There is no single, accepted, definition for a manufacturing system. One definition is that a manufacturing system is a collection or arrangement of operations and processes used to make a desired product(s) or component(s).[30] Another definition, states that a manufacturing system is a collection of value adding manufacturing processes used to convert raw materials into more useful forms and eventually into finished products.[31] Yet a third definition is that a manufacturing system is comprised of the equipment, processes, people, organization and knowledge, as well as the interactions of these, that are involved in the manufacturing of a given end product.[32]

Despite the similarities in these definitions, there are some differences. This selection and breadth of different definitions is indicative of a deeper problem – the lack of a fundamental manufacturing science that describes the behavior of these systems. Unlike the laws of physics and thermodynamics, the constitutive relations of manufacturing systems are unknown. In order to help create the basis of a manufacturing science and attempt to model a manufacturing system or the design process, a common set of definitions should be established. The basis for creating any type of science is to establish a common nomenclature and set of definitions.

In this section the definition and scope of a manufacturing system is presented. But first, the basic concept of a system and systems engineering are introduced.

Systems Engineering

A "system" can be defined in several different ways. The dictionary defines a system as a set or arrangement of things related as to form a whole.[33] Another definition contains more detail that a system is a collection of elements aggregated by virtue of the links to form, process or function, which tie them together and cause them to interact.[34] These two definitions show that a system is probably comprised of some elements that interact to form a larger whole. The last two definitions presented shed even more light on what a system may be. One definition is that a system is a physical or virtual object that performs a function that cannot be fulfilled by its constituent parts alone.[35] And the last definition of a system presented here is that a system is a collection of components organized to accomplish a specific function or set of functions.[36]

From these definitions the critical aspects of a "system" can be derived. Systems are comprised of elements that interact with one another to do something, or perform a specific function. The

[30] Black, J T., Design of the Factory with a Future
[31] Wu, B., Manufacturing Systems Design and Analysis
[32] ESD Terms and Definitions
[33] Webster's New World Dictionary
[34] Rubenstein, M., Patterns of Problem Solving
[35] Crawley, E.F., Notes from 16.882 System Architecture
[36] IEE, definitions

function that this system performs cannot be accomplished by the elements of the system alone and this system interacts with the environment across its boundary. These elements of a system lead into the idea of "systems thinking" or "systems engineering" which is thinking and solving problems from a systems point of view.

A systems perspective is also referred to as a "holistic" perspective. In this approach, individual components are viewed more in terms of their interactions with other elements of a system and in the light of the overall goals, or function, of the system.[37] This is in contrast to a "reductionist" perspective where analysis is done by looking at smaller and smaller components of an overall system.[38] The difference in scope of these two different perspectives of a system is illustrated in the figure below.

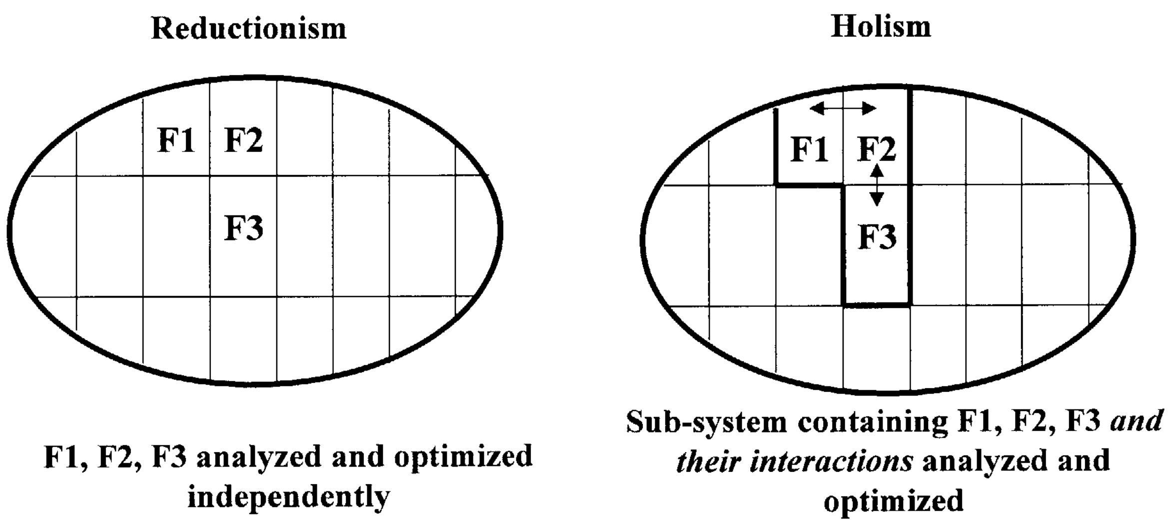

Figure 7: Reductionist versus Holistic perspectives of a System

The difference between a reductionist and holistic approach to analysis of a system is that a reductionist approach cannot guarantee a solution that takes into account all of the interactions between the components.[39] This difference means that reductionist thinking leads to the optimization of functions (elements like F1, F2 and F3 in the figure) rather than of the system as a whole.[40] The value of system level thinking, or systems engineering, is that it is a key contributor to successful system design.[41]

As imprecise as some of these definitions are the precise form of the definition of a system and systems engineering is not what is critical. What is critical is that the common aspects of all the different definitions of a system and systems engineering are utilized. One of these common aspects is the theme that the whole is greater than the sum of the parts. This can be interpreted as the concept of an emergent function. It is only when all the elements are taken together that a

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[37] Hopp, W. and M.L. Spearman, Factory Physics

[38] Wu, B., Manufacturing Systems Design and Analysis

[39] Fernandes, P., *A Framework for A Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor*

[40] Shingo, S., A Study of the Toyota Production System

[41] Shingo, S., A Study of the Toyota Production System

spacecraft produces information or that an aircraft produces transportation or delivers its weapons to the target.[42] Thinking of a product or a system in this way is systems thinking, or a holistic perspective. And these systems fulfill a need or meet a goal that initiated their creation.

Manufacturing System

From the fundamental concepts of systems and systems engineering, a definition of a manufacturing system can be introduced. It is an application of the principles of systems engineering into the manufacturing environment. A manufacturing system is defined as an objective oriented network of processes through which entities flow.[43] As short as this definition is, there are many things in it that require additional clarification.

The first element in this definition is the "objective". It was mentioned in the discussion of systems and systems engineering that one commonality in the different definitions of a "system" was that they exist to fulfill a need or meet a goal. In the context of manufacturing and a manufacturing system, this is embraced by the manufacturing strategy. The manufacturing strategy identifies the need or the goal that the manufacturing system must fulfill.

"Objective oriented" is the next element of this definition. This is the need of the system to be oriented to fulfill its objective. This includes the creation of a manufacturing strategy that includes all the various needs of the different stakeholders of the system. Stakeholders are any person or organization impacted by the success or failure of the system.[44] In the case of a manufacturing system, the stakeholders can be the contractor, the government, the end user (the warfighter), Congress, the public, the shop floor workers and even the environment as examples.[45] The following figure shows the increase in stakeholder inclusion through the development of different manufacturing systems.

[42] Maier, M.W. and E. Rechtin, Art of Systems Architecting
[43] Hopp, W. and M.L. Spearman, Factory Physics
[44] Crawley, E.F., Notes from 16.882 System Architecture
[45] Little, T., *The Concept of Value: a DoD Program Manager's Perspective*, presentation

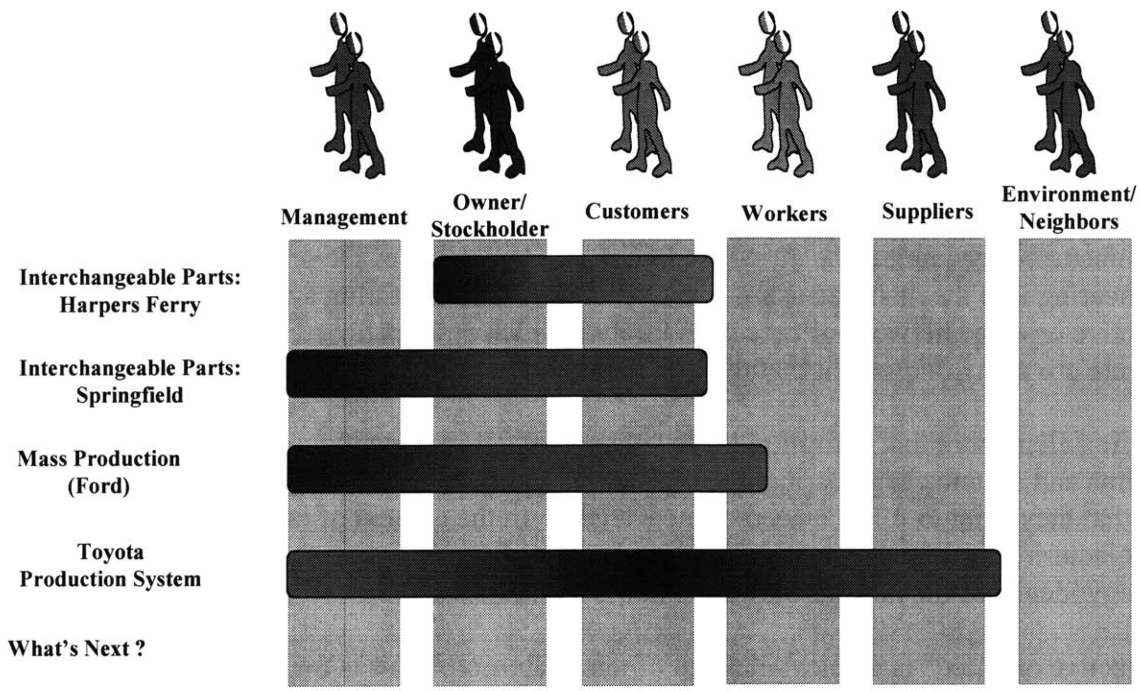

Figure 8: Historical perspective of stakeholder inclusion of manufacturing systems

This trend of increased stakeholder inclusion is an important one in the history of manufacturing. From the first industrial revolution of interchangeable parts to Henry Ford's revolution of the moving assembly line and mass production, each system was more capable, more efficient and more productive than the previous. The most recent industrial revolution occurred in Japan in the years following World War II, but was not popularly known until The Machine That Changed the World was published in 1990.

Contained within this "objective oriented network through which entities flow", are the steps that the entities flow through, or the processes they experience. Processes are the physical transformations that the materials are subjected to[46] or the steps that directly support these physical transformations like order entry, kitting, maintenance etc. Information is required to initiate and assist in these various processes.[47]

The definition states that these processes are connected in a network. This is where the aspect of a manufacturing system actually being a *system* is introduced. In this sense a manufacturing system is comprised of interacting sub-systems. These sub-systems are the processes were just defined to be the physical manufacturing operations, or the supporting processes. These sub-systems interact and form a network of processes. In a single factory, a particular machine shop or chemical milling facility, could be a sub-system of the overall manufacturing system. Or in the case of the F-22, the Lockheed Martin factory in Fort Worth, Texas, could be a sub-system of the complete F-22 manufacturing system. Using a systems engineering perspective allows the sub-systems to be defined differently depending on the context of the analysis and how the network of processes need to be organized.[48]

[46] Shingo, S., A Study of the Toyota Production System
[47] Shingo, S., A Study of the Toyota Production System
[48] Miltenburg, J., Manufacturing Strategy

"Flow" is the next part of the definition of a manufacturing system that needs to be expanded. Flow describes how various entities move and are processed throughout the system.[49] The entities flowing through this network, or system, can be the parts being manufactured, or the information that is needed to control the processes, the tools required to perform the process, or the people themselves.[50]

This discussion of a manufacturing system that is an objective oriented network of processes through which entities flow introduced the concept of a manufacturing system being a system comprised of interacting sub-systems that aim to achieve a particular objective. Given this definition, the analysis and design of a manufacturing system can then be approached with systems engineering principles.

The "Infrastructure" and "Structure" of a Manufacturing System

Given the definition of a manufacturing system, the scope of this type of system can be determined by exploring the concepts of the "structure" and "infrastructure" of a manufacturing system. The manufacturing system infrastructure includes the activities associated with the overall operating environment of the manufacturing system while the manufacturing system structure are the activities associated with the factory floor.[51]

The manufacturing system infrastructure includes the manufacturing strategy, the operating policy, partnerships with suppliers and organizational structure details.[52] This is the aspect of the manufacturing system that ensures the manufacturing system structure (the physical layout etc.) is aligned with the overall strategic views and business objectives of the enterprise.[53]

The manufacturing system structure is comprised of the physical aspects of the system. This includes the machines, people, physical layout, processes and inventory levels.[54] These are the tangible aspects of the manufacturing system.

The structural and infrastructural aspects of a manufacturing system are equally important. Both depend on each other.[55] These two aspects are important because the manufacturing infrastructure will determine the manufacturing strategy that creates the environment that the structure will exist in. The manufacturing system structure has to exist in a manufacturing system infrastructure that is appropriate to ensure that the system will be effective.[56] All too often, companies fail in the implementation of new manufacturing systems due to conflicts between the existing infrastructure and the new structure. Any given system only works well when the infrastructure and structure are appropriate for each other.[57]

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[49] Hopp, W and M.L. Spearman, Factory Physics
[50] Shingo, S., A Study of the Toyota Production System
[51] Hayes, R.H. and S.C. Wheelwright, Restoring our competitive edge, Competing Through Manufacturing
[52] Hayes, R.H. and S.C. Wheelwright, Restoring our competitive edge, Competing Through Manufacturing
[53] Utterback, J.M., Mastering the Dynamics of Innovation
[54] Hayes, R.H. and S.C. Wheelwright, Restoring our competitive edge, Competing Through Manufacturing
[55] Miltenburg, J., Manufacturing Strategy
[56] Muhamad, M.R., *The deployment of strategic requirements in manufacturing system design*
[57] Maier, M.W. and E. Rechtin, Art of Systems Architecting

2.3 Definition of Manufacturing System Design

As the previous section about systems engineering and manufacturing systems illustrated, a manufacturing system is a major system. All too often manufacturing is treated as if it were but one step in the development of a product, but it has all the qualities of being its own major system with a system architecture, emergent functions, sub-systems, and finally, its own development process.[58] Manufacturing systems are complicated and expensive, and therefore, should be designed rigorously.[59]

Like a vehicle, or a boat or a plane, a manufacturing system can be designed to do something well, but always at the expense of other abilities. For example, no one today can design a 500-passenger plane that can land on an aircraft carrier and also break the sound barrier. The same is true of manufacturing – the variables place limits on what a manufacturing system can do.[60] Because of this, there is no simple, uniform solution that will work across all possible manufacturing environments.[61] This is why the manufacturing system must be designed and not merely copied.

Engineering design typically encompasses many activities, creative as well as analytical, and the synthesis aspects of design create potential solutions. Engineering design produces a description of a system that will exhibit the desired behavior.[62] The design of a manufacturing system has its own engineering development process.[63] Manufacturing system design can be viewed as the process of selecting the manufacturing resources and designing the operating policy to produce the strategically chosen products at the right time and in the right quantities.[64]

The way to begin the process of creating the system to support the strategy of the manufacturing operation and to make the firm more competitive is to view manufacturing system design as a process with a certain set of considerations and constraints. The following figure and description is a product of the Manufacturing Systems Team of the Lean Aerospace Initiative. This was the rough model created to depict the act of designing a manufacturing system.

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[58] Maier, M.W. and E. Rechtin, Art of Systems Architecting
[59] Fernandes, P., *A Framework for A Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor*
[60] Skinner, W., *Manufacturing – missing link in corporate strategy*
[61] Hopp, W. and M.L. Spearman, Factory Physics
[62] Antonsson, E.K., *Formal Engineering Design Synthesis: Application to Robust Microsystem Design*
[63] Maier, M.W. and E. Rechtin, Art of Systems Architecting
[64] Fernandes, P., *A Framework for A Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor*

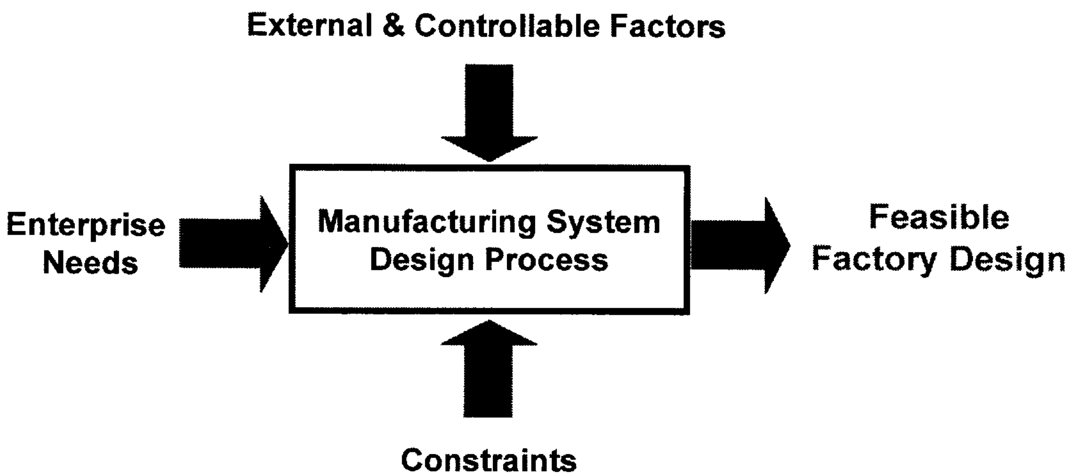

Figure 9: P-Diagram representing the manufacturing system design process

The arrows depict the different factors from the environment outside the system that influence the design process. The box houses the actual manufacturing system design process that creates the factors, or complete system design. Each of these aspects of this model will be described in turn.

Manufacturing System Design Inputs

The arrows going into the manufacturing system design process box represent the inputs feeding the process. These are the inputs from the environment around the system that influence the design of the system. These inputs are categorized as being either external or controllable factors, needs of the enterprise or constraints imposed on the design process.

First of all, the external factors are the things that fall outside the sphere of influence of the manufacturing operation. Market conditions, regulatory influences, offset requirements or customer requirements may be some of the things that will dictate the result of a manufacturing system design process. The people involved in the manufacturing operation may not have any power to change these items. In aerospace manufacturing, this can be particularly apparent since no technology sale can be made to a foreign government without the express approval and participation of the U.S. government.[65]

The other aspect of this arrow is the controllable factors. These are the factors that do fall under the control of the manufacturing operation. These may be things like the investment on new tooling as opposed to re-using old tooling, when to introduce new versions of a product into the system or the skill level of the workforce. But these are the factors that the decisions makers of the manufacturing system design process can influence.

The next major input into the manufacturing system design process is the interpretation of the enterprise needs. This input into the manufacturing system design process contains the higher level needs imposed on the manufacturing operation from the enterprise. This may be to design a system that provides the stockholders with the best possible return, helps the company grow

[65] Lockheed Martin Tactical Aircraft Systems, *Application for the Shingo Prize for Excellence in Manufacturing*

profitably or helps the firm reduce costs. The enterprise needs help to formulate the manufacturing strategy. And this manufacturing strategy has a close and significant relationship with the manufacturing system design decisions.[66]

Constraints are the things that the manufacturing operation will be subjected to. These items are beyond the control of the manufacturing system and can sometimes come from interesting places. Some constraints can be similar to the external influences and emerge from regulations, but some are more colorful. For example, in the early production units of the Atlas V launch vehicle, the hydro test of the Common Core Booster (CCB) uses an older facility where the booster has to be lifted and placed into the tank. But there is a 9-knot wind limit for hoisting the booster into place. Generally, the constraints will limit the boundaries of possible outcomes of the manufacturing system design process, but will not prohibit the system from meeting the enterprise needs and goals.

10-Inputs

The collection of external and controllable factors, enterprise needs and constraints yield many factors that influence the design of a manufacturing system. Even though all of these factors are involved and will have impact on the final design of the manufacturing system, many of them will not be directly involved in the manufacturing system design process. The endless list of potential influences on the manufacturing system design process can be brought down to a manageable level of 10-inputs. These 10-inputs divide the different potential influences amongst inputs that are derived from the enterprise strategy, market conditions and the product design. The 10-inputs for manufacturing system design are:

- Market Uncertainty
- Product Volume
- Product Mix
- Frequency of Changes
- Complexity
- Process Capability
- Worker Skill
- Type of organization
- *Time to first part (a constraint)*
- *Investment (a constraint)*

This list of 10-inputs are defined and explored in detail in Appendix C.

Manufacturing System Design Process

The inside of the box in Figure 9 represents that actual manufacturing system design process. The external and controllable factors, enterprise needs and constraints all influence this process and what may be considered a feasible factor or system design in the end. This is the process by which infrastructure and structure of the manufacturing system is designed. The infrastructure is designed by the enterprise needs mapping to specific functional strategies and then down into measures of functional, in this case manufacturing, performance. Then the structure is designed

[66] Muhamad, M.R., *The deployment of strategic requirements in manufacturing system design*

by determining the necessary sub-systems for the system and the appropriate linkages and control of the interactions of those sub-systems.[67]

This is the process that this research intends to model. This research proposes a framework in Chapter 4 of how these different inputs can be used to design a manufacturing system that meets the performance goals of the system and satisfies the needs of the enterprise and its stakeholders.

Difficulties of Manufacturing System Design

Designing a complex system is not an easy task. Whether the "system" being designed is an airplane, a new spacecraft or a manufacturing system, system design in a complex environment yields a long and difficult engineering design process. But unlike the design of an airplane or a spacecraft, designing a manufacturing system is often more difficult to accomplish. Even though the general engineering process is understood, the manufacturing system design process is not. This is partly because manufacturing system design is a multi-disciplinary field and often involves many non-engineering fields and because a manufacturing system is difficult to see and visualize in its entirety since it deals with a complete supplier network and people.[68] The largely integrated and multi-disciplinary nature of the design process makes it more complicated to manage and control the design process.[69]

But the cause of difficulty in the manufacturing system design process is the lack of an underlying manufacturing science. An airplane can be designed and verified on paper using scientific principles before building any physical part. But in manufacturing, there is no underlying science to determine the constitutive relations that describe the relationships between variables in the process. Manufacturing systems cannot be modeled since these constitutive relations are not known and because manufacturing systems are highly non-deterministic in nature.[70] To deal with this, randomness is incorporated into models to explain complexity.[71] But this does not get at the root cause of the source of the complexities.

The development of a manufacturing science would allow for more precision in the manufacturing system design process. It would allow the phenomenon to be studied consistently by other researchers since there would be a common theoretical basis and mathematical technique.[72] Researchers have tried to circumvent the problem of having a lack of a manufacturing science but trying to model small portions of the manufacturing system. But this has led to research that has been focused on finding only more elegant computation methods and these models have never been expanded to accurately describe the real world.[73] Research has used the reductionist approach and lost the holistic perspective required to view how the complete manufacturing system interacts with the environment to produce products.

[67] Pine II, B.J., et. al., *Making Mass Customization Work*
[68] Cochran, D.S., et. al., *A Decomposition Approach for Manufacturing System Design*
[69] Fredriksson, B., *Holistic Systems Engineering in Product Development*
[70] Fernandes, P., *A Framework for A Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor*
[71] Gleick, J., Chaos: Making a New Science
[72] Gleick, J., Chaos: Making a New Science
[73] Hopp, W. and M.L. Spearman, Factory Physics

The wide variety of tools and methodologies available in the industry is another indication of the lack of fundamental manufacturing science. A manufacturing science would give rise to some fundamental principles that will always (or almost always) remain valid. Tools and methods are the contemporary ways to facilitate processes and using those fundamental principles.[74]

There are a wide variety of tools, methods and frameworks that have been developed to assist in the manufacturing system design process. Samples of the different types of tools and methods that are available are supplied in P. Fernandes, *A Framework for A Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor*. But, generally, these tools do not give a complete picture of the manufacturing system design process. A review of available tools shed light on different shortcomings. Many tools available assume a particular solution at the beginning rather than allowing equal consideration of all possibilities. Some "maps" of the manufacturing world are too simplistic. Many use just volume and mix to determine an appropriate manufacturing system design, meanwhile, it was established in the last section that there are, at least, 10-inputs that are required to define a manufacturing system. Many tools available are not appropriate for the aerospace industry and do not consider many of the unique constructs that make the manufacture of aerospace products so difficult. These unique constructs that require attention for development of a tool for use in the aerospace industry are outlined in the following chapter. Another failing of many tools available for use is that the tools may be too detailed to assist in early decisions making. They are adequate simulations but require such detailed input that they are not useful in the early planning stages. Generally, the tools reviewed were incomplete because they did not capture the complete manufacturing system infrastructure and structure design decisions.

This research views the manufacturing system design process in a holistic way to observe the underlying principles that could become fundamental to the development of a manufacturing science.

2.4 Chapter Summary

This chapter began by exploring the role of manufacturing as an element of the competitive skill set of a company or enterprise. A manufacturing strategy should be developed to guide the development and operation of a manufacturing system to ensure that the system meets the goals and needs of the overall enterprise. The benefits of having a manufacturing strategy were outlined.

Next, the definition and scope of a manufacturing system was presented. A manufacturing system is a strategically guided system that aims to meet the objectives of the enterprise, which are derived from the various needs of the stakeholders. Manufacturing systems are complex systems and should be viewed in a holistic way that utilizes the principles of systems engineering. Manufacturing systems are comprised of two distinct parts – the system infrastructure and structure.

[74] Crawley, E.F., Notes from 16.882 Systems Architecture

Manufacturing system design is the process of designing this particular manufacturing system infrastructure and structure. This process has many different external and controllable factors, enterprise needs and constraints that influence it. The manufacturing system design process is difficult since there is no fundamental manufacturing science to guide it.

This research plans to model this manufacturing system design process and tries to shed light on some of the fundamental principles that could help advance the development of a manufacturing science.

3.0 The Role of Manufacturing in the Aerospace Industry

Chapter Overview

The last chapter defined a manufacturing system and manufacturing system design as well as illustrated how manufacturing fits into the overall role of an enterprise. This chapter expands this and explores how the manufacturing function is perceived in the aerospace industry. Then, this chapter explores the unique constructs of aerospace products. These are the characteristics that make these products unique from other industries. These constructs are the aerospace-specific things that need to be addressed in methodologies or tools to assist in the manufacturing system design process. Finally, given these constructs, the application of the concepts of lean manufacturing as applied to the aerospace industry is explored.

3.1 The Perceived Role of Manufacturing

If you ask an executive from a major aerospace company to describe what their company does and what the identity of their company is, they may answer that it is an engineering firm, or a design firm.[75] The answers will probably not be "we make airplanes". Manufacturing usually has been, and in some cases still is, simply considered a necessary evil that must occur for an item to be sold.[76]

What may not be immediately obvious to a typical citizen, or even a person working for a major aerospace firm, is that national defense depends on production. High-tech or low-tech, weapons must be produced. Nations with little production capability must use scare resources to buy them from others, and what they buy is seldom the latest model. A nation that is able to design weapons but not produce them with quality and quantity also has a major weakness.[77]

Concern about the lack of flexibility and rapid response time in the aerospace industry is not new. In 1940, General James H. "Jimmy" Doolittle (MIT S.M. '24 Sc.D. '25) conducted a benchmarking survey of aircraft manufacturers in the United States and Europe. He traced throughput times and documented sources of delay in manufacturing systems and was distraught at the lack of maturity in the aeronautical firms in the United States. He wrote that most of the problems he saw were managerial and that "we could never get any fighters in the air…unless attitudes were changed among the foremen and the supervisors." The same statement holds true today. Without embracing a paradigm shift toward the importance of manufacturing and its role in industry, the aerospace industry of the 21st century will be even slower to respond putting our level of military readiness at risk in the potential conflicts of the future.[78]

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[75] As an example, Al Haggerty, Boeing VP (retired), responded in an interview, "Boeing is design, integration, test, checkout and support. Boeing is a large-scale system integrator."

[76] Based on 14 telephone interviews with vice-president level (or higher) executives in the aerospace industry. For a full report on the results of these interviews, please refer to P. Fernandes, *A Framework for A Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor.*

[77] Hall, R.W., Attaining Manufacturing Excellence

[78] Doolittle, J.H., I Could Never Be So Lucky Again

During the time of Doolittle's study and throughout World War II, production capability was an important factor. How much this has continued is subject to debate, but there is less question that political weight in the world is substantially affected by manufacturing capability.[79]

More recent studies than Doolittle's tell much the same story. In many industries, not just aerospace, top management unknowingly delegates a large portion of basic policy decisions to lower levels in the manufacturing area. The delegation results in manufacturing strategies and policies developed on an assumption of the corporate level strategy, which may be incorrect or misconstrued.[80] This is then coupled with the culture that exists in aerospace companies that are mainly driven by a product focus and many production issues are subjugated to product concerns.[81]

If manufacturing capability is such an important factor in the outfitting of the warfighter, then why is it not deemed an integral part of the identity of a company that produces the weapons for the warfighter? The answer is that manufacturing is not seen as an element in the producers competitive skill set. The first step to improve the manufacturing capabilities of the defense aerospace industry is to acknowledge the added benefits of a manufacturing operation to the overall competitive skill set of a company. This overall research project attempts to address the issues that exist in the manufacture of air and spacecraft today to help build a stronger industrial base for the country and the warfighter of the future.

3.2 Unique Constructs of Aerospace Products

The challenge facing the aerospace industry is enormous. The warfighters are being asked to do more and more with less and less. The tools that are needed to accomplish the wide-ranging tasks have to be more nimble, more interoperable, and more affordable than any aerospace systems that have been created before. The aerospace industry has four core missions:

- Enabling the global movement of people and goods,
- Enabling the global acquisition and dissemination of information and data,
- Advancing national security interests, and
- Providing a source of inspiration by pushing the boundaries of exploration and innovation.[82]

These missions will never be routine. They will forever challenge the people and stretch the technologies that make up this industry. But in the changing nature of a global economy and global security, the same principles that have been successful for the aerospace industry in its first century are not the same principles, which will guide it in the future.[83]

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[79] Hall, R.W., Attaining Manufacturing Excellence
[80] Skinner, W., *Manufacturing – missing link in corporate strategy*
[81] Dobbs, D., *Development of an Aerospace Manufacturing System Design Decomposition*
[82] Murman, E.M., et. al., Lean Enterprise Value
[83] Murman, E.M., et. al., Lean Enterprise Value

Many industries span multiple sectors, but none seem to have the breadth of the aerospace industry. This industry deals with the complexities of being government contractors and commercial entities simultaneously. With complicated relationships amongst each other and their customers, business is never conducted in the same manner twice. The aerospace industry is also faced with a breadth of technologies that make it difficult to generalize across - from the space sector and one-of-a-kind spacecraft to the electronics sector of rapidly changing technologies and large production volumes. These disparate groups have to come together to produce amazing aerospace products.

Despite the large scope contained within the aerospace industry, there are unique characteristics, or constructs, that apply generally throughout. These are the unique constructs that differentiate aerospace products from others and account for much of the difficulty in their design and production. Because these constructs are frequent sources of difficulty, these are the constructs that must be considered when developing a methodology, a tool or a framework to assist in the product development or manufacturing system design processes.

These constructs were derived by the researcher's individual literature search and through observations made over three years of case study work in the aerospace industry on LAI research.

Product Complexity

Most people, if asked which product was more complex when shown a pencil and an F-22 Raptor would probably answer that the F-22 is the more complex product of the two. Aerospace products, from flight management systems to satellites are all treated as "complex". Complexity can be defined as the amount of difficulty people have to understand or work with something[84], or something with many interconnected, interwoven or interrelated elements that all have to work together.[85] Complex products are typically those that have many interdependencies between subsystems making the products highly integrated and coupled. Whatever the definition, aerospace products are dealing with large part numbers, exotic materials and tight tolerances, which may be indications of the complexity of the products.

In the aerospace industry, complexity of a product can also capture much more than the actual physical product. Complexity can refer to the intricate supplier base and the organizational, regulatory and industrial environment that these products are produced within.[86]

Production Volume

The manufacture of aerospace products is also unique in the relatively low volume of the items produced. It is hard to justify substantial changes to the infrastructure of a manufacturing system for a low volume product.[87] When production volumes are not high enough to justify dedicated resources, a job shop emerges with batches, setups and resource sharing which is difficult to coordinate without sufficient inventory. This results in a gradual increase in inventory, expense

[84] Boppe, C.W., *16.870 – Aerospace Product Development*, Course Reader
[85] Crawley, E.F., *System Architecture*
[86] Murman, E.M., et. al., Lean Enterprise Value
[87] Cool, C., *Journey To A Lean Enterprise*, presentation

and loss of response time of the system.[88] Low production volumes also lead to companies that do not want to cross train shop floor workers since tasks are not repeated frequently.[89] Such low production volume leads to other problems. In most cases, commercial goods for an aerospace product are inserted into commercial production when there are gaps in orders. This translates into a schedule that is not under control of the program manager.[90]

Market uncertainty and the cyclic nature of aerospace production exacerbate this issue. Historical trends of the defense budget show that operations is the most stable portion while procurement varies to surge in the high-budget times and plunge in the low-budget times.[91] This cyclic nature of demand can lead to long periods of low activity for the aerospace manufacturers[92], which, in turn, impacts the retention of workers that are heavily relied on.[93]

Waste and Weight Considerations

Another consideration for aerospace manufacturing is weight and waste. Manufacture of air and spacecraft is inherently more wasteful than other products because of the strength and weight restrictions. To have the needed strength in a particular part, reinforcements could be added to it in a car, for instance. But in aircraft where every pound has a profound impact on performance, parts are machined out of single pieces of raw material to avoid adding reinforcements. This is being made more easily possible by high-speed machining. Composites are also being used more frequently in aerospace products since they offer benefits in strength and weight.[94] But composites are often more labor intensive and making composite parts will be a future challenge to incorporate into production flow.

Product Size

Aerospace products like military and commercial aircraft, engines, launch vehicles and some spacecraft are very large. The large size and sometimes awkward shape of these products makes them difficult and costly to move frequently. One interviewee remarked that aerospace products are typically examples of "clump manufacturing" where the product stays put and all the tools, people and parts come to the product. Black also mentions this and even uses the 747 as an example of a fixed position manufacturing system in a book that is not a specifically aerospace directed book.[95]

The large product size is becoming more manageable and more companies are moving their products more frequently and, in some cases, continuously, as will be shown in the later case studies. But, the case still holds that moving a product like and airplane or a spacecraft is not a trivial action. Moving a product of this size makes it susceptible to damage and is difficult to accomplish.

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[88] McKay, K.N., *The Evolution of Manufacturing Control – What Has Been, What Will Be*
[89] Dobbs, D., *Development of an Aerospace Manufacturing System Design Decomposition*
[90] Murman, E.M., et. al., Lean Enterprise Value
[91] Lundquist, J.T., *Shrinking Fast and Smart in the Defense Industry*
[92] Fernandes, P., *A Framework for A Strategy Driven Manufacturing System Design in an Aerospace Environment*
[93] Wang, A., *Design and Analysis of Production Systems in Aircraft Assembly*
[94] Wang, A., *Design and Analysis of Production Systems in Aircraft Assembly*
[95] Black, J T., The Design Of The Factory With A Future

Supplier Diversity

Aerospace products can also be characterized by the broad selection of industries that all contribute to the final product. The number of suppliers to make different systems incorporated into a single product is immense. Frequently these suppliers are scattered all over the country, if not around the world. This makes face-to-face communication with suppliers difficult[96] and complicates the relationships that exist between companies and their suppliers.[97] The geographic separation between companies and suppliers also introduces significant transportation delay into the total manufacturing system.[98]

This industrial and geographic diversity has led to an industry that is good at dealing with a large perspective when it comes to designing and manufacturing their products. "Macro Value Stream Mapping" is the latest tool which takes the power of value stream mapping and applies it to multiple sites involved in the production of a product. The aerospace industry had been doing this without a second thought – it was just natural to them that they had to deal with multiple sites and multiple companies to be able to see the complete value stream. For example, unlike the final assembly of a car that takes place in a single factory, major aerostructure components for the F-22 come from Seattle, Fort Worth and many others to Marietta, Georgia, to be integrated into a final aircraft. Lockheed Martin is aware that the "factory floor" that produces the F-22 consists of hundreds of factory floors all over the country that have to work together.

Design Changes

The need for frequent (and often late) design changes in aerospace products severely limits the capability of the manufacturing system to maintain a consistent output. Requirements and specifications in military programs are often more unstable than commercial programs.[99] And even though military requirements and specifications are rigorous, they are not always precise.[100]

Changes to the design also emerge as a product enters the real world of prototyping and testing.[101] These changes occur late in the value stream and make improvement efforts on the product and manufacturing system difficult.

Dealing with this high frequency of changes in the products makes maintaining stable processes in the manufacturing system difficult.[102] This impacts the ability of a manufacturing system to continuously produce defect-free products and makes mistake-proofing processes impractical.[103] This can be seen on the F-16, which has been in production since the mid-1970s and still exists in a constant state of change to the design. This leads to little stability in work content from unit to unit.

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[96] Dyer, J.H., *Dedicated Assets: Japan's Manufacturing Edge*
[97] Spear, S. and H.K. Brown, *Decoding the DNA of the Toyota Production System*
[98] Wang, A., *Design and Analysis of Production Systems in Aircraft Assembly*
[99] Murman, E.M., et. al., Lean Enterprise Value
[100] Lundquist, J.T., *Shrinking Fast and Smart in the Defense Industry*
[101] Lundquist, J.T., *Shrinking Fast and Smart in the Defense Industry*
[102] Wang, A., *Design and Analysis of Production Systems in Aircraft Assembly*
[103] Dobbs, D., *Development of an Aerospace Manufacturing System Design Decomposition*

Ultra-Quality

Ultra-Quality is a concept that stems from quality requirements that are so stringent that no matter how complex the system is it must be reliable.[104] For example, nuclear power plants and commercial airliners simply cannot fail. There cannot be errors when producing large complex systems like these. Aerospace products are not just complex and technologically sophisticated products. These products are expected to operate with zero failures.[105] Exacting quality levels are a first-order requirement, rather than just a competitive advantage, in the aerospace industry.[106] As a manager for Atlas V product at Lockheed Martin Astronautics remarked of their expendable launch vehicle, "We must maintain 100% Mission Success – we only get *one* chance in our business."

This impacts the manufacturing systems of aerospace products. Defect-free production is always a goal for a manufacturing system, but in aerospace production a defect cannot be allowed to pass through the system. To meet the stringent quality requirements the aerospace industry frequently uses 100% inspection and test with the intention to rework anything until the product can pass.[107] This further impacts the manufacturing system because many of these inspection, testing and rework procedures do not fit into the product takt times and inhibit flow.[108]

Ultra-quality further impacts the manufacturing systems of aerospace products when the manufacturing system is viewed as part of the overall architecture of the final system. Like a launch vehicle for a space system, the manufacturing system is lost architecture. Lost architecture is required for the system to serve its final purpose but is not part of the final architecture that carries out the final function.[109] In this context, manufacturing systems are ultra-quality systems just like the aircraft and spacecraft they produce. No matter how complex the manufacturing systems become, they have to perform and produce products of perfect quality, ultra-quality. Without an ultra-quality manufacturing system, creating an ultra-quality aerospace product becomes more difficult.

System Process Capability

In order to achieve the quality levels demanded by ultra-quality requirements, the manufacturing system must be completely capable.[110] This means that the processes must be predictable and repeatable. But this is frequently not the case in an aerospace context.

Aerospace assembly frequently deals with large parts or assemblies coming together in tools or jigs that require shimming or trimming because the compliant parts are unable to hold the necessary dimensions.[111] Aerospace has not yet achieved the simplicity of the Ford production system in ensuring the interchangeability of parts to allow the implementation of standard work and standard processes.[112] Alan Mulally, the CEO of Boeing Commercial Airplane Group

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[104] Maier, M.W. and E. Rechtin, Art of Systems Architecting
[105] Murman, E.M., et. al., Lean Enterprise Value
[106] Lockheed Martin Tactical Aircraft Systems, *Application for the Shingo Prize for Excellence in Manufacturing*
[107] Wang, A., *Design and Analysis of Production Systems in Aircraft Assembly*
[108] Dobbs, D., *Development of an Aerospace Manufacturing System Design Decomposition*
[109] Maier, M.W. and E. Rechtin, Art of Systems Architecting
[110] Maier, M.W. and E. Rechtin, Art of Systems Architecting
[111] Wang, A., *Design and Analysis of Production Systems in Aircraft Assembly*
[112] Jaspering, D., *Geometry Assurance: An Application of the AIMS-Metronor Software*, presentation

commented that despite all the manufacturing improvements over the years, commercial airliners are "still pretty much handcrafted".[113]

This lack of capability further impacts aerospace manufacturing systems in another way. There are different types of flexibility that a manufacturing system can be designed to accommodate. Manufacturing systems for aerospace products frequently are designed with product flexibility to accommodate the product design changes and volume flexibility to accommodate the cyclic production schedules typical in the industry. But to withstand product and volume flexibility, the processing capabilities of the system have to be high. The processes must be capable and reliable to deal with the other uncertainties that will alter the performance of the manufacturing system.[114] Since many processes in aerospace manufacturing systems are not fully capable, the companies then rely on worker skill to overcome the shortcoming and rework the parts to bring them within tolerances. But, the low production volumes and market uncertainties make retaining this workforce difficult, leading to increased skill shortages and a greater impact on the performance of the system.[115]

Capable processes are the key to a manufacturing system becoming "lean" since a tenet of lean manufacturing is that every person and every process must be completely capable.[116]

3.3 Lean Manufacturing in the Aerospace Industry

The introduction of the unique constructs of aerospace products and production serve to show how the principles of lean manufacturing cannot just be blindly applied in an aerospace context. The traditional lean principles were created in the automotive industry. Manufacturing, in general, accounts for a much smaller portion of the value associated with aerospace products than in automotive, or other, industries. Combine this with the instabilities that exist in the aerospace industry and the difficulty in dealing with a very different type of customer with incentives that do not always support lean ideals, and the aerospace industry faces a unique challenge.[117]

But there are some aspects that are advantageous to the aerospace industry. To begin with, production of aerospace products typically occurs at much slower takt times than in other industries and some sectors have fairly stable demand over about a 1-year time span.[118] Also, the aerospace industry is uniquely suited to the idea of "mass customization". The objectives of mass customization match that of lean manufacturing to have the ability to create any variation of a product, as efficiently as possible and at the lowest possible cost.[119] Finally, the aerospace industry has one unique advantage over all other industries and that goes back to the four core missions of this industry – to inspire. People in the aerospace industry love what they do. Engineers and technicians alike. Engineers could frequently move into another industry and

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[113] Squeo, A.M. and A. Pasztor, *Boeing seeks to overhaul aircraft manufacturing*
[114] Shewchuk, J.P. and C.L. Moodie, *Flexibility and manufacturing system design; an experimental investigation*
[115] Sleigh, S. and J. Cutcher-Gershenfeld, *Building the 21st Century Workforce*, presentation
[116] Womack, J.P. and D.T. Jones, Lean Thinking
[117] Murman, E.M., et. al., Lean Enterprise Value
[118] Reynal, V., *Production System Design and its Implementation in the Automotive and Aircraft Industry*
[119] Spear, S. and H.K. Brown, *Decoding the DNA of the Toyota Production System*

make more money, but choose to stay in the aerospace industry simply because of their fascination with the products.

There are already some indications that lean principles do, in fact, apply in an aerospace context and they have worked to improve the design and manufacture of aerospace products. In an early study that unearthed the success of the Toyota Production System (TPS), The Machine That Changed the World, the plants in the study with the highest under-the-skin complexity of the product also had the highest productivity and quality.[120] This was shown in the aerospace industry engine sector through an LAI study that the most complex engine was produced in the best performing system. This shed light on the fact that perhaps complexity in the traditional sense is not indicative of the difficulty of production and that aerospace products could be produced efficiently.[121] This study went on to show that the difference between the various engine manufacturers was the design of the manufacturing system. When another company changed their system, their performance and output improved dramatically.[122] In another, more simplified example of a steering gear, two of the same products were compared and the more complex product that was made of 3 parts instead of 1 was built more efficiently. The manufacturing system design was the difference between the two products, not the product complexity.[123]

The success of the Lean Aerospace Initiative as a consortium may be another indicator of the amount of interest in the application of lean principles, with the acknowledgement of these unique constructs, to the defense aerospace industry. Currently, the consortium is made up of 22 member companies, 7 Air Force Program Offices, NASA, DARPA, the National Reconnaissance Office (NRO), a labor union, international partners in England and Sweden and academia through MIT. It is a consortium, such as LAI, that has the potential to change how manufacturing and these issues are viewed in academia which, in turn, could make industry more productive and innovative.[124]

3.4 Chapter Summary

This chapter outlined how the manufacturing function is typically perceived in an aerospace environment and then offered a set of unique constructs that differentiate aerospace product design and production from other industries. The implication of these unique constructs to the possibility of implementing the principles of lean was then explored and some early indications that lean may still work in an aerospace context were offered.

The set of unique constructs offered in this chapter give the starting point of what needs to be considered when creating and proposing a framework, or evaluating other existing tools, to assist in manufacturing system design processes in the aerospace industry. These unique constructs

[120] Womack, J.P., et. al., The Machine The Changed the World
[121] Ramirez-de-Arellano, L., et. al., *Summary of Research Conducted in the Engine Sector*
[122] Ramirez-de-Arellano, L., et. al., *Summary of Research Conducted in the Engine Sector*
[123] Reynal, V., *Production System Design and its Implementation in the Automotive and Aircraft Industry*
[124] Utterback, J.M., Mastering the Dynamics of Innovation

need to be considered for the tool or the framework to be appropriate for use in the aerospace industry. Previous research does not deal with these unique constructs of the aerospace industry.

Chapter 2 introduced the concepts of manufacturing systems and the manufacturing system design process as a strategic addition to a company. Then the difficulties of the manufacturing system design process were outlined including the gaps that exist in available tools and methods available to assist in this design process. This chapter added to this overall idea of how manufacturing fits into the aerospace context. The perceived role of manufacturing was first introduced, followed by a set of unique constructs that differentiate aerospace products and production from other industries and how those constructs impact the application of lean principles in this industry. Now that the background on how manufacturing should fit within an enterprise and the unique construct of the aerospace industry, in particular, have been introduced, the Manufacturing System Design Framework will be introduced.

4.0 Manufacturing System Design Framework

Chapter Overview

The Manufacturing System Design Framework is introduced in this chapter. The framework, and each phase within it, is outlined. The use of the framework in either a green or brownfield environment is then discussed. Next, the test hypotheses that the framework generates are outlined to guide the next steps of the research effort. Key insights and unique qualities of the framework are highlighted throughout the chapter. This leads into Chapter 5 and 6 where the framework is compared to manufacturing system design processes in use in a set of case studies.

4.1 The Need for a Methodology

The previous chapter discussed the various tools and models that are available and used throughout industry and why those tools are either incomplete or inappropriate for use in the aerospace industry. The variation in available tools prompts the need to develop a meta-framework which can show where all these other tools fit in the overall design process and add the considerations unique to the aerospace industry. In addition to adding in the aerospace considerations, a model is needed to help provide a common language for communication between the various functions and programs involved with the design process. It also must provide a common means for measuring and benchmarking the progress of the design process.[125] Also, proposing a methodology for this process helps make what can become a rather undefined process explicit as well as helping to ensure that important issues are not forgotten.[126]

When creating a methodology, or framework, for the manufacturing system design process, there are a few concerns that must be addressed. This methodology must incorporate a system level perspective to enable the user to view the manufacturing system holistically and it must be a strategic framework showing how this design process fits into the overall enterprise view of the system.[127] The framework must also strike the right balance between difficulty of application and usefulness of results. Namely, the process of following the framework must not be so complex as to be impractical, and not so simple that the results are of no use.[128] Whatever purpose a framework must serve, it must simplify as well as mimic the system or process of interest.[129] Finally, creating a framework to describe this process will help define the process helping to further the creation of a theoretical base to assist in the decision making involved with designing a manufacturing system.

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[125] McManus, H., et. al., *Generic Product Development Model*
[126] Ulrich, K.T. and S.D. Eppinger, Product Design and Development
[127] Muhamad, M.R., *The deployment of strategic requirements in manufacturing system design*
[128] Miltenburg, J., Manufacturing Strategy
[129] Gleick, J., Chaos: Making a New Science

4.2 Introduction to the Framework

The Manufacturing System Design Framework is a product of the Manufacturing Systems Team of LAI. It was created based upon the experiences, knowledge and observations of the team members and has not been scientifically validated. It is an attempt to describe the manufacturing system design process in a holistic manner. It is a meta-framework, meaning that the framework itself contains other tools, methods and frameworks within it. The framework organizes the tools in a manner that helps reduce abstraction through the design process.[130] It is an attempt to structure those tools into a single framework that utilizes the principles of systems engineering, addresses the unique constructs present in aerospace products and acknowledges that manufacturing is a strategic addition to a company's competitive skill set. The framework is also meant to be a visual tool that shows how manufacturing system design extends far beyond the layout of machines on a factory floor.

The framework is divided into two main portions, the top half representing the manufacturing system "infrastructure" design and the lower "structure" design. The infrastructure portion contains the decision making or strategy formulation activities that precede a detailed manufacturing system design. The framework does not assume any specific corporate objective and, therefore, does not lead to any particular solution. The structure portion contains the detailed design, piloting and modification of the manufacturing system. These two portions are linked by a new concept, the product strategy, which is discussed in more detail below.

Figure 10 on the following page is the Manufacturing System Design Framework.[131]

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[130] Maier, M.W. and E. Rechtin, The Art of Systems Architecting

[131] For a more extensive description on the development of the Manufacturing System Design Framework, please refer to P. Fernandes, *A Framework for a Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor.*

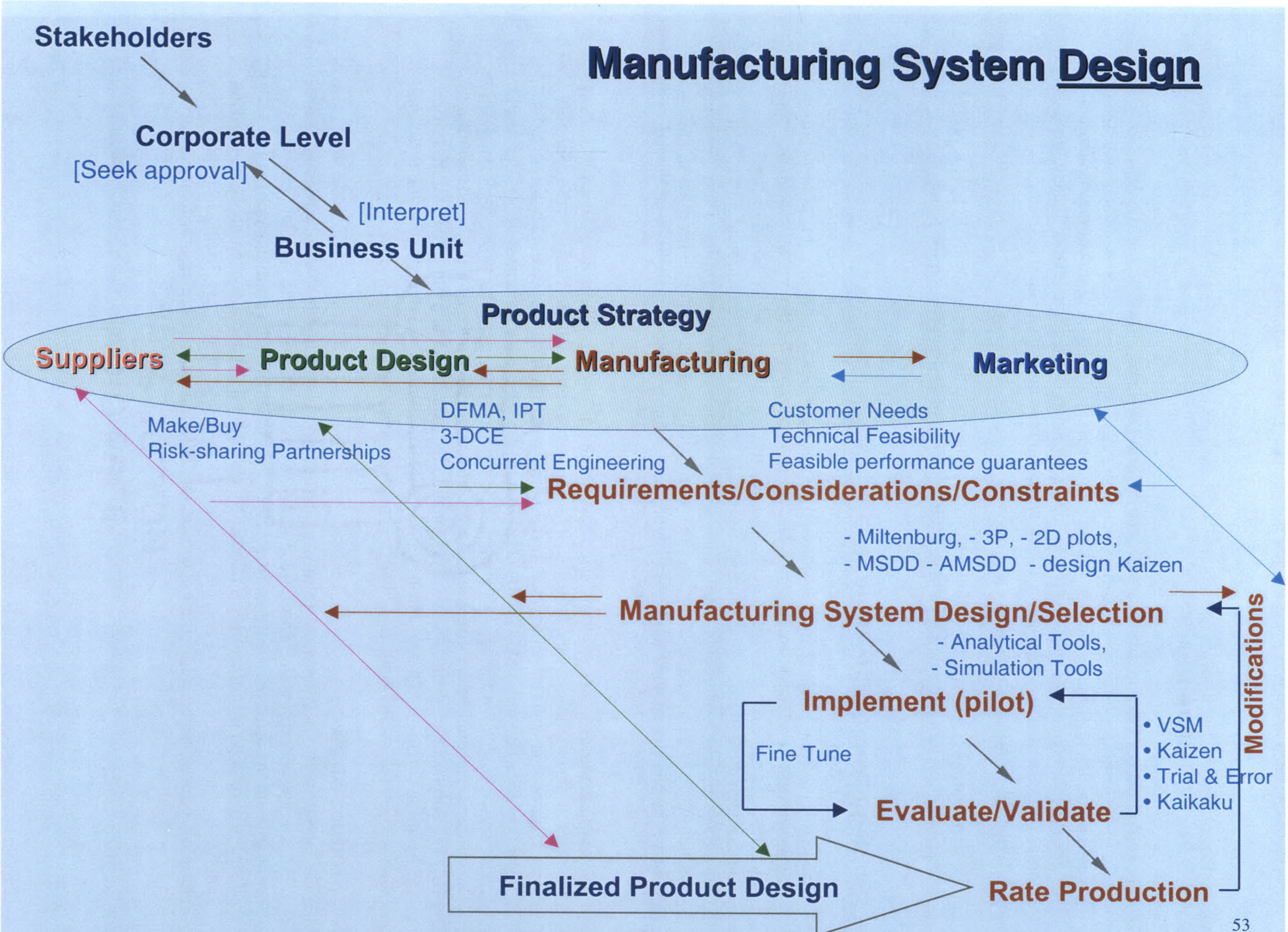

Figure 10: The Manufacturing System Design Framework

4.3 Infrastructure Design

The top portion of the framework is the manufacturing system "infrastructure" design. To review, the manufacturing system infrastructure contains all the activities associated with the overall operating environment of the system – the operating policy, organizational structure, choice of location etc.[132] The infrastructure design consists of the three levels: Stakeholders, Corporate Level and Business Unit. Together, these three units make up the Strategy Formulation Body.

The framework begins with this infrastructure section since the commitment of upper levels of management plays a key role in the manufacturing system design process, for better or for worse.[133] [134]

Strategy Formulation Body

The strategy formulation body is where the needs are processed for the enterprise as a whole. The first level in the strategy formulation body is entitled "Stakeholders". This nomenclature was specifically used to not emphasize a particular stakeholder for the overall system or enterprise. The manufacturing system has numerous stakeholders which could be the stockholders, the customers, the employees, society at large or the environment, just to name a few. Each different stakeholder has unique needs that the system must fulfill. These needs could conflict with one another and it becomes the responsibility of the corporate level leaders to balance the conflicting needs and establish priorities of how those needs will be addressed. This is the formulation of the corporate level strategy.

The corporate level strategy is transferred down to the different business units, or profit centers, throughout the corporation or enterprise. This corporate strategy helps maintain the common threads across the business units since the corporate level links all the separate business units. But this is not a one way link. The business unit is responsible for accurately representing all the resident functions up to the corporate level. The business unit passes up to the corporate level its capabilities, potential future directions and what a reasonable strategy for the business unit may be. The corporate level strategists are responsible for balancing the input of possibilities from the business units with the needs from the stakeholders to create the overall strategic focus and direction for the corporation.

Product Strategy

The next level in the framework, following the strategy formulation body, is the product strategy. This is a new concept, which ensures congruence between the corporate level and business strategy with the different functional strategies. Fundamentally, the product strategy is an instrument to align manufacturing and other functions with the overall corporate strategy. This applies to a single product, or to a family of products. For example, the Boeing Company could have a product strategy for their Next Generation 737, or a product strategy for their narrow-

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[132] Hayes, R.H. and S.C. Wheelwright, Restoring our competitive edge, Competing Through Manufacturing
[133] Monden, Y., Toyota Production System: An Integrated Approach to Just-in-Time
[134] Miltenburg, J., Manufacturing Strategy

body commercial airliners, or a product strategy for all commercial aircraft. The same concepts apply to all the various cases.

The concept of the product strategy is included in this framework for a few important reasons. First, product strategy emphasizes the importance of establishing manufacturing on the same level as the other functional areas of the corporation and, secondly, because the interaction of technological change, organization and a competitive marketplace is much more complex and dynamic than most models describe.[135] The product strategy is an attempt to address the importance of these interactions.

The structure of the product strategy is an extension of the Fine's 3-D Concurrent Engineering (3-DCE) model.[136] The traditional view of 3-DCE consists of suppliers, product design and manufacturing. Marketing is added to this model because of the impact marketing can have in the aerospace industry with things like foreign sales and is considered a core function in other literature.[137] The figure below is the representation used for the product strategy where the product strategy is the overlapping area between the different functions. The shape of the figure implies interactions between the different functions occur and that all functions are represented together with the same status. This emphasizes that manufacturing system design is supported by these other functions of product design, supplier integration and marketing.[138]

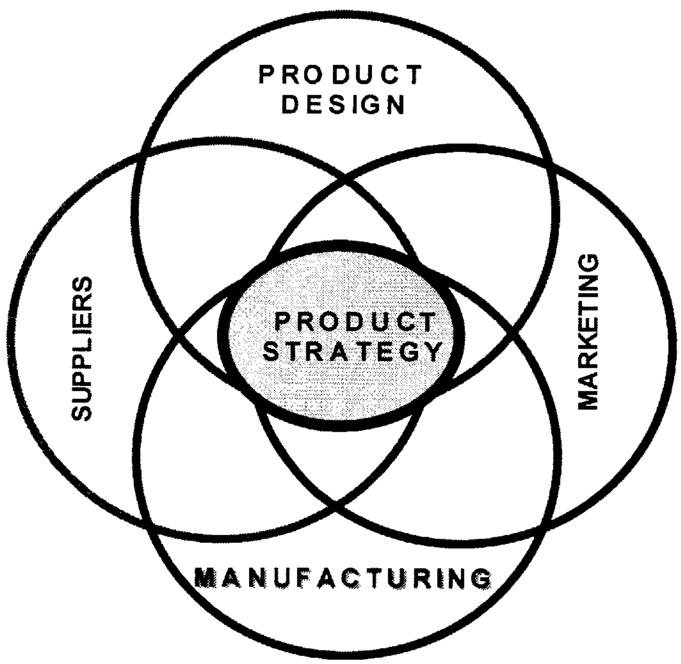

Figure 11: Product Strategy[139]

[135] Utterback, J.M., Mastering the Dynamics of Innovation
[136] Fine, C. H., Clockspeed
[137] Ulrich K.T. and S.D Eppinger, Product Design and Development
[138] Reynal, V., *Production System Design and its Implementation in the Automotive and Aircraft Industry*
[139] Fernandes, P., *A Framework for A Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor*

The formulation of the product strategy requires collaboration between these functions. Between product design, manufacturing and the suppliers, make/buy decisions and the formation of risk sharing partnerships can be formulated. The relationship between marketing, manufacturing and product design leads to an understanding of the true customer needs and technical feasibility of those needs.[140] The relationship between product design and manufacturing is what will lead to the design of a manufacturable product which will be more conducive to high performance in the factory.[141]

Utterback argues that products, as they mature, first experience predominately product innovation followed by a period where process innovation dominates. Where the product is in terms of its product and technology life cycle could shift the focus of its product strategy. For instance, a mature product may wish to choose a product strategy that emphasizes the incorporation of more efficient process technologies as its core objective to win market share or contract awards where price is the discriminating factor.

For ease of incorporation into the framework, the product strategy is represented like an oval in Figure 12. The arrows inside the oval depict the interactions between the different functions but not all the arrows are drawn between all the functions for clarity.

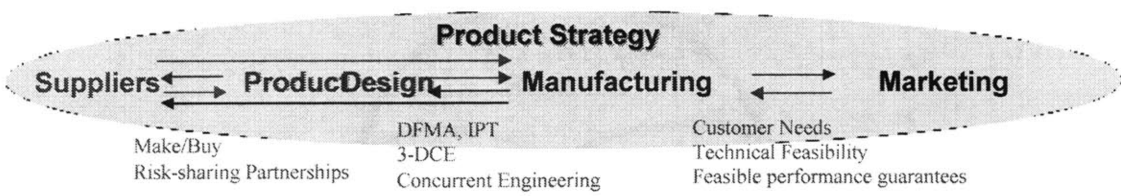

Figure 12: Product Strategy representation within the framework

In summary, a well formulated product strategy provides alignment of manufacturing (and other functions) strategy with business and corporate strategies and helps ensure that decisions made within the function are based on that strategy and long-term objectives of the corporation or enterprise. The structure of the product strategy ensures that manufacturing is an integral part of the corporate structure and allows for clear communication between functions and management levels. The goal of the product strategy is to ensure consistency between decisions made within each function and overall corporate goals.[142]

The product strategy provides the link between the manufacturing system infrastructure and structure design, corresponding to the top and bottom portions of the framework. It does this because the strategy itself, along with the input from the other functions, generates a set of requirements, considerations and constraints for the manufacturing system design.[143] This leads to the design of the manufacturing structure.

[140] Piper, L.J. and W. Pimblett, *A Systems Approach to Manufacturing System Design*
[141] Womack, J.P., Jones, D.T. and D. Roos, The Machine That Changed the World
[142] Rosenfield, D., *Manufacturing Strategy*
[143] Maier, M.W. and E. Rechtin, The Art of Systems Architecting

4.4 Structure Design

Below the product strategy the actual physical manifestation of the manufacturing system design is conceptualized, piloted and refined. Each element is addressed as a separate phase with specific characteristic events and a set of tools that are applicable in transitioning between phases. The remaining phases within the framework comprise the manufacturing system structure design, which follows the formulation of the product strategy. Each phase is one of the major demarcations on the framework beginning with "Requirements/Considerations/Constraints". Since this research is primarily concerned with the design of manufacturing systems, it is the manufacturing portion of the framework that is presented in detail. But following the product strategy formulation, design activities of all the functions would begin and proceed in parallel. The manufacturing system structure is made up of the activities that actually deal with the factory floor such as people, machines and processes.[144]

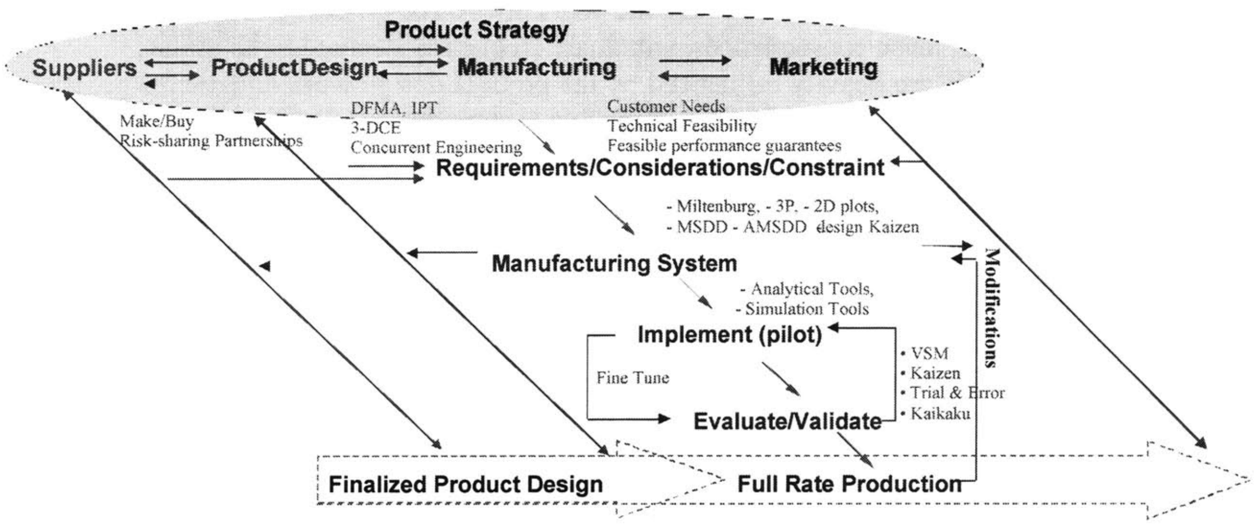

Figure 13: Manufacturing System "Structure" Design portion of framework

Each of the phases within the manufacturing system structure design process will be discussed in turn.

Concurrent Product Design, Manufacturing, Supplier and Marketing Activities

The concurrent design activities for the different functions are represented by the arrows extending from each function in the product strategy oval down to the rate production level. This indicates that the various design activities are all performed concurrently. For example, the product design is progressing at the same time as the manufacturing system design and the

[144] Hayes, R.H. and S.C. Wheelwright, Restoring our competitive edge, Competing Through Manufacturing

suppliers are designing or modifying their own systems or processes to incorporate the new part or components.

Another aspect of the framework and the concurrent design activities is the breadth throughout those activities. At each subsequent phase of the framework, the same concept that derived the product strategy as being the intersection between the circles for the functions applies. This is represented by the arrows that extend from the phase of the manufacturing system design process to the arrow indicating the progression of the other functional design processes. The goal of this view of the framework is to emphasize breadth throughout the design processes. The product strategy is the result of a combination of the different functions. This emphasizes that the breadth and communication should continue through the remainder of the design process, whether it be for the manufacturing system or the product.

Following this concept of breadth in the framework is important to alleviate the classic "thrown over the wall" scenarios in manufacturing system design. Previous research conducted in the aerospace industry illustrated that it is difficult to look at the manufacturing system in isolation from the product design.[145] This can be because the product design will determine most (estimated at 80%) of the cost of the product and will either directly, or indirectly, determine the tooling concept.[146] So, these consequences, which are frequently deemed to be in the manufacturing domain, are heavily influenced by the product design work and, therefore, should not be considered in isolation from the manufacturing system design. By incorporating more input from manufacturing into the early product design slows the product design considerably. But, the overall design time can still be reduced because the need for later (and more lengthy) iteration is lessened.[147]

Another benefit of the emphasis on breadth across the functions through the design process is the result of manufacturing emerging to be an equal member of the competitive skill set of the enterprise. It is no different than the product design or supply chain or any other functional necessity. Maintaining this perspective through the design process will make it easier to sustain it through subsequent improvement activities across the enterprise. This is beneficial in the long run since a full enterprise view encompassing all the different functional areas can be seen as a requirement to maximize the benefit of these improvements.[148]

One characteristic of these concurrent design activities is that they should all be completed, that is, they should all converge to the finalized product and system designs, at the same time. The finalized product design arrow represents that the product should be designed at the same time as the manufacturing system and the supply chain is ready to support its production. All too frequently in practice, however, one function will complete their design activities long before the others meaning that part of the overall design effort is stalled waiting for the others to catch up. Frequently, the product design will be completed first. This results in using a low-rate system configuration to carry the company through the early high-rate production levels.

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[145] Dobbs, D., *Development of an Aerospace Manufacturing System Design Decomposition*
[146] Haggerty, A., presentation for LAI
[147] Eppinger, S., Whitney, D.E., et. al., *A model based method for organizing tasks in product development*
[148] Kessler, W., Lean Enterprise presentation

Requirements/Considerations/Constraints

The next phase in the framework is the determination and definition of the requirements, considerations or constraints that will guide the detailed design effort. These requirements, considerations or constraints could result from internal or external influences, be mandatory or voluntary, but the effect on the manufacturing system design process is the same. These are the goals that must be met for the system to be a success.

These requirements, in part, flow down from the complete product strategy as well as from the various component functions. There will be circumstances when the requirements from different functions, or external agencies will conflict. The framework attempts to resolve these tensions. The framework emphasizes breadth across the different functions, as was mentioned earlier, throughout the design processes. This creates ample time for feedback between the different functional groups and reinforces the idea of collaboration between these groups for the purpose of achieving the strategic goals of the company rather than individual component goals.

Guidelines for the requirements to be defined were presented earlier. These inputs to the manufacturing system design process are:

- Market Uncertainty
- Production Volume
- Production Mix
- Frequency of Changes
- Product Complexity
- System Process Capability
- Type of Organization
- Available Worker Skill Level
- *Time to First Part*
- *Investment*

These inputs fit into the context of the manufacturing system design framework because they require input from the other functional areas. The product designers provide the information that translates into the product complexity, frequency of design changes and capability of processes to do what the designers require. Marketing provides the knowledge of needed production volume and mix and variability of those values. The suppliers and the capability of their processes could potentially impact the make/buy decisions or supplier selection for different components. Finally, the manufacturing component contains the information of the internal processes capabilities, available skill levels, core competencies, as well as what resources and investment are required to pull everything together.

In all, the different functional areas that make up the product strategy all impact the requirements set for the manufacturing system. A manufacturing system is then designed or selected to meet the established requirements.

Manufacturing System Design or Selection

A manufacturing system is either selected from existing proven systems or designed from scratch based on the finalized set of requirements. Some of the manufacturing systems that are used widely in practice include job shops, cells, FMS, transfer lines, project shops, flow lines, assembly lines and moving or pulsed assembly lines. This particular research effort focuses on assembly lines and the potential derivatives, but the framework applies to assembly and fabrication operations equally.

This phase is placed in the framework explicitly to emphasize the need to make a conscious decision when selecting or designing a manufacturing system. A strategy formulated for the product and for the manufacturing operation is useless if the associated manufacturing system is just chosen arbitrarily. Careful analysis must be performed to design or select a manufacturing system that supports the strategy while simultaneously fulfilling the requirements.

This is not a trivial step and this is made more difficult because it is not a predictive step since a "manufacturing science" does not exist. But the framework includes tools that are available to assist in, or guide, the design or selection process. Some of these tools include the 2-D maps of production volume and mix, Miltenburg's strategy worksheet and the MSDD or AMSDD. These and other tools are included in the framework.[149] [150]

Implement (Pilot) ←→ Evaluate/Validate Loop

The implement and evaluate loop is the smaller loop in the framework which calls for implementing the chosen manufacturing system on a smaller scale, either in terms of rate or capacity, to test the concepts embedded within the manufacturing system design. This allows the system design to be tested, fine tuned and eventually brought to rate or full-scale production.

This can be accomplished using either computer simulations, scale models, full-scale models operating at a low rate, moonshine shops, physical mock-ups or pathfinders. Whatever the method, the objective of the piloting activity is the same, to subject the system design to practical tests to pinpoint problems. Like flight testing of a new aircraft, no matter how detailed and careful the analysis, things always turn up in flight test that were not anticipated.

But, also like in flight test, what is tested, or piloted is important.[151] The piloting loop is intended to find and fix problems so the system can function smoothly when it is brought up to rate-production levels. Another benefit of the piloting step is that it allows an additional opportunity for creative, new ideas to make their way into the system. Throughout history, the "experimental" plant has played an important role in the development of radically new ideas for production concepts and the piloting activities help instill this creative atmosphere into the manufacturing system design process as well as helping to smooth the transition to rate production when the time comes.[152]

[149] For more information on these, and other, tools to assist in the Manufacturing System Design/Selection phase, please refer to P. Fernandes, *A Framework for A Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor.*
[150] For an introduction to these, and other, manufacturing system design infrastructure and structure design tools, please refer to P. Fernandes, *A Framework for A Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor.*
[151] Da Silveira, G., *A methodology of implementation of cellular manufacturing*
[152] Karlsson, C., *Radically new production systems*

Rate Production

The next phase of the manufacturing system design framework is the rate production phase. The large arrow represents the finalized product design, and at this stage, the manufacturing system is ready to support the production effort. "Rate" production can be interpreted many different ways and does not necessarily mean "Full-Rate". In the aerospace industry, especially, low-rate initial production (LRIP) certainly counts as rate production and should take place in a manufacturing system that will be used for full-rate production.

The arrow for the finalized product design spans all the different functions of the company maintaining the focus on breadth throughout this process. And as was mentioned in the need for concurrent design activities, these design activities should all converge at the rate production level. A mismatch in the timing of completing the design activities could delay the start of production, or require starting production in a system that was not intended to support rate production levels.

Modification Loop

The last phase of the manufacturing system design framework is the modification loop. This is the cycle that represents continuous improvement, showing that the manufacturing system design process is never complete. This loop is active as long as the manufacturing system is in operation. The modification loop can be active to fix problems that have emerged since the system has entered rate production, accommodate a manufacturing process change or design change or perhaps incorporate new technology into the product or the manufacturing system design process. The modification loop captures the essence of the Toyota Production System where the quest for perfection through continuous improvement never stops. As examples from Toyota illustrate, continuous improvement requires the continuous redesign of the manufacturing system. It is a way of life for companies striving to become lean.[153]

The modification loop, like the rest of the framework, also requires the different functions within the organization to be linked. Success in continuous improvement activities requires equal emphasis on product and process design, which must be closely integrated.[154] This also means that improvement activities don't necessarily have to occur on the factory floor. There is a potential of benefiting from improvements and modifications in the other functional areas.[155] Also, the improvement efforts cannot be done in isolation of the system strategy. Rather than improving the system for the sake of improving the system, the goals of the system that were established by the product strategy need to be revisited.[156] This will help ensure that the improvement activities will support the corporate strategy in the long run.

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[153] Black, J T., *Lean Manufacturing Cell Design - Tutorial*
[154] Utterback, J.M., Mastering the Dynamics of Innovation
[155] Kessler, W., Lean Enterprise presentation
[156] Cool, C., *Journey To A Lean Enterprise*

4.5 Greenfield and Brownfield Application

The manufacturing system design framework applies to both green and brownfield environments. True greenfields are rare; therefore, this framework was created to assist practitioners in either setting.

Brownfields are simply existing manufacturing systems or facilities. Rather than designing a new system from scratch, an existing system is being re-designed or heavily modified. Since manufacturing systems and facilities are capital intensive, it is more common to accommodate new product introductions, manufacturing process changes, new technology insertions or system relocation within existing facilities using common machines and equipment.

The framework still applies by using the idea that a re-design of this magnitude is the same as a greenfield design effort, but with more constraints. A brownfield design activity will have additional constraints emerge in the Requirements/Considerations/Constraints phase. Using the framework in a brownfield environment will help ensure compatibility between a new process insertion or a new product introduction and the existing system.

4.6 Chapter Summary

This chapter served as an introduction to the manufacturing system design framework. The framework will be tested against case studies, which are detailed in the Chapter 7 following an in-depth description of the research design.

In summary, the manufacturing system design framework is a visual meta-framework that contains many other useful tools. It guides the manufacturing system design process and does not assume any particular solution. It is comprised of two halves which represent the design of the manufacturing system infrastructure and structure. These two halves are linked by a new concept of the product strategy that is based on collaboration between different functional elements of the company. This idea emphasizes the need to treat manufacturing as a source of competitive advantage for the enterprise. Each phase within the framework represents the necessary decision making activities that should be occurring at that point in the design process.

There are also some key insights to be gained from studying the manufacturing system design framework. The breadth of the framework across the different functions and the inclusion of the high-level strategy formulation body show that manufacturing system design extends beyond the factory floor and includes all functions of the corporation. The presence of the strategy formulation body emphasizes that the key decision-makers are part of this design process and the manufacturing system design process should have a strategy that supports the core competencies of the enterprise. The formulation of this strategy will have an impact on the product characteristics and requirements on the manufacturing system. Also, the modification loop of the framework emphasizes the fact that manufacturing system design never ends. There are always improvements to be made. This framework applies the principles of systems engineering in a rigorous manner to a domain where systematic principles have seldom been used before.

At this point, the framework is based on practical knowledge and requires more rigorous validation activity. This thesis presents only preliminary data collection that seems consistent with it.

5.0 Research Design

Chapter Overview

The framework will be tested by comparing it to manufacturing system design processes actually used in industry. This section outlines the important aspects of the framework validation and supporting cases. The cases only focus on assembly operations and span multiple sectors of the aerospace industry. Multiple sectors were addressed to try and determine the generalizability of the framework. But it was also a goal to match case studies on similar products where some of the external influences to the system and the nature of the product designs are similar. This allows a small number of differences in the manufacturing system design processes to become more readily apparent.

Conducting these case studies to attempt to validate the framework applies to two of the research objectives stated in the introduction. First, it will help gain an understanding of how manufacturing systems are designed in the real world. Second, it addresses the actual framework validation.

This chapter opens with a more detailed description of how this comparison will be carried out including the scope of the studies, site selection, mechanics of the framework validation and how the performance of the systems and system design processes are measured.

5.1 Test Hypothesis

The creation of the manufacturing system design framework generates a test hypothesis to guide further efforts. The framework prior to this research was based on experience and previous research and requires validation. This research will help substantiate the manufacturing system design process proposed by the framework and illustrate that it can be used in industry to design new manufacturing systems. So, the framework validation will be guided by the following test hypothesis:

> *Following the process proposed by the framework will result in a company developing an effective manufacturing system that meets the established goals of the corporation.*

"Effective" means that the actual system performs as desired and meets the established goals. The measure of effectiveness is described in detail in the description of the research design in the following sections.

This hypothesis will be tested in industry through a structured interview of each case study, which are captured in the following chapter.

5.2 Assembly Operations

Studying existing manufacturing systems is a tremendously complicated task. In order to make comparisons between different systems and different system design processes, some simplifying assumptions must be made. The first assumption exercised in this research is to focus only on assembly operations. This greatly simplifies the problem since the outputs of the manufacturing system design process are going to be some type of assembly line (varying from fixed position to continuously moving) and the nature of the work from one product to another will be roughly similar. Another benefit is that while assembly and fabrication operations are frequently spread out between multiple sites, the final assembly of a product or the assembly of a major sub-assembly usually takes place in a single location making actual observation of the system more practical.

In addition to the benefits resulting from the degree of simplification that this narrowed focus provides; assembly operations are also logical places to focus the initial work with the framework. Since final assembly is at the end of the value stream, it is highly visible to the customer. Also, in most cases, there is a definitive end to the work contained within the system. For military aircraft and electronics, there is a buy off process. The product has to be in final working order when the customer takes possession of the product. For the space sector, either launch vehicles or satellites, once the product is launched, the product can no longer be serviced. This definitive end of the system relates to the basics of systems engineering and principles of good engineering problem solving. When designing a system, whether it is a manufacturing system or a thermal system, does not matter. The first step is to define the boundaries of that system.[157] This is much easier to do in the assembly operations where the system has a more definitive end to the work content.

Focusing on assembly operations exclusively has other benefits for this research effort. To begin, assembly work is the only major part of the work that major aerospace firms are still doing. Many of the aerospace companies are outsourcing the fabrication work and machining operations in order to focus their efforts on the assembly, integration and testing procedures.[158] [159] Even though the final assembly operation may only constitute 10-20% of the cost of the product, it still provides a good starting point for testing the framework. If the framework can hold in this environment, the next steps would be to move back in the value stream into fabrication operations where some of these simplifications no longer hold. This will then allow greater portions of the value stream, as far as costs are concerned, to be addressed.

5.3 Site Selection

The case studies are an invaluable portion of this research. The exposure to real world manufacturing system design processes helped to initially define the scope of the framework as well as the subsequent testing. It is important that the cases expand the aerospace industry to

[157] Reynal, V., *Production System Design and its Implementation in the Automotive and Aircraft Industry*
[158] Fernandes, P., *A Framework for A Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor*
[159] From an interview with Al Haggerty, Boeing VP (retired)

ensure that the unique constructs of aerospace products (described earlier in Chapter 3) are addressed while simultaneously keeping the scope of the framework broad enough for use in other industrial environments.

Adequate testing of the framework requires that there are enough cases to span across multiple sectors of the aerospace industry. The case studies conducted include major aerostructures, electronics, launch vehicles and satellites, both military and commercial. This grouping of cases provides a generalizable data set as well as a data set that encapsulates the unique characteristics of aerospace products and business. Cases that span from major aerostructures to electronics show some of the differences in sectors of industry that function at very different clock speeds. The Rockwell Collins TDR-94 (transponder) is produced at a rate of over 100 units per month while the Boeing 737NG, which currently is the fastest production rate of any aircraft by a substantial margin, is produced at 28 units per month. This leads to very different inputs into the manufacturing system design process and helps support the generalizability of the framework. Also, cases that range from the major aerostructures to satellites show the breadth in technology and process maturity to which the framework can apply. Major aerostructures can be constructed out of sheet metal skins that have been around since World War II era designs, or from cutting edge carbon composites. A similar scope in technological maturity exists in any of the other sectors. Typically, newer, less mature technologies have less capable processes which have a major impact on the manufacturing system.

There were two different classes of case study sites used for this research. The first class consists of those cases where the manufacturing system design process was observed in real-time. This allowed for repeated visits to see progress and changes to the design process and supported prolonged involvement and contact with the sites. The other class consists of cases were retrospective where the manufacturing system design process was captured through interviews. A record of site visits and interviews is located in Appendix B.

5.4 Framework Validation

An evaluation tool was developed to rigorously validate the framework. This evaluation tool was developed to capture how closely the manufacturing system design processes used in the case studies match the process proposed by the framework. The use of an evaluation tool structured the data collection between all the cases to ensure that the same questions and scoring criteria were used for each site. The degree to which the process used by the case and the process proposed in the framework matched became the "framework congruence" value. This value is a measure of how well the process proposed in the Manufacturing System Design Framework matches the real world. This is not an evaluation of the manufacturing system design processes used by the case studies – this is an evaluation of the framework.

The measure of performance was the actual performance of the manufacturing system as compared to the planned performance and is described in detail later in this section. The data were collected from managers at the Business Unit level of the different case studies using a tool that has three goals, which are to determine:

- If a phase in the framework was addressed in the industrial process (phase presence).
- If the phase was addressed in the same order as proposed in the framework (timing).
- If the phase was executed with breadth across the different functional areas as addressed in the framework (breadth).

Those three themes of phase presence, timing and breadth will guide the analysis of the data. The results of the information gathered by the tool will be compared with the effectiveness of the resulting manufacturing system in meeting its performance goals to determine the framework validity. A description of the performance metrics follows this section.

For more detailed information about the framework evaluation tool, please refer to Appendix C. This appendix outlines the construction of the evaluation tool as well as what the tool attempted to assess.

5.5 Performance Metrics

In addition to the questionnaire to capture how closely the industrial practice matches the process proposed by the framework, the performance of the design process must also be captured. This will allow a relationship to emerge if there is a correlation between the degree to which a firm follows the framework and the performance of their manufacturing system and the ability of that system to meet the original goals established.

The determination of a suitable performance metric is not an easy task for a manufacturing system. Products are usually evaluated on commercial value, cost, quality, innovation or customer satisfaction.[160] But assessing a manufacturing system based on the performance of the product does not indicate how well the system was designed, operated or what its potential is.[161] What should be measured is how well the goals are satisfied by the system that results from the system design process. In devising the actual metric to be tracked, it must be ensured that the metric measures actual performance of the system and not perceived performance.

Given this, the framework validation will be based on a measure of actual performance compared to planned performance of the system. This was chosen since it was a consistent metric that could be applied to all the cases in this particular data set. After trying numerous other possible metrics, this was the one where specific metrics could be gathered from each site and normalizing it would be possible. The specific measure to be compared depends on the company (not all companies track the same data) and whether the product is in production, a first unit or developmental.

For each classification of status of the products, different information may be gathered to obtain the actual/planned metric. Production units, like the F-16, 737 or Iridium, metrics like throughput time, hours per unit, number of non-conformances or hours of rework will be captured. For the first flight units such as EELV and JSF the actual/planned metric for the first flight vehicle still holds. Finally, for the programs that are still in development such as

[160] Ulrich, J.M. and S.D. Eppinger, Product Design and Development

[161] Wang, A., *Design and Analysis of Production Systems in Aircraft Assembly*

Wedgetail or AEHF, the actual/planned metric can only be applied to the status of the design effort rather than any actual production performance. This concept of measuring actual to planned performance allows the design status of different products from different companies and sectors to be compared. For example, for the 737NG, which is assembled on a moving line, the throughput time will not change but the man-hours per unit can change. Meanwhile, on a product like the A2100 commercial satellite, the throughput time in days will change to reflect differences in the assembly operation from unit to unit. Again, in these circumstances, the actual/planned metric allows what is a suitable measure for one system to be compared against a suitable measure for another system.

But, in order to maintain construct validity it needs to be shown that this is measuring what is intended.[162] It is not intended to measure how accurately the company plans the assembly time of a first unit, so it must be shown that the method of creating the "planned" performance is roughly similar. This presents a threat to the validity of the metric because this was not done for the case studies used in this research. This research does not show that the planned performance states were determined in the same manner between the different cases. It is assumed that all the case studies use their own internal planning methods to the best of their ability to derive fair and realistic estimates of manufacturing system performance.

Despite this potential threat the actual/planned metric can be an accurate performance measure of the manufacturing systems. Previous LAI research has used the actual/planned performance measure successfully. It was used in the summary research for the engine, airframe and electronic sectors and in those focused research summaries, the consistency in the various planned states was shown.

5.6 Chapter Summary

This chapter outlined the research design that will guide the framework validation exercises. The test hypothesis, project simplifications and validation techniques were described. The project simplifications are to focus only on assembly operations. The framework will be validated using a tool to determine the framework congruence of an industrial manufacturing system design process compared to the proposed framework. This framework congruence will be compared with the ability of the actual manufacturing system to meet the planned performance.

[162] Robson, C., Real World Research

6.0 Application of the Framework in Industry

Chapter Overview

The objective of this chapter is to detail the manufacturing system design processes observed in 14 different case studies and compare these to the framework proposed in chapter 4. The introduction of the manufacturing system design framework led to the test hypothesis that a firm following it will develop a more effective manufacturing system. These case studies test that hypothesis by comparing how well a process matches the framework to the ability of the manufacturing system to perform as planned.

This is accomplished with in-depth descriptions of each case study. They are presented by sector and span major aerostructures, electronics, launch vehicles and satellites. The data and stories presented in the case studies were gathered on site by the author.

6.1 Major Aerostructure Assembly

The first section of case studies is major aerostructures from both military and commercial platforms. This section contains the results from the F-22 Raptor mid-body, wings and aft fuselage, F/A-18 E/F Super Hornet Enhanced Forward Fuselage, 737 Next Generation final assembly, F-16 Fighting Falcon final assembly and the assembly of the concept demonstrator aircraft for the X-35 Joint Strike Fighter. The F-22, 737NG, F-16 and X-35 cases were captured retrospectively and the F/A-18 case was followed in real-time.

For each product, the background of the need for a manufacturing system design or re-design effort is outlined including the actual design process used. A comparison between their process and proposed framework is also included.

F/A-18 E/F Super Hornet ECP6038 Forward Fuselage

The F/A-18 E/F is a multi-role tactical aircraft that comes in either a single seat (E) or two-seat (F) variant. The F/A-18 has both air-to-air (from the 'F' designation) as well as air-to-ground capabilities (from the 'A' designation). The F/A-18 family has been developed mainly for the U.S. Navy's aircraft carrier environment.

Figure 14: Boeing's F/A-18 E/F "Super Hornet"

The original family of the F/A-18 consisted of the A/B models developed in the 1970s. The C/D models came out 10 years later and consisted of mainly a systems upgrade from the original A/B models.

The F/A-18 E/F "Super Hornet" is the most recent addition to the F/A-18 family. The primary objectives of the E/F were longer range, greater bring back capability (return and land on the carrier with more weight – fuel or unused ordinance) and overall mission performance improvements. Another goal of the E/F was to give manufacturing fewer parts and to allow for a robust design and assembly operation.

The E/F differs significantly from the C/D, with the exception of a commonality in avionics with the C/D models and a limited similarity with the airframe. Some of the differences between the C/D and the E/F are summarized in the following table.

Table 1: Changes in attributes from F/A-18 C/D to F/A-18 E/F[163]

Attribute	Change from C/D to E/F
Part Count	C/D = 14,104 E/F = 8,099 42% reduction in total part count
Size	25% increase
Unrefueled Range	40% increase
Payload	25% increase
Bring-Back Ordinance	3 times greater
Survivability	5 times greater

[163] Harley, R. and W. Carrier, *F/A-18 E/F EFF Program Overview*

Case Study Background

The forward fuselage is the major assembly that changed the least from the C/D to the E/F since it was not a major driver of mission performance. While moderate affordability and quality improvements were made, the original E/F forward fuselage (known as the "Block 1" design) retains many of the original F/A-18 A/B and C/D structures and subsystems whose components are based upon late 1970's to mid 1980's technologies. Also, the forward fuselage is in the critical path for the F/A-18 E/F. It comprises a significant portion of the total assembly cycle time and rework costs accounting for 44% of the defects and 32.5% of the rework costs for the Boeing portion of the airplane.[164]

Since the forward fuselage is such a large portion of the cost and cycle time, it was a perfect candidate to apply new designs, technologies and "lean" processes to improve its affordability and quality. Boeing and the U.S. Navy combined a planned avionics improvement program with the affordability initiative in a program entitled the "ECP6038 Forward Fuselage (EFF)". In addition to affordability benefits for the U.S. Navy, the program will help achieve the goal of making the F/A-18 E/F a $40 million airplane by 2005.

The EFF project will also help the Hornet team to reduce the cycle time from 34 months to 18 months for the complete airplane, with an interim goal of 24 months for 2001. Other goals for the EFF include a defect reduction of 90% and future growth volume for additional avionics systems. The strategy for the ECP6038 Forward Fuselage development effort is to utilize more unitized structures to reduce assembly work content and improve routing paths to increase installation efficiencies.[165]

The forward fuselage on the E/F is already performing well, so they are working with something that is far from broken. Since the Block 1 fuselage is already a successful product, the team has to ensure that the EFF won't take away any good qualities. This need to create a product that can seamlessly replace the Block 1 fuselage creates a set of constraints and boundary conditions on the EFF development. One constraint is to keep the fuselage weight neutral to avoid going through re-certification processes. Another constraint is to not move the pilot's eye position or the location of the in-flight refueling (IFR) probe in relation to the pilot. This alleviates the need to retrain any pilots and retains what have been considered good qualities of the airplane. Other constraints include maintaining the outer mold line, the nose landing gear interface, canopy, the crew station, IFR probe and tanker interface, gun location, and the interface with aft fuselage.[166]

The final design of the EFF eliminates 1,029 structural parts, 15,441 fasteners and approximately 300 tooling details from the existing design. Traditional sheet metal skins were replaced with monolithic composite skins to significantly reduce the amount of frames and other substructure, thus reducing both fabrication and assembly costs. Cold working of joints has been eliminated as well as the number of fastener types. As far as sub-systems changes, there is a 15% part reduction while adding 6 new systems. There is also room for 25% growth volume so more systems can be added in the future. The EFF was kept weight neutral by using more composite

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[164] Haggerty, Al, presentation for LAI
[165] *F/A-18 E/F ECP 6038 Forward Fuselage Program Overview*
[166] *F/A-18 E/F ECP 6038 Forward Fuselage Program Overview*

materials, eliminating parts and fasteners and optimizing subsystem routings (shorter wire bundles and fluid tubing).

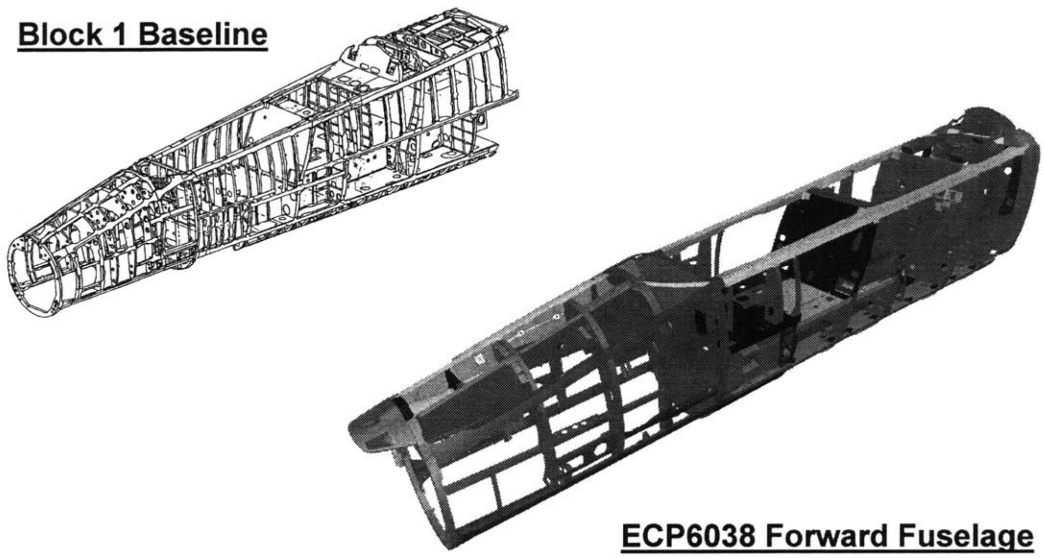

Figure 15: Comparison of Block 1 and ECP6038 Forward Fuselage[167]

Part of the design effort was dedicated to reducing the part count in the structure. Through unitization and overall elimination of parts a 40% reduction in detailed parts was achieved. Also, a reduction in parts leads to a reduction in necessary fasteners and rivets.[168] The following tables summarize the part and fastener reductions from Block 1 to the EFF.

Table 2: F/A-18 E/F Block 1 and EFF Detail Part Comparison[169]

	Block 1	EFF	Percent Reduction
Nose Barrel	707	375	47%
Fuselage	1855	1158	38%
TOTAL	2562	1533	40%

Table 3: F/A-18 E/F Block 1 and EFF Fastener Comparison[170]

	Block 1	EFF	Percent Reduction
Structural Fasteners	24,477	10,955	55%
3/32" Rivets	5,912	3,993	32%
TOTAL	30,389	14,948	51%

This reduction in part and fastener count leads to fewer parts to order, track, assemble and maintain leading to a substantial cost savings for the airplane. Also, it has been said that the most

[167] Harley, R. and W. Carrier, *F/A-18 E/F EFF Program Overview*
[168] *F/A-18 E/F ECP 6038 Forward Fuselage Program Overview*
[169] *F/A-18 E/F ECP 6038 Forward Fuselage Program Overview*
[170] *F/A-18 E/F ECP 6038 Forward Fuselage Program Overview*

reliable part on an airplane is the one that isn't there because it isn't needed.[171] The lowered part count infers that a part in need of maintenance is more difficult to repair, but this was accounted for by making the design more robust. The reduction in part count also requires more up front work and communication with the suppliers and forces issues that arise during assembly to be addressed in the part designs since things cannot be jury rigged on the floor as easily. Unitization of structures is helpful to the factory floor since there are fewer parts that can be late or defective, but if a problem does arise with a late or defective part, it can paralyze the system since the part is more integral to the structure. Work arounds cannot occur.

The program is facing some unique challenges. Only one test article for both fatigue and static tests will be produced to save the cost of constructing a second test article and the production of the EFF will begin when the test article is in fatigue testing. The EFF will also be introduced into production for an airplane that is already at full-rate while trying to help achieve the goal of making the F/A-18 E/F a $40 million airplane. This is a challenge different from any of the other cases studied for this research.

Need for a Manufacturing System Re-Design

Design for manufacturing was an integral part of the EFF program. The EFF Integrated Product Team (IPT) employed an immersive, virtual reality system as the principal design visualization/integration tool. Thus, all members of the IPT, including manufacturing personnel, could review and comment collectively on the ECP6038 design. Each night, hundreds of EFF CAD models were translated into the virtual reality (VR) system so every morning the daily design review used the current configuration. All the different disciplines were linked by this virtual prototype. Shop floor assembly workers participated directly in the development of the EFF design, contributing their knowledge and experience of existing issues and desired features. The solid models have given the design team the ability to apply new technology in a rapid and consistent manner.

This is also the pilot program for model based work instructions (MBIs). The MBIs are derived from all the engineering data and 3D solid models. Unlike traditional text-based instructions, the MBIs are graphical work instructions that use 3D solid models and informative text boxes, arranged in a build sequence, to illustrate the production process. The shop floor workers can manipulate these models to view the assembly from all directions and can access detailed engineering information directly from the model to help clarify an unclear instruction to solve a unique problem.

Variability analysis was another module of the integrated design tools. This allowed for the capability of the fabrication processes to be predicted. The model predicted C_{pk} for fabrication processes to ensure that it would be sufficient to maintain the outer mold line and assembly tolerances before any parts were actually fabricated. They could not, however, predict the capability of the whole assembly system – there is not enough time, staff and computing power available to make such a large calculation.

Yet another tool used in the design phase was the assembly simulation which determined the optimum build sequence. The fuselage was built thousands of times before the hardware existed.

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[171] Maier, M.W. and E. Rechtin, <u>Art of Systems Architecting</u>

Closely coupled with the assembly simulation was the maintainability simulation. The virtual reality tool described above was used to allow the Navy maintainers to evaluate maintaining the airplane virtually when it was still in development. Thus, "design for supportability" suggestions were incorporated during development, instead of waiting until the first aircraft was built. This work was so successful that the Navy waived the requirement to follow up with the on-aircraft maintainability demonstration.

The design for manufacturing initiative on the EFF meant that it was a goal to design out the manual crafting that is done on the shop floor for the Block 1 assembly processes. The facility can be impacted by significant workforce changes and the designers don't want to rely on learning curve and employee retention to be able to build the airplane. The EFF was fully intended to be easier to assemble. The following picture is from a presentation that was given by the EFF management to the overall F/A-18 E/F program management and is accompanied by the caption, "Why look at the production process?" It is intended to illustrate the difficult working conditions faced by some production personnel with the Block 1 design.

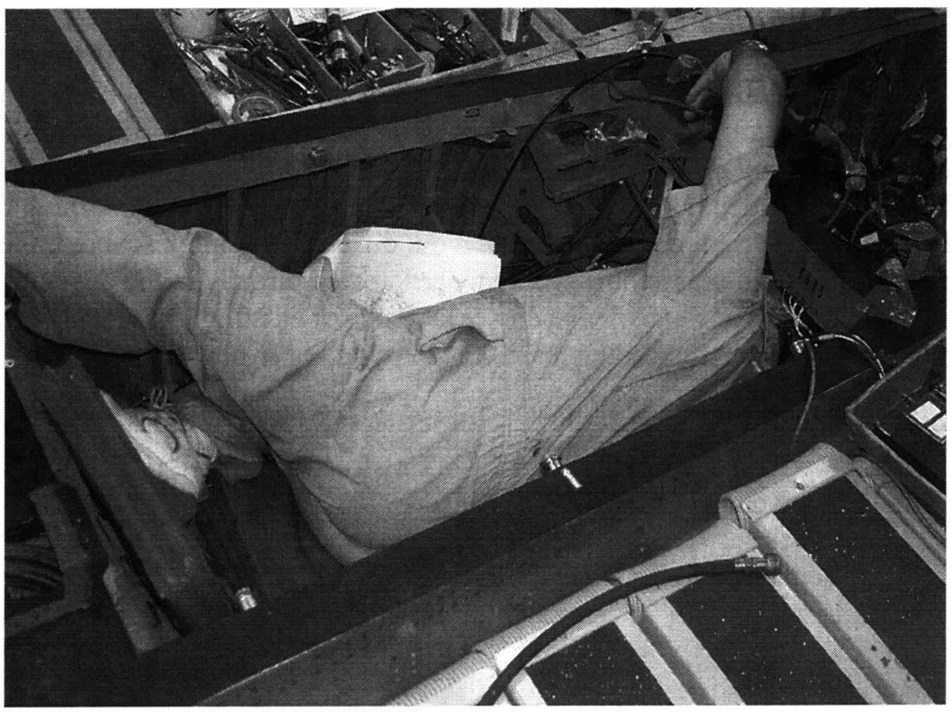

Figure 16: Systems installation on the F/A-18 E/F Block 1 forward fuselage[172]

But beyond eliminating the manual crafting in the assembly processes, it was planned to not change anything in the assembly system for EFF. They were going to use the same build plan for EFF as they had for Block 1. They had no real impetus for change when the system that they already had in place was producing a high quality fuselage. Doing this would also avoid the need for any additional tooling. Continuing with the existing assembly system was a low risk decision with low non-recurring costs when they couldn't think of something that was appreciably better.

[172] *F/A-18 E/F ECP 6038 Forward Fuselage Program Overview*

So the design of the product continued on and no work was done with the assembly area. The new design tools and assembly simulations would help determine the ideal sequence of work, but the overall assembly flow and tooling concept was to remain unchanged.

As the design was nearing completion, it was discovered that the goals of cost savings and cycle time reductions were not going to be met with the design alone. They were going to have to address the assembly processes and try to build the EFF differently. With the ideal build sequence from the simulations using their existing manufacturing system, the assembly time was reduced from 124 days to 120 days. Not a substantial improvement.

At this point it was decided to try and open the structure up and take advantage of parallel processing to get work off the critical path. It was decided to break the fuselage into three sub-assemblies: the nose barrel, upper and lower aft portions. A new manufacturing system would have to accommodate a new and faster assembly operation.

The F/A-18 E/F EFF manufacturing system re-design is the ultimate brownfield – not only is the system being redesigned, but it is being done while at full-rate. There will be no ramp-up in production rate for the EFF, it will break-in at a rate of 1 airplane a week.

Actual Manufacturing System Design Process

The existing manufacturing system is comprised of three main sections in the forward fuselage area. First of all, the fuselage is built up within the LRET (Low Rate Expandable Tooling) until it is a structurally complete assembly. The fuselage typically spends 70 days in the LRET tool in the existing system. The fuselage is then moved into the clean-up line across the aisle. This station installs numerous small details and the leading–edge extension (LEX). Next, the fuselage is moved into the "wagon wheel" for systems and canopy installation. The figure below shows the forward fuselage manufacturing system for Block 1.

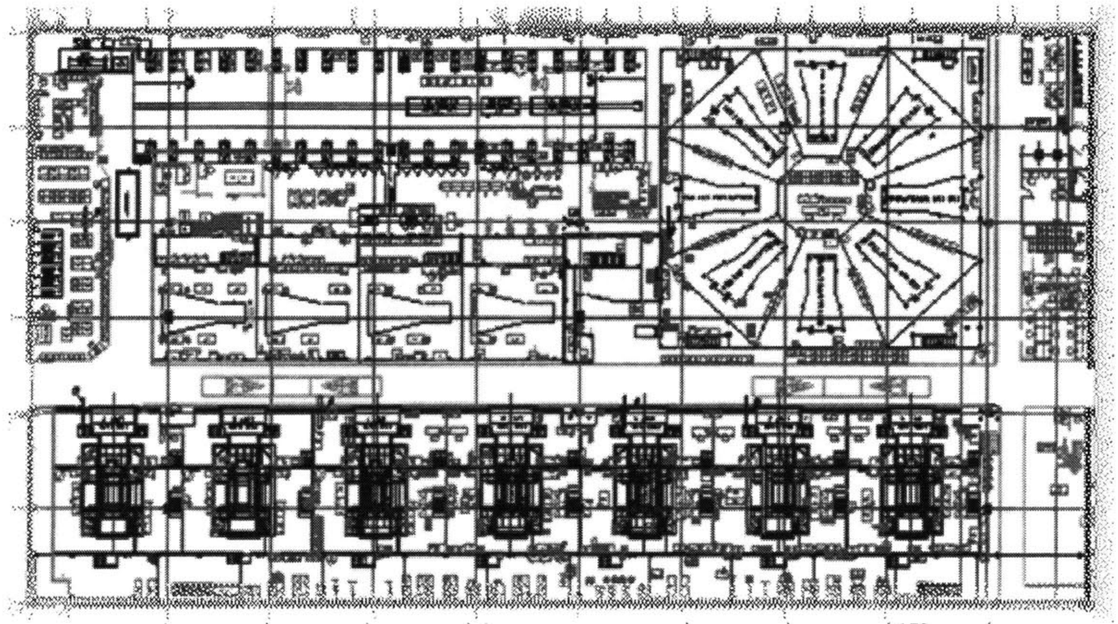

Figure 17: F/A-18 E/F Forward Fuselage Facility (April 2001)[173]

This existing manufacturing system was created around the LRET concept. It was a conscious decision to build up the fuselage in one location using one assembly tool unlike the C/D that was built of subassemblies on a moving line. Late parts and excessive dimensional variation on detail parts caused frequent work stoppages and rework on the C/D line which negatively impacted cost and cycle time. The Block 1 LRET concept, combined with the moderate DFMA accomplished during the E/F forward fuselage development, has created a very predictable product that achieves its planned costs and cycle time. The higher quality forward fuselage, combined with a laser-guided, numerically controlled splice fixture, provides an efficient, high quality splice between the Boeing forward and Northrop center fuselages. Overall, the U.S. Navy is satisfied with the performance of the Block 1 design and the LRET concept.

Once Boeing decided to make changes to the system in order to meet the cost and cycle time goals, they held a 3P (Production Preparation Process) event to look at other possibilities based on the concept of building the nose barrel, and upper and lower aft portions separately.

Some of the goals of the 3P event included taking work out of the LRET and trying to take advantage of parallel processing to get things off the critical path. Eliminating the need to use cranes throughout the process was another goal. Because cranes become bottlenecks, it was decided to have a system that did not rely on crane moves to enable the product to move through it. The wagon wheel will remain unchanged at this stage in the design effort – there may not be a need for all the stations, but that remains to be determined. The wagon wheel was not the focus of the redesign effort as much as getting work out of the LRETs.

The output from the 3P event created a system comprised of modular subassemblies built-up in separate assembly jigs and then spliced together in a simplified LRET, shown below. The nose barrel structure is assembled in a new tool that maintains the key interfaces of the LRET but

[173] *F/A-18 E/F ECP 6038 Forward Fuselage Program Overview*

provides greater operator access. Nose barrel skins are installed in an even more accessible station. The lower subassembly is assembled in a modified Block 1 tool while the mid subassembly is built-up in a new tool. When complete, the mid assembly is installed on top of the lower while the lower remains in its tool to preserve key interfaces. The nose barrel and lower/mid subassemblies are spliced together in the simplified LRET. Finally, the upper fuselage (crew station) is built-up on top of the spliced nose barrel and lower/mid in a manner similar to that of the Block 1 LRET approach. A separate upper subassembly was considered, but the upper fuselage DFMA effort resulted in such large part and fastener count reductions that its benefits were insignificant. The clean up line will be eliminated since that work will be done in the respective sub-assemblies. Again, at this point, the wagon wheel remains unchanged, to be addressed later.

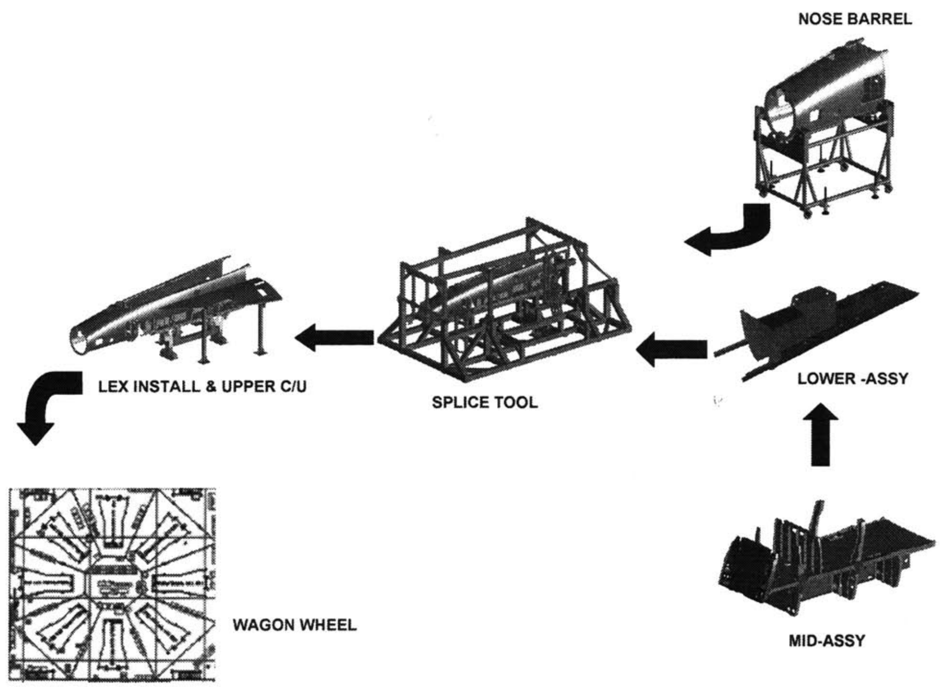

Figure 18: EFF 3P Modular Subassemblies

The 3P goal was to reduce the cycle time from the 124-day Block 1 baseline to 85 days and reduce the number of LRET tools from 8 to 4. This plan also reduces the cycle time in the LRET from 70 days to 35 days.

But the 3P idea floundered for quite some time. Eleven months after the original 3P event was held, the plan had started to revert back into the existing manufacturing system. The separate nose barrel concept remained, but some of the team members were proposing to place the upper and lower aft portions back into the LRETs. This would require more LRETs to meet the production rate and the rest of the floor would be unchanged from the current system. The morale on the team was slightly frantic and in one production review meeting, a remark was made that the plan looked no different from what was on the floor already.

Though the design effort of the EFF continued to progress, implementation of the 3P manufacturing concepts had stagnated. Much of this was due to the team's doubt of projected benefits and concern of the serious impact problems could have on aircraft deliveries. Randy Harley, the EFF program manager, determined that the 3P concept would perform as planned as long as implementation risks were mitigated through careful planning and execution. It took that act of leadership to make it stick. With this charter, the team went back to the 3P event output and began the necessary detailed design work. Assembly simulations with the different sub-assemblies were created to start modeling the work sequence and the details for the floor and tooling design. As of August 2001 the assembly area utilized the 3P output for taking work out of the LRETs, building sub-assemblies, one clean-up station remained for LEX installation and the wagon wheel remained the same with the determination of how many stations are required to be made later.

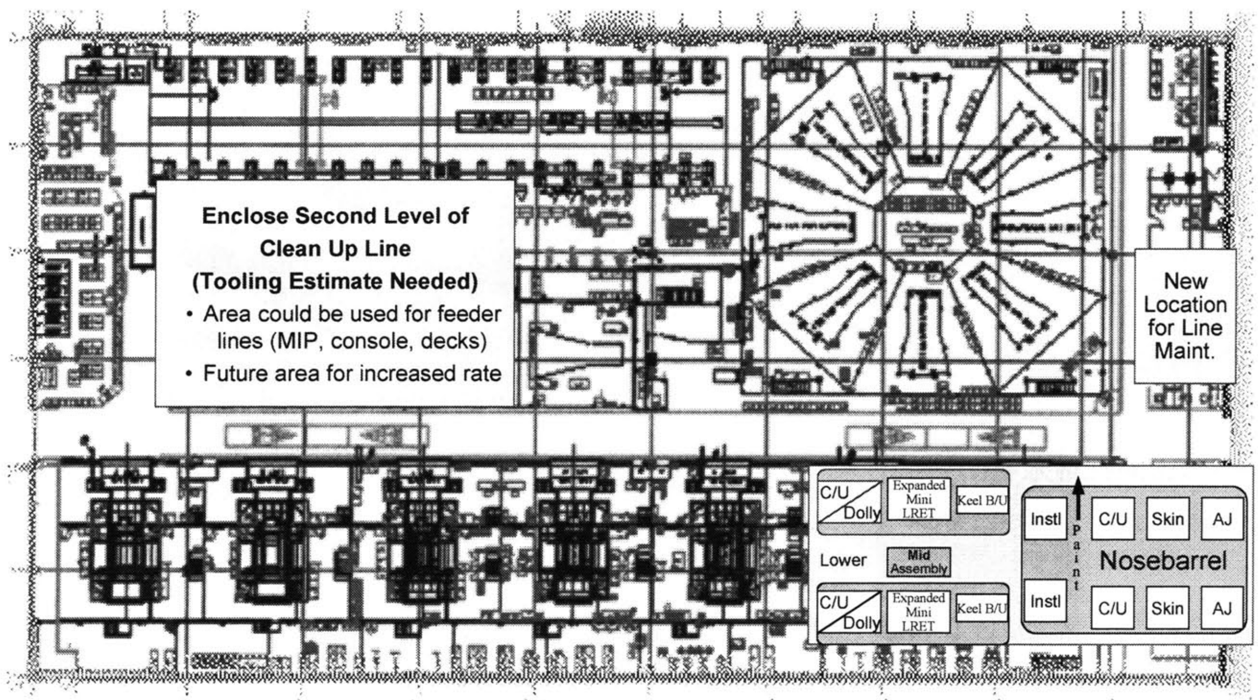

Figure 19: Forward Fuselage Facility for 3P Build Process (August 2001)[174]

Following the splice, the fuselage will be moved into a single clean-up station where some small structural details and the LEX will be installed. The floor space freed up by removing some of the clean-up line stations will allow other feeder lines to be brought into the forward fuselage room in the future, such as instrument build-up, canopy deck subassembly etc. The fuselage then moves into the wagon wheel for subsystem installations. Studies are underway to evaluate a pulsed moving line for subsystem installations. Options range from moving people, parts and equipment around the existing wagon wheel to new, moveable holding fixtures that would transfer the forward fuselage along five subsystem installation stations.

[174] *F/A-18 E/F ECP 6038 Forward Fuselage Program Overview*

The new floor layout and the continuing 3P studies are the beginnings of a U-shaped flow through the whole forward fuselage assembly area. This concept is consistent with similar system improvement efforts in the wing and final assembly areas of the F/A-18 E/F production building.

Framework Comparison

Now that the process that the F/A-18 E/F EFF team utilized in redesigning their manufacturing system has been outlined, a comparison to the manufacturing system design framework can be made. The following figure is a representation of the EFF specific manufacturing system design process resembles. A discussion on the degree to which the EFF framework follows the proposed framework in terms of the three goals (phase presence, phase timing and breadth in a phase) follows.

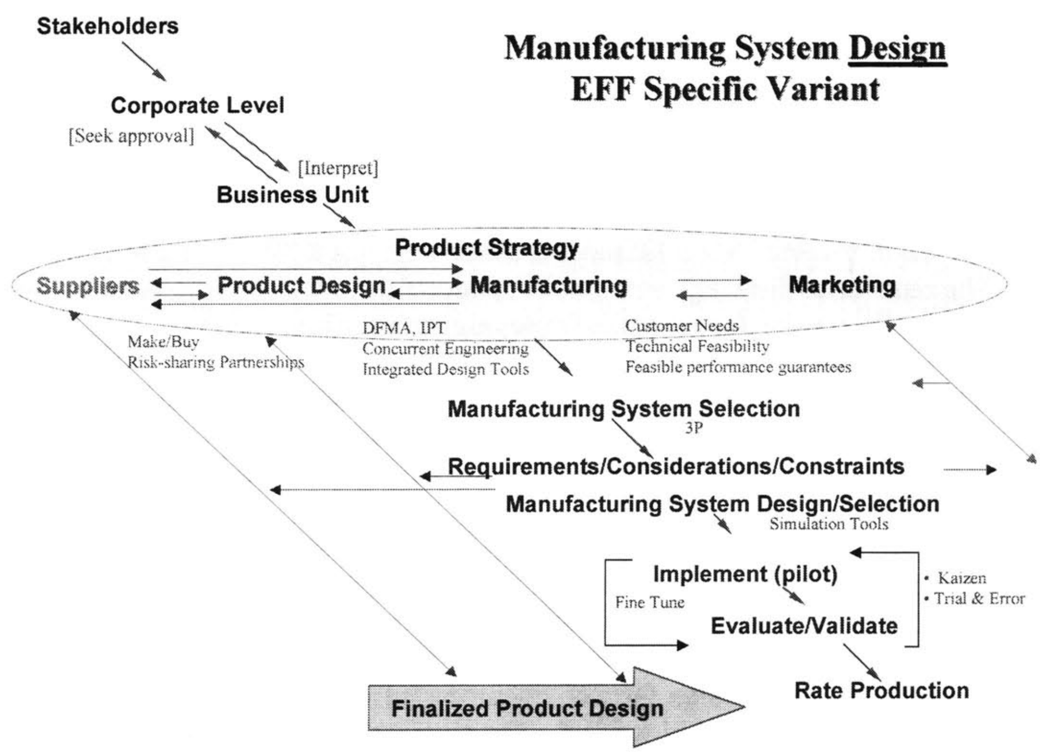

Figure 20: F/A-18 E/F EFF Specific Variant of the Manufacturing System Design Framework

The EFF variant of the framework matches closely with the framework proposed in Chapter 4. There was strong involvement from the Strategy formulation body in determining the needs of the stakeholders to be fulfilled. There was also a definite product strategy that existed and encompassed the different functions. In addition to the added capability, reduced part count and ease of manufacture was always a part of this strategy. The other phases of the framework are also present in the EFF variant, with one exception. Following the product strategy formulation, the EFF team thought that they would continue to use the existing manufacturing system. This was the plan for the EFF assembly until it was realized that the cycle time reductions could not be realized with the existing system and tooling. This prompted the team to design a new system which began with determining the requirements, considerations and constraints for that system. The new system was designed using a 3P event and the concepts derived in that event are being piloted on the test article as well as through extensive simulation activity. They are approaching the rate production phase, but are not yet in the modification loop at this time, so it has not been included.

The interaction between the different functional areas throughout the design process was present. It was important to the team on EFF to bring other people into the decision making processes to lead to better decisions with regards to the product, the tooling, the assembly, and supplier relations.

The interaction between the product designers, production operations and shop floor workers occurred daily in the virtual reality reviews. This was the opportunity for the engineers to get input on their design in the very early stages from the people that would actually be involved in building it. The meetings took time to become productive since the engineers and shop floor workers were not accustomed to working together, but eventually the team was able to establish trust and be successful.

The EFF program also dealt with the supplier base early in the EFF program life and made it integral to the product design work. The plan for EFF is to receive weekly deliveries of material from a smaller supplier base than was used for Block 1. Other work with the suppliers included the creation of "as fabricated" 3D solid models rather than just a 2D schematic of the final sub-assembly. The number of drawings was greatly reduced and the electronic links between the designers and suppliers allow for more timely passage of new information.

Marketing was also extremely important to this design effort as it established the basic need and strongly influenced the program goals. The main force behind the goal of creating the $40 million airplane is to obtain foreign sales – obviously the product of market research and projected sales growth.

Despite the extensive degree of concurrent activities throughout the design processes, for both the product and the manufacturing system, the manufacturing system design effort required a decision by the program manager to make a decision of what was to be pursued and placed on the floor. Luckily, the EFF's design for manufacturing initiative and integrated design tools were so pervasive that their plan still worked. The changes and detailed design decisions to the floor came easily when the leadership committed the team to making the 3P event output their new system design.

Currently the test article is being used as a pathfinder to refine the design and build concept, assess design features and tooling, test the model based work instructions and verify the simulated assembly order. The virtual prototype was also a key component of the pilot/evaluate loop. For a first try at the assembly sequence, technicians and engineers brain stormed then simulated it. The in-flight refueling (IFR) trough was originally planned to be installed near the end of the nose barrel build up, but through the simulation it was found that it wouldn't fit through the space remaining at that point in the assembly sequence. Now the IFR trough is about the third part installed in the nose barrel. This would have been a source for a large amount of rework and delay if it were found on the construction of the test article, as has been the case on previous programs.

The only major difference between the proposed framework and the EFF variant of the framework is the timing of the manufacturing system design/selection step which had to be duplicated. But the emphasis on producibility throughout the product design process made it possible to still design an effective manufacturing system even if they did start it later in the design process.

System and Process Performance

The 3P effort is the first step in a long term, F/A-18 E/F manufacturing improvement initiative. The wagon wheel, introduction of the feeder lines and other issues still require attention, but implementing the 3P output is the first step in establishing the U-shaped flow through the whole forward fuselage area. The EFF manufacturing system is still being designed since the system is currently in the piloting phase of the waterfall.

A Block 1 forward fuselage takes 132 days to assemble and it is done serially. With the new design of the EFF and the three modules being built up in parallel, the prediction is a throughput time of 85 days.

The first EFF unit, which will serve as the structural test article, was completed in late December 2001. When the program participants and management were asked about how the test article assembly was progressing, the response was "it's too quiet!" indicating that problems or issues were far below expectations. The first test article was delivered on time, for 15% less assembly labor than planned, and with 84% less defects than the initial full rate production units of the Block 1 design. Overall, the EFF program appears that it will exceed the required cost savings.

Despite the good performance in quality and assembly time, some ergonomic issues in the systems installation are still unresolved. Since advances in electrical wiring technology haven't progressed like the rest of the systems in the fuselage, the new manufacturing system does not significantly improve the installation of crew station wiring that was shown in Figure 11. This is the work on the critical path that remains to be addressed.

As far as a review of their actual design process, team members commented that more up front participation from production operations would have been beneficial, even though EFF accomplished greater and more effective coordination than any other major development program at Boeing A&M St. Louis. They also stated that they needed a better strategy for incorporating the build strategy into the product design – to somehow bring in more of a team effort to the decision rather than just having the program manager make the final decision. Another comment was that they struggled with their assembly strategy early on.

Overall, the F/A-18 E/F EFF is a successful program embracing the corporate strategy of producibility that will help the Super Hornet team reach their goal of creating a 21st century capable, $40 million strikefighter. The manufacturing system design process followed by the EFF team closely matched the proposed framework.

F-22 Raptor Center Fuselage

The F-22 Raptor is being developed as the next generation air superiority fighter for the U.S. Air Force to counter emerging world wide threats. It is designed to penetrate enemy airspace and achieve a first-look, first-strike, first-kill capability against multiple targets that literally redefines air combat.[175]

Figure 21: The F-22 Raptor - next generation air superiority fighter[176]

Stealth, maneuverability and supercruise characterize the F-22. The F-22 is powered by two 35,000-pound class, thrust-vectoring engines that allow the F-22 to supercruise (fly at super sonic speeds without the use of afterburner) at more than 1.5 Mach with only military power.[177] The F-22 maintains its stealth capability by utilizing a "clean" combat configuration where all the armament is carried internally in weapons bays.[178]

339 F-22 aircraft will be produced to replace the aging fleet of F-15s that are experiencing difficulties with parts obsolescence. The F-22 is currently in low rate production and the first aircraft will enter operational service in 2005.

Lockheed Martin is the prime contractor for the F-22. Lockheed Martin in Marietta, Georgia builds some major components for the aircraft and houses the final assembly operation. Lockheed Martin in Fort Worth, Texas is responsible for the center fuselage, electronic warfare systems, and communications equipment and is the focus of the first half of the F-22 case study. The Boeing Company in Seattle, Washington, is responsible for the main structure of the F-22

[175] From http://sun00781.dn.net/man/dod-101/sys/ac
[176] Photo courtesy Lockheed Martin
[177] From Lockheed Martin literature
[178] From http://sun00781.dn.net/man/dod-101/sys/ac

wings and aft fuselage. The last major contractor is Pratt and Whitney, who makes the engines that power the F-22.

One interviewee from Lockheed in Fort Worth summed up the F-22 development by saying, "We are making the F-22 because we don't believe in fighting fair".

Case Study Background

This first of two F-22 case studies focuses on the manufacturing system design experience of the Lockheed Martin facility in Fort Worth, Texas. In Fort Worth the center fuselage is made and shipped to Marietta for final assembly. The figure below is another view of the F-22 that accentuates the large center body of the aircraft as well as the doors that cover the internal weapons bays.

Figure 22: The F-22 in a bank showing the internal weapons bays[179]

The F-22 center fuselage is a complex portion of the airplane. Unlike the more traditional F/A-18 or F-16 airframes where the forward fuselage sections contain many of the systems of the airplane, the integral architecture of the F-22 moves much of this interior work installing systems into the center body. The F-22 center fuselage contains much of the equipment and the internal weapons bays that allow for the F-22 to have a clean combat configuration.

[179] Photo courtesy of Lockheed Martin

Need for a Manufacturing System Re-Design

In the prototype design phase of the F-22, the main considerations were to make the plane stealthy, fast and lightweight. This focus on speed, weight, stealth and design simplicity drove the engineers in this prototype phase to design a fuselage that was one large assembly with no sub-assemblies since it is the most lightweight configuration. Manufacturability was a consideration in this early design effort, but weight won out over the incorporation of subassemblies in the various trades performed for the prototypes. The one-piece center fuselage was also easier to tool and design quickly which was important to maintain the schedule to fly the prototypes.

Through the work on the prototypes, it became clear that building the center fuselage in one section would take too long to assemble for it to be a viable product to bring up to rate production levels. The center fuselage would require more man-hours and more tooling to support rate production than would be affordable. In order for the program to reduce production costs and remain within their cost targets, something had to change to try and reduce the number of hours needed to build the center fuselage.

Actual Manufacturing System Design Process

After the experience of the F-22 center fuselage prototype, the goals for a re-design of both the assembly processes and the product itself were determined. As was mentioned earlier, the center fuselage had to be built faster and more affordably. Manufacturing and industrial engineering led the effort to get the product designers to split the fuselage into modules that would accommodate parallel processing and more efficient assembly sequences.

Manufacturing and industrial engineering along with the product designers performed cost trade studies on various configurations to determine how many modules should be created and where the modules would be split. The center fuselage was split into 3 modules that are each built up independently then spliced together. Each section of the center fuselage ended up being approximately 6 feet tall allowing work to be ergonomically accomplished without expensive scaffolding. Modules were oriented vertically to facilitate work done in the inlets. Adding in these splices increased the weight of the complete fuselage, but the cost savings gained from splitting the fuselage was sufficient to justify the weight gain.

The program developed a relationship between the recurring dollars that could be spent to save a pound of weight and this was used to make decisions on module splits as well as material and structure combinations. Another example of this trade-off between recurring dollars and the amount of weight saved was that the fuselage was not just split into 3 modules for production, but the numerous composite frames and bulkheads prevalent on the prototypes were eliminated in favor of metallic components during the EMD design phase. Composites in these applications were found to not save sufficient weight to justify the increase in cost when compared to aluminum.

The main effort of the re-design process from the prototype to the beginning of the EMD program was to look at the product and create the three different modules. This alone greatly improved the cycle times of the center fuselage assembly processes. This allowed the build span on each module to be reduced in comparison to building the one piece fuselage thus reducing the required tooling costs. Now that the F-22 team had a design which was more amenable to rate production, the manufacturing function is continuing to try and redesign the assembly processes by instituting flow through reducing disruptions due to shortages of parts and components, nonconformances and additional cost effective engineering changes. The modules are so large that the work on the modules cannot be broken up into small work increments based on takt time. Rather than move the parts by the takt time, the F-22 program considered moving people in increments of takt time. Moving people is easier to do than moving the large parts, and allows for the workers to only have to remember 7 days worth of work and skills rather than 56 days worth of work if they just followed one piece through the whole system. But there are some limitations with this proposed means of creating flow. It presents problems of ownership or management of the individual aircraft in the system. Currently, it is not planned to adopt this moving at takt approach. Instead, supervisors will then be responsible for several large tools and move personnel around these to optimize learning instead of having crews flow through every tool at takt.

Work on the system is currently focused on trying to improve the processes to ease the system into rate production. The various improvement efforts are focused on areas other than the fundamental product design or basic tooling concepts since they are prohibitively expensive to alter at this point. F-22 is functioning within its set area of the factory floor as to not impact the available space for the introduction of JSF production into the same facility. Also, the Fort Worth facility is working with Professor David Cochran from MIT using the Aerospace Manufacturing System Design Decomposition (AMSDD) described in Chapter 4. This is helping the F-22 team see how their system relates to the higher level goals of the enterprise and justify how they make decisions for the F-22 manufacturing system in relation to those upper level goals. This approach helps them prioritize various improvement efforts and determine how changes in the enterprise level goals will impact their manufacturing operation on the F-22.

Framework Comparison

The F-22 center fuselage manufacturing system design process is represented in the specific variant of the framework below. There are some substantial differences between the F-22 center fuselage specific variant and the original framework proposed earlier in Chapter 5.

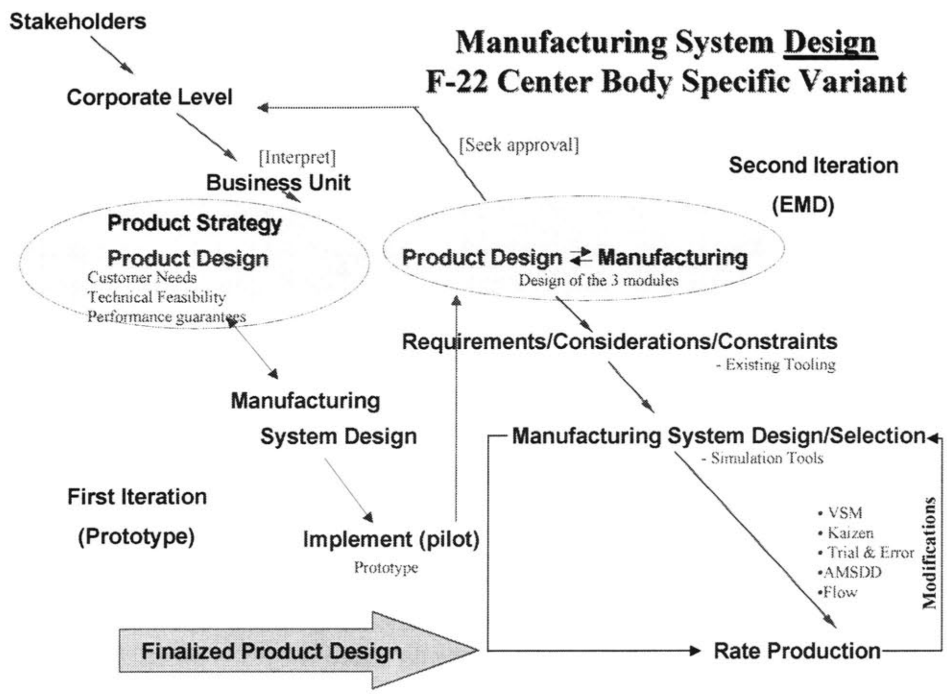

Figure 23: F-22 Center Fuselage Specific Variant of the Manufacturing System Design Framework

The most notable difference is the existence of two complete iterations. The first extends down the left side of the framework and the second iteration down the right side. In the first iteration the product strategy oval contains only the function of the product design. As was mentioned earlier, the original design effort for the airplane and the manufacturing system was completely devoted to building a flexible platform with internal, flexible weapons bays that would allow for the ultimate speed, weight and stealth capabilities.

This product strategy drove the product designers to create the tooling concept that dictated the manufacturing system design. Then, to complete the first iteration, the piloting phase of the manufacturing system design process was the creation of the prototype. The prototype, in essence, was a mock-up. It was less costly in the prototype phase to assemble the fuselage as one large piece since span time was not the primary requirement. It was after this experience that it was decided changes would have to occur to be able to make the fuselage at rate and without undue expense. This led to the second iteration.

The second iteration began with a new product strategy. This was a joint effort of the manufacturing and product design functions to try and develop a center fuselage that met the technical requirements for the F-22 but was less expensive to build. The goal for the re-design effort was to reduce the number of hours, and therefore the cost, of building the center fuselage. The fundamental philosophy of the redesign was to take advantage of parallel processing.

This led to a re-evaluation of the requirements, considerations and constraints the system would function within. The F-22 manufacturing system was geometrically constrained by their original need for high bay space, and now by the need to not encroach on the available area for other programs. They were also challenged to try to reduce the number of jigs, fixtures and other minor tools that were required to assemble the product. Following the definition of the requirements and constraints on the system, some new ideas were tried to see how many hours could really be removed from the build process. Some simulations and models were used for reporting up to corporate level and by Industrial Engineering to explore the tool rate requirements.

Following the manufacturing system design, the system was brought into low rate production to support the Engineering and Manufacturing Development phase of the program. The F-22 has been in the modification loop since. In this modification loop are the efforts to improve the flow of the work in the system and the efforts with the AMSDD as described earlier. The modification loop also contains the input from the early flight test results and some input for further assembly process improvements, which are still occurring today.

While Integrated Product Teams (IPTs) were utilized throughout the F-22 development, design considerations were sometimes given priority over manufacturing considerations. The positive interaction seen between manufacturing and product design is evident in that the engineers did, ultimately, split the fuselage into multiple modules. But, once major decisions on configuration and tooling had been made, the program had progressed to a point where any subsequent major changes would be cost prohibitive. This limited the scope of potential improvements by the manufacturing function in the second and any subsequent iterations.

The supplier community was part of the IPT structure during the initial EMD developmental phase, but it has only been with the more recent War on Cost initiatives that the overall supplier base became more engaged with their critical role in the F-22. This has initiated a new round of discussions for further cost reduction initiatives throughout the F-22 value stream.

System and Process Performance

The F-22 center fuselage experience for the prototypes started out as a design "thrown over the wall" to manufacturing where manufacturing concerns were subjugated to the product design. It was during the prototype development contract when it was realized that the product design and the system would have to change in order to be able to meet the rate and cost goals for the future. Following this experience, IPTs were established on the EMD contract and have been the norm in F-22 development ever since. Once the EMD contract was awarded there was little time to spend continually reviewing the configuration that was set during the prototype phase, so the redesign effort was confined in terms of scope and ability to significantly alter the system. The tooling concept was already determined, further restricting the ability of the manufacturing function to substantially change the system. The original system "was essentially designed with a few key decisions" remarked one interviewee, who was a design engineer on the program. "The [manufacturing] system must be designed along with the design of the airplane."

The center fuselage team in Fort Worth knows that potential improvements remain to enable their manufacturing system to produce efficiently at full rate in a few years. They have established an aggressive learning curve which is dependent on improvements in the manufacturing system including reduction of part shortages, disruptions, training, and the elimination of tasks through engineering changes. Another substantial factor helping the Fort Worth team is the improved morale of the workforce. Since Lockheed Martin won the JSF contract, things in Fort Worth are busy and exciting, further inspiring the F-22 team to try new ideas.

The F-22 specific variant of the framework reflects the change in manufacturing strategy from the first to the second iterations. In the second iteration, the involvement of product design and manufacturing into the redesign of the product and the changes to the system result in an iteration that more closely matches the complete process proposed in Chapter 4.

F-22 Manufacturing by Boeing

This case study was completed but not approved for release by the thesis publication deadline. This remainder of this description if based solely on personal interviews and observations by the researcher.

Framework Comparison

The F-22 wing and aft fuselage specific variant of the manufacturing system design framework is different from the original framework proposed. Down the left side of the framework is the first iteration of the system design and the right side is the second iteration. This variant of the manufacturing system design framework was constructed on the basis of personal interviews and observations.

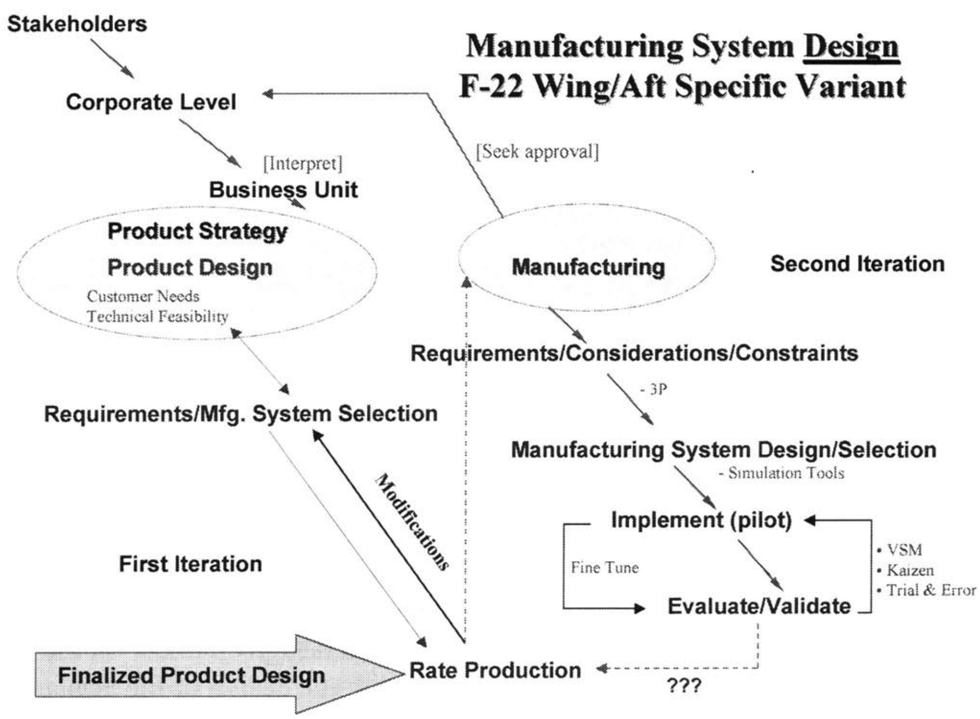

Figure 24: F-22 Wing/Aft Fuselage Specific Variant of the Manufacturing System Design Framework

The first loop begins with the product strategy determination with guidance from the strategy formulation body, primarily focusing on the product design function. The product design and past experiences with the B-2, A-6 Re-Wing and 777 empennage assembly determined the tooling concept and led to the design of the manufacturing system. As differences between the as-planned and as-built system emerged that would add risk when the system is brought up to full rate production, the modification loop started to improve this system. This was the beginning of the modification to the existing system and this is represented by the parallel track of the second iteration.

The second iteration began with the manufacturing function determining a new strategy for the system. The strategy guiding their redesign effort was to support the necessary rate, while eliminating crane moves, touching no part more than once to complete an installation and reducing the time spent working on scrap, rework and repair, therefore reducing costs. Once they determined an overarching strategy, the requirements were defined and a series of 3P events were held to redesign the tooling concepts and the flow for the wings and aft fuselage.

Following the 3P events, several of the ideas were piloted using wood models, full-scale PVC pipe prototype tooling, more accurate re-configurable tooling and, most recently, a scale model of the entire factory floor. Finally, the existing modification loop is primarily a series of kaizen events focused at the worker–level. Most of the kaizen events are focusing on kitting parts and defining work precedence networks.

The final dashed line labeled with question marks to the rate production arrow represents the current state of the redesign. It is uncertain which portions of the new manufacturing system will be implemented since there is much development that remains to be completed.

Supplier inputs or requirements were not specifically sought through the first or second iteration. Suppliers were handled in the traditional manner, with very close working relationships from a detailed part producibility and lean assistance standpoint. For the second iteration, it was a conscious decision by program management not to include the supplier base since most of the envisioned changes do not significantly affect the supplier statement-of-work.

The other major aspect of breadth is with the product design function. It was mentioned earlier that the product design function was primarily responsible for the first iteration of the manufacturing system design process, and while product design was represented through the second iteration, there was not a strong emphasis or interaction from the Integrated Product Teams. The Build Team made up a "Christmas List" of changes to guide the internal product design function as they refine the design for strength and other program requirements. Coordination of the product design changes are happening between the Build Team and the F-22 Program Integrated Product Teams. The major area of product redesign focus, the elimination of the cold worked stovepipe joints, is still under detailed negotiation. These joints were redesigned only conceptually and detailed re-design efforts are on going.

Next Generation 737

The Boeing 737 was originally launched in 1965, with a first flight in 1967, as a shorter-range airplane to compliment Boeing's successful and larger 707 and 727 airliners.[180] Through its history, the 737 family has won orders for more than 4,730 airplanes – more orders than Airbus has won for its entire product line since they began business, which makes the 737 the best

[180] From http://www.boeing.com/commercial/737-100/background.html

selling commercial jetliner of all time.[181] The 737 family was joined by its newest member, the Next Generation 737 (737NG), which first flew in 1997 and entered revenue service in 1998.

Figure 25: Next Generation 737 by Boeing[182]

The 737NG was developed to provide airline customers with an airliner encompassing advanced technology that allows for simplicity, reliability and low operating costs while maintaining flight deck commonality with the earlier 737s.[183] With the addition of the 737NG to the 737 family, 737s have carried the equivalent of the world's population – about 6.1 billion passengers.[184]

Case Study Background

The 737NG is the most advanced single-aisle airplane available on the market today and, like most Boeing products, it is a scale-based family of different models.[185] The family consists of the –600, -700, -800 and –900 which seat anywhere from 110 (-600) to 189 (-900) passengers depending on the seating configuration. Boeing has utilized the product strategy of changing the fuselage length in order to offer the scale-based family of airliners, which allows Boeing to remain competitive by increasing the product variety, shorten product lead-times and reduce development costs.[186] Boeing also hopes that this strategy allows them to upgrade their product lines and create more variations while Airbus pours all of their resources into the development of the Super-Jumbo A380.

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[181] From http://www.boeing.com/commercial/737-100/background.html
[182] Photo courtesy of Boeing Media at http://www.boeing.com
[183] From http://www.boeing.com/commercial/737-100/background.html
[184] From http://www.boeing.com
[185] From http://www.boeing.com/commercial/737family/index.html
[186] Simpson, T.W., *Architecting Product Platforms and Families of Products*, presentation

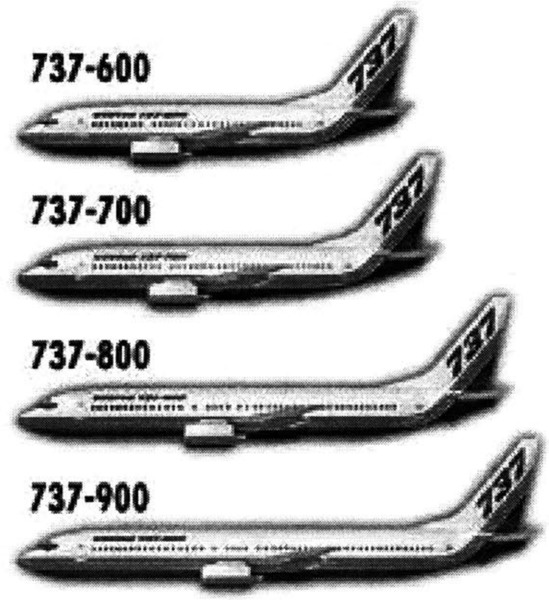

Figure 26: The Boeing family of 737NGs[187]

Since the development of the 737NG, it has become the primary earner for the Boeing commercial product line. It is currently produced at the fastest rate ever for a commercial aircraft at 28 airplanes per month.

Need for a Manufacturing System Re-Design

But if the 737NG is such a successful business venture for Boeing with a well-known product strategy guiding its development, why was there a need to re-design the manufacturing system? The assembly line for the 737NG was originally designed to be business as usual for another commercial airliner. The floor was set up with a set of traditional bays where the airplanes were parked amidst the catwalks and machinery for days at a time.[188] But when the 737NG was brought up to rate production, they experienced numerous difficulties. It was a very new product and the lines had to be shut down one at a time. This led to not meeting the required rate and compounded the problems.

After working through these initial difficulties, the 737NG team realized that they had to make up some ground financially, but without reducing headcount. Another aspect was the rework occurring on every airplane, which, if reduced, could improve their overall efficiency. Yet another impetus for change was the increasing threat of the Airbus line. At the end of July 2001, Airbus had a backlog of 1,602 orders compared to Boeing at 1,451. Phil Condit, Boeing Chairman, remarked, "It is hard to make big changes when you are the leader…until somebody starts eating your lunch."[189]

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[187] Photo courtesy of Boeing Media at http://www.boeing.com
[188] Lunsford, J.L., *Boeing rethinks how it builds planes with help from its "moonshine shop"*
[189] Lunsford, J.L., *Boeing rethinks how it builds planes with help from its "moonshine shop"*

What makes this experience different for Boeing is that they were going to make massive changes to their system after having reached rate production, and not in the downtime between models.[190]

Actual Manufacturing System Design Process

The early stages of the manufacturing system design process by the 737NG team consisted of benchmarking methods of increasing system efficiency as well as extensive value stream mapping activities through the 737NG areas of responsibility. These activities established the current state of the system as well as the possibilities for improvement. All of the lessons learned were then incorporated into the "9 Steps" which became the strategy guiding the remainder of the design process. The 9 Steps developed by the 737NG team are:

0. Tailor the investment to match the return
1. Value Stream Mapping and Analysis
2. Balance the Line
3. Standardize Work
4. Put Visuals in Place
5. Point of Use Staging
6. Establish Feeder Lines/Supply Chain Lines
7. Break-Through Process Re-Design along the main line
8. Convert the line to a Pulsed line
9. Convert to Moving Line

- Continuous Improvement – Measure and Improve

This list of 9 Steps helped the program determine the scope of the effort, how they would set goals and measure progress, determine the constraints on the system and capture the essence of continuous improvement. For the 737NG, it was decided to only use the pulsed line for 1-2 weeks and then transition to the continuously moving line since they saw the moving line as the best solution and the only way to instill the discipline for standard and balanced work.

Once the 9 Steps were derived, they had to be approved by the rest of the leadership structure of the Boeing Commercial Airplane Group (BCAG). The manufacturing strategy derived to support the re-design effort was essentially passed from the bottom up to become the true driver behind the changes.

For 737NG the manufacturing system was designed as a part of the determination of the 9 Steps. With the continuously moving line as the goal, they had to figure out how to make it work. The planning on how to physically move an airplane through the final assembly processes was done in what are known as "Moonshine Shops". Moonshine shops are so named because they exist on the floor, but outside of the normal work flow and use whatever materials are available to create whatever the workers can think of to try to make it easier to build airplanes.[191] It was in this environment where they began to devise a method to move the airplane through the facility with the additional constraint of not doing anything permanent, like dig a trench in the factory floor as had been done in Long Beach, California, for the 717 final assembly. Work continued on the

[190] Lunsford, J.L., *Boeing rethinks how it builds planes with help from its "moonshine shop"*
[191] Lunsford, J.L., *Boeing rethinks how it builds planes with help from its "moonshine shop"*

mechanism in the moonshine shop using mock-ups and simulations for over a year. Floor workers were encouraged to go over and play with the different prototypes that came out of the shop to see if they liked them. They were encouraged to make suggestions and try the prototypes out since it was going to be something that they would have to work with for a long time once it was deployed. During this period, over 200 changes were suggested by various employees to improve the different ideas. After the mechanism was brought out onto the floor, the workers really enjoyed it once they got used to it.

While the mechanism was in the design stage in the moonshine shop, 2 of the 3 assembly lines for 737NG were converted from the traditional bays to a straight line where the airplanes are oriented nose-to-tail. Also, most of the permanent tooling was disassembled to allow for a quick transition to the actual moving line. After the mechanism was designed, the transition on the floor began to happen quickly. In April 2001, a 737NG final assembly line began to move. Now, once the wings and landing gear are attached, the plane is slowly pulled by a giant tug toward the door at two inches a minute for 2 shifts a day.[192]

The system is now comprised of 2 parallel lines (1 of which is moving so far). Two of the lines produce aircraft at a constant rate of 21/month with the third absorbing any changes in demand from month to month. It is this third line that has begun moving to try the new mechanism and work out the bugs before it is implemented on the other two. With the new assembly process, there are no crane moves involved and all the work can be done while the airplane travels through the building. There is a magnetic strip on the floor which keeps the tug pulling the airplane in a straight line. Other new additions to the system are point of use staging areas along the sides of the three lines, a centralized kitting area to feed the floor and minimal tooling. Andon lights also grace the altered floor which alert supervisors and specialists when there is a problem, shortage, or help is needed. In addition to turning on a light to attract attention, each group picked the music that would play until someone came to help. One group picked Aretha Franklin's "Rescue Me".[193]

Framework Comparison

The 737NG specific variant of the manufacturing system design process framework contains major differences from the original framework. The main difference is the presence of two design iterations. The left half of the framework is the first iteration and the right half depicts the re-design of the second iteration, which was described earlier.

[192] Lunsford, J.L., *Boeing rethinks how it builds planes with help from its "moonshine shop"*
[193] Lunsford, J.L., *Boeing rethinks how it builds planes with help from its "moonshine shop"*

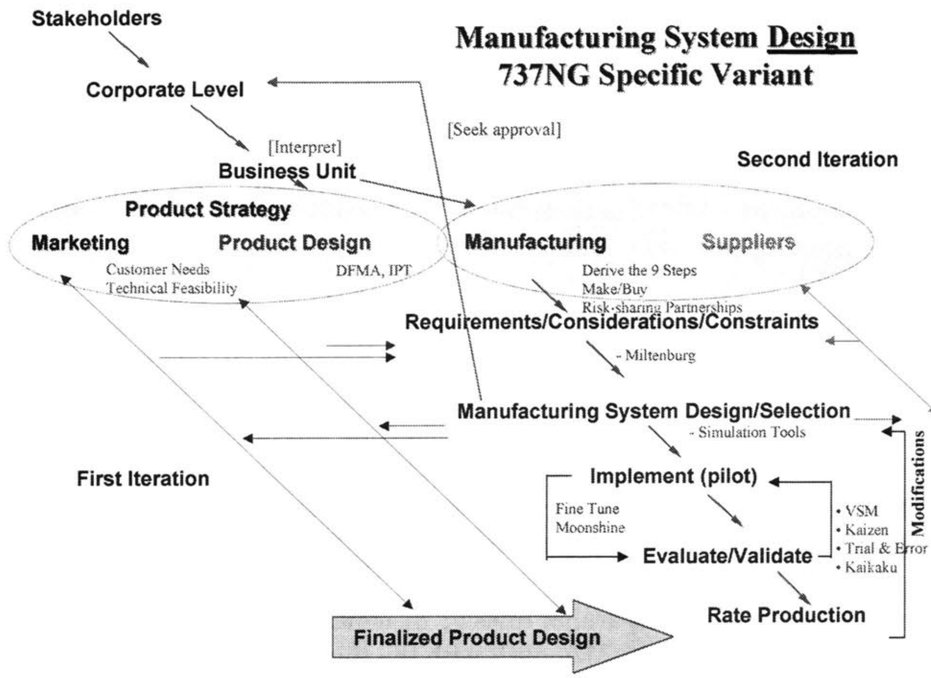

Figure 27: 737NG Specific Variant of the Manufacturing System Design Framework

In the first iteration, there was a product strategy passed down from the strategy formulation body that included the product design and marketing functions. This strategy of offering a family of scale-based airplanes is the one implied here. The implementation of this product strategy entailed designing the 737NG manufacturing system as business as usual. This copy of existing assembly operations was the system that was brought up to rate production.

The right side of the framework is the second iteration of the manufacturing system design process. This iteration begins with the creation of the manufacturing strategy, which included the suppliers, at the behest of the 737NG business unit. The strategy consisted of the requirements definition and manufacturing system design phases that are part of the 9 Steps. It was after the derivation of the 9 Steps that the strategy and proposed system design were passed up to the strategy formulation body for approval. Once approval was granted for the new manufacturing strategy, the rest of the framework process was followed. The simulate, pilot and evaluate loop took a year while different ideas for moving the airplane down the line were developed. Finally, the designed mechanism was deployed onto one of the three lines on the floor, marking the beginning of the rate production phase of the new system design.

The 737NG manufacturing system design process was unique. In the second iteration, all the phases were present and the timing matched that proposed by the framework, but this whole process occurred after the product had been initially brought up to full rate.

As for breadth in this process, the 737NG team did not have much influence on the design of the airplane since it was already being built at a rate of 28/month. But they did make critical changes that have had a profound impact on balancing the line and creating standardized work. In 2001, the 737NG went to service-ready wings, meaning that they require no work in final assembly. This change and the corresponding modifications to the wing and body joint, was directed by requests by the final assembly team. Another example of how this design process fed back into the engineering processes is in the galley. To make the galley installation fit into the flow of the moving line, floor workers proposed redesigning the galley assemblies so that it could split into three pieces. This would make it easier to get the pieces into the plane for assembly. The workers played with cardboard models of the galley and invited representatives from 737NG management and the galley manufacturer to begin implementing their suggestions.

The other aspect of breadth in the design process that 737NG utilized was with the supplier base. Interactions with the supplier base were captured in the development of the 9 Tactics to be an integral part of enabling the moving line concept. The kitting areas and point of use staging have already been implemented on the floor. 737NG is now ready to go back and work with the suppliers in more detail since they are more aware of the specific needs for final assembly. In one case where a lot of work with a supplier has already occurred eliminating batches and supporting just-in-time deliveries, there are 6 round trips a day made between the supplier and final assembly.

One last element of breadth that is playing a role in the design process for 737NG is in the modification loop. Part of the first tactic was the value stream mapping and analysis, which consists of creating a current and future state map. It is well known in the 737NG organization that improvement efforts are required in the white-collar areas in order to make reaching the future state a possibility. More events are being held in the white-collar functions as time progresses.

System and Process Performance

Currently, 3 out of 4 positions are moving on line 3, the overflow rate line. The fourth position will be added to the flow soon, following the remaining balance work that levels the work content between each station. Already there has been a reduction in the labor hours, and once that performance is more consistent, linking the stations will be much easier. Once the work content issues are solved and all of line three is moving, the system will then be implemented on lines 1 and 2 which together produce 21 airplanes a month. Throughput time is decreasing as the work content is leveled between the stations.

The 737NG team is also starting to implement visual control along the line. In the past, unless the observer was familiar with the build process, it was difficult to tell the status of the airplane with a visual scan. To correct this, the material to be installed on the airplane will be placed in designated places on the floor by its order in the build sequence and the time at which the airplane will make it to that position on the line. This will allow the state of each airplane on the line to be quickly ascertained. A missing part will be evident in an open slot, and an airplane that is behind schedule will have moved beyond a line on the floor with hardware waiting for installation. This is also an easy system to implement since the information and material flow is coupled. The parts themselves contain the information on the airplane status simply by their position.

The implementation of the new system has taken longer than originally anticipated, but the overall performance so far is very good. Now that one of the lines is moving, the process has momentum and things are starting to happen quickly allowing the workers to see a change and their impact on the floor. This has done a lot for the morale of the workers who have suffered a series of cultural setbacks as of late. Between the Boeing Company headquarters leaving Seattle, the tragic events of September 11 and the subsequent drop in commercial aircraft orders, it has been a positive thing for the workers to see their ideas and suggestions actually manifesting themselves on the floor. The robustness of their strategy and process also shows in the fact that the major system redesign activities occurred to reduce flow while increasing rate. When the moving line concept originated, they were producing 21 aircraft a month and that increased to 28 aircraft a month at the same time the first line began to move.

Probably the greatest impact that the 737NG manufacturing system design experience has had is in the diffusion of the manufacturing strategy that was created. The strategy contained within the 9 Steps are feeding into all other areas of Boeing – commercial and military alike. The 757 assembly line adjacent to the 737NG lines was turned so all the airplanes moved from their parking lot bays to a nose-to-tail line as have some lines in the wide-body assembly area in Everett, Washington, including the gigantic 747. The same 9 Steps are even being implemented in final assembly for the F/A-18 E/F Super Hornet in St. Louis and it has become an integral part of the Boeing rhetoric.[194] Boeing Chairman Phil Condit has incorporated moonshine shops into the corporate strategy to try and reduce costs by fundamentally changing how they assemble aircraft.[195] Alan Mulally, the CEO of BCAG, envisions the 9 Steps creating a system where airplanes can be assembled in the same manner as the Japanese assemble cars, "using fewer parts and moving assembly lines" that reduce required time and manpower combined with just-in-time relationships with suppliers.[196]

Despite the improvements realized and the progress made by the 737NG team, they may be unable to completely capitalize on the potential of the type of manufacturing system that the 9 Steps and their future state value stream map envision. This is due to the fact that in many cases it is the design of the airplane that dictates much of the inefficiency that results in production.[197] The 737NG team did not have the luxury of being able to redesign the complete airplane or design this manufacturing system when the airplane was still in development.[198] The ultimate test for Boeing will be whether it can incorporate all it has learned from 9 Steps, the availability new of technologies, and a new more inclusive product strategy into a single platform: the Sonic Cruiser.

The presence of the second iteration in the 737NG specific variant of the manufacturing system design framework brings in all the different proposed phases from the original framework. Between this, the development of the 9 Steps as a strategy and the incorporation of the different functions in the manufacturing system design process, the 737NG framework ends up looking similar to the original proposed framework.

[194] According to Al Haggerty, Boeing VP (ret.), September 2001.
[195] Lunsford, J.L., *Boeing rethinks how it builds planes with help from its "moonshine shop"*
[196] Squeo, A.M. and A. Pasztor, *Boeing seeks to overhaul aircraft manufacturing*
[197] According to Al Haggerty, Boeing VP (ret.), September 2001.
[198] Lunsford, J.L., *Boeing rethinks how it builds planes with help from its "moonshine shop"*

Joint Strike Fighter

The Joint Strike Fighter (JSF) is being developed as a family of stealthy, next-generation replacement strike fighter aircraft for the U.S. Air Force, Navy and Marine Corps as well as the UK Royal Navy and Royal Air Force. The supersonic JSF evolved from the Joint Advanced Strike Technology program, which entered the concept design definition phase in December 1994. The JSF program entered its current phase, System Development and Demonstration (SDD), in the fall of 2001 following the down-select between the Lockheed Martin and Boeing concept demonstrator aircraft. [199]

Figure 28: JSF Joint Strike Fighter[200]

The team developing the JSF includes Lockheed Martin, Northrop Grumman and BAE Systems in addition to the propulsion system suppliers of Pratt and Whitney, GE Aircraft Engines and Rolls Royce. This team will design, develop, produce and support three variants of the JSF: conventional take off and landing (CTOL), short take off and vertical landing (STOVL) and a carrier vehicle variant (CV).[201] These variants all share the same fuselage and internal weapons bay, structural arrangement, have identical wing sweeps and similar tail shapes. The radar, ejection system and most of the avionics will be common between the variants and all will be powered by a modification of the same engine, the Pratt and Whitney F135.[202] The commonalties between the three variants goes beyond the appearance of the airplane in that all the references will be based on the same datum[203] and all the variants will have the same bill of material even though the numerical control code run on the machines may be different.[204]

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[199] http://www.lockheedmartin.com/factsheets/product20.html
[200] Photo courtesy of Lockheed Martin
[201] http://www.lmaeronautics.com/products/combat_air/x-35/index.htm
[202] http://www.lmaeronautics.com/products/combat_air/x-35/index.html
[203] McLaughlin, M., *JSF Airframe Collaboration*
[204] Mecham, M., "Digital Bloodlines Make JSF a Different Breed"

The JSF is currently in development and is scheduled to become operational in 2008.[205]

Case Study Background

A primary objective of the JSF program is to reduce the costs of development, production and ownership for the different customers. Significant economies in production and ownership are realized through extensive commonality among the variants. Sharing the development costs decreases the expense for each branch of the military.[206]

From this goal of affordability of the airplane to the customer, capitalizing on commonality becomes the main approach for the product design and the manufacturing system design. This early focus on commonality and affordability is a change from previous acquisition programs where the product performance was the main concern and cost was dealt with secondarily. For JSF, cost and producibility were concerns up front and the whole purpose of the program.

This programmatic focus on affordability and producibility formed the manufacturing strategy to capitalize on commonality.[207] The JSF team also set some additional goals for the assembly process of a 30% cost reduction over other fighter aircraft, utilize unitized structures, achieve a 5-month assembly time for the aircraft, eliminate fasteners wherever possible and ensure there is no need for drilling during mating operations. JSF was also going to attempt to use electronic information throughout the manufacturing process rather than relying on traditional process sheets and drawings.

Actual Manufacturing System Design Process

The JSF design process was set up with a set of structured phases with entrance and exit gates for each phase. This design process contained the gates for the product design, the manufacturing system design, the supply chain preparation and the information flow structure. The manufacturing aspect of the design process is the focus here.

The JSF team first defined the requirements of the program and how that would impact the manufacturing system and its capabilities. First of all, there is an anticipated production volume of about 3,000 airplanes between all the customers. And even though this figure is just a forecast at this point, what is known is that the products will be mixed for the existing customers. Unlike previous programs where the U.S. Air Force is the only customer for the early production vehicles and the customer base diversifies later, JSF will be producing airplanes for all flying services of the U.S. military and the UK at the same time.[208] This combination of production rate and mix will require the manufacturing system to output 17 aircraft a month.

These requirements led the design team to work to simplify their processes – both production and business and to value creative ideas that would enable their simplification. These requirements on the system also mandate that the manufacturing system be flexible to accommodate rapid change in rate and configuration.

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[205] http://www.lmaeronautics.com/products/combat_air/x-35/index.html
[206] http://www.lmaeronautics.com/products/combat_air/x-35/index.html
[207] http://www.lmaeronautics.com/products/combat_air/x-35/index.html
[208] Mecham, M., "Digital Bloodlines Make JSF a Different Breed"

The manufacturing system design process for JSF was more than that – it was a "production system reinvention".[209] This design effort was a culture change for the JSF team. Through a series of early "pre-design kaizen" events it was evident that manufacturing had as much influence over the product design as the design engineers did. This was seen in some of the early work on the program in 1997 when the major aircraft component breaks and producibility requirements were set.[210] This early decision was made to determine where the major aircraft breaks should be located to ensure producibility. The design engineers were then constrained to these component breaks.[211]

The pre-design kaizen events aimed to incorporate lean thinking into the early production system configuration and product design. These events applied the principles of lean thinking in a disciplined manner in the early design activities. To assist in the integrated design process, extensive simulations and computer models were used, which were developed in the Virtual Product Development Initiative (VPDI) by Lockheed Martin.[212] JSF was committed to create a solid 3D model of every part of the airplane that would feed into the models of the factory floor. So while the product was in development, discrete event simulations were applied to the models of the factory to improve the factory operations. The tool permitted engineers to input various assumptions allowing the entire production operation to be optimized for those assumptions. Among the assumptions considered in the simulations were production rates, process variability, resource availability and time. The later simulations also included the workers themselves. This allowed the team to consider the ergonomic implications of some decisions.

Through repeated use of the integrated design tools and the pre-design kaizen events, the JSF team designed a single production line with single fixtures or machining stations that can accommodate "cousin" parts, unitized structures, fiber placement and laser-positioning. The cousin part approach is to fabricate an aircraft part common to all JSF variants using a dynamic fixture that accommodates the slight variations of the different configurations.[213]

The result of the manufacturing system design process is a system capable of meeting the 5-month assembly span. The manufacturing system is comprised of modular tooling that fits all of the variants of the aircraft. The system will also contain a raised factory floor to avoid the need for any subsequent leveling in case tooling is moved to a new location. This raised floor also allows wiring and piping to be run virtually anywhere without confining the possible layouts. Currently there are plans to install the floor for parts of the Forward Fuselage during SDD. The system will contain only 1 final mate tool which will force the system to keep moving and not allow parts to stagnate and not flow. This will also make bottlenecks visible since work will not have alternate paths.

In addition to those design decisions, there are additional enablers to achieve the 5-month assembly span time. The first additional enabler is capability and trying to simplify processes.

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209 Packer, M., *Lockheed Martin JSF Manufacturing Strategy*
210 Packer, M., *Lockheed Martin JSF Manufacturing Strategy*
211 Packer, M., *Lockheed Martin JSF Manufacturing Strategy*
212 Lockheed Martin Tactical Aircraft Systems, *Application for the Shingo Prize for Excellence in Manufacturing*
213 http://www.lmaeronautics.com/products/combat_air/x-35/index.html

Stealth requirements create difficulties for assembly operations since tolerances on the outer mold line become confining. So, on JSF and unlike what has been done on earlier stealth aircraft, a gap was designed into all the areas where the skins are attached. This creates a predictable gap where liquid shims are mandatory. Quick mates are another enabler of the JSF team to meet the 5-month assembly span time. As was mentioned earlier, the location of the major aircraft component breaks was determined in the early stages of the product and system design. A final enabler for JSF to meet the 5-month assembly span time was to change the way sub-systems were installed into the aircraft. Typically, subsystems are installed into an existing aerostructure. There are a large number of parts like clips and brackets that are only used for sub-system installation. But, on JSF, sub-system design was part of the aerostructure design.[214]

Framework Comparison

The X-35 specific variant of the manufacturing system design framework is shown below. As a first observation, their process closely matches the process proposed by the original framework.

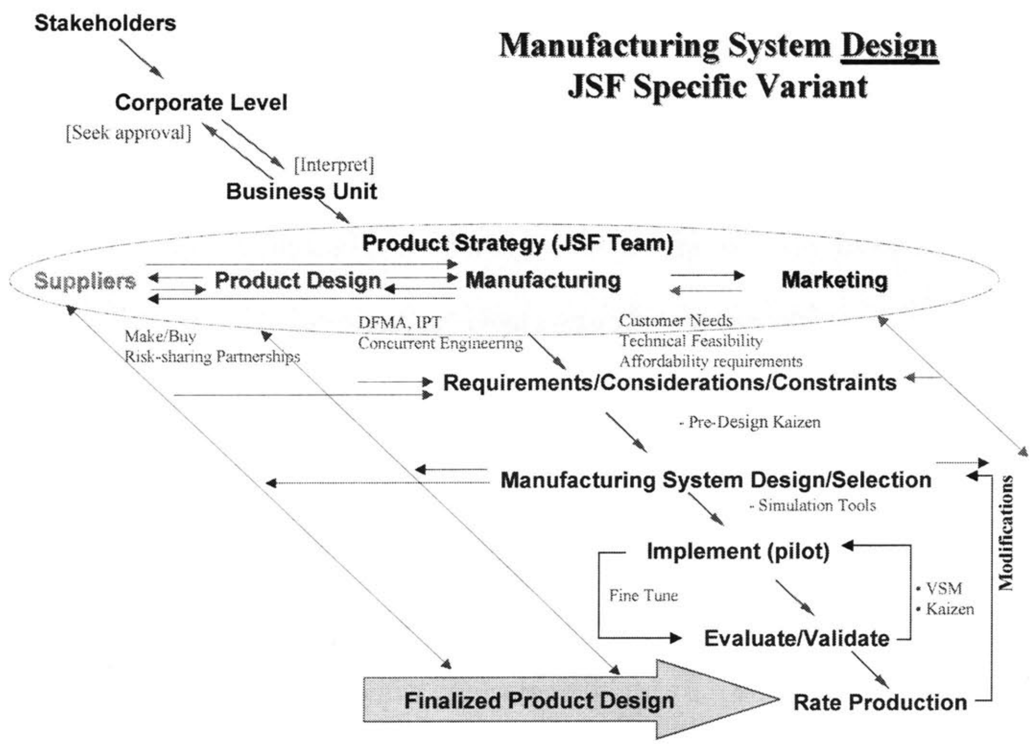

Figure 29: JSF Specific Variant of the Manufacturing System Design Framework

The JSF framework begins with the strategy formulation body feeding into a product strategy. The strategy formulation body, incorporating the needs and desires of the customers, helped create a product strategy that included making the airplane affordable and producible. The product strategy was not only integrated across all the functions within Lockheed Martin, but across the different functions of all the different team members, including Northrop Grumman, BAE etc. This JSF team level product strategy contained the emphasis on affordability and commonality between the different variants of the airplane.

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214 McLaughlin, M., *JSF Airframe Collaboration*

The manufacturing portion of this product strategy included the product itself. It was realized at this point that to meet the cost and schedule goals for this airplane, manufacturing had to focus on the product itself and not just on the factory floor.[215] This manufacturing strategy then included the design of a producible product that could be made easily and quickly.

The next phase is the definition of the requirements, considerations and constraints. The production rates and mix were forecasted to help determine the needed flexibility and capacity of the system. Process capability was also a consideration, both in terms of what they were currently capable of and what processes would require work to be able to sustain rate production levels.

The next few phases to design the manufacturing system in detail and test the ideas were accomplished through the use of integrated design tools that allowed for rapid virtual prototyping and assembly. These simulations were refined as the design of the system, the product and the design process itself matured. In the piloting phase of the design process, some future users, workers and customers of the JSF were brought in to use the different models. This use of digital mockups helped find interferences and other potential problems.[216]

Throughout the various design processes, interaction between the different functions was common and necessary. The goal of affordability and the emphasis on trying to build the product in a "lean" manner required up front involvement with the product designers. As one interviewee said, "It doesn't matter how lean your factory floor is if you don't have a good product designed."

The interaction with the supplier community was just as important and useful to the JSF development as the interaction between manufacturing and engineering. The prime partners in the JSF development were involved with the critical part suppliers starting in concept development. This early involvement helped foster plans for long term relationships which are evident in the relationship between the various companies going into the SDD phase of the program. Cost of parts and materials were arranged for the whole JSF team rather than specific companies for the life of the program.[217] This means that any member of the JSF team can get the same type of material for the same price allowing the suppliers to benefit from economies of scale while allowing the JSF team to have the flexibility to order through different companies for different portions of the airplane. The JSF team also determined major tiers of suppliers based on the modularity and commonalties across the airplane.[218] For example, one supplier received a contract for the 36 different types of flight-operable doors on the airplane.

System and Process Performance

This integrated design process for the product and manufacturing system resulted in the construction of two concept demonstrator aircraft. The advanced manufacturing methods that were expected to earn their way into the production phase were demonstrated in a parallel

[215] Kessler, W., Lean Enterprise presentation
[216] Mecham, M., "Digital Bloodlines Make JSF a Different Breed"
[217] McLaughin, M., *JSF Airframe Collaboration*
[218] McLaughlin, M., *JSF Airframe Collaboration*

activity called the Advanced Affordability Demonstration (AAD). This AAD activity was conducted in parallel to the building of the three concept demonstration aircraft and showed that the processes posed low risk to the program.

This design process has allowed JSF to realize the vision of manufacturing speed and affordability. The baseline for assembly was 15-months and the goal for JSF assembly was set at 5-months. Some of the early producibility work helped get the JSF to the 13-15 month range. The introduction of rapid mate joints showed they could reduce this time to 8-months. Then through the pre-design kaizen events, this was taken down to 3-months under optimum conditions – even past their 5-month goal.[219] The 5-month throughput time in assembly is possible on JSF because of the advantage of parallel processing with the subassemblies and the quick mate joints.[220]

In addition to designing a system that appears to be capable of meeting a 5-month rate, the tooling requirements are far improved over baseline programs. Only 19 tools are required for production of all 3 JSF variants. Similar production would require around 350 tools for the F-16. And in terms of capability, 3,000 holes were drilled on the wing carry through of the concept demonstrator aircraft. Only 3 of these 3,000 holes were out of tolerance by 0.002" and the mistakes were caused by an error in the software rather than an inability for the process to perform.

The JSF program shows a major shift in mentality in the aerospace industry. Manufacturing was involved in the product design and the product design engineers were integrally involved in the development of the manufacturing operation. This was the first time that manufacturing was considered this early in development. This is exemplified by the fact that the aircraft breaks were determined by this cross-functional team and the team had to work within those boundaries.[221]

The JSF manufacturing system design process can be characterized by following a structure process that incorporated all the various functions to help the system achieve the 5-month assembly span time goal. The JSF specific variant of the framework closely matches the proposed framework.

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[219] Packer, M., *Lockheed Martin JSF Manufacturing Strategy*
[220] McLaughlin, M., *JSF Airframe Collaboration*
[221] Kessler, W., Lean Enterprise presentation

F-16 Fighting Falcon

The F-16 is a small, lightweight fighter. There are two main types of the F-16 currently in production, the C is the single seat version while the D is the two-seat version. The latest version of the F-16, the Block 60, is shown below.

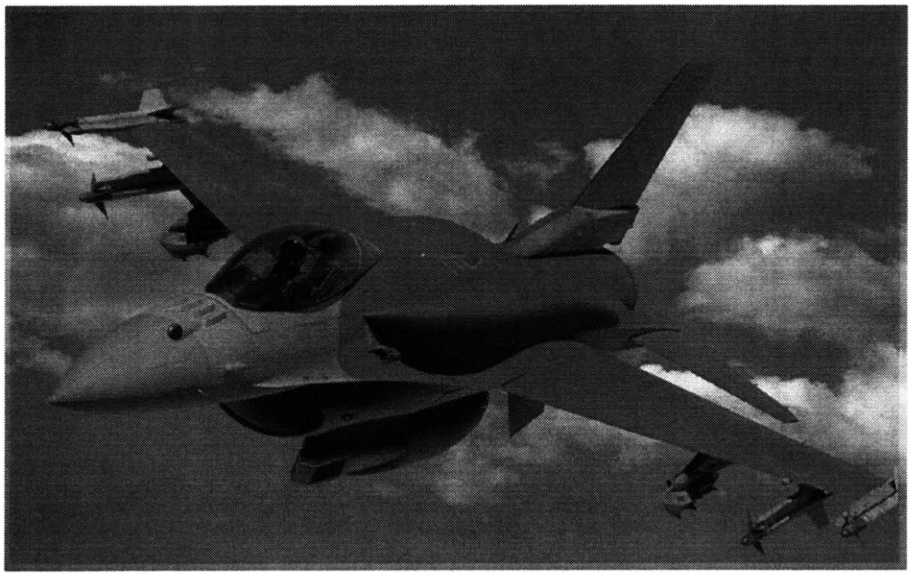

Figure 30: F-16 Block 60 by Lockheed Martin[222]

The F-16 was originally developed in the 1970's for the U.S. Air Force lightweight fighter program with the first production aircraft delivery for the U.S. Air Force taking place in 1978. The key F-16 design approach was to employ advanced technologies where there was a high payoff and to use existing systems and materials otherwise.[223] This led to an aircraft that is a smart blend of advanced technologies and proven equipment. Since then it has survived significant changes in the global environment by being flexible enough to adapt to changing needs of the warfighter. The program has accommodated numerous customers from all over the world and is currently operated by 19 different countries;[224] with three more scheduled to receive their F-16s in 2003-2005. The specific needs of each customer are incorporated in a unique development effort to tailor the product to their intended use. It is available with many versions of avionics, aircraft systems, radar weapons, cockpits and other attributes.[225]

The F-16 is the backbone of the U.S.A.F. fighter force and will remain the most popular fighter for quite some time. As the graphic below shows, in 2015, the F-16 will account for 42% of the U.S.A.F. fighter arsenal.

[222] Figure courtesy of Lockheed Martin Aeronautics

[223] Lockheed Martin Aeronautics, *The F-16 Fighting Falcon*

[224] Lockheed Martin Aeronautics, *The F-16 Fighting Falcon*

[225] Lockheed Martin Tactical Aircraft Systems, *Application for the Shingo Prize for Excellence in Manufacturing*

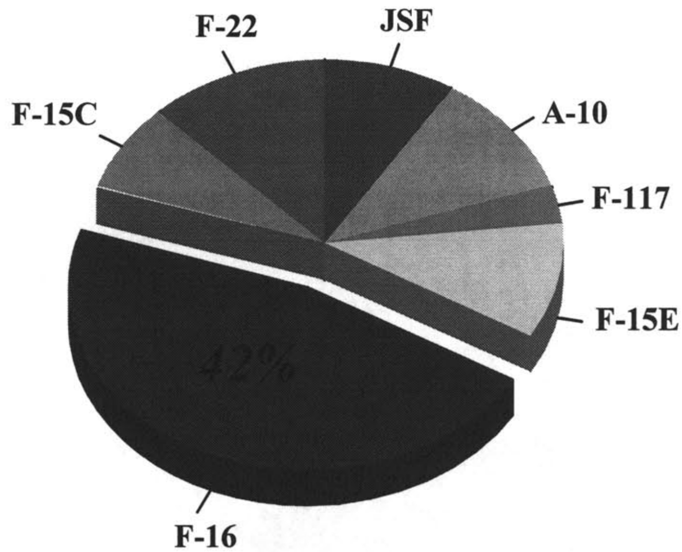

Figure 31: U.S.A.F. Fighter Force in 2015[226]

The F-16 has gone through a series of block and model changes. The three most recently developed are the Block 50/52, Advanced Block 50/52 and Block 60. All of the design efforts have increased the capability and functionality of the aircraft without increasing the size of the airframe. The external lines of the airplane have not been changed from the original aerodynamic and structural design. This makes it difficult to differentiate between the 100+ different variations of the more than 4,000 total aircraft that have been produced.[227] The block upgrades have predominately given the F-16 greater mission capabilities and improved its multi-role utility.[228]

Throughout F-16 production, there have been as many as 25 different versions of the F-16 on the production floor at any one time and there are currently 8 versions in development and several blocks being manufactured. Multi-variate production has been commonplace for the F-16 program.

Case Study Background

The Block 60 set of design changes is the most recent in the F-16 development. This is a major set of changes that incorporates all new avionics, electronic warfare capability and a new cockpit design. Internally, Block 60 incorporates more unitized structures to improve the producibility of the airplane and to maximize the commonality between the different variants being produced. Conformal fuel tanks are another new feature that will also be introduced on some Advanced Block 50/52 models. Block 60 and Advanced Block 50/52 also contain a set of changes that are the result of numerous producibility suggestions that have been collected over time.

All of these changes result in a more capable F-16 that looks different from its predecessors with the addition of the conformal fuel tanks. But it is the addition of new systems that will have a greater impact on the assembly processes.

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226 Lockheed Martin Aeronautics, *F-16 Overview*
227 Lockheed Martin Aeronautics, *The F-16 Fighting Falcon*
228 Lockheed Martin Aeronautics, *The F-16 Fighting Falcon*

The F-16 program is also introducing new models for the start of production of the aircraft for Greece, Israel and Chile. With these new production runs and Block 60 all occurring in the near future, the production rate for F-16 will be increasing from the current 2 airplanes per month to 6 airplanes per month over the next year.

Need for a Manufacturing System Modification

The F-16 manufacturing system has been in a state of continuous modification since 1991. In 1991 the customer had made quality requirements more stringent. The F-16 program was slow to react to these new requirements and dealing with numerous quality issues caused them to fall 129 airplanes behind schedule. This was the crisis that caused the F-16 team to commit to making changes. Following this wake up call, they re-organized their processes, both on and off the factory floor. This allowed them to understand the current production state and to start catching up on their schedule.

At the same time that the F-16 program was wrestling with improving the capability of its processes to deliver an aircraft that met the more stringent quality requirements, Lockheed Martin started to focus on core competencies. This was a strategic shift to try and keep the cost of the airplane constant while their production rates declined. They decided that rather than trying to do everything on the F-16, they should only focus on what they could do well. This led to outsourcing more operations to suppliers where they could be done more affordably and with improved capability. In addition to just outsourcing specific operations, they also outsourced larger pieces of work. Rather than suppliers just sending components, they were now responsible for complete sub-assemblies, decreasing the work content for the final assembly operations.

The latest manufacturing system modification is a result of the incorporation of major changes in the Block 60 and of Lockheed Martin winning the JSF contract with their X-35 concept demonstrator. Since a new program will be starting production in the same facility, F-16 final assembly has to move to make room. F-16 production is currently at a low rate of only 2 aircraft per month, so this is an opportune time to modify the system.

Since major changes have to occur, with introductions of new versions and the necessary move, the F-16 program decided that since they have to move everything anyway, they should take advantage of it and try and incorporate better production flow into the new layout. Because the F-16 has been made on the same production line for 25 years, the fundamental flow of work and the tooling is legacy. The tooling will remain the same for the new layout, but the flow can be changed.

The goal guiding this new redesign effort is to reduce the required hours per unit in the assembly of the aircraft. This goal has become a requirement for F-16 assembly in the planning of their future work. A U.S. Air Force Block 50 single seat aircraft is quoted to take 54 weeks to complete engineering development and manufacture before delivery to the customer. A 2-seat aircraft for Greece has been promised in the same amount of time regardless of the fact that the Greek variant is a completely new development and has a larger work content both in engineering and production. From this it can be seen that some hours of work are going to have to come out of the build process.

Actual Manufacturing System Modification Process

The F-16 manufacturing system modification processes have been evolutionary since they began in 1991. There have been small pockets of improvement activities slowly moving through the system. But at any one time, there is always something being changed or re-evaluated. All of the modifications to the system have maintained the legacy tooling concepts and drawings.

The more recent modification efforts have utilized value stream mapping and analysis to find opportunities for improvement and used structured kaizen events to make changes on the floor. Many of the modifications result from suggestions from workers on the floor in these kaizen events. Some examples are the slide line, "rocket launcher" and swinging gate which are all ideas that help improve individual worker efficiency. These, and other, concepts are being copied around the floor where the work is similar.

The last major reason to move the assembly operations is in response to winning the JSF contract. Since everything has to move anyway, they are using the opportunity to improve the product flow through the processes. In the new layout, parts will come down one aisle and flow through the appropriate work center then out the other side. Bringing in all material down one aisle will help with point-of-use deliveries. Other changes to the layout will place work centers that deliver or receive material from one another will be adjacent to each other so products can flow easily. They will make the parts flow through the factory rather than the stockroom.

The analysis for the new layout is also considering changes to optimize the build sequence. They are using simulation tools developed for JSF to test out some of their ideas and to test the key build processes.

Framework Comparison

The F-16 specific variant of the manufacturing system design framework is shown below. At first glance it looks similar to the framework proposed in Chapter 4, but the F-16 manufacturing system design process depicted here must be taken in a different context.

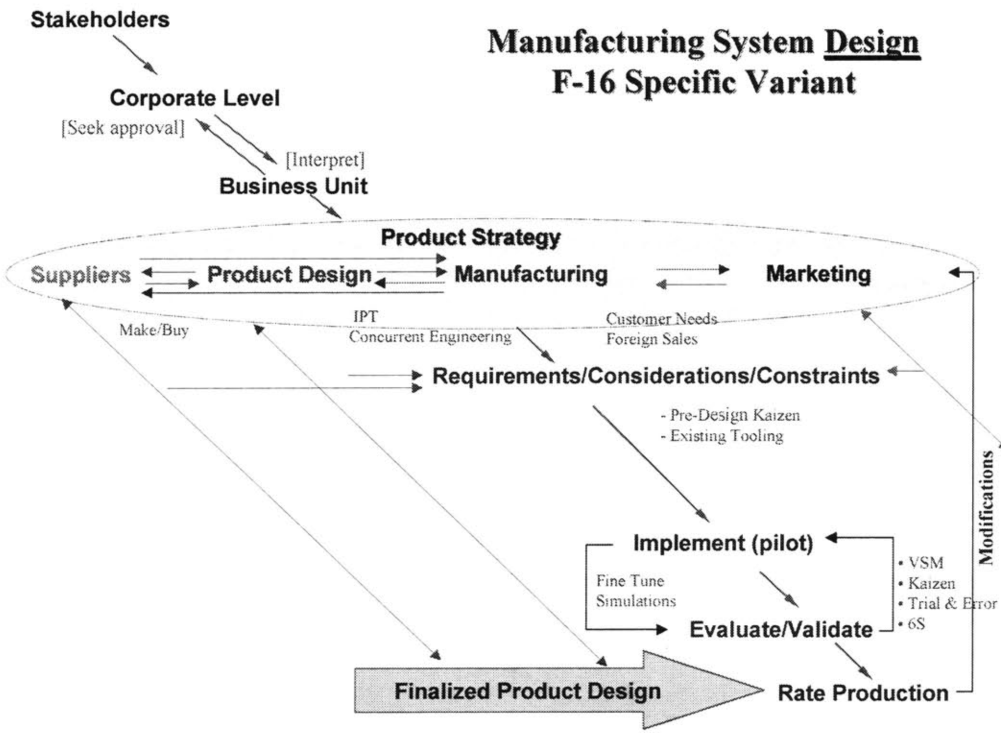

Figure 32: F-16 Specific Variant of the Manufacturing System Design Framework

Rather than this framework showing the complete manufacturing system design process for F-16, this is showing the modification loop that the system has been in since 1991. And, this modification loop is not indicative of all their modification efforts, but rather just the large changes that have been made to their system. This modification loop that extends from rate production back to the product strategy represents the process used when changes were first made at the time of crisis in 1991, later when the system was changed to cater to core competencies, and now when the system is being redesigned for its move and the introduction of major design changes.

The modification loop reaches from rate production to product strategy for the F-16 design process. The product strategy changed for the different modification efforts in response to changes in the environment and corporate strategic structure. The first shift in the product strategy was to focus on the core competencies and outsource more responsibility to the supplier base. Now the product strategy is shifting to a complete enterprise perspective of what they need to do to support the production of all the fighters at the Lockheed Martin Aeronautics. And the single product strategy for F-16 is also shifting to support Block 60 and to accommodate all the new changes being incorporated into the aircraft.

The requirements definition phase is the next phase in the F-16 manufacturing system modification. The F-16 program is always re-evaluating its requirements since they are in flux. The production rates and mix of configurations is always changing and the interactions with the supplier base with the introduction of unitized structures impacts the requirements on the manufacturing system.

The next phase on the original framework, the manufacturing system design phase, is not present on the F-16 specific variant of the framework since they are not designing their system again. The F-16 program has maintained the same tooling and build concepts through all of the passes through the modification loop.

Piloting activities have been present in the various modification events both on large and small scales. In general, most new ideas are piloted on a small area of the factory floor to test it. While mock-ups and such are not formally part of their improvement event structure, some areas opt to make mock-ups. Probably the largest piloting activity present in the F-16 system is the ALE-50 pylon program. The ALE-50 is located in a missile launcher pylon that houses towed decoys on the F-16. The Lockheed Martin facility in Fort Worth builds the structural part of this pylon. This small manufacturing area was converted to a cellular layout and the area has been made completely self-sufficient. After the transition in the area, throughput time for the pylon dropped from 166 days down to only 14 days. This area gave the F-16 team a success to show other areas of the program. The piloting loop of the framework is also appropriate for F-16 since some things were piloted on F-16 as proof of concept for JSF. For the new layout when the F-16 assembly area is moved, the same computer simulation tools developed for JSF were used to test out various ideas.

The final element of the framework is the interaction between the different functions during each phase of the design process. When Lockheed Martin began to modify its manufacturing system, they were also beginning to use integrated product teams (IPTs), which proved to be a huge success on this program.[229] This framework highlights the interactions with product design, suppliers and marketing.

Engineering interaction is critical on the F-16 program. F-16 is dealing with the constant flow of design changes, which are prevalent in aerospace design and production, but they are also dealing with the engineering differences in customer and block variations. Without careful configuration control, the production operations could easily become chaotic. One of the ways that the interaction between engineering and manufacturing has improved is with the introduction of the Build-to-Package Support Center. This is an area on the factory floor where all the resident expertise resides to support the factory floor in the change process. It is, in effect, an engineering cell in the same way that the ALE-50 pylon is a production cell. An item enters the center and the design change flows through the required personnel within the Build-to-Package Support Center then onto the floor.

The next element of interaction is with suppliers. The F-16 program understands that this is an important part of the modification work on the manufacturing system since most of the cost of the airplane resides in the supply chain and not in processes resident in the Lockheed Martin factory. Because of this, they have tried to establish long-term contracts with suppliers, but then arrange for smaller shipments to the factory floor. The supplier interaction is re-evaluated each time a large change is made, whether it is for a block change or the introduction of a new configuration for a new customer. For each new configuration, the supplier base may be slightly different since the work may not be divided the same way between different versions of the airplane. And as has been the trend; these strategic relationships are fostered since the program

[229] Towle, M.D., "Tearing Down Fences"

is giving suppliers more substantial pieces of work such as complete subassemblies rather than component parts. The F-16 program is also looking at detailed aspects of the supplier relationships as well. They are exploring the different ways to kit parts, signal shipments and start to implement "pull" with their supplier base.

The final element of functional interaction addressed by the framework is the interaction with the marketing function. For the F-16 program, this interaction is extremely important. Foreign sales will keep the program in production through at least 2008, with the possibilities of entering new markets to extend this even further. Throughout the F-16 program, foreign sales have constituted a large portion of the work. There have been 48 follow-on buys by 14 different countries through the lifetime of the program. This aspect of the program is becoming more important since the U.S. Air Force is now beginning to acquire the F-22 for operational units and the Joint Strike Fighter will be the next-generation workhorse of the fighter forces. Foreign sales are the future of the F-16 program.

System and Process Performance

The F-16 program has seen a remarkable turn around from their bleak moments in the early 1990s. They went from struggling to match quality expectations and being behind schedule, to having a record of 104 months of consecutive on-time deliveries. The success of the F-16 program is also seen in the fact that unit prices were reduced by 38% while production rates fell 75% from the earlier peak production rates.[230] This also resulted in the F-16 production facility in Fort Worth to receive numerous prestigious manufacturing awards, such as the Shingo Prize for Excellence in Manufacturing.

The modifications of the system and the diffusion of lean areas on the floor are starting to propagate through the system. Where lean principles have been applied on the factory floor, a 20-33% drop in hours per unit has been realized. But since the whole system has not yet utilized lean thinking to improve their processes, these results are not universal so there has not been an analogous impact to the bottom line. But if the program continues to slowly spread the improvement events across the floor and link more of the successful areas, then the impact to the total aircraft cost should become evident.

The F-16 has been in production since 1977 and is currently scheduled through 2008. The program is also trying to generate new orders with the prospective customers of Poland, Austria, Oman and Brazil.[231] This length of service and the frequency of follow-on buys by 14 different customers is a testament to the success of the F-16. It is the versatility and robustness that have allowed the F-16 to become the most popular fighter in the world.

The manufacturing system design process followed by the F-16 program has been a series of modification efforts to allow the system to evolve. This leads to the F-16 specific variant of the framework covering all the various areas of the proposed framework but through repeated modification efforts. The F-16 framework is similar to the original framework, but just used in a different context.

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[230] Lockheed Martin Aeronautics, *The F-16 Fighting Falcon*
[231] Lockheed Martin Aeronautics, *F-16 Overview*

6.2 Electronics Assembly

The next section of case studies took place in the electronics sector of the aerospace industry. The electronics sector is unique in that it is dealing with technology that changes at a much faster clock speed when compared to the major aerostructures as described earlier, or the launch vehicles, which follow. Also, electronic components are frequently produced in much larger volumes than complete air or spacecraft. But there is still the potential for striking similarities in the electronics assembly with other sectors of the aerospace industry.

The cases contained in this section are from the two extremes of the electronics sector. The first, Wedgetail assembly by Northrop Grumman, can be more closely compared to the assembly of a satellite than electronics. It will be produced at fairly low volumes and the products themselves are quite large. The second case study is a transponder (TDR-94) made by Rockwell Collins. The TDR-94 is a more traditional electronics assembly in terms of size and cycle time. The TDR-94 manufacturing system design process was captured retrospectively and Wedgetail was followed real-time.

Wedgetail

Project Wedgetail is a next-generation “middle range” 737 airborne early warning and control system (AEW&C) selected for the Royal Australian Air Force.[232] It is a Boeing and Northrop Grumman designed platform that is based on the Next Generation 737-700 increased gross weight (IGW) aircraft (737-700 with the wing of a 737-800). 737 AEW&C is interoperable with existing platforms like the E-3 and venerable AWACS aircraft and is scheduled to enter service with the Royal Australian Air Force in 2007.[233]

Figure 33: Artist's Conception of the Boeing/Northrop Grumman Wedgetail platform[234]

[232] From the Flug Revue
[233] From http://www.boeing.com
[234] Figure courtesy of Boeing Media at http://www.boeing.com

The initial contract with Australia is for 4 737 AEW&C systems with later options for 3 additional systems. Turkey and South Korea are also interested in the 737 AEW&C system to add significant capability to their military forces.[235]

Case Study Background

Northrop Grumman makes the Multi-Role Electronically Scanned Array (MESA) Radar that sits prominently atop the 737. The MESA Radar consists of the "top hat" and dorsal array. It is an L-band active electronically scanned radar system with a 360-degree steerable beam.[236] The 120-degree side arrays are housed in MESA's dorsal fin while the 60-degree nose and tail coverage is provided by an electronically steered end-fire array called the "top hat" that is mounted in a flat radome about the MESA arrays.[237]

The MESA Radar assembly is a highly capable system that is able to track air and sea targets simultaneously in a 190 nautical mile radius with additional beam steering flexibility to extend segment detection beyond a range of 400 nautical miles.[238] It is also able to track high-performance aircraft while continuously scanning the operational area.[239] In fact, Wedgetail has enough initial capacity to evaluate more than 3,000 targets simultaneously.[240] 737 AEW&C has an advanced identification friend or foe (IFF) system and an expanded, passive surveillance system. It is built as a flexible, open system architecture to allow for additional capabilities to be added in the future.[241]

The MESA Radar consists of internal electronic equipment in addition to the top hat and dorsal array that are visible on the exterior of the aircraft. The radar is controlled by electronics housed in two main cabinets and a smaller module inside the aircraft visible in the following figure. It is the assembly of these internal cabinets that this research follows. These two cabinets and smaller modules are to be made in the Systems Test and Integration Facility (STIF) where the cabinets are stuffed full of electronics and then tested.

[235] Demir, M., *Selection by Turkey Bolsters Boeing's AEW Drive*
[236] Demir, M., *Selection by Turkey Bolsters Boeing's AEW Drive*
[237] Demir, M., *Selection by Turkey Bolsters Boeing's AEW Drive*
[238] Demir, M., *Selection by Turkey Bolsters Boeing's AEW Drive*
[239] From http://www.boeing.com
[240] From http://www.boeing.com
[241] From http://www.boeing.com

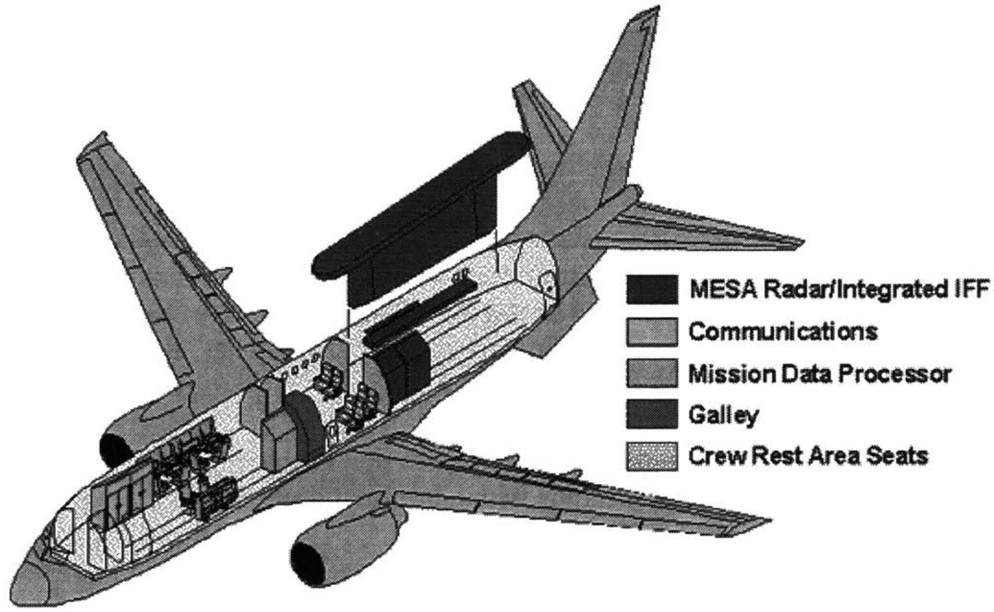

Figure 34: Schematic of the Wedgetail platform[242]

In the STIF, the cabinets and electronics are received, the cabinets are stuffed and the complete system is tested. Even though the MESA Radar is a high-tech product, the assembly work in the STIF is fairly low-tech. The assembly processes of building up boards and placing them into cabinets is unaffected by the increase in internal complexity over earlier programs. The complexity of the system comes into the software for the product itself and the testing procedures. The hardware is simple.

Initial Manufacturing System Design Process

The initial strategy for the design of the Systems Test and Integration Facility (STIF) was for it to function as a joint engineering-development-manufacturing facility. The engineers would be co-located with production throughout the detailed design and development of the system included the manufacturing of the early prototypes. This idea is a major change for how Northrop Grumman has traditionally developed new programs, and guided much of the design of the STIF.

The design of the STIF took place over an 18-month period and was largely requirements driven. The early portion of the design process was to meticulously and rigorously identify and define the requirements and constraints on the system. The requirements identified to guide the STIF design stemmed from testing requirements, capacity requirements, and geometric requirements.

The testing requirements were dictated by the product and what would be entailed to ensure a system level test. This required glycol cooling and the use of 400 Hz power which impact the infrastructure needed to support the testing areas. The use of 400 Hz power also brings with it additional safety requirements to ensure the safety of the workers. Wedgetail also has more

[242] Figure courtesy Northrop Grumman

stringent test requirements since there are more commercial, off-the-shelf (COTS) goods included in the system.

The capacity requirements were derived from the potential production rate and qualification work of the system. This determined the number of required test bays, which will be the main bottleneck for the STIF.

The last group of requirements was determined by the geometric constraints placed on the STIF design team. The original testing scheme was to place a MESA Radar antenna on the roof of the factory building and perform the complete system test with the cabinets in the test bay, connected to the roof mounted antenna. This confined the STIF to be placed in a certain corner of the existing facility that had the connection for the antenna, which constrained the design geometrically.

Following the definition of these requirements, the STIF was designed. But, the area of the factory floor where the STIF was confined was so small and the requirements were so stringent, that there were not many options available to the design team. The STIF was basically designed to just be able to somehow fit in the given space.

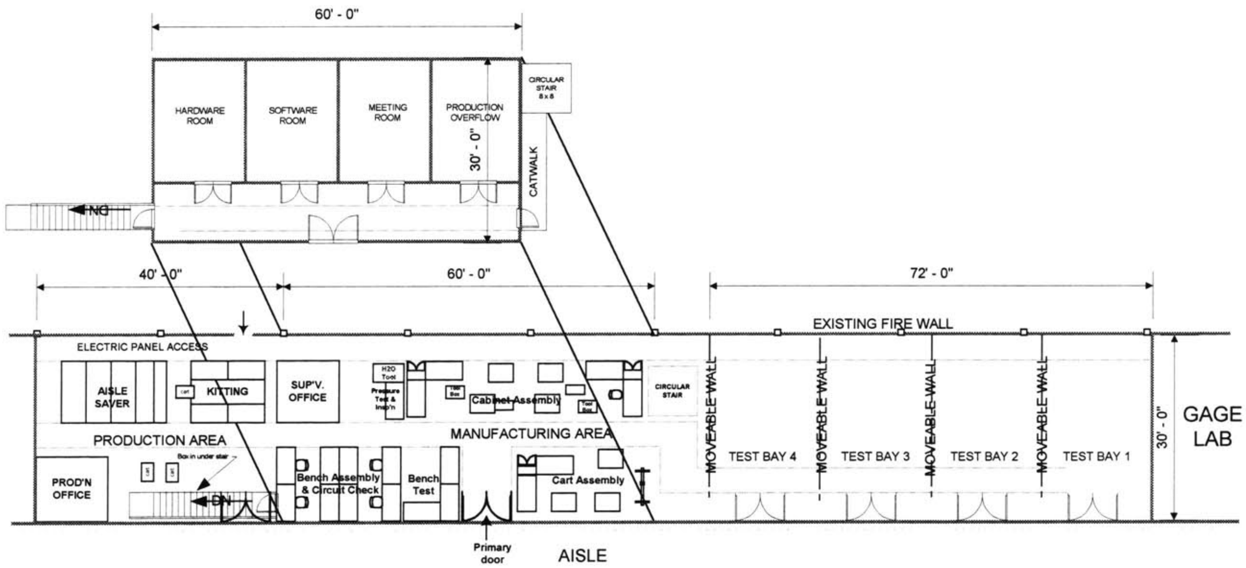

Figure 35: The initial design for the Wedgetail STIF

With these requirements and constraints, the STIF was designed to be a long, skinny area that would fit between the main aisle of the existing factory and the wall with the test bays in the corner that contained the connection to the roof mounted antenna. The remainder of the floor space contained the production supervisor office, kitting area, storage of common minor materials, bench level assembly and cabinet assembly. The STIF also contained a mezzanine to house the engineering lab, a conference room and space for additional hardware or production support equipment.

By early September 2000, the STIF was designed and the first architectural plans were made. Construction was due to start on the facility in October 2000 to house the early work on the system prototype in early 2001.

But then Australia had to slow down the contact negotiations since they were financially unable to sign when they originally intended. This delay prompted Australia to conduct a review and prioritize the different programs competing for funding.

At the same time Australia delayed the contract signing, there was a serendipitous meeting that occurred at Northrop Grumman. The Lean Enterprise Institute (LEI), founded by Lean Thinking author Jim Womack, had some representatives in the facility to look at another program. The Wedgetail program management thought it would be a good idea to talk to them a bit since they had some time now to re-evaluate and possibly tweak the STIF design a little.

The LEI representatives looked at the STIF plans. When they noticed that it was only 30 feet wide, they asked why the STIF was designed in a hallway. They charged the STIF design team to start with a clean sheet of paper and not confine themselves to a section of the factory floor. Their assignment was to ignore their constraints and just focus on the product and what would be required to make the product flow smoothly through the system.

A few days after this meeting, on 20 September 2000, the first "lean layout" emerged. And on 5 October 2000, construction of the STIF officially stopped until further notice.

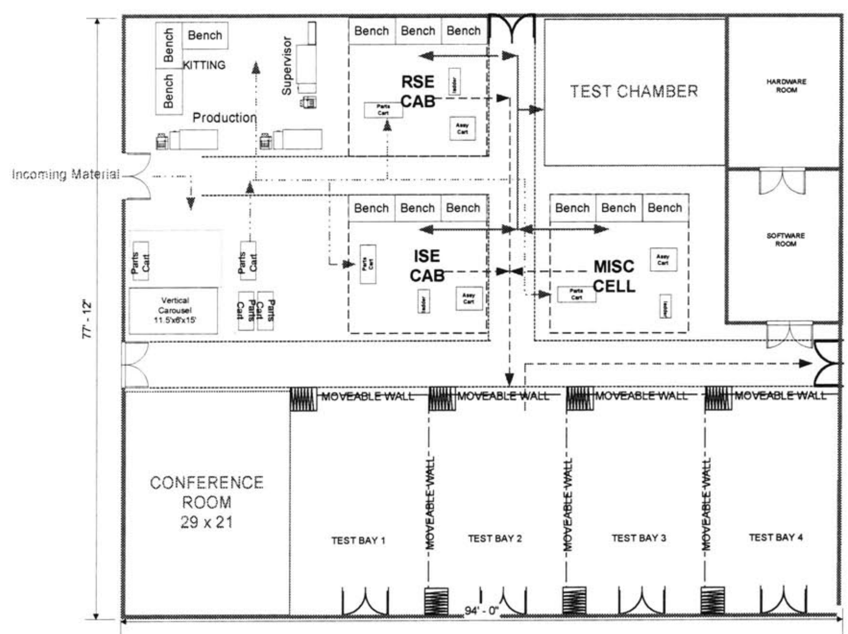

Figure 36: An early "lean" design for the Wedgetail STIF

This major change in events led to the team to decide to re-evaluate the design of the STIF.

Second Manufacturing System Design Process

Given the slip in the timeline, and the education by the LEI representatives, the STIF design team decided to revisit the design and pursue some other possibilities. The overall assumptions guiding the re-design effort were to stick to the original idea of co-locating engineering, assembly and testing procedures, but now to try and incorporate some of the principles the LEI representatives taught them.

The new design process began by reviewing the original requirements to determine which, if any, of the requirements that initially constrained the design effort could be challenged, or relaxed. The testing and security requirements remained the same while the capacity requirements changed slightly, but did not change the required number of test bays. The geometric constraints, however, had been relaxed. Before the construction of the STIF was due to originally begin, it was determined that the antenna could not be mounted on the roof to conduct the complete system level test. It would emit too much RF energy to be considered safe. But, in the interest of time, the STIF was still going to be built as originally planned. The change in requirement of having to be in the corner with the roof mounted antenna connection allowed the STIF design team to relax that constraint and think about new STIF designs on a clean sheet of paper. In the initial interviews with the STIF design team members, they all felt that the geometric constraint was the hardest to satisfy in the initial design. Relaxing it will be the most important factor in allowing the redesign effort to take hold and be effective.

This re-evaluation of the constraints shaped the design of the new STIF and helped establish some additional goals they now wanted to consider. The new design would also try and reduce the material movement of the product. A large portion of this would come from trying to incorporate a test chamber into the STIF that in the hallway was outside the secure area. Bringing the test chamber into the STIF would allow the product to remain in the secure area for the whole process, and greatly reduce the travel. It was also determined to try and reduce the throughput time by building the three different sub-assemblies (the two cabinets and one smaller module) in parallel with all three arriving at the test bay together. They also wanted to ensure that the STIF was flexible so it could accommodate a range of production rates, as well as the frequent changes that were anticipated to be needed for the early units. One other item that was considered was to try and receive material directly into the STIF. Part shortages have historically been their biggest barrier and they thought that if they were in charge of their own material receipt, they might be able to impact that. This would entail bypassing the normal procurement procedures, which entailed all incoming material to be received and placed into the Automatic Retrieval System (ARS).

After creating the first "lean" layout, shown in the earlier section, the group started to work with those ideas as well as the new goals established. Another concept they embraced was the concept of cellular manufacturing. The LEI representatives had just introduced the idea of the ergonomically designed U-shaped cells to the design team and they were enamored with the idea. Designing the different cells for the system was accomplished by looking at the proposed part list and assembly times to try and level the work between the different cabinets and the smaller module. It was decided to have three cells, one for each cabinet and one for the smaller module. The kitting area and engineering areas were also maintained. Other additions to the new STIF design were to increase the flexibility of the cells by having all the benches and equipment on rollers so things could be easily reconfigured.

After the product design progressed and the STIF design team had a more accurate idea of the contents of the cabinets and the predicted processing times, they eliminated one of the cells and combined the assembly of both cabinets into a single cell.

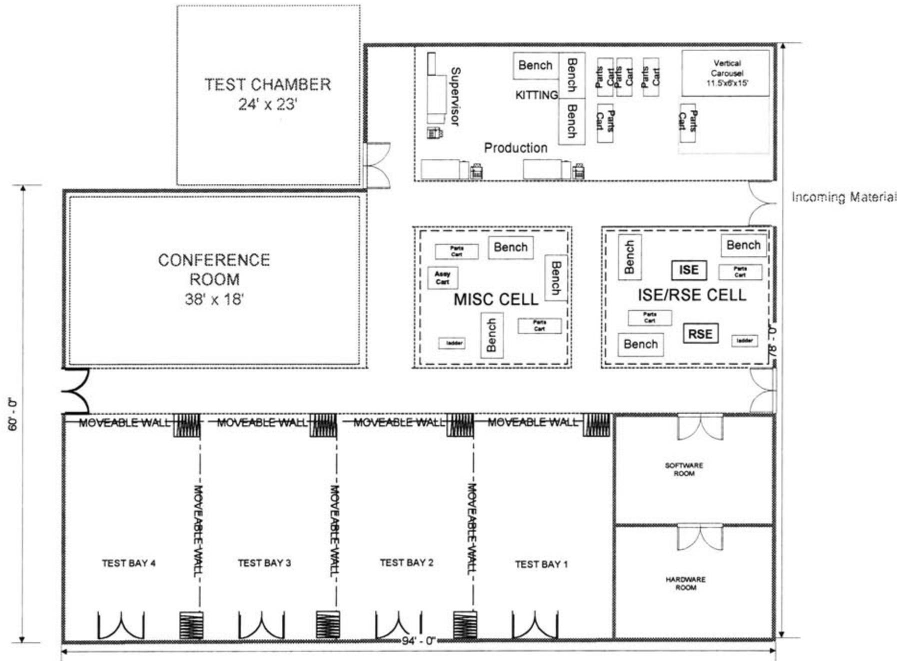

Figure 37: "Lean" Option VI of the Wedgetail STIF

An issue with the new design was the level of detail that existed in this schematic. The drawing shows the exact location and number of benches in each cell, which is a fairly detailed design decision that was made before the product characteristics were even close to the same level of definition. This level of detail in a layout at this stage was based on mainly assumptions of what would be required. But this level of detail did not change in the later iterations. At this point, the only remaining challenge was to modify the STIF design as appropriate to ensure that it fits into the actual factory floor. This led to some additional small modifications and the final layout shown below.

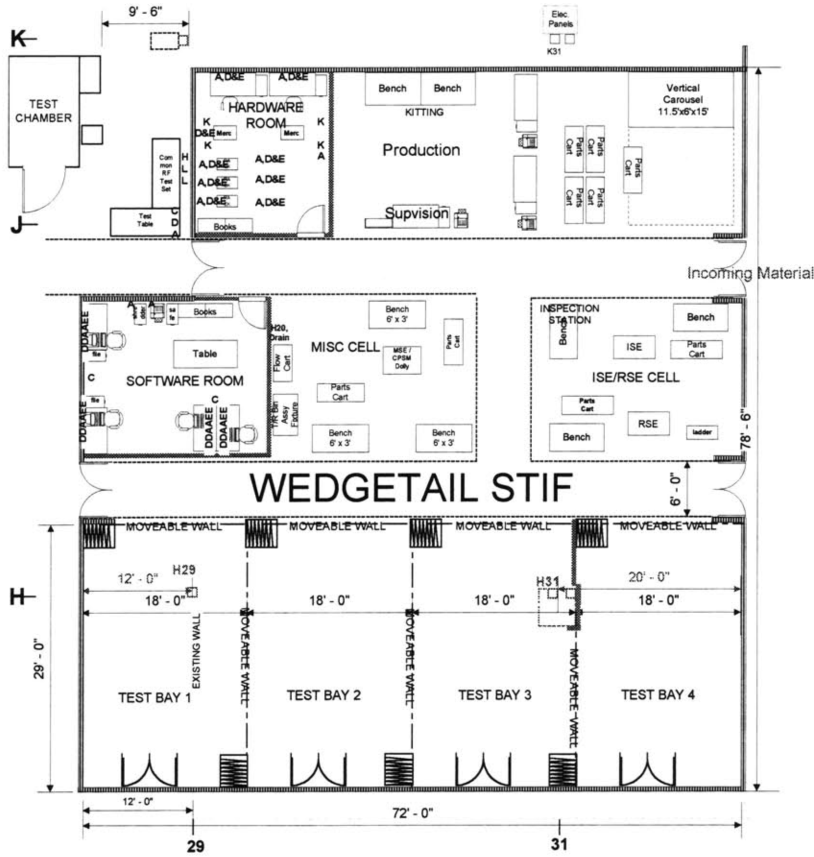

Figure 38: The final design of the Wedgetail STIF

The entire design process shows that the main change was from the initial design of the hallway to the first of the "lean" options. The remainder of the design work was on detailed changes to facilitate the actual implementation. But, the redesigned STIF allowed for some drastic improvements over the original hallway design. The part travel was reduced from 450 to 140 feet and the test chamber is located right next to the facility. Also, the engineering areas in the hardware room and software room can now be located on the main floor, rather than requiring the costly construction of a mezzanine level. This was a substantial cost savings for the program.

The final issue to ensure that the new STIF design could be realized was to acquire the needed area on the floor. Since the STIF was almost built once before, an area of the factory floor had been cleared out. Now the program management had to ask for a different area of the factory floor to be cleared out instead. With some skillful maneuvering by program management, Wedgetail was able to take the floor space they desired which will allow the STIF redesign to be implemented.

Framework Comparison

The Wedgetail manufacturing system design process is a unique one. It begins with the strategy formulation, which contained all the functions, but not all the functions interacted with each other to determine the product strategy. The development of the manufacturing strategy consisted of determining that the engineering and production operations would be co-located in the same facility. The product design and manufacturing functions interacted with the suppliers to go through the make/buy decisions.

Following the strategy development, the requirements were defined for the manufacturing system. This was done meticulously and in great detail with input from the product design and marketing functions. Following the determination of all the requirements, considerations and constraints acting on the system, the STIF was designed, but it was so constrained that the design effort mainly consisted of trying to fit everything needed in the available space. This was when the hallway layout was designed. Following this, the Wedgetail manufacturing system design framework takes a unique turn.

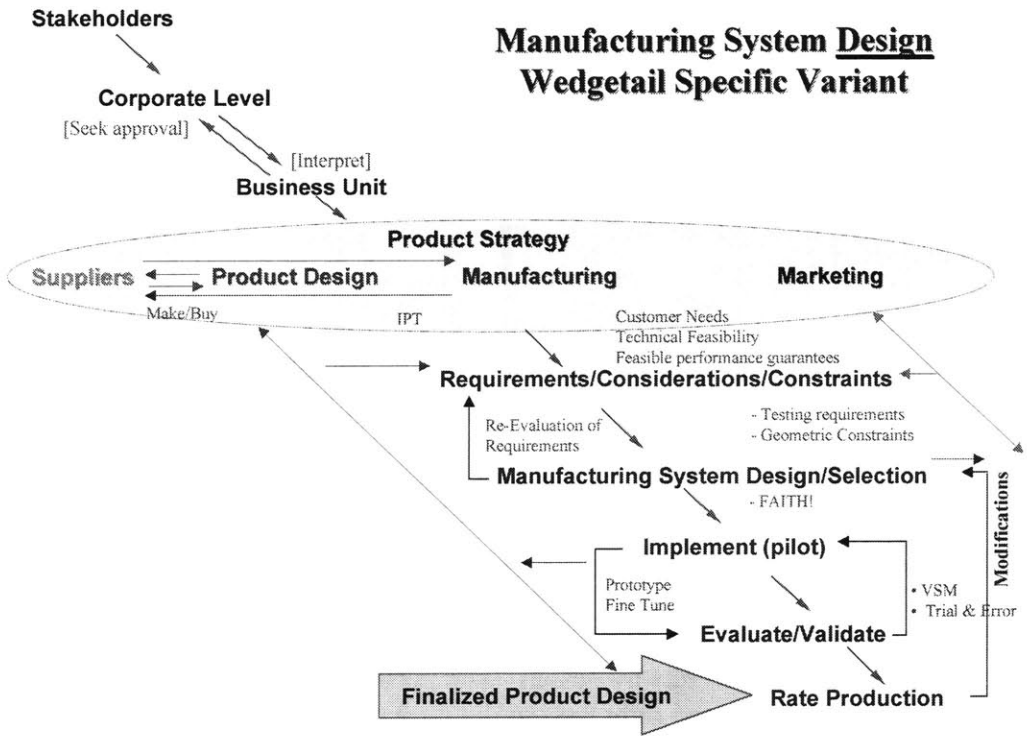

Figure 39: Wedgetail Specific Variant of the Manufacturing System Design Framework

After designing the STIF, the slip in timeline with the Australians, along with the visit from the Lean Enterprise Institute prompted a re-evaluation of the requirements. This is marked as an arrow back up to the requirements level. At this point, the geometric constraints had been lifted and the team decided to re-design the STIF without the constraint of fitting in the hallway.

The manufacturing system design phase in the second iteration is an example of "faith based" manufacturing system design. With the re-evaluated requirements in mind and the challenge to think outside the box, the team was enamored with the idea of cellular manufacturing and used it throughout the remainder of the process. It was at this level where numerous iterations of the STIF were created that became increasingly detailed as the product and processing times became more defined.

When a finalized layout had been determined, the team moved into the piloting phase. Ideas for the part presentation and part carts were experimented with to try and implement some visual control of incoming material. These ideas of the part carts and some of the other layout differences proposed in the STIF design were used on a similar product, to test them out. Finally, the STIF will house the prototype development which will act as a pathfinder for the complete system. It is planned that any major problems encountered in the assembly of the prototype will feed back into the product design.

Finally, the modification loop is present on their framework because improvement activities are common throughout their facility and certainly planned to occur in the STIF once it is built. But the majority of the modification efforts are on fairly easy projects and not after the major bottlenecks to the flow.

Some interaction with the product design function was quite good as a result of the manufacturing system redesign effort. When the STIF design team wanted to start exploring the design of the part carts for the different cells, they caught engineering mistakes where place holding parts had not been removed, or where COTS goods could easily be substituted.

The manufacturing system design was influenced by the marketing function throughout the process. The status of the different contract agreement processes changed the required capacity of the system repeatedly. Throughout the course of following the design process of the STIF team, forecasted demand shifted regularly between 2 units per year to a maximum of 12 units per year.

The last element of breath is the interaction with the suppliers. This interaction was not present beyond the initial make/buy decisions, but it should have been. It was mentioned earlier that historically, their biggest problem was part shortages. It was said in one interview by an engineer, "we can make anything, if we only had the parts". But beyond the initial discussion that receiving their own material directly would give them tremendous leverage of their total value stream, all work done with the supplier interaction was internal and on superficial items like part presentation, kitting and the part carts. They did not look at the supplier interactions beyond their sphere of influence. The Wedgetail team was a victim of an enterprise push to use the existing system which was, unfortunately, only purchased a short time ago.

System and Process Performance

The process of designing the Systems Test and Integration Facility (STIF) for 737 AEW&C was truly a change for business as usual for their facility. It will, in the end, be a joint use facility for engineering, development and manufacturing.

But, the amount of impact this new facility will have may be limited. Wedgetail did well in the small portion of the value stream that they have control over, but it is obvious that they do not have the ability to impact the overall program. For example, the main cause of problems historically has been part shortages and that problem was not tackled for the new STIF design. Incoming material will continue to cycle through the existing system and will only be kitted once it enters the STIF.

Finally, some of the items needed for project Wedgetail have long lead times, which will seriously impact the ability of the system to be flexible and responsive to changes in demand. Shortening the approximately 1-month throughput time in the STIF will have little impact on an overall system with lead times over a year.

In the end, the Wedgetail team had a unique experience where the system design changed from the hallway layout to more open and accessible manufacturing system that will be beneficial to the product. The Wedgetail specific variant of the framework illustrates this process and the benefits gained from their re-evaluation of the requirements and trying to structure the remaining design activities that allowed this major change to occur.

TDR-94 Transponder

Rockwell Collins is a global company providing aviation electronics and communications equipment for aircraft around the world. The Rockwell Collins, Inc. facility in Melbourne, Florida is the focus of this case study. The facility in Melbourne makes avionics for commercial and military aircraft. The processes in the facility range from surface mounting components to assembling boards in progressive builds into a "top level" product. The Melbourne facility has 25,000 active part numbers for over 200 different product families.

This combination of a large product variety and a relatively high rate of production for aerospace products makes this a great addition to the aerostructures, launch vehicles and spacecraft in this research.

Case Study Background

This case study focuses on just one of the many products made in the Melbourne facility, the TDR-94 transponder. The active transponder, used in aircraft, replies to ground based radar interrogations to provide air traffic controllers with aircraft position, identification and altitude information. The TDR-94 also responds to interrogations from other aircraft and serves as a modem for data link, performance, navigation information and Air Traffic Control (ATC) transactions between the aircraft and ground based radar.[243]

The TDR-94 itself is small unit that is part of the aircraft instrument panel and is shown in the picture below. The TDR-94 is all solid state with a crystal controlled receiver and transmitter. It receives pulsed and phase-shift modulated interrogations from ground and airborne surveillance radar and replies with a pulse amplitude modulated transmission at high peak power. The Mode S capability allows for long range surveillance with radar through a GPS interlink.[244]

[243] Product information from http://www.rockwellcollins.com/ecat/br/TDR-94_94D.html
[244] Product information from http://www.rockwellcollins.com/ecat/br/TDR-94_94D.html

Figure 40: The Rockwell Collins TDR-94 transponder[245]

The TDR-94 is designed for use in business or regional jets like the new Premier made by Raytheon Aircraft shown below. Raytheon Aircraft and Bombardier are the main aircraft applications for the TDR-94.

Figure 41: Premier I by Raytheon Aircraft is a typical application for the TDR-94[246]

Need for a Manufacturing System Re-Design

The TDR-94 has been in production since 1990. In 2000 a manufacturing system redesign began. This effort was born out of the corporate level thrust for all of Rockwell Collins to become "lean" to improve the value of the company to all stakeholders. The corporate goals established to lead this effort were to achieve:

- 35% improvement in productivity
- 50% reduction in inventory
- 50% reduction in cycle time

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245 Photo courtesy of Rockwell Collins at http://www.rockwellcollins.com/ecat/br/TDR-94_94D.html

246 Picture courtesy of Raytheon aircraft at http://www.raytheonaircraft.com

- 30% reduction in cost
- 25% reduction in floor space

In Melbourne, there are 27 different product groups that together account for 80% of its revenue and 70% of the total quantity of products sold. This made these products attractive to begin a lean transition.

Actual Manufacturing System Design Process

Given the thrust from the corporate level of Rockwell Collins to lean the various manufacturing operations, the Melbourne facility started in May 2000 with a top level value stream. This led to the selection of the TDR-94 and the DME (Distance Measuring Equipment) as the first two candidates for a transition into cells.

The process of converting an existing manufacturing area into a cell takes 5 or 6 lean events that start with detailed value stream mapping, then co-location of all the needed processes and finally the creation of the cell with the incorporation of standard work.

One major hurdle in co-locating all the needed processes to create a dedicated cell was to "right-size" some operations. Some processes require equipment that is physically too large to fit into a cellular layout, and other processes have long cycle times, such as a heat treating operation, that make them difficult to incorporate into cellular flow. The TDR-94 had a particular coating operation that would have been difficult to fit into a cellular layout. Previously, the low process capability required workers spend substantial amounts of time in preparation for the coating operation rather than the operation itself. But for incorporation into the cell, this operation was right-sized to fit into the cellular layout and this machine proved to be more capable than the original eliminating the lengthy preparation processes. This improved their process capability and enabled the process to be incorporated into the cell to help create flow.

This series of lean events to convert the TDR-94 area into a cell took place over several months and resulted in a cell that carries the TDR-94 through the processes following the surface mounting of the components onto the boards through to the finished, or "top level" product.

Following the initial set of lean events to convert the TDR-94 area into a cell, re-evaluation activities were conducted. The break up of the different tasks into standard work was to be re-evaluated to ensure that the work content is consistent in each station. Also, it was planned to co-locate the cell support personnel with the cell itself to ease communication when a problem arises. Another proposed change was to pull the cell supervisors out of their current positions as full-time inspectors and make them flow managers to oversee the complete flow of work through the cell.

The original plan and focus for the Melbourne facility was to create cells for the various products. These cells would then be connected, impacting the overall value stream throughout the facility.

Framework Comparison

The TDR-94 specific variant of the manufacturing system design framework is presented below. There are many differences between this specific variant and the proposed framework from earlier. First of all, the goals that drove the design effort came directly from the corporate level and not from a product strategy, or even from the manufacturing function. That is why the oval normally marked "product strategy" is instead labeled "corporate goals" in this specific variant.

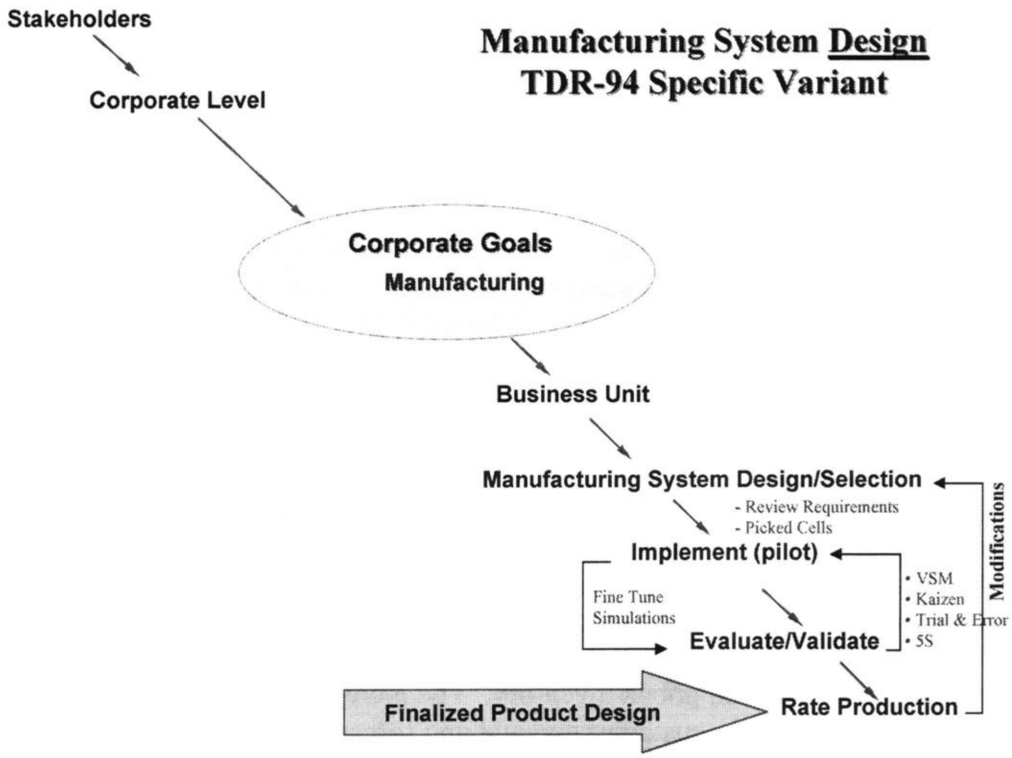

Figure 42: TDR-94 Specific Variant of the Manufacturing System Design Framework

These corporate goals were translated to the various business units throughout Rockwell Collins to realize them. These goals did not translate into a specific manufacturing strategy at the business unit level; instead they kicked off the lean efforts to transform the Melbourne facility from a traditional manufacturing operation into a more efficient cellular manufacturing layout.

The next phase on the TDR-94 specific variant of the framework is the manufacturing system design and selection phase. Within this phase, cells were decided to be the goal for the facility and the requirements, considerations and constraints were evaluated to determine which areas would be the best starting points for the cellular conversions.

The implement/evaluate loop was used in this redesign effort to determine how the cell layouts would fit into the existing floor plan of the facility. Simulations were made to explore this. Following the determination of the final floor plan, the machines and stations were moved and the cell functioned at a rate that was scheduled to meet the TDR-94 takt time.

Following the conversion to a cell, the process entered the modification loop. In the TDR-94 cell and throughout the Melbourne facility, there are numerous improvements going on. Many of these activities are small events with no real prioritization other than weighted average demand in light of the higher level goals to guide the activities.

Another characteristic of the TDR-94 specific variant of the framework is that there was no input from the engineering, supplier or marketing functions. The interactions between the different functions were traditional, where manufacturing and suppliers were brought into the development after the preliminary design had been completed. In the scope of the initial redesign efforts, the interactions with the engineering and supplier communities were not changed. But there have been more recent changes that are outlined in the following section.

System and Process Performance

There are interesting observations to be made of the TDR-94 experience. First of all, as far as any manufacturing system design process, the work done to right size the equipment and bring all the processes into the cell was successful. The changes to the coating operation mentioned earlier not only brought it into the cellular flow but improved the capability of the process.

Another lesson to be gained from the TDR-94 experience was brought to the attention of Rockwell Collins management with a follow on value stream mapping event held in August 2001 after the initial cellular conversion. This event found that inventory and waiting time had, in fact, increased through the cellular conversion process. There was a few days' worth of inventory between stations in the cell, which led to no synchronization in the flow through the cell. Workers had been adding more units into the flow to account for defects rather than repairing the defective units. In addition to an increase of work in process within the cell, there was also an increase in finished goods inventory. The increase in finished goods inventory was due primarily to fluctuations in customer demand and forecasting. The major learning point was that targeted inventory levels were in synchronous with actual demand.

The other issue the TDR-94 value stream mapping experience discovered was the impact of not having a strategic focus to guide the redesign efforts in the current state. The corporate level goals did flow down to the business units but were not connected to this new manufacturing approach.

In the framework comparison it was mentioned that the initial manufacturing system redesign efforts occurred without changes in the relationships with the other functions. But the impact of breadth in the manufacturing system design process became evident when a particular cell was unable to meet their required takt time. The issues were traced back to a design problem. Through interaction with the product designers, this issue was resolved within a month and the cell now has no problem meeting its takt time.

The nature of their products is such that many of the unique constructs described in Chapter 3 do not impact their work. Their products are physically small and produced at a relatively fast rate for aerospace products with processes that do not have the low capabilities of some other aerospace sectors. But now that Rockwell Collins has seen the difficulties of quickly trying to introduce cellular manufacturing and what the lack of strategic focus has done to their performance they are now modifying their systems to address these issues and possibly become an example of lean manufacturing in the aerospace industry. An example of this would be the way in which Rockwell Collins is now implementing a directive to obtain more "buy-in" from lower level management and production level employees.

The comparison of the Rockwell Collins manufacturing system design process to the proposed framework shows the impact of integration between a corporate level and functional strategy and the improvements that can be gained through increased interaction with other functional areas.

6.3 Evolved Expendable Launch Vehicle (EELV) Assembly

The Evolved Expendable Launch Vehicle (EELV) is the Air Force space lift modernization program, which addresses the national need for a new launch vehicle.[247] The US currently builds about ¾ of the world's satellites, but conducts only 30% of the world's launches.[248] The EELV program will reduce launch costs by at least 25% over the current Delta, Titan and Atlas launch systems and save the Air Force $6 billion in launch costs between 2002 and 2020. The EELV program consists of two companies tasked to develop and demonstrate their platforms – the Boeing Company's Delta IV and Lockheed Martin's Atlas V.

In addition to developing the launch vehicles themselves, the two companies are developing the launch pads, satellite interfaces, support infrastructure and will demonstrate that the systems meet all government requirements. Boeing will launch the Delta IV from both US coasts while Lockheed will launch the Atlas V from only the east coast. The first launches of medium lift vehicles are scheduled for summer of 2002 with an operational Heavy Lift Demonstration Launch scheduled for 2003.[249]

Another aspect of the EELV program is Air Force acquisition reform. The EELV Program Office strives to reform how the Air Force acquires space lift in order to reduce government resources necessary to manage the system development, the development cycle time and effectively acquire the launch capability as a commercial service. This helps the Air Force shift from an object to a solution focus, meaning that they are less concerned about buying rockets and more concerned with procuring a launch service.[250] [251] The program is a radically different way for the Air Force to do business and the lessons learned in that process are already starting to make their way into other new programs.[252]

This research followed the manufacturing system design processes for the boosters on both the Delta IV and the Atlas V. In both cases the manufacturing system design process was completed at the time of observation and the first flight vehicles were followed through the system.

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[247] According to Dr. Sheila Widnall, former Secretary of the Air Force, March 2001.
[248] Kuhn, T. (Chief Master Sergeant, USAFR), *EELV: A New Rocket for the Millennium*
[249] From EELV Program website at: http://www.losangeles.af.mil/SMC/eelvhome.html
[250] Womack, J., *Lean Thinking for the Next Era in Aerospace*
[251] Kuhn, T. (Chief Master Sergeant, USAFR), *EELV: A New Rocket for the Millennium*
[252] Specifically, Advanced EHF and Wide-Band Gap Filler. According to Colonel Susan Mashiko (USAF), Deputy Program Manager for EELV.

Delta IV

The Boeing development for the EELV program is the latest in the family of Delta launch vehicles – the Delta IV. The Delta IV will be available in 5 different configurations as shown below. The family consists of the Medium, three types of Medium + (distinguished by the number of solid boosters and the size of the payload fairing and upper stage), and the Heavy configuration. These different variants are capable of replacing the medium lift Delta II and Delta III as well as the heavy lift Titan IV rockets.[253]

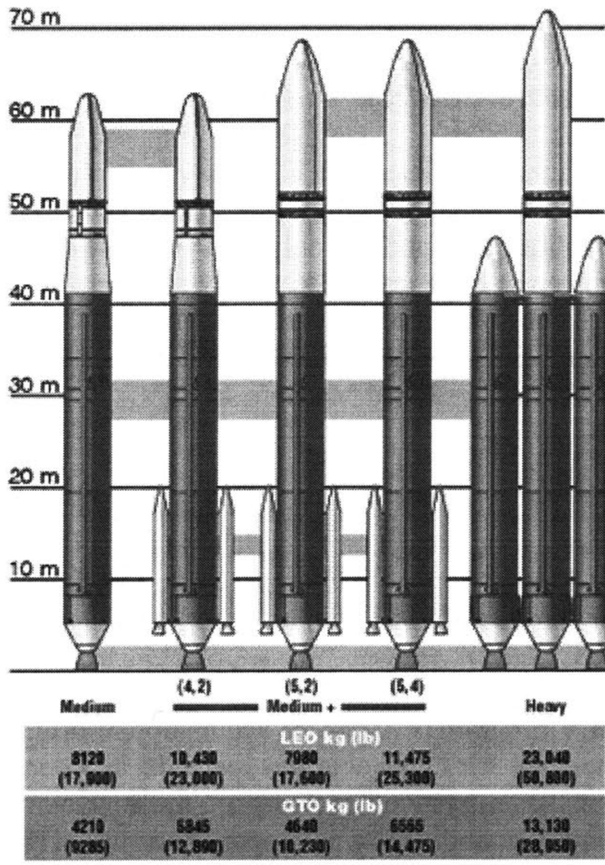

Figure 43: The Boeing Delta IV family of launch vehicles[254]

The Delta IV blends new and mature technology to launch virtually any medium to heavy payload into space. The Delta IV carries over features and technology from the earlier Deltas like friction-stir welding and a derivative of the Delta III upper stage. New technologies and processes were incorporated where they added capability or reduced cost like the new Common Booster Core (CBC) and RS-68 main engine.[255] The first Delta IV is scheduled to fly in 2002.

Case Study Background

The Delta IV is built in a new facility in Decatur, Alabama. It is a rare occurrence in aerospace manufacturing that a new facility is constructed to house a new product. Boeing broke ground

[253] From www.spaceandtech.com/spacedata/elvs/delta4_sum.html
[254] From www.boeing.com/defense-space/space/delta/delta4/delta4.htm
[255] From www.boeing.com/defense-space/space/delta/delta4/delta4.htm

for the new 1.5 million square foot facility in 1997 in an area which was previously just farmland.[256] [257] The Boeing Company constructed the facility in the spotlight of the aerospace industry to be an example of lean manufacturing for aerospace products.

Figure 44: The new Boeing facility in Decatur, Alabama for the Delta IV EELV[258]

The Decatur team defines the lifecycle of their product as:

Acquire → Define → Produce → Support

Decatur is the "Produce" part of this model. In Decatur, the complete fabrication and testing occurs for the Common Booster Core (CBC) and the upper stage of the Delta IV. The CBC contains the liquid oxygen (LOX) and liquid hydrogen tanks, the mounting of the Rocketdyne RS-68 engine along with the inter stage for the subsequent fitting of the upper stage and payload. The CBC serves as the main booster for the Delta IV and has a mere 4.5-minute useful life. The following picture is the CBC for the first Delta IV flight vehicle as it is rolled from the factory to the Delta Mariner in the nearby Tennessee River for transport to either Cape Canaveral Air Force Station in Florida or Vandenberg Air Force Base in California. This research focuses on the design of the system used to assemble these massive boosters.

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[256] From www.boeing.com/defense-space/space/delta/delta4/delta4.htm

[257] Donatelli, T. and J. Fortune, *Boeing and the Alabama Technology Network: A Case Study for Quality Systems Management*

[258] Photo courtesy of Boeing Media at http://www.boeing.com

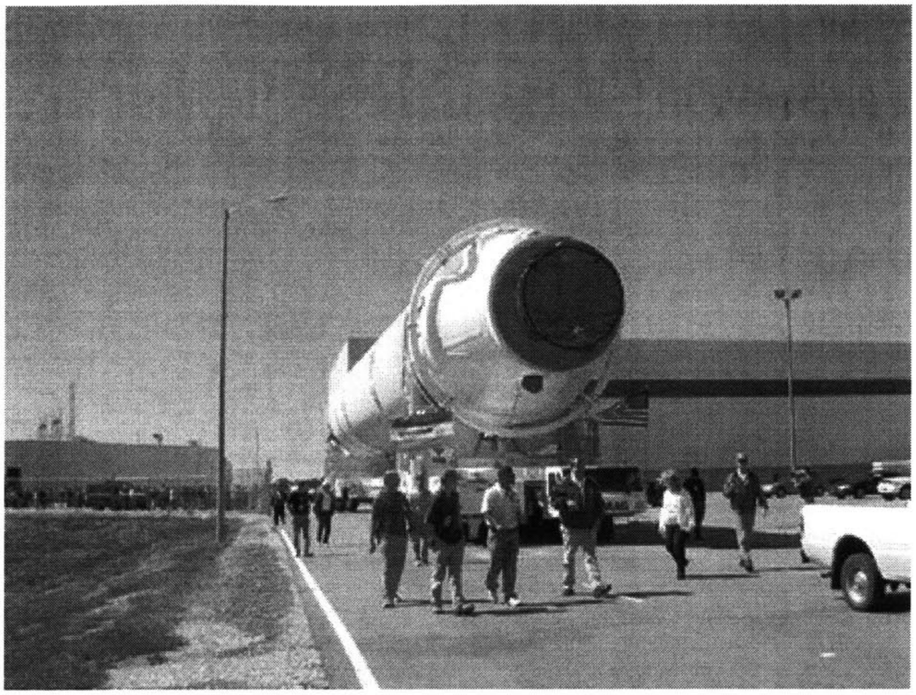

Figure 45: Roll-out of the Delta IV first flight vehicle CBC[259]

Early in the development of the Delta IV, Boeing made strategic decisions regarding the manufacture of the booster. Boeing needed to improve their internal profits on the Delta IV vehicle compared to the earlier Delta II and III to make it a competitive commercial venture. One way to do that was to find a place where the entire vehicle could be constructed under one roof. This led to their strategy of co-locating the complete production system for the vehicle. The traditional flow for Delta vehicles required that heavy structural parts travel 6,257 miles to the final assembly point and then an additional 1,197 miles to the cape via escorted truck. The time between fabrication and launch was 23 months. On the contrary, the facility in Decatur requires that heavy structural parts travel 2.1 miles through a single building, then 1.5 miles to the dock for environmentally controlled shipment in the Delta Mariner. The time from fabrication to launch is reduced to a predicted 15 months at rate.[260]

Actual Manufacturing System Design Process

Given the corporate strategy to assemble the booster under one roof, site selection for the new facility was a careful decision. The new approach would require a large amount of space, access to a waterway for shipment to the launch site (since the CBC is too big to fly or use a train), access to railways for ease of material receipt and consideration of location to be near the major suppliers. Another aspect of this strategy was to not only assemble the booster but perform all the necessary tests prior to shipment to the launch facility. Integrating check out with the final assembly operations will allow the Delta IV to have much shorter preparation times on the launch pad than have been achieved with earlier Deltas. Also, because rockets are typically shipped to the launch sites for flight hardware checkouts, this would allow the Delta team to immediately resolve any booster issues before it leaves Decatur.

[259] From www.boeing.com/defense-space/space/delta/delta4/delta4.htm

[260] Saxer, R. (Col., USAF), *EELV Lean Aerospace Initiatives*, presentation

Once a site was selected for the new facility, the system was designed to accommodate the maximum production volume predicted for the Delta IV. Production capacity of the boosters is dictated by the Heavy configuration since it utilizes three CBCs that have to go through the system together. This requires the facility to be designed to accommodate a rate of 40 CBCs a year giving a takt time of 6.25 days. In addition, it was planned to have a surge capacity of 50 CBCs in a year. In order to meet this demand, the facility was designed to be 2.5 million square feet with the Integrated Assembly and Check Out (IACO) area taking up 1/2 million square feet with 10 pulsed lines and a maximum of 20 CBCs in process.

After construction had begun on the facility, the Delta program based in Huntington Beach, California, thought it would be beneficial to revisit the system design to see if any additional lean principles could be applied. This resulted in a meeting of the Decatur facility senior management with a group of lean experts. The lean experts were dressed in all black suits which led to them becoming known as the "Men in Black" and the meeting as the "Men in Black Incident". The "Men in Black" were representatives from the Shingijitsu Corporation.[261] At the time of this meeting, construction on the building had begun, most of the new building had been designed, and raw material had been purchased for most of the building construction. The "Men in Black" activities were directed to consider certain areas of the factory as off limits for change due to potential penalties for breech of contract with material suppliers. The only area where construction had not yet started was the IACO area so it was the only candidate for re-design by the Men in Black. The Men in Black emphasized the idea of single piece flow and that if only a single CBC is needed at a time there is no need to build 10 in parallel. This meeting resulted in the senior management deciding to reevaluate the IACO design to see if the 10 pulsed lines could somehow be reduced in number saving floor space and significant amounts of tooling.

Following this strategic shift, the redesign of the IACO area took place over the next 8 months through a series of Production Preparation Process (3P) events. These events reduced the 10 pulsed lines down to 6, then down to 3, and finally down to 1 moving line. The final design of the IACO area is a moving line that will move at 4/10 of an inch per hour at the 6.25-day takt time and hold a maximum of 7 CBCs resulting to a throughput time of 42-50 days in IACO. The overall layout of the IACO area is a modified "U"-shaped cell. The area will have three moving stations where the booster is serviced by "rainbow" bridges that will move with the booster. The bridges are on stops, so the work content of one station must be completed before the bridge reaches the end of its possible travel. After the last test station, the booster is lifted onto its transport in the center of the room and it is shipped out the door to the awaiting Delta Mariner vessel for transport to the launch site. The team also tried to eliminate the need for crane moves in the assembly of the rocket to avoid the possibility of crane utilization becoming a bottleneck for the remainder of the system. The team developed simulations to help sell their concept, but mainly used physical mock-ups to develop and test their ideas.

This redesign resulted in the elimination of two-thirds of the square footage from the original floor plan and substantial cost savings from not needing tooling, test equipment, cranes and personnel to support 10 parallel process lines.

[261] Murman, E.M., et. al., Lean Enterprise Value

Framework Comparison

At the beginning of the manufacturing system design process, the Decatur team had a strong strategic focus. There was good definition of the requirements and breadth across the different functions in the strategic planning. The major difference in the Delta IV specific variant of the framework shown below is the iteration that occurred to revisit the manufacturing system design following the Men in Black incident and the lack of breadth in the phases following the strategy development.

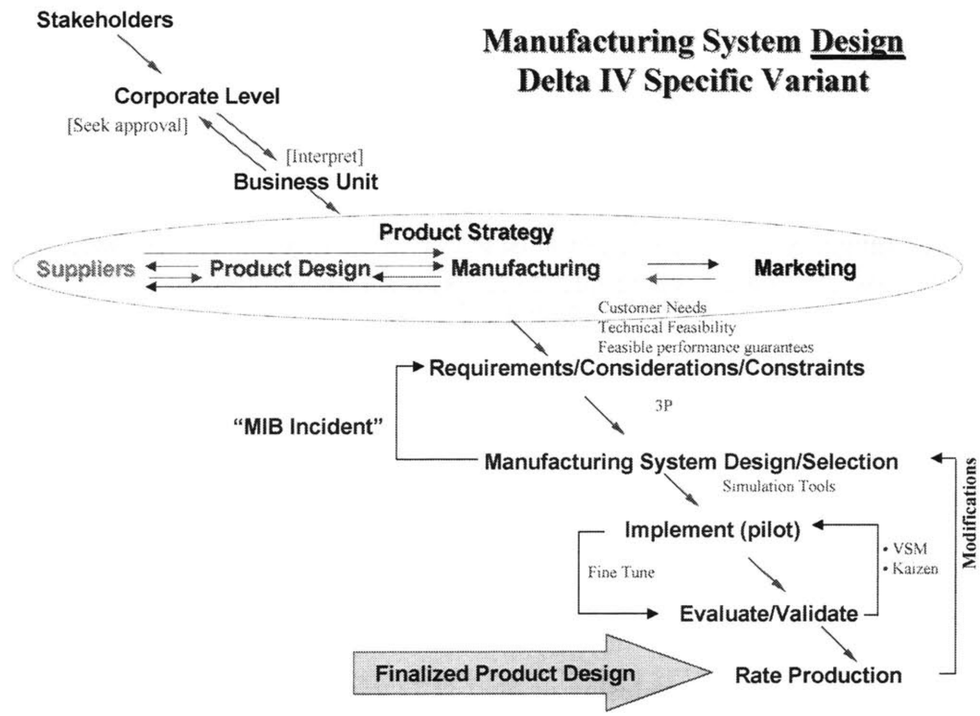

Figure 46: Delta IV Specific Variant of the Manufacturing System Design Framework

The iteration in the design of the IACO area caused the Decatur team to go back and review the requirements of the system. The requirements hadn't changed, but they were viewed differently and challenged to try and incorporate principles the Men in Black had taught them. Following the Men in Black incident, the series of 3P events to redesign the IACO area follow the proposed process of the framework.

Another difference with the Delta IV specific framework is that no other functions were involved in any of the phases beyond the strategy formulation. In the strategy development, it was decided that the Decatur facility would receive material from their suppliers Just-in-Time directly to the floor. The facility was designed without stockrooms to hold inventory and there was never a plan to use a warehouse. Supplier management was tasked with supporting a faster mission model. But as the demand for launch services throughout the entire market fell short of expectations, Decatur had to hold on to the material. Because the facility was designed without room to hold inventory, the material sits in the open on the floor. Also, design engineering is removed from Decatur and was not integrally involved in any of the detailed steps in the manufacturing system design process.

Where Decatur does have breadth across functions is in the modification loop. Every area in the facility, white and blue collar alike, work on what they term WRAP (Workshop Readiness Assessment Profile) Process, and are challenged to improve their scores by the end of the year. The WRAP Process is a time-phased, team and process maturity model outlining the specific attributes for process improvements. The WRAP Process requires each area to define their processes, determine their suppliers and customers as well as what they need from their suppliers and must give their customers. This helps an area learn what is truly required of them and finds the gaps or excesses in those supplier/customer relationships. It is only after an area has maximized their WRAP Process score that they can hold improvement events. The only problem with this approach is that it is applied to Decatur functions of the Delta IV only, not across the complete business enterprise. The WRAP Process goes beyond the Decatur facility by linking back to the program office in Huntington Beach where the IPTs are engaged for process improvements.

The Delta IV framework has seen some recent changes. The framework shown here depicts what was done during the actual design of the IACO area and not what may happen as a result of the recent changes in the Decatur environment. The Delta realignment of work and people was implemented to utilize facilities more efficiently in the downturn of the launch vehicle market. The manufacture and launch of large spacecraft in 2001 was predicted to be between 60-70 and was actually only 25-30.[262] The fall out in the spacecraft market affects the business prospects of launch vehicles as well. This severely impacts what work is occurring in the facility as well as the predicted production rates. How the system will deal with these changes remains to be seen.

In summary, the Delta IV manufacturing system design process closely matches what is proposed by the manufacturing system design framework for the manufacturing function. The product strategy included a manufacturing system that used an IPT structure in Huntington Beach and a process for buying material. It was implemented for a higher rate than that which exists today due to the recent downturn in the launch market.

System and Process Performance

The first flight vehicle was the product used to look at the performance of the Decatur manufacturing system design process. Overall, the original strategy of building the booster under one roof is strong and led to the design of a robust system. One element of success of the lean manufacturing companies in Japan is the proximity of a facility to its suppliers and the benefits of not requiring movement between many facilities.[263] But despite this strength, the assembly of the booster for the first flight vehicle took longer than expected. The build process was plagued with design issues and part procurement problems even though the Decatur system worked according to plan.

Throughout the build process, the lack of breadth in the design processes was evident. The product strategy called for Just-in-Time delivery to the factory floor. But as the market conditions unexpectedly changed, unit cost goals could not be met with the single piece approach. As a result, Delta leadership ordered large lots of inventory to achieve strategic goals of maintaining lower unit costs. This resulted in approximately 26 vehicles' worth of skin

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[262] de Selding, P., and S. Silverstein, "Lockheed Takes Steps to Offset Weak Satellite Launcher Sales"

[263] Dyer, J.H., *Dedicated Assets: Japan's Manufacturing Edge*

material to be stacked around the facility and an excess of inventory domes for the tanks. Despite these problems that occurred from lack of integration across functions, it should be noted that integration was not the goal for the system. The goal for the system was to reduce part travel and design a system where the vehicle could be built under one roof. This, the Decatur team certainly achieved.

Another accomplishment by the Decatur team is the amount of new work that has been able to move into the facility. The Decatur facility was originally conceived and designed to hold Delta IV work but now houses the manufacture of the Delta II booster tank subassemblies and wire harness builds for the Delta III and Delta IV. This is attributable for the success of the design efforts to make room for the additional work and without requiring any additional support.

The system level view that was taken by the Decatur team shows in the organization of the facility. The facility is divided into product centers (skins, rings, IACO, tank center, etc.) that are managed independently. Each product center has its own budget and area of responsibility. This creates a system that is composed of a set of these interacting product centers, or sub-systems, which matches the concept of a manufacturing system presented earlier in this thesis. But, there are disconnects between the sub-systems. On one visit to the facility, the first flight vehicle had not yet entered IACO but the skin center was working on flight vehicle 8. The WRAP Process will help different areas within the facility to define the customer/supplier handoffs within the system and make those interconnections more fluid.

The Delta IV manufacturing system design process was a close match to the proposed framework. Their process could be characterized by a strong product strategy formulation, followed by well-defined use of each of the subsequent phases in the manufacturing function. Breadth between the different functions was clearly seen in the strategy development and in the WRAP Process guiding the modification loop.

Atlas V

The Atlas V is the Lockheed Martin launch vehicle developed for the Air Force Evolved Expendable Launch Vehicle (EELV) program. It is intended to provide reliable, cost effective launch capability for government and commercial customers. The Atlas V incorporates a structurally stable booster propellant tank (the Common Core Booster, or CCB), enhanced payload fairing options with the Centaur Upper Stage and optional solid strap-on boosters.

Case Study Background

The Atlas V is the latest in a long line of Atlas launch vehicles. Atlas began as the first US intercontinental ballistic missile. At the same time Atlas was being developed as an ICBM the Air Force supplied NASA with the vehicles for various space applications. In 1958, the first communication from space was broadcast from an orbiting Atlas with a recorded Christmas message from then President Eisenhower. Atlas went on to launch numerous government, military and commercial payloads for the US space program. Today, over 550 Atlas boosters have flown.

The history of the program includes the Atlas II, the Atlas IIAS, the Atlas III and the new Atlas V. The purpose of the Atlas III is to demonstrate some of the design innovations to be incorporated into the Atlas V, including the Russian built RD-180 engine and the Centaur Upper Stage.[264]

Figure 47: Artist's conception of the Atlas V Launch Vehicle[265]

The Atlas V is a family of vehicles that include the 400, 500 and Heavy Lift Series. They are capable of lifting 18,080 kilograms to GTO (Geosynchronous Transfer Orbit) or 13,100 kilograms directly into GSO (Geo-Stationary Orbit) with the Heavy lift vehicle. It is a single stage main engine on the Common Core Booster (CCB) that uses the Russian RD-180 engine, which produces up to 860,000 pounds of thrust at sea level, and can utilize up to 5 solid strap-on boosters. This research focuses on the assembly of the CCB portion of the Atlas V, which is comprised of the large RP-1 (kerosene propellant) and LO2 (liquid oxygen) tanks, the aft skirt and engine mount as well as the inter stage adapter that connects the CCB to the Centaur Upper Stage. The following figure is the inside of the CCB LO2 tank and clearly shows the size of this 12.5 foot diameter, 110 foot long booster.

[264] Atlas V program information from Lockheed Martin's web site: http://www.ast.lmco.com/launch_atlas.shtml
[265] Figure courtesy of the Lockheed Martin Company. http://www.ast.lmco.com/launch_atlas.shtml

Figure 48: An inside view of the LO2 tank of the Atlas V Common Core Booster (CCB)[266]

As the Atlas V program began, it became a necessity for Lockheed Martin to treat this program differently than it had the design and development of its previous launch vehicles. First of all, with the development of both the Delta IV and the Atlas V, the commercial launch industry could become over-populated. Between Lockheed Martin, Boeing and Ariane there is the potential for an over capacity of launch vehicles and not all the companies could have viable business solutions to survive in a competitive market environment. In addition to the launch vehicle market pressures, there is pressure from the satellite providers. The customers are no longer willing to pay for a complex spacecraft 48 months in advance. The customers would rather spend their money closer to the due date for the spacecraft. This, in turn, impacts the cycle time for the launch vehicles as well so the launch vehicles do not slow down the ability of the customer to place their new spacecraft on station on time. Finally, as was mentioned earlier, it is a goal of the Air Force to manage and treat this program differently than has been done in the past.

All of these factors led Lockheed Martin to set the goals of designing a standard, producible rocket that will allow the assembly cycle time and the time on pad to be reduced. This drove them to design a greatly simplified booster. The part count and total number of engines have been reduced which decreases the overall complexity of the system. These changes are highlighted in the following table.

[266] Photo courtesy of the Lockheed Martin Company. http://www.ast.lmco.com/launch_atlas.shtml

Table 4: Comparison of Lockheed Martin family of launch vehicles[267]

	Atlas IIAS	Atlas V – 400	Titan IV	Atlas V- Heavy
Performance				
Performance (lbs.)	8,200 GTO	10,900 GTO	12,700 GSO	14,000 GSO
Number of Engines	9	2	7	4
System Design Reliability	0.9873	0.9954	0.9817	0.9880
Single-Point Failures	>250	128	>430	198
Booster Parts				
Booster Tank Parts	>100	16	>1,000	48
Booster Welding	Manual	Automated	Manual	Automated
Parts per Adapter	>100	8	104	8
Aft Transition Structure Parts	>100	25	>100	75
Launch Availability				
Winds Aloft	90%	100%	85%	100%
Ground Winds	80%	99%	90%	100%

The corporate strategy of the Atlas V has been to achieve total mission success for the customer. They accomplished this by matching the name of the program for which the Atlas V was developed; namely, they created a truly evolutionary launch vehicle. The main areas of technological risk were incorporated into the Atlas III by flight proving most of the new hardware that is integral to the Atlas V.

Actual Manufacturing System Design Process

Given the nature of the product and the emphasis for a change from business as usual for launch vehicle development, Lockheed Martin created a corporate strategy which guided the design of the manufacturing system. Part of the corporate strategy existed before the Atlas V did, which is to assemble all the boosters in one facility. This is done in the Final Assembly Building (FAB) which houses the assembly of all Titan, Atlas boosters and Centaur Upper Stages. In effect, Atlas V is just a new product inserted into an existing system. Lockheed Martin created an enterprise-wide booster facility. In addition, the corporate strategy also intends to reduce the cycle time of the booster assembly for Atlas V. The manufacturing strategy was created from the corporate strategy and the culmination of lessons learned from the other boosters both in terms of assembly and design.

The strategy that guides the manufacturing system design is to assemble the booster in one place and make the work flow in an orderly way to the booster. There are two main drivers for this strategy. First, the building that became the FAB was originally built to be an inventory warehouse, not a factory, so the facility is geometrically constraining. Also, the boosters are stationary since it is costly to move them and they are susceptible to damage when moved. A benefit of this strategy is the cost savings by not purchasing tooling. Atlas V final assembly has actually eliminated of some tooling in order to make more of the work based on crane moves. This is in stark contrast to the manufacturing strategy of the Delta IV described earlier, which has a moving line to create the organized workflow and the goal of eliminating all crane moves.

[267] Saxer, R. (Col., USAF), *EELV Lean Aerospace Initiatives*

The key tenet for the Atlas V assembly operation is to keep the booster stationary and implement standard work that flows to the rocket in an organized manner.

The goal of standard work has been hard to achieve on the heritage Atlas and Titan boosters because of extensive part shortages and the lack of capable, repeatable assembly processes. These experiences led the Atlas V development to be highly integrated with the supplier and engineering communities.

Atlas V is trying to redefine the relationships with the suppliers, both on and off the factory floor. First of all, Atlas V utilizes many more single source contracts with a smaller supplier base to foster strategic relationships with each supplier. The number of suppliers was reduced from 847 different suppliers on the Atlas II to 575 for the Atlas V.[268] With this smaller supplier base, they are changing how parts are ordered and delivered so the FAB receives just a single ship set at a time. The kitting and staging area in the FAB audits the kits before they are released to the floor to determine if there are any consistently late parts and other problem areas. By AV-003 (the third Atlas V) the goal is to have 50% of the parts kitted and delivered straight to the factory floor. In addition to kitting, replenishment of parts, tools and consumables has also been standardized across all the boosters. Visual cues are implemented with the carts themselves or kanban squares painted on the floor.

Integration with the engineering community was the other area of leverage to create a producible rocket conducive to standard work. Previous programs considered process reliability too late in product development to impact the system design. For Atlas V, it was a specific point to deal with process design early in the product design phases.[269] Early in production, manufacturing drove the engineers. Part of the product strategy was to be the first to market, ahead of the Delta IV, so manufacturing drove engineering to stick with their drawing release dates to prohibit late design changes that would slow assembly. Another factor allowing the design of a producible rocket is contained within some of the basic design decisions. All of the heritage Atlas boosters up to this point were not by themselves structurally stable (pressure stabilized). The fuel inside the booster is what provided structural rigidity and the booster was not fueled until it was erected on the pad. This meant that the boosters had to be under tension and pressurized at all times in assembly processes to keep it from collapsing in on itself. The Atlas V is a structurally sound member alleviating all those difficulties. The Atlas V system design includes integrating testing into the assembly operations. A production engineer was put in charge of the testing group to incorporate testing into the normal flow of production.

These various changes in the design and development of the product and assembly processes, and the improved relationships with the supplier and engineering functions are helping the production operations move closer to realizing the goal of standard work.

Finally, to pilot many of their ideas, simulations were made to look at mechanical fits, and mock-ups were built for different portions of the system. A full-scale mock-up was built to see if the booster could fit inside a C-5 for transportation to the cape. Also, AV-001 (the first Atlas V

[268] Saxer, R. (Col., USAF), *EELV Lean Aerospace Initiatives*
[269] Blake, S., *Lockheed Martin Astronautics' Atlas Production System*

flight vehicle) has served as a pathfinder for AV-002. AV-002 will incorporate numerous changes suggested by the assembly workers to improve many of the processes.

Framework Comparison

The following figure is the Atlas V specific variant of the manufacturing system design framework. The Atlas V variant exhibits congruence with the proposed framework with only a few exceptions. The Atlas V variant has been customized to show the specific tools and methods that were used for their manufacturing system design process. The only major change is that the Requirements/Considerations/Constraints phase was indistinct from the Manufacturing System Design phase. In the case of Atlas V, these phases were not separate. The system was designed for all the boosters, then tweaked to deal with the differences in the requirements presented by the introduction of Atlas V. This refinement of the requirements then resulted in a change to the manufacturing system design, specifically, the introduction of a structurally sound member and standard work to achieve the desired reduction in cycle time. The modification loop is present in the Atlas V framework because AV-002 is already in progress utilizing changes proposed from experience gained on AV-001.

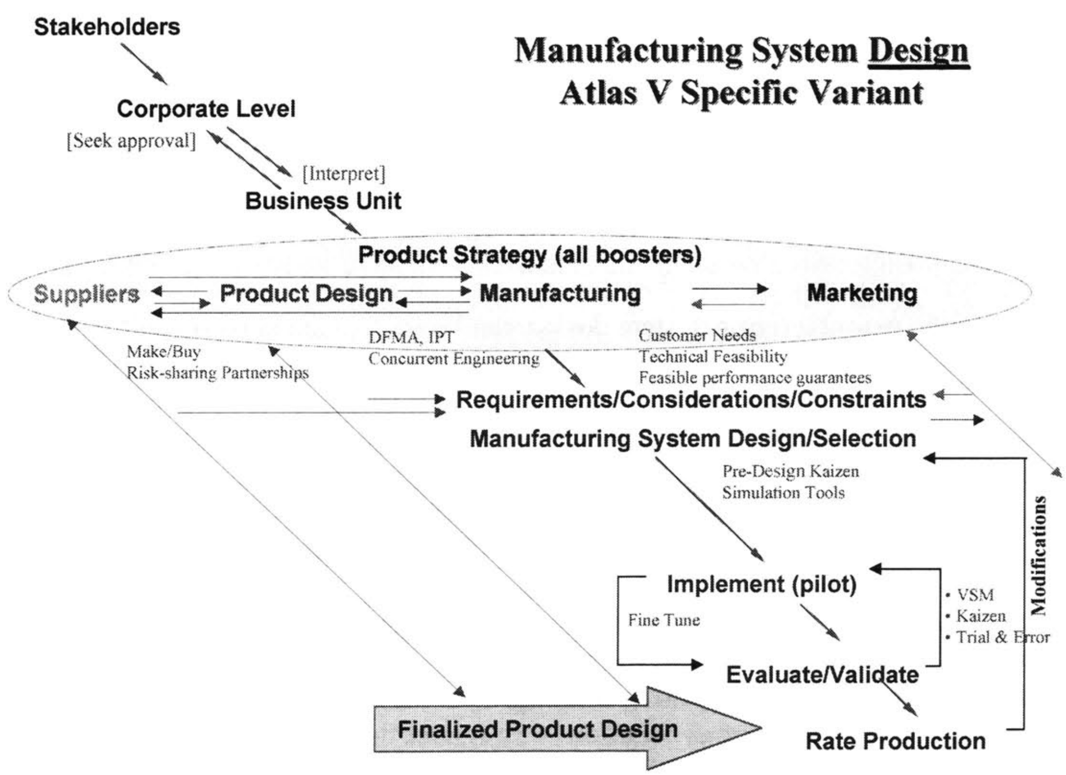

Figure 49: The Atlas V Specific Variant of the Manufacturing System Design Framework

There are a few things to note about the Atlas V framework. First, there was breadth in each phase of the design process. DFMA and part reduction was of primary importance to the design and processes were discussed with the engineers early on to ensure the design of a producible rocket. Also, supplier integration was paramount to their effort. A reduction in the number of suppliers allowed them to focus on establishing strategic relationships with those suppliers. In addition, making deliveries to the factory floor and in single ship sets was part of the design effort.

The other point of interest in the Atlas V framework is the strength and expanse of the corporate strategy. The corporate strategy applied to the assembly of all the boosters, not just Atlas V. This allows the progress made on implementing standard work on Atlas V to be applied to all the other boosters in the facility and reduces the chance of programmatic stovepipes preventing communication or learning across platforms. The introduction of the Atlas V presented the organization with new possibilities that could be extended to the manufacturing strategy of all the boosters within the facility.

Also, the corporate strategy was formulated to balance the needs of multiple stakeholders. The needs of the Air Force were certainly considered in the development efforts, but so were the needs of the satellite manufacturers and their customers. That was part of the reason to aim for the reduction in cycle time. Also, the awareness of having to remain competitive in the world marketplace for continued success was certainly a factor. This applies to their well being as a company as well as continued employment for their workforce.

System and Process Performance

The design of the Atlas V Common Core Booster assembly system is a good example of corporate strategy feeding down into the different functional strategies. One element of the success of the design process is in the design of the product itself. Part of the strategy was to reduce the part count to make a simpler booster and this, as was shown earlier, is certainly the case.

The success of the manufacturing system design can be seen in the performance of the system to date. Previous generations of the Atlas took 48+ months to assemble while AV-001 (again, the first Atlas V flight vehicle) took only 18 months. All the while, AV-001 came in with fewer defects than the baseline predicted for the first build. For the work done in the FAB, there was a 10% improvement in non-conformances compared to the baseline. This is not only better than the baseline, but that is 40% fewer defects than were experienced on the first Atlas III. So a larger rocket was produced faster and with fewer defects than its smaller predecessor.

The Atlas V is one of the few examples where there is an enterprise level plan that considers manufacturing as a way to achieve the overall enterprise goals. This translates into a corporate level strategy that applies to all the different programs. Also, the Atlas V process shows the effects of breadth between the other functions throughout the design of the product and the manufacturing system and how those interactions can help create a truly producible rocket.

6.4 Satellite Assembly

The final section of case studies is from the space sector. The satellites followed for this research include A2100, AEHF, a platform-based architecture by TRW and Iridium. A2100 is a family of commercial satellites built by Lockheed Martin Commercial Space Systems. Advanced EHF (AEHF) is a next-generation military communications satellite which is based on the A2100 bus. The next case study is a platform architecture for a spacecraft bus which is a new venture by TRW in Redondo Beach. TRW has historically been a low-volume, highly-customized satellite producer and this new platform approach will let them become more competitive in commercial, government and military markets. Finally, Iridium is the infamous venture where 66 satellites were placed on station to provide customers with world-wide telecommunications. Motorola was the developer and deployer of the Iridium satellites and it is their system that is detailed here.

Studying the design of assembly operations for space systems is particularly interesting and important since production and test can cost 35% for conventional systems, but 66% for many space systems.[270] A2100 and Iridium manufacturing system design processes were captured retrospectively while AEHF and TRW's platform approach were observed in real-time.

A2100 Commercial Satellite

The A2100 is the latest spacecraft bus designed by Lockheed Martin Missiles and Space. The A2100 is available in four variations of size and available power, making it a versatile platform for any unique payload. All of the A2100 variations have a common bus and propulsion system. It is a modular design with fewer moving parts than its predecessors making it more reliable and lightweight.[271] Since its introduction, there have been 19 successful launches of A2100 satellites.

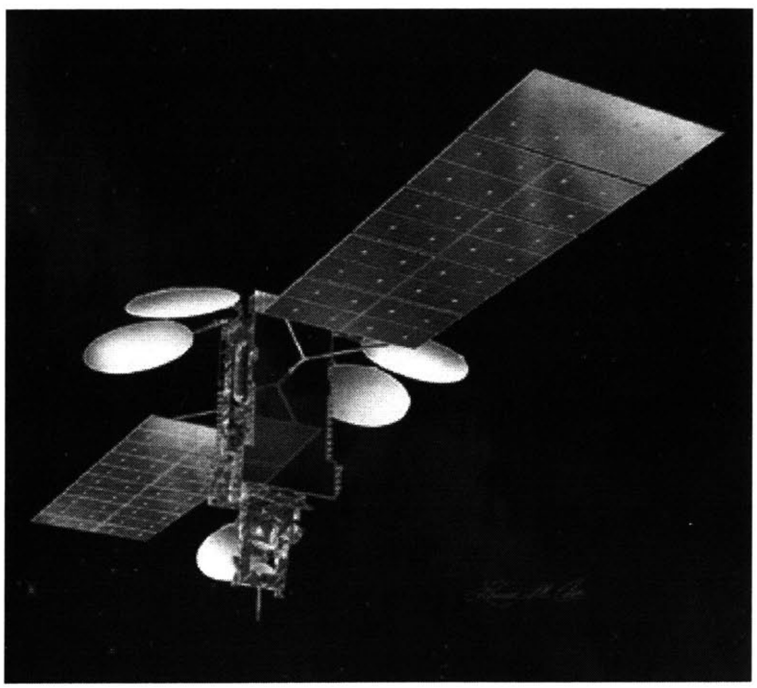

Figure 50: A2100 commercial spacecraft[272]

[270] Temmesfeld, A., *LAI and Space Sector Activity*
[271] From http://www.lockheedmartin.com/factsheets/product438.html
[272] Figure courtesy of Lockheed Martin

Case Study Background

The A2100 was originally assembled in a Lockheed Martin facility in East Windsor, New Jersey. This was later split into payload design, fabrication and assembly, integration and test (AI&T) that moved to Pennsylvania and spacecraft AI&T that moved to the Sunnyvale campus in 1997. The AI&T facility for A2100 is one of the largest Class 100,000 clean rooms in the world and is shown below.[273]

Figure 51: A2100 Assembly, Integration and Test facility at Lockheed Martin in Sunnyvale, CA[274]

The bus and payload are each built up separately then mated together and sent through the remainder of the integration and testing procedures as a spacecraft. The following diagram outlines the top-level flow of a typical spacecraft through the facility. The work on the factory floor begins with the payload assembly and bus preparation. This is followed by the side by side testing and mate operation where the bus and payload are joined together to become a single spacecraft. This is followed by the solar array installation, vibration, acoustic, thermal-vacuum and range tests. After the testing is complete, the spacecraft is prepared for shipment and then shipped to the launch facility to meet the launch vehicle.

[273] From http://www.lockheedmartin.com/factsheets/product438.html
[274] Photo courtesy of Lockheed Martin

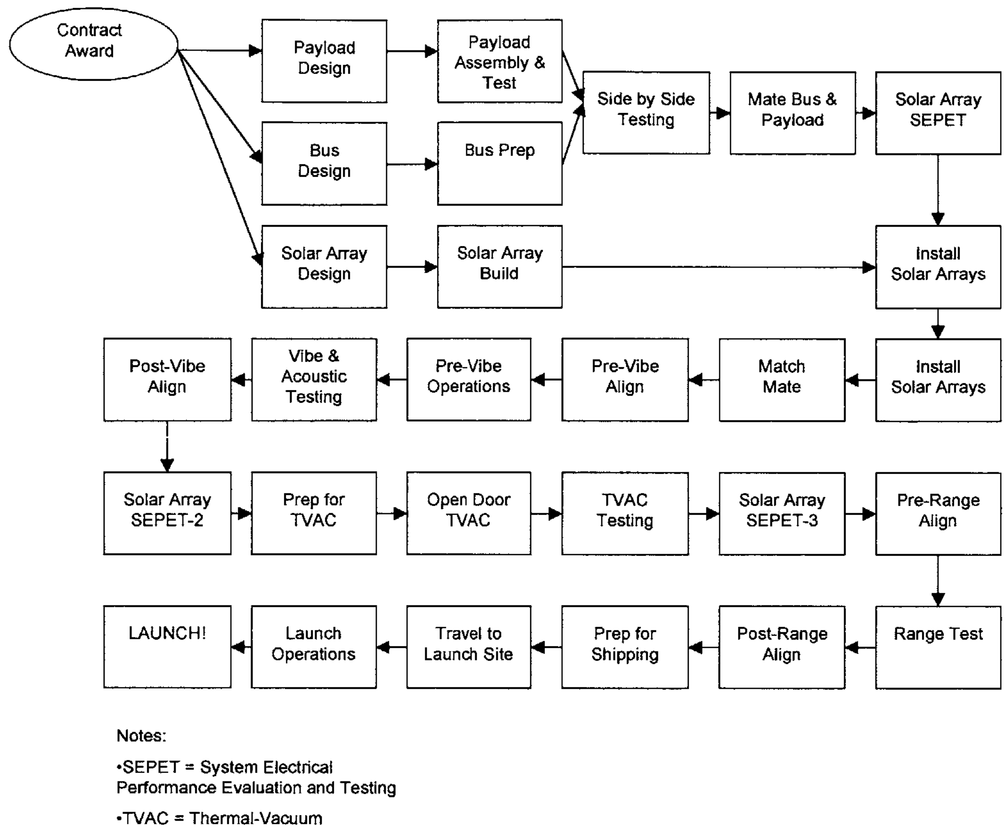

Figure 52: Top-Level Process Flow for A2100 Assembly, Integration and Test[275]

The assembly, integration and test portion of the design and manufacture of spacecraft typically only accounts for 8-10% of the total program costs. But the AI&T facility in Sunnyvale receives a lot of attention from the customers since it is at the end of the value stream.

Need for a Manufacturing System Re-Design

When the AI&T operation moved from East Windsor to Sunnyvale, the system was just copied. The East Windsor operation was a traditional manufacturing mentality that had satellites placed wherever they could fit around the factory floor and they would only be moved when they needed to be relocated for another testing procedure. Everything was centered on the different programs including the engineering and the technicians. There were few standard processes where common procedures were used for the assemblies and there were problems with conflicting resources. Spacecraft would spend anywhere between 150 and 200 days in the operations following mate. There were no predictive metrics tracking when they should move from one testing center to another.

The payload is unique for every spacecraft, but the remainder of the work with the bus and testing procedures is similar. Commercial Space Systems set out to standardize the post-mate operations. Most of the time in this section of the flow is spent on testing procedures that every

[275] Crowley, D., Guthrie, K. and S. Wesley, *Lockheed Martin Commercial Space Systems Satellite Production Simulation*

spacecraft has to go through. They decided to try to standardize and reduce those test times by improving the efficiency of their procedures.

In addition to standardizing a common flow, Lockheed Martin had an opportunity for change. The Sunnyvale facility was built on the expectation that the global market for large tele-communication satellites would be 60-70 a year in 2001 and Lockheed Martin was hoping to garner 25% of that market for a production volume of 15-18 spacecraft per year.[276] But the market has only demanded 25-30 spacecraft per year and Lockheed Martin met their goal of 25% by producing 6 of those each year.[277] Given this drop in market opportunities, the Sunnyvale facility is not as busy as they had predicted and this gave them the chance to make changes in the slower production periods without impacting any product deliveries.

The A2100 team decided to create a flow of the common work between spacecraft to reduce the total throughput time. Their goal was to reduce the 150-200 days down to 120 and ultimately to a consistent 100 days.

Actual Manufacturing System Design Process

A2100 AI&T dove into the redesign of their assembly operation without a formal process or set of tools to guide them. It was treated as a group project with all the functional areas represented and asked the question, "what do we do?"

The AI&T management began by decomposing the work on A2100 to determine what steps were occurring and how the work could be divided up and resequenced to permit flow. Processes were divided between electrical and mechanical work. It was determined when the different functions should work together or independently to optimize the build process. One example of how the relationship between electrical and mechanical work has changed is in the mate process. The new mate cell does not have any electricity running to it so no electrical work can be done on the spacecraft. This forces the work done in the mate cell to be only mechanical in nature. This proves to be better for the spacecraft since the goal for the mate cell is for the spacecraft to be mechanically complete. Trying to install more mechanical components later, when the electronic work is progressing, only increases the chance of damaging something and makes the work more difficult.

Another example of waste that became evident in the work decomposition was what was happening to the support equipment. When the payload is built up, there is electronic support equipment next to the spacecraft that works with the payload. The next time this support equipment was used was for the different testing operations. When the spacecraft went through the various test procedures, the support equipment would follow it. This requires a large amount of electronics and computers to be moved every time the spacecraft is moved. This increases the system cycle time since there is an associated set-up cost with every move. The solution to this problem was to install a switchboard so the support equipment only moves from the payload build up area to the testing area once. The support equipment can be set up only once then have access to all the test bays via the switchboard. This allows the support equipment to be in contact with the payload in any test bay without the intermediate set-up times.

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[276] de Selding, P. and S. Silverstein, "Lockheed Takes Steps to Offset Weak Satellite Launcher Sales"
[277] de Selding, P. and S. Silverstein, "Lockheed Takes Steps to Offset Weak Satellite Launcher Sales"

An area of focus in the work decomposition was to eliminate the waste that became evident in the different testing procedures. For example, the thermal vacuum test is the bottleneck for the complete process since it is a long duration test. Through this redesign, they installed a modular infrastructure inside the test chamber for various hook ups. This allows for spacecraft to be changed in a matter of days and not weeks, as was previously the case.

The AI&T team also started to measure the performance of their system in this redesign process. In 2001 they started to track the progress of the work on the spacecraft against a predicted baseline to see when a unit is falling behind schedule. This is still in its infancy since the first few units will help them establish a realistic baseline on which to compare the subsequent spacecraft builds. Even more recently, they started to track the time spent on planned versus unplanned work. This highlights variability in certain processes for later focus.

Through the changes made in resequencing work, establishing dedicated stations for the product to flow through and eliminating waste, A2100 was able to transform their manufacturing system. The resulting system contains a first station where the payload is built up. This is the only customized part of the system. Following the payload build up, the payload is mated with the bus in the mate cell then flows through the "single line flow" which is the same for every spacecraft. At the end of the mate process, the spacecraft is mechanically complete. It then travels down the side of the factory between stations for solar array installation, alignment, the different testing operations and finally, shipment.

A final element of the redesign effort was to create a wish list of items that would allow them to further improve the flow of the product through their system, but are outside the control of the AI&T function. These items would require work from systems engineering to be realized. The systems engineering organization has received this list and is evaluating it for incorporation into future builds.

Framework Comparison

The A2100 specific variant of the manufacturing system design process framework is shown below. There are some differences between this and the proposed process. First of all, the A2100 manufacturing system redesign effort came from within the AI&T organization. This is depicted on the framework by what is occurring with the business unit level. The A2100 business unit in Sunnyvale created the manufacturing strategy inside the oval. This is a "manufacturing strategy" and not a "product strategy" because the product had already been designed and was in production. This manufacturing strategy has arrows from the manufacturing function to the product design and supplier functions to show the one-way flow of information of the strategy development. The AI&T manufacturing strategy is trying to change business with the other functions. Also, this strategy development is different from the framework because the business unit only has the "seek approval" arrow between it and the corporate level. The corporate level passed a strategy to the business unit via the corporate wide LM21 program that started this redesign effort.

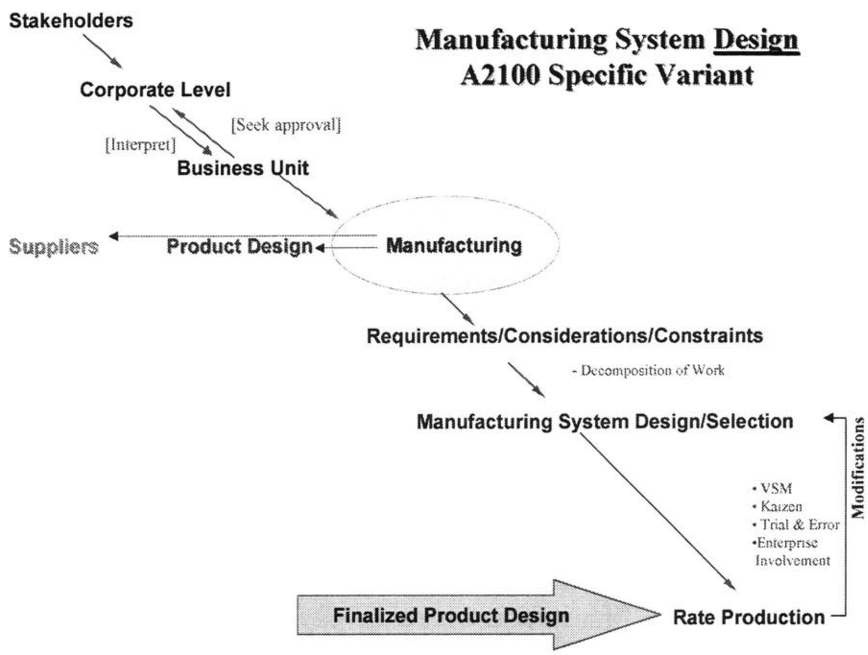

Figure 53: A2100 Specific Variant of the Manufacturing System Design Framework

The requirements definition phase followed the formulation of the manufacturing strategy and the approval from the corporate level. The requirements on the system were defined through the decomposition of work performed on the product. This helped the A2100 team determine exactly what they needed to do in the system, the current performance and capabilities of the system, and how they could be changed. This also showed shortfalls in what the AI&T function was receiving from internal and external suppliers.

The next phase is the manufacturing system design phase where the AI&T team took the decomposition of work and tried to find common paths and sequences to enable standard work and flow through the system. This required them to resequence the work and remain within the constraints of the existing facility with the existing resources. The result of this phase was the first try at the revised single line flow. This would allow the spacecraft to follow a common path, ease the burden on the shared resources and improve the cycle time through the system. It also allowed this flow to be achieved while minimizing moving the spacecraft around the facility.

Since the facility was already at rate production, the first attempts with the single line flow concept were on production spacecraft. The A2100 manufacturing system redesign process then entered the modification loop to further improve the single line flow. Kaizen events, value stream mapping and 6-S are common activities for the modification loop. At first, the kaizen events were targeted at low-hanging fruit and obvious impasses on that factory floor. But now they are determined by a steering committee that revisits the high level goals of the system and the impact on cycle time before they hold an event. Also, there are many changes made as part of the modification loop that are results of employee suggestions.

Another aspect of the modification loop for A2100 that isn't easily depicted on the framework, is the attempt to broaden their perspective. Rather than just focusing on A2100 AI&T, they are trying to look throughout the enterprise and see how links with other areas could further improve their system. An example of this is a recent change of how the spacecraft alignment is checked. A2100 previously had their own alignment team that was only involved on A2100 spacecraft. Since they were only at a rate of 6 spacecraft per year, and the enterprise has an alignment function for other areas, this seemed redundant. So, now A2100 shares the alignment resources with the remainder of the enterprise and this has turned out to be a huge success. The shared team has more expertise from working on other programs and by sharing the team there is enough work to actually justify having a dedicated alignment team.

But, despite this increase in scope by the AI&T team, the other functions involved in A2100 are not as integrally involved in this manufacturing system redesign. First of all, product design was not involved in the early portion of the manufacturing system redesign since the product was already in production and this was an effort that emerged within the AI&T organization. But, there have been many situations where interactions with the product designers could help quickly resolve problems that occur. For example, technicians made a template to test a particular component on the payload buildup. This is a useful tool to the technicians since they now find a potential interference before installation. But, this is indicative of a deeper problem of lack of communication between the factory floor and the product designers since not all interference problems are caused by manufacturing mistakes.

The interactions with the supplier community have also been a frustrating point for the AI&T team. One of their most significant problem is part shortages on the factory floor. AI&T used to request material 30 days before the start date of the whole spacecraft. With a cycle time of 150-200 days, this means that a portion of this material was sitting in inventory. In light of this, in the manufacturing system redesign AI&T changed how they ordered from suppliers and instead gave them a deadline of 30-days before AI&T actually needed the component. AI&T has also changed how they deal with inventory that is kept on hand. Common minor materials like fasteners, tape and such are just ordered en masse and kept on hand. Kanban bins are refilled with these materials when needed on the floor. These common minor materials used to be ordered and sent to the factory floor in kits for 1 spacecraft. But for simple items like fasteners and tape, this was more trouble than it was worth.

System and Process Performance

Throughout the period of this research, the throughput times of the assembly, integration and test processes on A2100 improved. They are not yet meeting the goals set and some of the process times are still highly variable depending on part shortages or testing anomalies. But, there has been significant improvement. In addition to the early indications of improvement in the throughput times, the facility now has a standard flow and an organized way to sequence work. Changes have been implemented and are visible around the factory. AI&T is off to a good start in impacting the 8-10% of the program cost that they influence. The way for Lockheed Martin to realize benefits to the total cost of the program beyond this 10% requires engaging A2100 product design and tackling the supplier community at the business unit level. The leverage of all the different business units comprising the Lockheed Martin space sector will far outweigh what A2100 AI&T can do alone.

What is probably the most substantial improvement A2100 has already made is to start changing the culture. Over this transitional period, management has received feedback from the technicians that said they enjoy their work and the feeling of being a member of a team that they have had lately. Communication and trust between the technicians and management has improved. This is seen in the rapid response on the part of management to implement ideas proposed by technicians and the sense of humor that has emerged. This culture change must extend throughout the A2100 enterprise.

There are some early indications that the new approach to spacecraft production taken by A2100 is starting to find its way through other areas of the Lockheed Martin space enterprise. It has come to the attention of the remainder of the enterprise that if they can create a capable, robust system for A2100, it gives them a capable, robust system to base new ideas on for other ventures. This can be seen in the next case study since the Advanced Extremely High Frequency (AEHF) satellite is capitalizing on the new thinking brought into spacecraft production by the A2100 team.

Advanced Extremely High Frequency (AEHF) Satellite

The Advanced Extremely High Frequency (AEHF) system is the next generation of highly secure communications for the Department of Defense.[278] It will provide a global, secure and survivable communications system for warfighters in all the military services.[279] As follow-on to the MilStar communication system, AEHF satellites will provide a greater total capacity and offer higher channel data rates. This higher data rate will permit transmission of tactical military communications such as real-time video, battlefield maps and targeting data.[280] AEHF satellites will also have increased coverage flexibility and be backward compatible with the MilStar I and II system.

[278] de Selding, P. and S. Silverstein, "Lockheed Takes Steps to Offset Weak Satellite Launcher Sales"
[279] From http://www.lockheedmartin.com/factsheets/product430.html
[280] From http://www.lockheedmartin.com/factsheets/product430.html

Figure 54: Advanced EHF system spacecraft[281]

Lockheed Martin Missiles and Space division is the prime contractor for AEHF and will provide the spacecraft bus and mission control segment. TRW will be the payload integrator.[282]

Case Study Background

The AEHF system will consist of 4 cross-linked satellites providing coverage around the globe from about 65-degrees north latitude to 65-degrees south latitude.[283] A fifth satellite could be launched as an on-station spare or to add additional capability to the complete system.[284] Like MilStar, the spacecraft making up the AEHF system are processing satellites. Unlike the traditional bent-pipe architectures of commercial communication satellites, AEHF is a switchboard in space.

The AEHF spacecraft are based on Lockheed Martin's commercial space system bus, the A2100, but hold a classified payload. It was bid on being based on the commercial platform to help keep the spacecraft affordable. AEHF is the first opportunity for Lockheed Martin Missiles and Space to meld the new ideas and practices gained from the A2100 onto a government contract.

This is not the first time that the A2100 has been used as a basis for a military program, but this is the first that has come along since the changes were made in the A2100 assembly, integration and testing procedures as were outlined earlier. The Space Based Infrared Radar (SBIRS) High component of the new missile warning and tracking system is also based on the A2100 bus.

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[281] Figure courtesy of Lockheed Martin
[282] From http://www.lockheedmartin.com/factsheets/product430.html
[283] de Selding, P. and S. Silverstein, "Lockheed Takes Steps to Offset Weak Satellite Launcher Sales"
[284] de Selding, P. and S. Silverstein, "Lockheed Takes Steps to Offset Weak Satellite Launcher Sales"

SBIRS High had A2100 review their drawings to ensure they were using common parts across the two platforms and perform some crude producibility checks. But that was the extent of the involvement between the two programs. In contrast to this relationship, AEHF is trying to be much more integrated with A2100. In fact, there are several people from the A2100 team that are working on AEHF full-time through the early development efforts.

Since AEHF was bid on the A2100 commercial platform, the idea of assembling the AEHF spacecraft in the same facility that houses A2100 assembly, integration and test (AI&T) operations was explored. In the end, this will not be the course of action for AEHF since the incorporation of AEHF into the A2100 "single line flow" would impact the standard work that is still being developed for A2100. AEHF would also impact the ability of customers of A2100 satellites, who are frequently foreign, to be able to enter the facility to see their spacecraft. Another problem with incorporating AEHF into the same AI&T facility would be the additional testing for AEHF that is not required on A2100 that would disrupt the flow through the already shared resources of the testing stations. Because of these security issues, AEHF will use the existing MilSatCom building and infrastructure for AEHF AI&T, but will use the same processes as the A2100 team does in commercial operations.

Actual Manufacturing System Design Process

From the beginning of the AEHF program, it was part of the strategy to use the best available commercial practices for the product to help reduce costs. Another aspect of their strategy was to try and reduce the amount of needed testing on the system. Then, with AEHF AI&T using the same commercial practices as A2100 AI&T, this emphasizes the intent of the program to take the thinking from the commercial building and put it into the military building. The shape of the flow in the "single line flow" portion doesn't matter as much as the ideas and the division of work content.

To design the system to support AEHF, the team started with the optimized flow for A2100 then added the unique aspects for AEHF that would need to be considered. AEHF has additional testing requirements because of the need to validate a new design and because of the additional capability possessed by the payload over a typical commercial payload.

In order to account for these unique additions, the AEHF team identified the inputs to their AI&T processes including what is required of internal and external suppliers. Then the team mapped the AI&T processes. For each task, there were numerous data elements that needed to be calculated. They made a description of:

Key subtasks	Trigger
Exit criteria	Set up time
Cycle time	Touch labor
Number of required people	Work in process
Yield on script/flight software	Rework hours
Distance traveled	Top 3 defect or rework issues

The detailed metrics to estimate these parameters were derived from what was known about the A2100 AI&T processes. Then for each of these steps, the team assessed the value-added work in each step and used this to define the ideal state for AEHF AI&T. The creation of an ideal state flow allowed them to create a potential future state map. To make the ideal state a reality, the AEHF team came up with the necessary enablers to reach it. These enablers contain items like, no testing, no software bugs, no hardware failure, no cost constraints, JIT hardware deliveries etc. It is true that there are some items on the list that are impossible to achieve, but creating this list gave them projects to work on which helps them focus on the areas of high leverage that can substantially help them to improve their performance.

Another area where the work on the A2100 AI&T system redesign came through to influence AEHF is in the wish list to try and reduce the amount of required testing. Space vehicles 1 and 2 for AEHF will undergo verification and acceptance testing procedures. Space vehicles 3-5 will only be required to pass acceptance tests. So the value stream for space vehicles 3-5 is a subset of the value stream for space vehicles 1-2. AEHF has set the precedent that if someone believes there is a need to test beyond this, the additional test spans must be justified.

Framework Comparison

The AEHF satellite specific variant of the manufacturing system design framework is shown below. This specific variant of the framework is fairly similar to the original framework shown earlier.

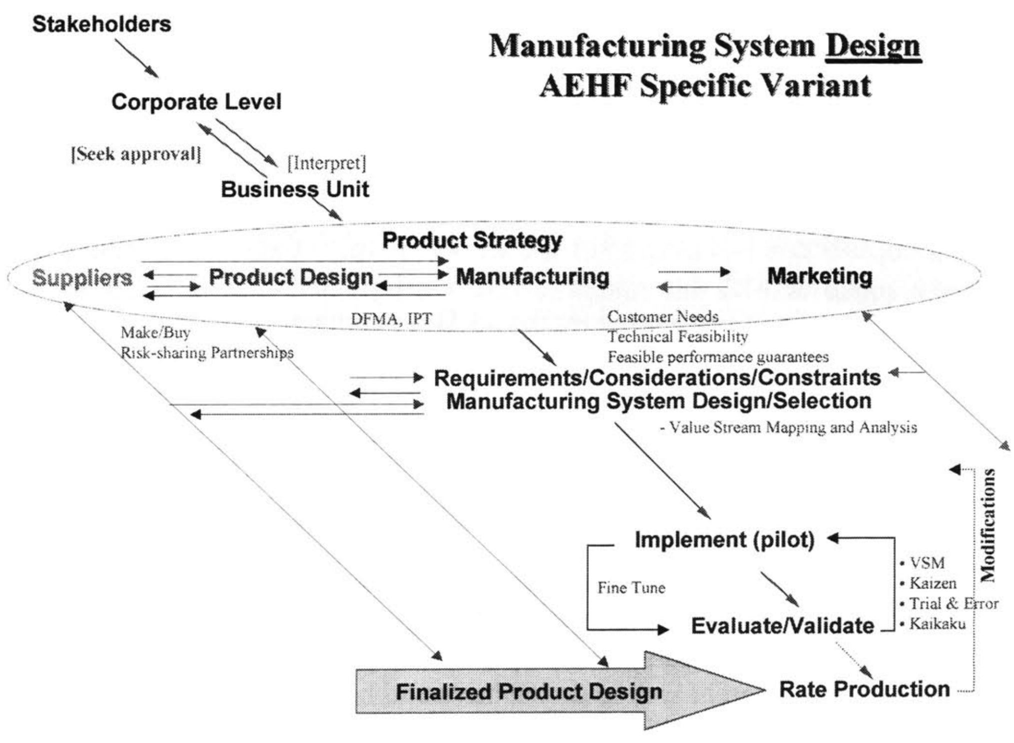

Figure 55: AEHF satellite Specific Variant of the Manufacturing System Design Framework

The product strategy for AEHF was created with all of the functions involved. The program manager was the proponent for using commercial practices on their spacecraft and this created the link between product design and manufacturing. Not only did this link those two functions for AEHF; it linked the manufacturing, product design and suppliers from A2100 as well. The corporate level approved this product strategy since it supports the corporate strategy that was established earlier. This product strategy helps establish credibility and improve their relationship with their customer by delivering a military product at a fixed price using commercial processes. This will increase their stakeholder value.

Following the strategy development, AEHF conducted a detailed value stream mapping event that contained the subsequent analysis of developing an ideal state and potential future state value stream maps. This activity consisted of the requirements definition and the detailed manufacturing system design phases of the framework. The next phase in the AEHF framework is the piloting phase. SBIRS-High will be in the final assembly and test activities when AEHF starts. AEHF should gain additional synergies from this.

The lines for rate production and modification are dotted since these phases have not yet been reached. The phases are included anyway since rate production will start soon and the modification activities are already planned. Since future and ideal state value stream maps were created and a list of projects generated to help AEHF reach those states, modification projects with the original goals are already outlined.

AEHF has had extensive integration with engineering throughout the manufacturing system design process. The AEHF program manager welcomed involvement from the A2100 team to help them base the AEHF processes off of the optimized flow for A2100. The AI&T team is involved in the AEHF program very early in the development and there is still ample opportunity to have leverage over the design, if need be. The manufacturing function has been more involved in the AEHF design process. Also, the assembly flows are part of the design reviews for the customer – not just the product alone.

The manufacturing function is taking a holistic view to prepare their own manufacturing system design process to integrate with the supplier and marketing functions. Interactions with the supplier community has been considered by the AEHF manufacturing system design team as well as a firm grasp on the value proposition for the customer. The AEHF manufacturing system design process identified what the customer wanted from the system and this identification of customer value helped guide the AEHF in determining the requirements on their manufacturing system.

System and Process Performance

Like the Joint Strike Fighter, AEHF is a new government acquisition and there is more evidence of up-front thinking about overall program affordability and efficiency. This mindset has driven AEHF to structure a program based upon a very different premise utilizing commercial best practices. This is a very different way to do business and helps the A2100-based products function more like their own enterprise.

The key for AEHF at this point is to hold on to this commercial spirit and not revert to a typical government space acquisition, so hopefully it can maintain that uniqueness throughout the program development.

The early work on AEHF is encouraging that manufacturing is an up-front concern for how the product will be easily, and affordably realized for their customer.

Platform Spacecraft Production

TRW has a long and unique history of supporting the U.S. space program. From space based communications, surveillance and specialized science missions, TRW has made a name for itself in providing its customers with highly specialized, one-of-a-kind spacecraft. Some of the many NASA missions TRW has supported include Pioneer, the Earth Observing System (EOS), the Compton Gamma Ray Observatory and the recent star performer, the Chandra X-Ray Observatory shown below.

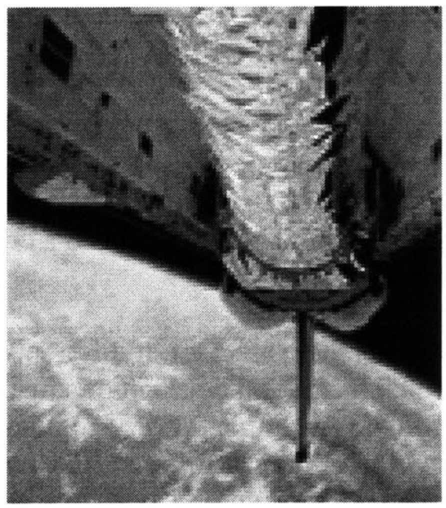

Figure 56: Chandra X-Ray Observatory inside the Space Shuttle cargo bay[285]

Figure 57: Chandra X-Ray Observatory deployed[286]

[285] Photo courtesy NASA from http://www.trw.com
[286] Figure courtesy of the Chandra X-Ray Observatory Center at http://chandra.harvard.edu

The work on military space missions includes supporting MilStar, the Defense Support Program (DSP) and many others. Historically, TRW's work in space has been focused on producing spacecraft for one-of-a-kind specialized missions.

Only now is this legacy being challenged with some of TRW's more recent efforts starting to move from the niche markets to more popular market segments in the government and commercial sectors.

Case Study Background

This expansion into other market segments is driven by the desire to increase their market share. TRW has usually made only 2-4 spacecraft each year in the open world and they are trying to maneuver their marketing strategies to increase that to about 10 spacecraft per year. This is coupled with an ongoing multi-faceted lean transition.

The first objective of this lean transition is to attain economies of scale while maintaining their unique capability to produce the highly complex one-of-a-kind space systems for which TRW is known. Also, the lean efforts aim to reduce cycle times and to establish a testing strategy to assure product reliability and reduce rework as well as build a culture of continuous improvement throughout the company.[287]

The TRW case study is unique in that there are a lot of different things going at one time leading to this overall lean transition, which includes the design of a manufacturing system. First of all, TRW is currently on contract with the Air Force for the Program Definition and Risk Reduction (PDRR) phase of the SBIRS Low (Space Based Infrared Radar System – Low) program. This is the low orbit portion of the complete SBIRS architecture for space based early warning and missile tracking. And, as has been the case in recent government procurements like JSF and EELV, the customer requirements include improvements in producibility and the affordability of the product.[288] But the changes underway at TRW extend far beyond the work for SBIRS Low.

A major portion of the work going into creating a producible spacecraft is part of the design of a spacecraft platform. Traditional architectural options for spacecraft include completely custom spacecraft, standard spacecraft and configure to order spacecraft. Configure to order spacecraft is a spacecraft strategy based on a multi-level standard architecture with inherent flexibility to be configured to meet specific customer or mission needs. This is a modular architecture, not just a common bus that will allow TRW to enter more competitive commercial markets and produce spacecraft at higher volumes.[289]

The new spacecraft architecture dictates a production process shift from what TRW has done before. This is being done under the MASS program (an AFRL Manufacturing Technology effort entitled Manufacturing Affordable Space Systems). Part of the MASS effort is to create the Flexible Space Vehicle Production Line (FSVPL). The overall concept behind the flexible production line is similar to what Toyota does in the automotive industry. When Toyota has a concept for a car, one of the early decisions is determining where it will be made since that

[287] Emery, B., *Space Vehicle Production at TRW: The Transition from Craft to Lean*
[288] SBIRS Low program information from TRW Marketplace at http://www.trw.com
[289] Emery, B., *Space Vehicle Production at TRW: The Transition from Craft to Lean*

dictates what the car will look like, in part, because it has to fit into that existing manufacturing system. This is similar to the ideas behind the flexible production line that will produce these modular satellites in a single factory. TRW will establish a flexible, multiple mission production line that will integrate diverse payloads with a standard modular spacecraft architecture for any mission in any orbit.

Actual Manufacturing System Design Process

To create this new lean ideal state complete with a flexible space vehicle production line (FSVPL) and a platform approach, TRW has outlined the key tasks of the transition approach.[290] First, they must build a lean infrastructure and try to utilize their existing facilities as much as possible to reduce the non-recurring costs. Next, they plan to define and document value throughout the different build and business processes. This will show where the key issues and barriers are that need to be addressed to create enterprise wide flow. When these barriers have been identified, kaizen events can improve them. And finally, this transition approach will hopefully infuse the need to continuously improve throughout the culture.

In addition to creating a new way of building products in the development of the lean infrastructure (described in detail below) this overall transition includes creating a new way to design products.[291] Concurrent engineering is helping to determine the various families of spacecraft that will comprise the platform families. Also, the new design processes are looking to minimize risk in the spacecraft while, at the same time, trying to leverage new technologies that can be incorporated into next-generation spacecraft. This thrust into concurrent engineering practices is also aimed at simplifying the production processes by establishing design requirements that allow a producible product to show up on the factory floor.

Part of the strategy to leverage new technologies and yet still minimize risk is through another effort called Integrated Avionics (IA). IA is developing, alongside the platform approach development effort, the software and hardware architectures that can be used on any vehicle or any mission.

Another part of the new design process is trying to simplify the manufacturing, assembly, integration and testing of the spacecraft. This is being accomplished through concurrent engineering efforts to compartmentalize portions of the spacecraft so, for example, wires don't have to be run the length of the spacecraft and simple disconnects are there when needed.

The final major thrust of the changes in the product design processes is the early integration of testing. It has long been argued that while in the pure world of lean manufacturing, testing is a non-value-added activity. But in spacecraft, testing is wholly value added since the customer is, in most cases, keenly interested in that spacecraft being certified that it works. The customer wants assurance that the product will work and testing is, therefore, a value-added activity. In contrast to this, when a customer purchases a car they are assured that there are sufficient quality control measures in place that alleviate the need to test every car. This shows the differences in what the customers of a car and a satellite deem as value-added. Spacecraft are an example of ultra-quality where the products cannot be repaired once they are placed on station. But, less

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[290] Emery, B., *Space Vehicle Production at TRW: The Transition from Craft to Lean*
[291] Emery, B., *Space Vehicle Production at TRW: The Transition from Craft to Lean*

than 25% of the actual Integration and Test time is spent on conducting the test.[292] So there is ample opportunity to attack the waste involved with the testing procedures. All of these activities are progressing to develop processes to improve the designing of new spacecraft.

To create the FSVPL[293], first the marketing function was brought in to determine what potential production rates would have to be accommodated. The maximum predicted peak takt time was determined to be 1 spacecraft every 24 days. So the system would have to be able to accommodate a wide range of takt times with this maximum. The actual flow of the system was determined and established with the required system capabilities determined. Currently, the spacecraft made at TRW are only moved when they must be relocated into test chambers and it is hard to do. TRW practices "clump" manufacturing and they seem to not like the idea of moving a spacecraft, yet this is a product that will have to withstand the stresses of a launch. The flow that will be implemented will include the payload, panels and bus being built up in parallel then after all the components are mated, the spacecraft travels through 5 more stations to install additional equipment, test, check and prepare for shipping. Not only will a single facility accommodate the feeder lines and the final flow line, but it will also contain stations dedicated for developmental products that are not yet moving along at rate.

Since the new production line needs to remain flexible enough to accommodate a larger volume production, like SBIRS Low, as well as still service the unique specialty spacecraft, maximizing the system flexibility is a major concern in the design of the manufacturing system. Universal tooling and test equipment is being designed for use on different families of spacecraft to maximize system flexibility. This mechanical and electrical ground support equipment would allow for the spacecraft to be easily moved without cranes and repositioned for the greatest access by the workers. Modular tooling that can be used across all the different spacecraft families will help minimize the non-recurring costs associated with bringing a new spacecraft into production. Another issue being addressed that will enable the mixing of production and unique spacecraft are the security requirements. TRW is trying to determine the security requirements to ensure success of mixing NASA programs (which frequently have many foreign partners) with secure programs for the U.S. government. Some programs will never be appropriate to mix, but the goal of the new FSVPL is to mix as much as possible into a single system.

A major part of the development of the FSVPL is the pilot plant activity currently on-going. The pilot plant activity is intended to validate the overall concept and details of the spacecraft platform designs and the production facility. A mockup is used as a mechanical pathfinder to test the modular design concepts and workflow. The pathfinder is testing the proposed layout and mechanical ground support equipment. Through this pilot plant exercise the technicians will use the same tooling and processes as on a real spacecraft to see where problems arise that can be fed back into the design of the new modular spacecraft, the tooling or the overall production system.

[292] Emery, B., *Space Vehicle Production at TRW: The Transition from Craft to Lean*
[293] Highlights of this process from Emery, B., *Space Vehicle Production at TRW: The Transition from Craft to Lean*

Framework Comparison

The TRW specific variant of the manufacturing system design process framework is shown below. Their framework is very similar to the original proposed earlier in Chapter 5. This version has been customized to show what specific tools TRW used throughout their manufacturing system design process for the FSVPL.

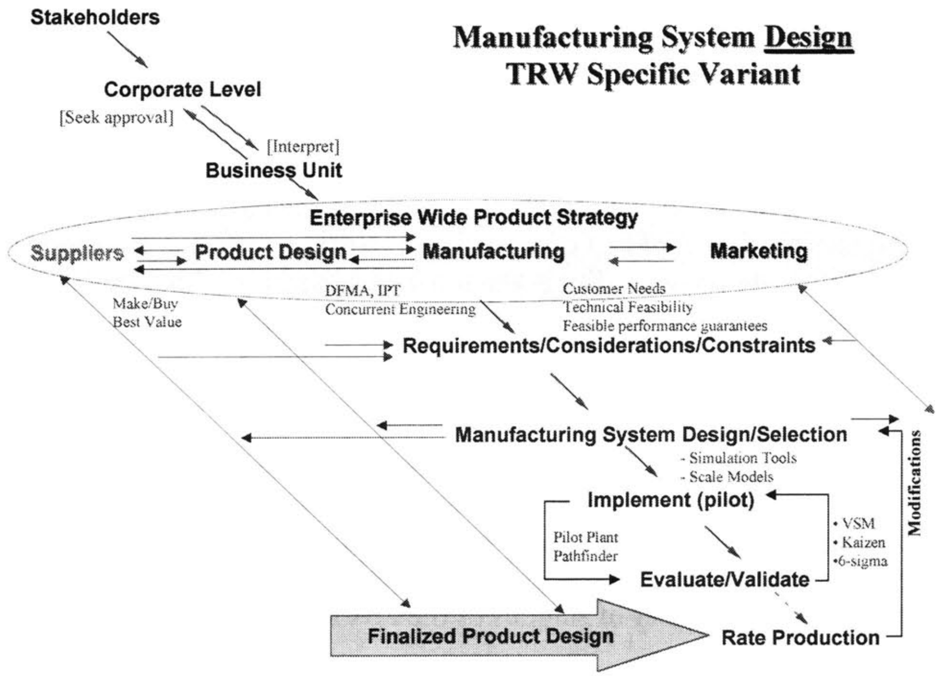

Figure 58: TRW Specific Variant of the Manufacturing System Design Framework

The first difference in the TRW specific variant of the framework is that the product strategy at TRW was enterprise wide. Since the overall concept behind the platform architecture was to be a broad base for multiple platforms, this product strategy also expands across multiple platforms to most areas of TRW space business. From this overall product strategy to be able to accommodate platforms like SBIRS in addition to unique niche markets, the different functional strategies were developed. The product design strategy was to develop the platform approach and the manufacturing strategy was to create a single flexible production line that would accommodate a wide range of products at a substantially reduced cycle time.

The manufacturing system design process progressed with the determination of the requirements for the system. Marketing functions provided the information that determined the capacity needed in the system. The manufacturing system design was also constrained by the existing facility that they do not want to change unnecessarily. To actually design the system a 1/30th-scale model of the factory floor was made. At first it didn't seem like it would be a useful tool, but it has allowed many people to see the system design ideas and play with the possible station layouts. Computer simulations were also used to try and develop the stations and the overall flow for the production line.

Next, in the implement-evaluate loop, TRW is passing a spacecraft mock-up through the different production stations. This pathfinder activity is an integral part of this design effort that will feed back into the design of the platform components. The line from the implement-evaluate loop is dotted since TRW has not yet brought this new system up to rate production.

Finally the modification loop exists in their design process since kaizen events and 6-sigma is occurring on current processes and planned to continue with the introduction of the new production line and platform. Before each improvement event, the overall goals of the new production line model are reviewed to determine the scope and overall need for the improvement effort. The modification loop also extends beyond the factory floor into the change processes, the hiring process and other white-collar areas.

The interactions between the various functions through the design of the platform architecture and the FSVPL have been routine and fruitful. Manufacturing has had continuous contact with the product designers since part of this complete lean transition effort is to change how they design spacecraft to ensure producibility in the product realization. The decision to pursue a platform architecture means that the design process they are going through now is much more difficult and time consuming, but the benefits will be seen in subsequent designs for individual customers.

The manufacturing function interacts with the marketing functions throughout the manufacturing system design process as well. The determination of the potential markets for different families of spacecraft weighs heavily on the decisions made by all the other functions. And this leads to the predicted production volumes and takt times for the different spacecraft families as well as the required capability and number of stations of the FSVPL.

Finally, the suppliers have been involved throughout the entire design process for both the manufacturing and product design activities. The potential changes with the supplier interactions are as much of the manufacturing design process as the design of the production line itself. It seems to be well understood at TRW that the main leverage point to improve their production performance is in part shortages. Evaluations of their make/buy decisions and the best value decisions for many of their products are indicative of the attention being placed on improving this interaction. Also, suppliers are involved in the detailed design of the FSVPL since it affects the level of spacecraft integration the line must be able to support.

System and Process Performance

TRW has started down a very difficult design process that is tremendous in scope. But the fact that this lean transition impacts the product design and the manufacturing system equally has created a synergy in trying to make the total program succeed. This also leads to an enterprise level perspective. The FSVPL will serve TRW throughout the manufacture of all the different programs that will be based on the new platform approach.

TRW is currently in the pilot plant phase of the system design process and things are progressing well. This approach is starting to take hold in the TRW culture as it makes its way into proposals for other programs. This will propagate the different initiatives into following products. Another indication of the success of this approach taken by TRW is the acceptance of this approach by the SBIRS Low customer, the U.S. Air Force.

The manufacturing system design process followed by TRW closely matches the original process proposed by the framework. The manufacturing system design process possessed each of the phases in the same sequence with interaction between the various functions throughout.

Iridium

"It was the best of times. It was the worst of times."[294]

That statement summarizes the saga of Iridium. Iridium is a tale of "engineering genius" and, unfortunately, also a tale of a failed marketing strategy.[295]

Iridium was a remarkable feat. It was the world's first truly global communication system, comprised of satellites that would communicate with each other. Iridium smashed the industry standard, producing satellites in mass quantities in a few days, not months. 72 satellites were launched in just one year from three different countries creating the largest satellite constellation in history.

Yet, just 16 months after Iridium became operational, it was to be "switched off".[296] Only 55,000 phones had been sold by 2002 instead of the 5 million Iridium had predicted.[297] And while Iridium users had huge, awkward and expensive phones, normal cell phone users were able to make calls around the globe courtesy of Global System for Mobile Communications (GSM), which was a land-based digital cell technology. Not only were cell phone users able to call around the globe on normal phones for less money, they could browse the Internet and send text messages using the same phones. Iridium users were out of luck.

Case Study Background

Iridium was named after the 77th element in the Periodic Table since the system was originally planned to contain 77 satellites. The constellation is actually comprised of 66 satellites and on station spares for a total of 88 satellites launched between May 1997 and June 1999 orbiting in one of 6 different orbital planes at an altitude of 450 miles. Together, this constellation of satellites created a global telephony network that changed the basic architectural premise of satellite communications.

[294] Dickens, Charles, A Tale of Two Cities
[295] Hodson, H., *The phone that fell to earth*
[296] Hodson, H., *The phone that fell to earth*
[297] Hodson, H., *The phone that fell to earth*

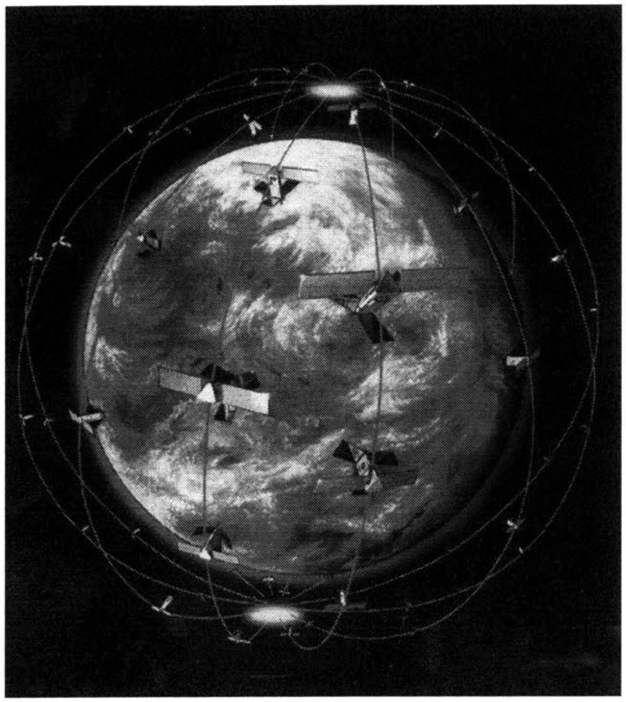

Figure 59: Illustration of the Iridium Constellation[298]

Rather than utilize traditional bent-pipe architecture with a handful of satellites in GEO, Iridium was a constellation of LEO satellites where the signals would bounce between satellites to link the users. This lessened the needed signal strength (and therefore the size) of the phones, reduced the number of gateways needed to redirect the signal on earth, and significantly shortened the delay the users would experience because of the reduced distance the signal had to travel.[299] This was accomplished by creating a small satellite that could function as a switchboard in space.

[298] Figure courtesy of http://www.iridium.com
[299] Hodson, H., *The phone that fell to earth*

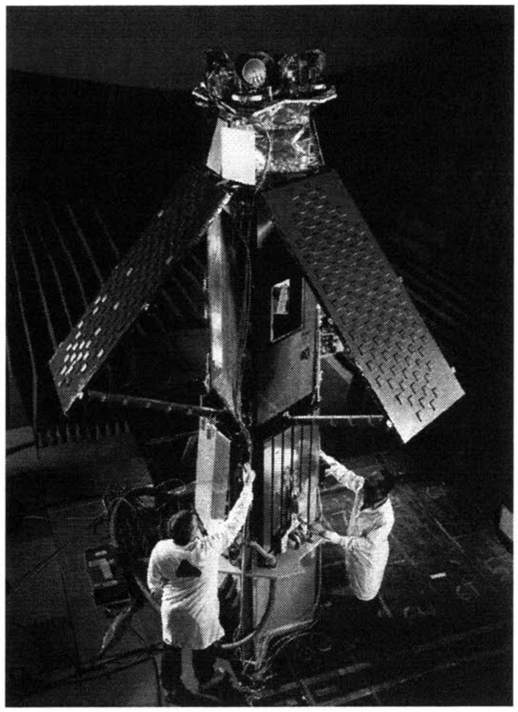

Figure 60: An early Iridium satellite undergoing system testing[300]

Motorola in Chandler, Arizona, was the prime builder of the Iridium satellites. Together in partnerships with Lockheed Martin, Sanders, Raytheon and Com Dev, Motorola changed all paradigms associated with the manufacture of spacecraft.

Actual Manufacturing System Design Process

At the onset of the Iridium project, Motorola had no previous experience as a prime contractor for spacecraft. The early stages of the manufacturing system design process consisted of benchmarking activities with Lockheed Martin to gain some insight of spacecraft assembly. Motorola also looked at automobile assembly, specifically the Suburban, and even the Rolling Stones. Benchmarking the Rolling Stones show demonstrated the ability to quickly take down, move and set up a massive stage and production. This type of creativity is indicative of their entire manufacturing system design process.

Also in the early stages of the system design process, the manufacturing strategy was derived. The overall Iridium program was born into an existing culture at Motorola and their Six-Sigma program. The Six-Sigma initiatives drive for capable processes and for production processes to be standard and repeatable. Another overarching strategic element was to get the Iridium constellation on station and operable as soon as possible. They didn't want to have too many launches, so it was determined to cluster the satellites and get them on station and working quickly. Yet another driver was Design to Unit Production Cost (DTUPC). This strategy tracked the overall costs, as well as Quality and Reliability predictions, through the design and development phases to help ensure that they were going to stay on budget and on schedule. The manufacturing system and the work contained within it for Iridium was also influenced by the

[300] Photo courtesy of Lockheed Martin

Motorola mindset as well. The strategy was to build each satellite and test only for operations at the system integration level. The factory required "Known Good Product" which meant significant test at lower levels reducing the amount of test at the system integration level. This drastically reduced the number of issues to resolve at the system integration level, which is substantially more difficult and frequently more costly. It was determined that following final assembly, they would perform only one system level test to ensure spacecraft integrity.

The main constraints bounding the manufacturing system design were geometric constraints and schedule limitations. The final assembly area for Iridium is in Motorola's Chandler, Arizona facility in what used to be a stock room. In addition to this tight fit, the final integration and assembly process had a constrained schedule. The suppliers stayed on pace throughout the design effort, but Motorola was late starting the final integration of the satellites. So the market driven schedule tightened for the final assembly processes.

The manufacturing system was determined to be a set of stations where the spacecraft would be wheeled from one station to the next on a dolly. The station concept was designed in detail with close interaction with the design engineers since the break up of the spacecraft into stations determined the modules for spacecraft design. The stations were broken up around work content, namely, what modules would come together there and what tools would be required to perform that portion of the work. Simulations were used to try out multiple layouts and to balance the work between the stations.

The overall system was designed to support a 21-day throughput time with 7 equivalent units in process at any one time. This led to the design of 16 individual workstations. To control the system, the shipping crates and dollies were used as the signal kanban triggering work and shipments. Also, since these crates and tools were expensive to purchase and qualify, using a set number of them allowed non-recurring costs to be kept to a minimum. In the same manner as the design of the different stations, simulations were used to predict the use of these tools and where the different containers, crates and dollies would be throughout the build process.

In addition to using the tooling as a control mechanism for the build process, Motorola introduced a unique tooling concept for Iridium. Motorola engineers and manufacturing representatives wanted to build the bus horizontally. Building horizontally is safer, and it would allow the cycle time to be reduced since the spacecraft would be more easily accessible and moved while it was on the production floor. So they designed a dolly that the bus would be built up on. The bus is then shipped to Motorola on the dolly. The only time the bus leaves the dolly is when the satellite is hung for a system test and for final placement on the launch vehicle. Otherwise, it stays in the same tool for all other functions.

Testing is always a unique issue in spacecraft production. It is frequently the most time consuming portion of the final integration process. To try and reduce the testing cycle time for Iridium, Motorola sent the first five production units to Lockheed Martin in Sunnyvale for acoustic and thermal-vacuum testing. These initial tests served to qualify the Motorola build processes and these tests did not have to be performed on any subsequent spacecraft.

This whole process of determining the work content for the different stations and the design of the tooling and floor layout occurred concurrently with the detailed design of the spacecraft. The total design process lasted for 3 to 4 years and was followed by rate production which resulted in 88 satellites being produced in the next 2 years.

Framework Comparison

The Iridium specific variant of the manufacturing system design process framework is very similar to the original framework. The upper portion, the strategy formulation body, provided the manufacturing function with a portion of their strategy, namely, Six-Sigma. The manufacturing strategy was also driven by the need to reach the market quickly and to try and shorten assembly times by only testing what work they actually did and not spend time testing components.

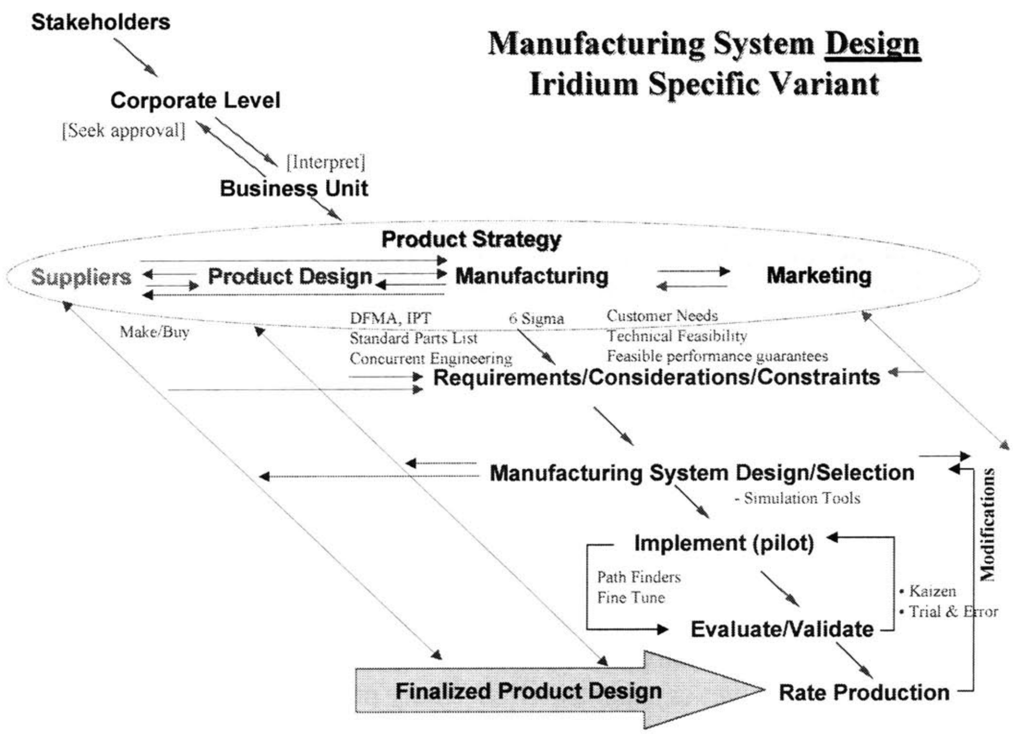

Figure 61: Iridium Specific Variant of the Manufacturing System Design Framework

Early in the design process, the requirements, considerations and constraints were identified and defined. This determined the required takt time to drive production which impacted how the work content would have to be divided in between multiple stations. The detailed design phase for the manufacturing system improved the definition of work between the different stations and created the possible layouts to fit the complete system into the stockroom they were given.

This was followed by extensive work with pathfinders to try out the various ideas. Mechanical pathfinders were used to test out all the processes, workstations, tools, carts, cable lengths/routings and shipping containers. This work was done to see if they could really build a satellite. It helped them see where they did not have the right tooling or accessibility to a part of the bus, or where there was the potential for a mis-mate between parts. Pathfinders were also used to test out the launch processes, logistics, component shipping containers, interfaces with the launch vehicles, fueling and shipping. The extensive piloting work took place throughout the design effort. It started about 3 years before rate production to give them ample time to find and correct mistakes.

Finally, the modification loop was an integral part of the total manufacturing system design process for Iridium. Most of the improvements that were implemented were process related, but there were design changes made at this point after the early units were placed on station. Many of the improvement activities were upgrades to the tooling and test software to make the work even easier to do. But in all cases, the impact on cycle time was reviewed before a change was made.

The manufacturing system design process included interactions between all the various functions throughout the various design activities. There was extensive work with the supply chain to ensure that Iridium would not be plagued with part shortages, as is the case in far too many aerospace programs. The carts and shipping containers were built to not just hold parts for Iridium, but to act as signal kanban for the suppliers. Also, Motorola designed the innovative dolly that held the bus throughout the build process and acted as the signal kanban.

Manufacturing and design engineering were tightly coupled throughout the design process. In the interest of being able to meet the cycle time goals, the satellite had to be designed so things could not be plugged in incorrectly. For many interfaces on the satellite, guides were added to the connectors to prevent partial mis-mates and cables were tied so as to also prevent mis-mates. Another aspect of the interaction between engineering and manufacturing was in the overall design of the satellite. The engineers were given a list of standard parts up front from the manufacturing function. If the engineers wanted to use a part that was not on the list, they had to defend their choice and explain why something else would not accomplish the same purpose. Also, the modular design of the spacecraft had some extended benefits. The design of the stations for the factory floor helped determine the physical splits in the product, and it also helped take more work off the critical path in the assembly operation. If there was a problem in assembly, the whole module could be removed allowing the engineers time to fix it. Iridium was also designed to be a simple, yet capable satellite. Many new technologies were incorporated to shrink the overall size and complexity of the satellite. The completed spacecraft was comprised of approximately 3500 parts. Finally, the extensive use of pathfinders throughout the design processes helped the manufacturing and design functions find and prevent mis-mates, solve problems with the needed tolerances, determine needed cable lengths throughout the spacecraft and address overall producibility concerns.

There was also extensive interaction with marketing throughout the design process. The pace driving the manufacturing system and the need for short cycle times was determined by the marketing function. The marketing function determined the launch interfaces based upon when and where a cluster of Iridium satellites would be launched.

System and Process Performance

First and foremost, when outlining the performance of the system it must be noted that Motorola was able to meet the cycle time required supporting the Iridium launch dates. The 21-day cycle time was met, and varied little depending on if there were any test anomalies along the way. The schedule became a drumbeat for the operation and the work in the stations became consistent.

But Motorola didn't just produce the spacecraft predictably; they did it with some additional twists. The facility in Chandler had previously built boxes for military payloads but never dealt with producibility issues or standard work because they historically built 1 or 2 of each product. Even with this heritage, they were able to produce spacecraft consistently. The other obstacle they overcame was continuing to meet the required cycle times while adding more test procedures into the final assembly operations. Originally, there was only 2 days of system level tests planned in the final assembly sequence with no thermal cycling. Later, some thermal cycling was added into the sequence, but through parallel processing, and shifting manpower, the 21-day cycle time was still achieved.

There was more accomplished by this system design process then just the clockwork manufacture of spacecraft. The operation was run completely electronically. This was the only truly paperless factory encountered in this research. Also, Motorola saved considerable expense by only making this stock room a 100,000-class clean room rather than a 10,000-class clean room as was originally intended. The logic was that the spacecraft were only going to be in there for 21 days, so how much dirt would really settle on it? Not much.

Motorola produced and launched the Iridium constellation over about a 2-year time frame. And it was only 16-months later when Iridium defaulted on nearly $7 billion in debt and was prepared to decommission the constellation.[301] Iridium was originally marketed to normal cell phone users who didn't want to use the large, bulky phones and deal with delays in their communications when they could use a normal cell phone for less than Iridium's $6 per minute. Following Iridium's liquidation, Dan Colussy picked up the assets for less than a half cent on the dollar.[302] Less than two weeks later, he signed a 2-year $27 million contract with the Department of Defense to provide unlimited airtime to 20,000 government users.[303] Now Iridium is marketing to vertical organizations instead of the common user – customers like the government or people in remote locations such as oil fields and war zones.[304]

To support the new purchase of the Iridium constellation, Motorola is completing 7 more spacecraft on the last buses that were made. These 7 spacecraft will be placed on station as spares. Then, according to one source, Motorola "is going to get rid of the tooling and move as far away from the name 'Iridium' as possible".

The manufacturing system design process used by Iridium closely matches the proposed framework. The process went through each of the proposed phases and there was interaction between the different functions throughout. There are not many differences between the Iridium process and the process proposed in the original framework.

[301] Menduno, M., *Making Dead Birds 'The Deal of the Century'*
[302] Menduno, M., *Making Dead Birds 'The Deal of the Century'*
[303] Menduno, M., *Making Dead Birds 'The Deal of the Century'*
[304] Hodson, H., *The phone that fell to earth*

6.5 Chapter Summary

This chapter outlined the actual manufacturing system design processes used in the aerospace industry. The sectors of the aerospace industry included were the major aerostuctures, electronics, launch vehicles and spacecraft. For each case study the need to design or re-design their manufacturing system was outlined followed by an in-depth description of their unique process. This was followed by a comparison of their process to the process proposed by the Manufacturing System Design Framework introduced in Chapter 5. Finally, the performance of each system was briefly described.

These case studies served as the basis for the framework validation activities. The cumulative results of how the case studies matched the proposed process from the framework are shown and explained in the following chapter.

7.0 Data Analysis

Chapter Overview

This chapter outlines the analysis of the data to validate the manufacturing system design framework. For each case study described in the last chapter, the actual manufacturing system design process was compared with the proposed process in the original framework. This is then compared with the performance measurement of actual/planned performance. Following the analysis of the general framework testing, other key characteristics are explored and supported based upon observations from the cases. This chapter concludes with a collection of "lessons learned" from the various case studies gained through their experiences with designing their manufacturing systems.

7.1 Framework Validation

The first goal of this research is to propose the framework that was introduced earlier. Then the research tests this framework by comparing it to the actual manufacturing system design processes used in industry. This is done with each case study. The final step in validating the framework is to use the framework evaluation tool and compare the congruence of an actual industrial process with the proposed process to the actual/planned performance measure. These results are presented here.

For each case study, a "framework congruence" score was determined using the framework evaluation tool. This score was determined by exploring the total phase presence, phase timing and breadth between functions in a given phase for each case. The framework congruence score can range from 0 to 100, with 100 indicating that the industrial process matches the proposed process completely. This framework congruence score was then compared to the actual/planned performance measure. An actual/planned performance measure of 1 indicates that the actual performance matched the planned performance and the product was made in the allotted time, or with the anticipated resources. An actual/planned performance measure of 3, for example, would indicate that the industrial practice took 3 times as many resources as were initially forecasted.

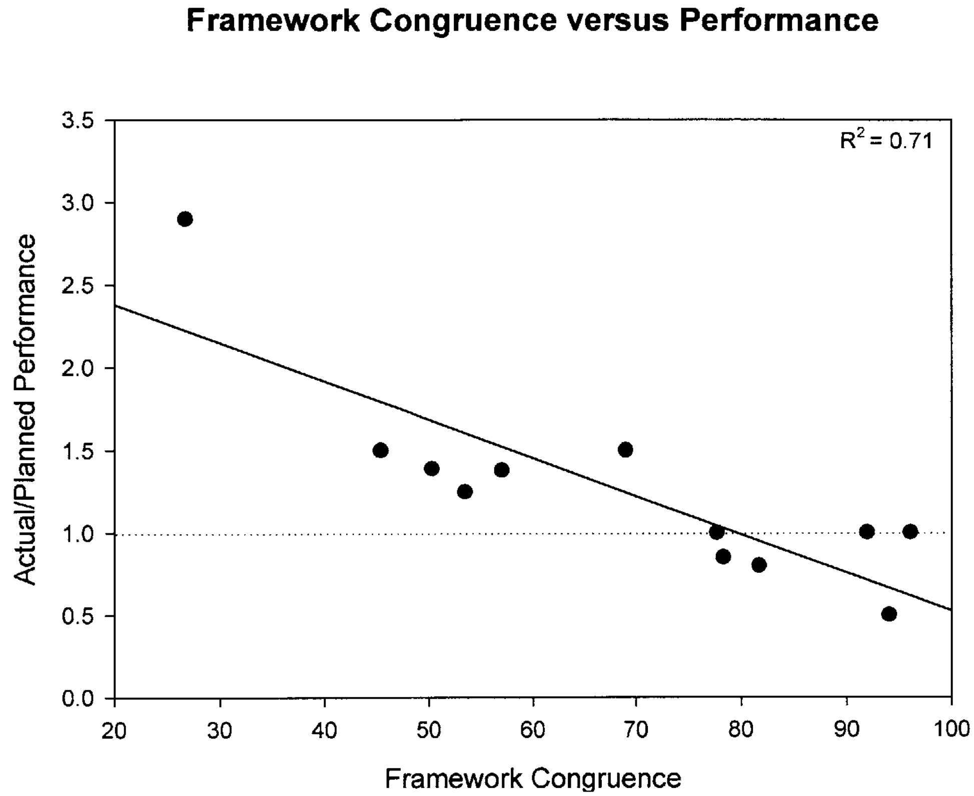

Figure 62: Framework Validation Results

This graph depicts the results of this scoring for the case studies. The x-axis shows the framework congruence score, which is the degree to which the industrial design process matched the process proposed by the original framework. The y-axis is the actual/planned performance measure. The dotted line at 1 indicates that the actual performance matched the planned performance. The dots above this line required more resources to finish the product and dots on or below this line, either met their goals, or were able to assemble the products with fewer resources than anticipated.

At first glance, these results show a trend between framework congruence and system performance – the higher framework congruence scores correspond to actual performance at least matching planned performance. To test the strength of this relationship, a linear curve fit was added to find an R^2 value of 0.71. A linear curve fit was used since there are not enough data points to justify the higher degrees of freedom associated with various other types of fit curves. But, even the relatively high value for R is not the important aspect of this data. It is not important that all the points lie neatly on a line. There are many ways to design system that will not meet the planned performance which could lead to substantial scatter in the lower framework congruence scores. But this is showing that, since all the points where the system performance was met had high framework congruence scores, there may not be many ways to design a system that does meet the planned performance. Given this, if there had been scatter in the lower framework congruence scores, this would have lowered the R^2 value, but not changed this trend.

These results show that the cases with higher framework congruence scores met, or beat, their planned performance.

7.2 Numerical Analysis

In the original descriptions of the case studies, they were grouped by the sector to which they belonged in the aerospace industry. This grouped the cases together by the types of products they produced whether it was airframes, electronics, launch vehicles or satellites. But, the framework validation results suggest grouping the cases differently. Rather than grouping the cases together by sector, instead they will now be classified based upon where they fall onto the framework validation curve. From the original framework validation results, there are two natural groupings that emerge – those cases that met their planned performance measures and had higher framework congruence scores and those that did not meet the planned performance targets and had middle framework congruence scores. These groupings are illustrated with the data below.

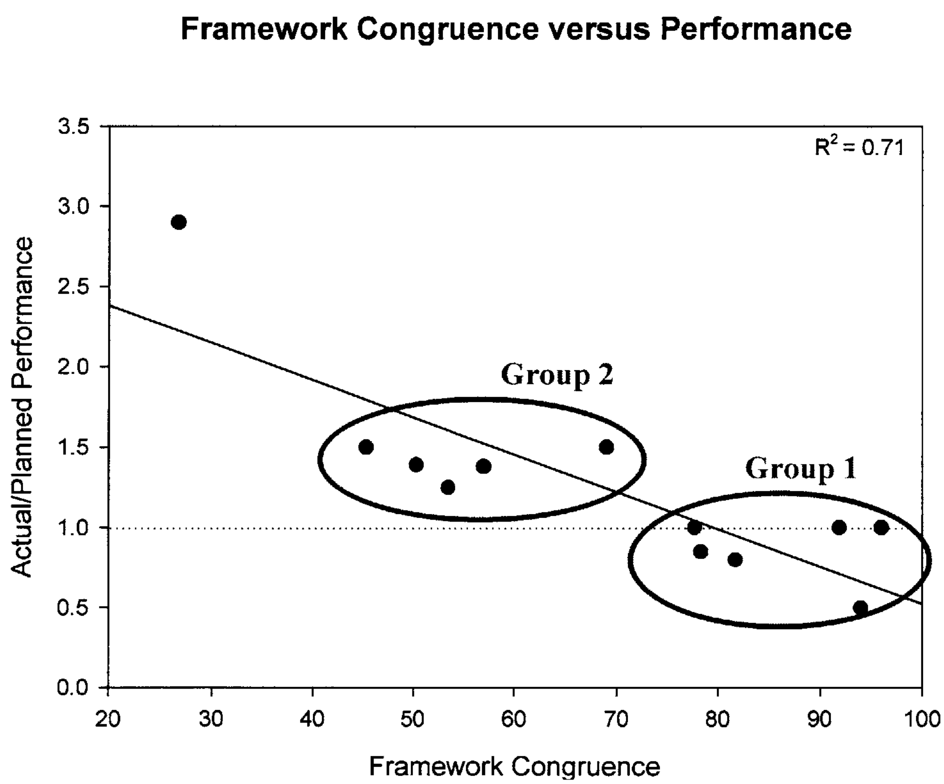

Figure 63: Framework Validation Results with Groups added

Dividing the data into these two groups will guide the remainder of the numerical analysis. This will allow the commonalties between the different cases in each group to emerge as well as differences between groups 1 and 2 that could explain the differences in performance between them.

Scoring Breakdown

Subsequent analysis was performed with these two groups. Group 1 consists of the cases that had higher framework congruence scores and at their system at least met the planned performance targets of hours per unit or days of assembly time. Group 2 consists of the cases that had middle framework congruence scores and whose system did not meet the planned performance targets. This analysis was performed both with and without the one outlying point included.

Before any causes for the differences between the two groups were determined, an independent t-test was performed on these groups to determine if this classification is fair. The t-test showed that there is a statistically significant difference between these two groups so this division can be used.

The framework congruence score is a culmination of phase presence, phase timing and breadth in phase points for all the different phases of the manufacturing system design framework. To try and determine if one of those factors could account for the jump in framework congruence score, the scores for each case were broken down into the data shown below.

Table 5: Framework Congruence Scoring Breakdown by Factor

Framework Congruence	Phase Presence	Timing	Breadth	
96	25.90	30.71	39.38	
94	25.90	30.00	38.05	**Group 1**
91.9	22.48	29.00	40.38	
81.7	18.57	26.62	36.62	
78.3	23.24	24.19	30.86	
77.67	20.90	25.90	30.86	
69	21.24	26.62	21.19	
57	17.24	19.76	20.14	**Group 2**
53.5	13.33	15.90	24.29	
50.3	12.33	17.90	20.14	
45.3	15.00	18.76	12.29	
26.73	7.33	11.76	7.67	

By inspection it appeared that there was a possible jump in the breadth in phase scores between group 1 and group 2. To test this, a t-test was performed for each factor. The relationship between phase presence and performance as well as the relationship between phase timing and performance was not statistically significant. Only the breadth in phase t-test showed statistical significance between groups 1 and 2. This can be seen in the three graphs making up Figure 64. This is a set of graphs depicting each factor – either phase presence, phase timing or breadth in phase – against the system performance. On each graph the same groups are marked showing the overlaps in scores on the phase presence and phase timing graphs, but the complete separation on the breadth in phase graph.

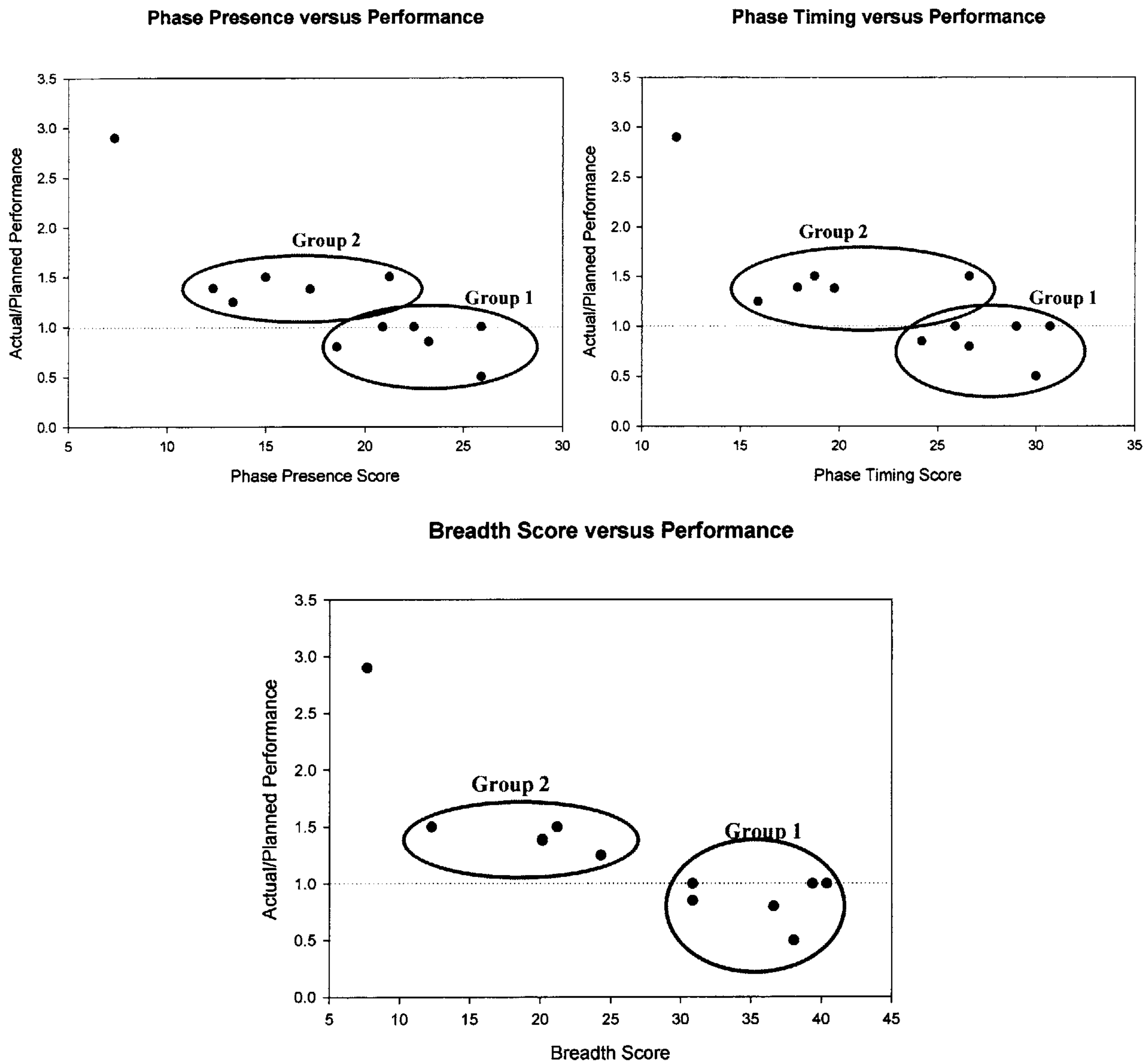

Figure 64: Scoring Breakdown by factor and groups

These results mean groups 1 and 2 are statistically separate groups in terms of their performance measures and that the breadth in phase portion of the total scoring can explain this difference. These statements of statistical significance hold through the analysis both with and without the one outlying point included in the group 2 data set.

7.3 Observational Support for Determinants of Performance

Breadth in Phase

This numerical analysis matches with what was experienced and observed in the different case studies. Differences in the inclusion of the product design functions 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 interaction between the various functions extended throughout all of the phases on the framework.

The typical experiences for cases in group 2 were that manufacturing and product design worked independently of one another. For example, one spacecraft manufacturer redesigned their system when they instituted their new assembly and testing concepts and this did not impact or involve the design of the spacecraft bus. Just the opposite of this was the experience of a major aerostructure builder. In this case, the product was completely redesigned when it was broken into manufacturable modules, but the major concepts determining the build processes and tooling were not altered. Yet another example of this independence between the manufacturing system design and the product design was seen in a space sector manufacturing system design experience. This firm had a structured method to design their system. Their specific variant of the framework shows that every phase was present and the timing matched that proposed by the original framework. The only difference in the manufacturing system design process by this firm, as compared to the original framework, is the breadth in each design phase. Following the strategy formulation, the breadth and interactions between functions through the detailed design did not continue.

On the other end, the cases in group 1 can all be characterized by extensive interactions between manufacturing and product design throughout all the phases present in the framework, and in many cases this interaction included the suppliers and marketing functions as well. Part of the manufacturing system design process for one particular space system is to devise a method in which a manufacturable spacecraft is designed. This calls for a change in the requirements generated by the product design functions and what they demand of the technicians that actually build the spacecraft. Another example of this is a new aircraft where manufacturing was an early consideration in the concept development since they wanted to capitalize on the commonality in variations of the production without requiring unique tooling or assembly processes for each variant. Without manufacturing and product design interacting in the early stages of the concept development the aspects of the product that make it easy to build, such as the hard joints and common datum, would not have been designed into the airplane. These features are not the only evidence of extensive interaction between product design and manufacturing for this product. The manufacturing function initially set the major breaks for the airplane and the product designers had to design around those breaks. Another example of the interaction between manufacturing and product design in a group 1 case is another major aerostructure case redesigning an existing product. In this design process the floor workers were involved through the design process to check the design each morning. This gave the engineers daily contact with what the workers could or could not assemble.

Strategy Presence

The next determinant of performance that differentiates groups 1 and 2 is the presence, and role, of a manufacturing strategy. The figure below shows the split between the cases that had a manufacturing strategy and those that did not, corresponding to their framework congruence scores. All of the cases in group 1 fit into the category of having a manufacturing strategy.

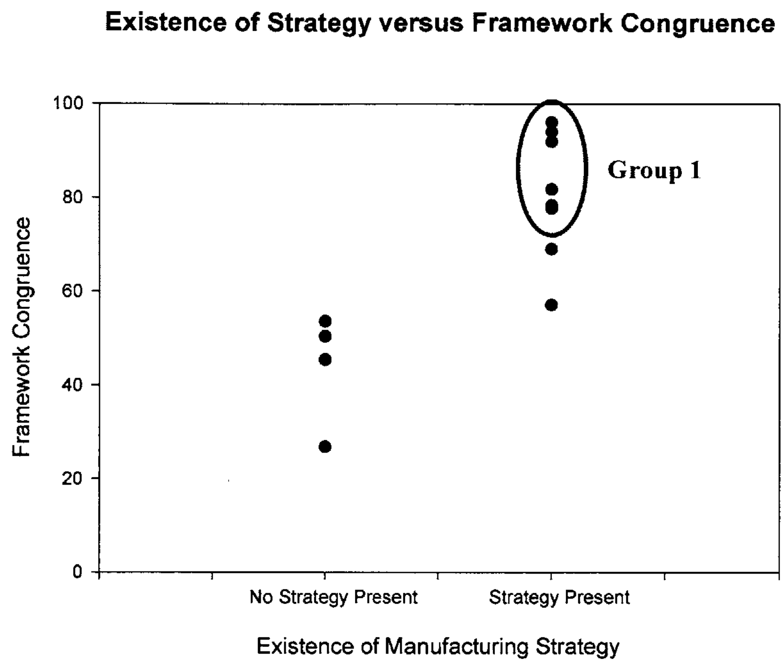

Figure 65: Existence of a Manufacturing Strategy and Framework Congruence Scores

Again, these results show that all the cases in group 1 that had a manufacturing system that at least met the planned performance, had a manufacturing strategy. The manufacturing strategies of the group 1 cases include a strategy of capitalizing on the commonalties between product variants and another that is trying to reduce the amount of craftsman type work occurring on the production floor, as examples. In the higher scoring cases, these manufacturing strategies went beyond just a single product and encompassed the entire enterprise. The manufacturing strategy devised for a launch vehicle was implemented on all the boosters being assembled and not just the new booster for the EELV contract. The same is true for a spacecraft manufacturer. Rather than the manufacturing strategy applying only to a new program proposal, the new platform approach and the flexible production line were to be used on all their products. This is a substantial shift in focus from one product or program to a whole family of related programs extending across and enterprise.

There are two cases that had manufacturing strategies that were not members of group 1 in terms of performance. These two cases had explicit manufacturing strategies developed but did not make the leap into group 1 in terms of performance since neither one of those cases had the breadth between functions to capitalize on those strategies. Following the integrated product and manufacturing strategy formulation, they did not follow through with the interactions in the detailed design processes.

One last characteristic of the cases in group 1 that had manufacturing strategies was the role of manufacturing in the organizations. All too often, manufacturing is viewed as a "necessary evil" of a lower status than the product design functions.[305] But, in these cases, manufacturing was just as important to the realization of their products as the design. This can again be seen with the

[305] For more extensive research supporting this fact, please see P. Fernandes, *A Framework for A Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor.*

JSF experience. Manufacturing was an integral part of the proposal put together by Lockheed Martin. They realized that in order to win the contract and meet the requirements set out by the customer, manufacturing had to be considered and utilized as a weapon and not a burden. Iridium also illustrated the need for manufacturing to be an addition to the competitive skill set of a company. Iridium was aware that they were going to have to do what had never been done in the space industry before – they were going to have to mass produce satellites and not allow each spacecraft to be crafted. Manufacturing was needed for them to accomplish what they did. A traditional "thrown over the wall" relationship between manufacturing and the rest of the enterprise would not have resulted in the production and launch of 88 satellites in 23 months. The experiences of the cases in group 1 show that it is when manufacturing was an accepted part of the overall business plan that the manufacturing system was developed to support the enterprise strategy and help the enterprise meet its goals.

Production Volume

One lack of commonality, which should be mentioned, is the role of production volume in the performance of the manufacturing system. The performance of the manufacturing systems of the cases detailed in this research is independent of the production volume. This is shown in Figure 66.

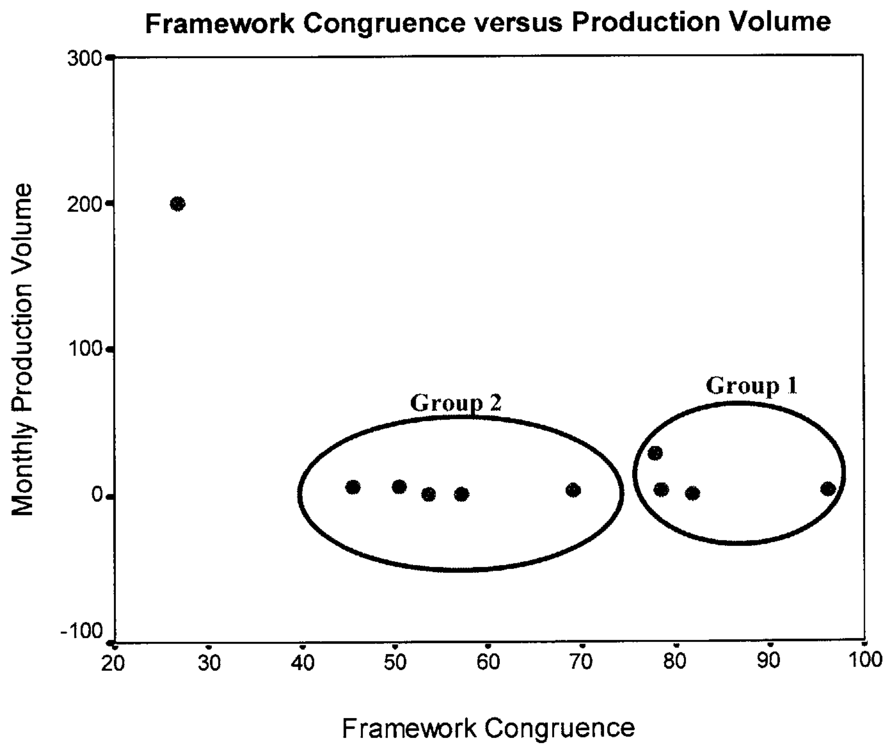

Figure 66: Framework Congruence and Monthly Production Volume

This may be a somewhat surprising result. It seems like the larger production volumes would greatly impact the performance of the system. In a company that will produce a large quantity of a product, manufacturing becomes more of a concern and more of a driver in the development. This is partially true here in that only 339 F-22s will be produced compared to a potential 3,000

JSFs. This difference in volume certainly supports the increased interaction between product design and manufacturing for the development for JSF. But as these results show, this is not always the case. These results show that the product with the highest production volume of about 200 units a month is the same product that has the lowest framework congruence score and, therefore, the highest actual/planned performance measure. These results still hold in the following plot that is the same data but with the one outlying point removed for clarity.

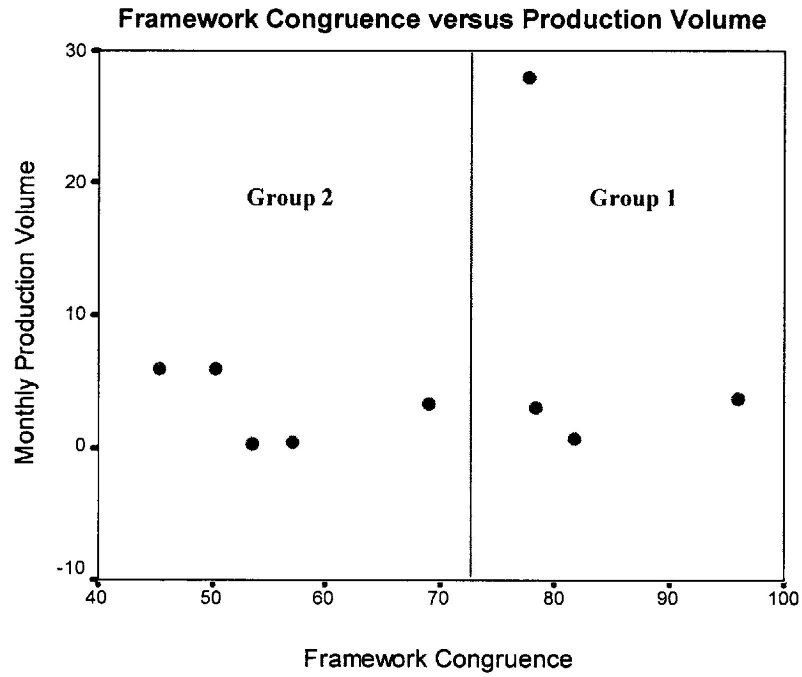

Figure 67: Framework Congruence versus Production Volume (detailed)

This more detailed view of the relationship between framework congruence and monthly production volume shows that a higher volume is not necessary for a successful system. This can be illustrated in the difference between the two EELV platforms. One vehicle has more launches scheduled and boosters ordered but the other was able to design a manufacturing system that produced the first flight vehicle using the planned resources.

One strategy used by the companies with the lower production volumes was to create the volume where it really does not exist. In other words, aggregate across different products or programs to create a production volume when individual production volumes are low. This enterprise view is what one spacecraft manufacturer is doing with a flexible production line that will accommodate all the various platforms. One new aircraft is doing this by producing all the variants on a single line. The EELV platform mentioned above that has the lower rate of the two is doing this by aggregating across the whole booster family. This allows the new manufacturing concepts to be successful.

Customer Involvement

Customer involvement and consideration of the ability to manufacture the product, or for the contractor to supply an affordable product, seems to have 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 defense aerospace industry has been able to rise to meet the challenge. Joint Strike Fighter and TRW's work with the platform architecture to help benefit SBIRS Low, as well as other future government products, are cases where the customer said that affordability was a requirement. In these cases, product designs that can be assembled reliably and in greatly reduced throughput times were developed.

This is completely opposite the experience of the F-22 program where affordability came along as a customer requirement later and the program is experiencing difficulties in trying to reach the affordability goals.

According to the theory and model proposed by Utterback that was introduced earlier, this emphasis on affordability and reduction of acquisition costs can be an indication of the lifecycle phase of the industry. Utterback determined that an emphasis on acquisition costs and not just product performance might be an indication that an industry may be in the post dominant design, or transition, phase.[306]

This attitude with a focus on affordability is certainly prevalent in many of the newer programs. JSF, SBIRS Low and AEHF are all off to a good start where the customer is concerned about manufacturing and acquisition costs, manufacturing has become an integral part of the program development, even in the early stages like on AEHF.

Organizational Structure

Another commonality in the group 1 cases 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. As Figure 68 shows, 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.

[306] Utterback, J., Mastering the Dynamics of Innovation

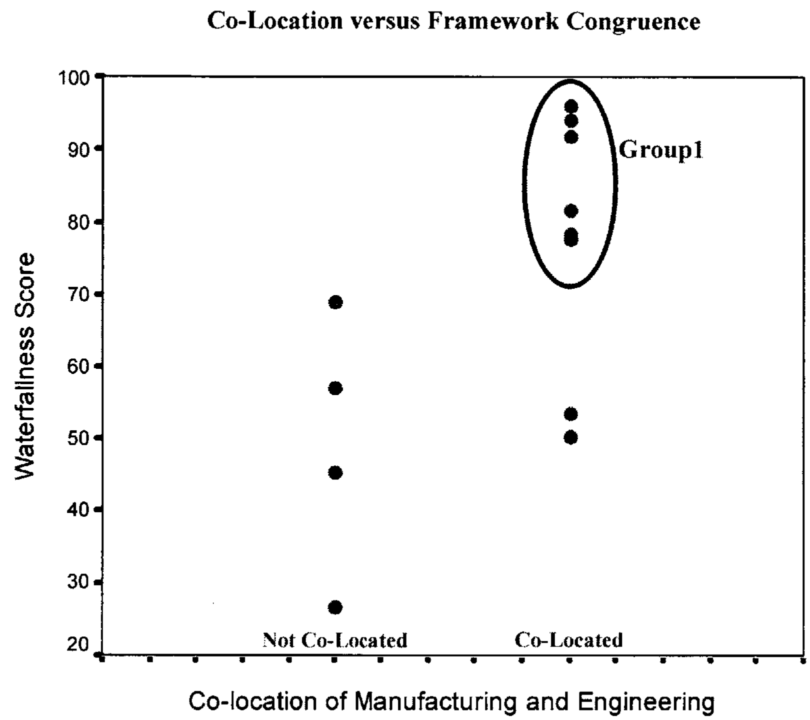

Figure 68: Organizational structure versus Framework Congruence

All of the cases in group 1 had the product design functions at least in a building near the manufacturing area. Most had product design in the same building. The two cases that had manufacturing and product design co-located did not have strong interaction between the functions. This is a result of the lack of breadth in the design process as was mentioned earlier.

The cases where manufacturing and product design were not co-located had 1,500 – 3,000 miles separating them. These are cases where products are being assembled while the design function is, literally, across the country.

This result shows that co-location is an enabler, but not a sufficient condition, for a system design process to be able to meet its target performance measures, like the cases in group 1. Just because these functions are located in the same vicinity does not mean that they will interact, as is the case for the two co-located cases that did not meet the performance standards of the cases in group 1. What is important about this result is that all the cases in group 1 that meet their performance targets were co-located.

Enterprise Perspective

A few of the cases in group 1 exhibited a unique, and quite 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 difficult to illustrate in a general sense on the framework, but in the cases where it applied, it was noted in their specific variants.

Not all of the cases in group 1 showed this complete enterprise perspective either because they only made a single product which made this impossible, or they just had a more traditional interpretation of the product strategy and didn't look across the enterprise. But the handful of cases where the enterprise perspective was used, it was a powerful tool in guiding the manufacturing system design effort.

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. But the exposure to the design processes where the product strategy extended across an enterprise, or a large portion of an enterprise, led to a change in thinking about the role of the product strategy in the framework.

The role of manufacturing in the design and manufacture of aerospace products has always been debated since manufacturing accounts for a much smaller portion of a total program or product cost than in automotive, or other, industries.[307] But in these cases where the firms had an enterprise perspective of the manufacturing system, the system was designed to be an integral part of their competitive strategy in 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.

7.4 Lessons Learned from the Case Studies

One thing that was gathered from the case studies was a compilation of the lessons learned. As they went through the manufacturing system design process, or looked back on a recently completed design process, many things became obvious that they would try and improve the next time.

One of the lessons learned was from a major aerostructure manufacturer who said that they would try and determine an assembly strategy early in the design phase if they could do it all over again. Rather than determine the overall manufacturing strategy once the detailed design process is moving along rapidly, they wanted a strategy already determined to mature along with the product design rather than always being behind. A similar comment was made by another aerostructure assembly team who said that if they had to do it all over again, they would benchmark assembly processes and not just fabrication processes or specific part manufacture.

Some of the determinants of performance that were outlined in the previous section also emerged in some of the lessons learned. Many of the cases stressed that breadth between the different functions must exist for the system to be able to perform as planned. One person on an aerostructure mentioned that the system must be designed along with the airplane to be effective. An engineer from a new aircraft commented that it would not matter how efficient their manufacturing system could be if they did not end up with a good product design. A manager from a spacecraft producer remarked that while the redesign of their area of responsibility of integration and test impacts 8-10% of a total program cost, if their company wants to see bottom line improvements beyond that, they have to engage product design.

[307] Murman, E.M., Lean Enterprise Value

In addition to the benefits of interactions between the other functions, the role of and the need for a manufacturing strategy and its role within the overall product strategy emerged as a lesson learned. Another spacecraft producer remarked that the same management team for design should be given the responsibility of overseeing production as well. This would make them feel more responsible for designing a producible product. A representative from an electronics company mentioned that the various business functions need to be integrated with manufacturing. Strategies must align meaningful goals trickle down throughout the enterprise and not just create targets for manufacturing operations without considering the unique environment of each manufacturing site or product. Finally, Lockheed Martin mentioned in their application for the Shingo Prize for Excellence in Manufacturing that "a vision without action is dreaming; action without vision is random activity."[308]

7.5 Chapter Summary

This chapter showed the results from the framework validation activity utilizing the framework evaluation tool that captures the phase presence, phase timing and breadth in phase for the case studies that were carried out in industry and described earlier. The framework validation results show that there is a relationship between framework congruence score and the ability of the manufacturing system to meet its planned performance. Only the cases with high framework congruence scores met or beat the planned performance of their manufacturing systems.

This chapter went on to determine the cause of the gap between the two groups that emerged in the data; those that were able to meet their performance in group 1, and those that were not able to meet their planned performance in group 2. The numerical analysis shows that the differences in the breadth in phase scores can explain the statistically significant difference between the two groups.

This statement is supported by observations from the case studies. Observational support of other determinants of performance was also presented. The role of having a manufacturing strategy was outlined, the fact that the cases were split between groups 1 and 2 without a relationship to production volume was shown, the role of the customer and organizational structure as commonalties in group 1 cases were also explored. Finally, lessons learned by the case studies were captured and reported in this chapter.

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[308] Lockheed Martin, *Application for the Shingo Prize for Excellence in Manufacturing*

8.0 Conclusions and Recommendations

Chapter Overview

This chapter summarizes the research and results gained from this research experience. First the conclusions and key characteristics are summarized. Then recommendations for future research are presented and the changes that have occurred to the framework throughout this research experience are mentioned.

8.1 Conclusions and Key Characteristics

The manufacturing system design process proposed by the framework presented earlier was compared against actual manufacturing system design processes observed in a set of case studies. These industrial processes were compared to the proposed process, in terms of which phases of the framework were present, how the phase timing compared and the interaction between functions in each design phase. This comparison was then matched with the performance of the actual manufacturing systems in terms of the ability of the system to produce products with the planned resources. The hypothesis was that an industrial process that matched the proposed framework would be more likely to produce products within the allotted resources. The results show that there is, in fact, a relationship between the congruence of the industrial process to the proposed design process and the ability of the system to produce within the allotted resources. This relationship supports the hypothesis that the process proposed by the framework will result in a more effective manufacturing system. The results also allowed the key characteristics, or determinants of performance, of those cases able to meet their planned performance to be drawn out.

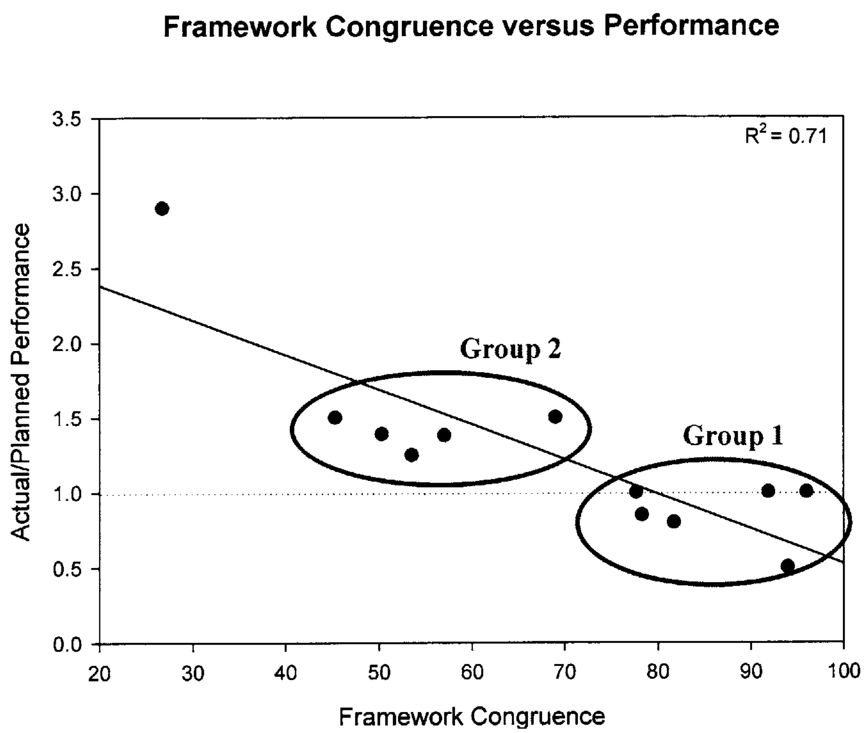

Figure 69: Framework Validation Results

The cases in group 1 were the only cases that were able to produce their products with the planned amount of resources. The key characteristics common to the cases that are in group 1 were derived in detail in Chapter 7. To review, these determinants of performance are:

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

Interaction between the various functions through the design process, breadth in the design phases, was the main determinant of performance. The difference in the breadth portion of the total framework congruence scores was statistically significant and explains the difference in the two main groups. The second determinant of performance, strategy, refers to the existence of a manufacturing strategy that guides the manufacturing system design effort. These strategies were well defined and guided the decision making throughout the design process. This matches closely with the next key characteristic, the status of manufacturing. Common to all the cases in group 1 was the attitude that manufacturing is an element of the competitive skill set of the company. Manufacturing was not treated as a function of lower status than the product design. Organizational structure of the cases in group 1 showed that co-location was another commonality. In all the group 1 cases, engineering and manufacturing were located either in the same building, or at least the same complex of buildings. Co-location can be seen as an enabler of system performance, but not the only requirement, since some cases in group 2 were also co-located. The level of involvement by the customer also impacted the performance of the cases in group 1. In the cases where the customer had an explicit requirement or emphasis on the affordability of the product, the role of manufacturing was elevated and integrated with the product design process. The last determinant of performance was the enterprise level perspective. In only a few of the cases in group 1, the product strategy extended beyond the product that was of interest in the case study and was applied to a family of products. In these cases, the product strategy and the component strategies were applied to all of the programs and products and led to a substantial benefit in terms of system performance in the ability of the company to sustain and propagate the improvements.

8.2 Generalizability of Results

The framework was tested against a set of case studies from different aspects of the aerospace industry, but the data set consisted of only 14 possible manufacturing system design processes. Also the type of manufacturing system design processes executed in the aerospace industry may be different from similar processes in the automotive industry or in the consumer electronics industry, etc. Despite this seemingly narrow view of how the framework was tested, the results are generalizable, not only throughout the aerospace industry, but into other areas of manufacturing as well.

The construction of the framework includes numerous tools and methods that are useful in many different industries. For example, Value Stream Mapping or 3P can be used in a wide variety of environments from aerospace to automotive to operating rooms.

The cases conducted for the research showed the applicability of the framework to help in manufacturing system design processes for either greenfields or brownfields. The selected cases also demonstrated framework applicability for a new product introduction, product re-design or simply a system modification without changing the product. The selected case studies also expanded across different scales. The cases studies focused on a variety of products that range from the shoebox sized TDR-94 to the huge Delta IV booster, or the 737NG commercial jetliner. The selected cases also extended across a range of products that are produced from 8 units a day to perhaps just 1-2 units per year. The cases showed framework applicability to new products and systems like SBIRS-Low and JSF as well as modifications to existing products like the F-16. Disparate portions of the industry including aerostructures, electronics, launch vehicles and spacecraft were used to test the framework.

The applicability of the manufacturing system design framework across the case studies and beyond demonstrates that the principles of systems engineering, which were used to derive the framework, can be effective in design processes in complex environment. These systems principles apply to the domain of manufacturing where they have not been fully utilized before. The power of applying systems thinking to manufacturing systems could possibly extend well beyond the 14 case studies presented in this research.

8.3 Recommendations

This research made progress in proposing and validating a framework for use in complex environments like the aerospace industry to design manufacturing systems. But there is further work to be conducted that would substantiate these results and follow-up on some of the determinants of performance.

Further Research

First of all, the framework validation contained in this research consisted of observations from the sites and a structured interview using the framework evaluation tool. This means that the framework congruence scores were determined by only a single interview. In order to substantiate these framework congruence scores, more interviews should be conducted at each of the case study sites across multiple levels and multiple functions. Ultimately, it would be beneficial to collect data from other industries as well to test the generalizability of the framework to very different manufacturing and business environments. This additional data could help establish the manufacturing system design framework as more of a model of the actual manufacturing system design process.

More specific measures for framework validation would be required in the framework evaluation tool to gather this more wide spread data. More tangible pieces of numerical evidence should be gathered to determine a specific framework congruence score. For example, rather than just inquiring whether manufacturing was an integral member of the design IPT with influence over the design, perhaps future questionnaires could inquire about the frequency of design IPT meetings and the definite areas of responsibility of the different functions contained on the design IPT.

Another area that should continue to be developed is the detailed relationships between manufacturing systems and the "10 Inputs" to the manufacturing system design process that were introduced in Chapter 3. These 10 inputs are defined in the requirements/considerations/constraints phase of the manufacturing system design framework, but the specific relationships between each input and the resulting manufacturing systems is not yet clear. It would be possible to further the development of a manufacturing science if constitutive relations between these 10 inputs and resulting manufacturing systems could be determined. Doing this would then allow a manufacturing system to be defined in terms of market conditions, product characteristics and enterprise strategies.

The framework development also highlights areas where tools may be lacking to help industrial processes with the execution of a particular phase. First, there are not many strategy formulation tools that were found and included in the framework. Second, there is a need for the development of factory models that take into account enterprise strategies.

One last aspect of the framework that could be developed would be to more clearly identify the activities that define each phase and how much of the manufacturing system design and product design should be completed in each phase.

The last recommendation for future research is to follow-up on the case studies that were in the early developmental phases to observe the final results of the manufacturing system design processes. Cases like JSF, Wedgetail, AEHF and TRW's platform architecture are currently in progress and a follow on study could be useful.

Changes to the Framework

Throughout this research project the manufacturing system design framework has been changed only slightly on paper, but substantially in concept. The framework presented in Figure 70 is the original manufacturing system design framework that was originally proposed by Pradeep Fernandes in 2001. This is followed by the framework in Figure 71 that was presented in Chapter 4 and used throughout this research.

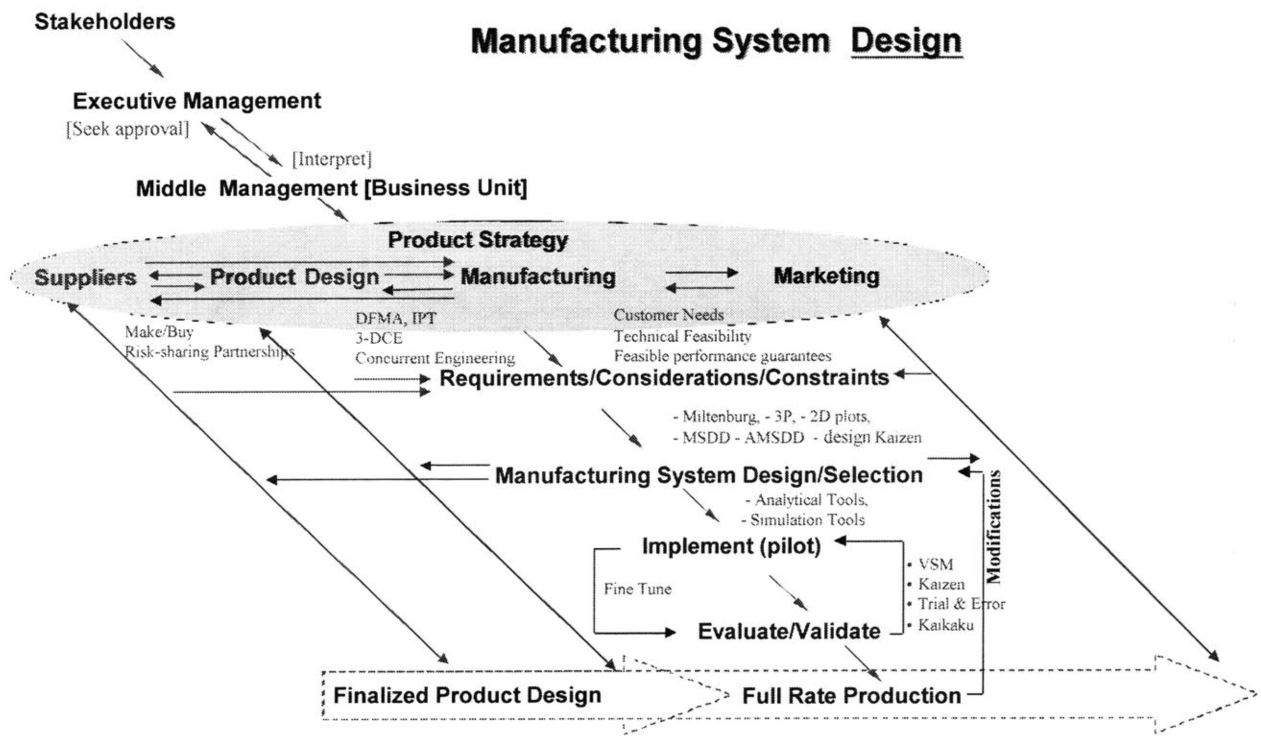

Figure 70: The original version of the Manufacturing System Design Framework[309]

[309] Fernandes, P., *A Framework for A Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor*

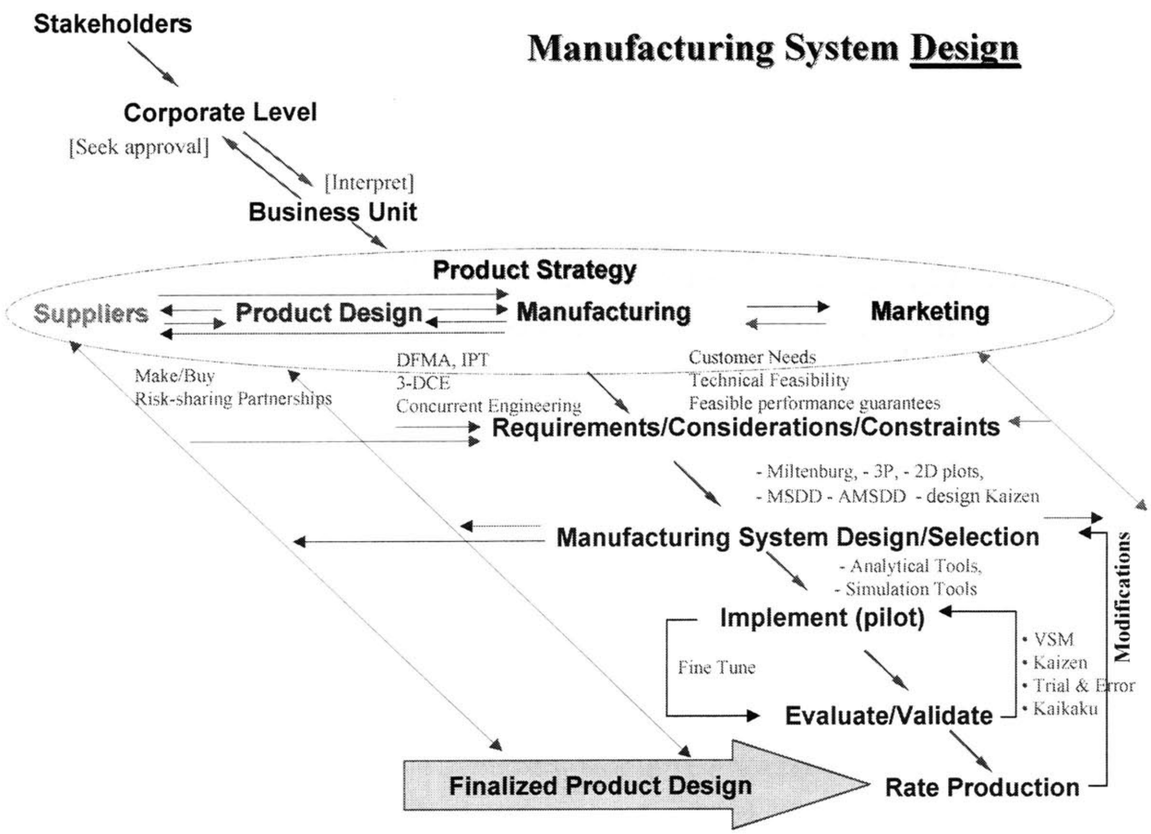

Figure 71: Latest version of the Manufacturing System Design Framework

The first change that was made to the framework was to change the "Full Rate Production" to simply "Rate Production". This seemed more appropriate since, especially in the aerospace industry, programs and products could be a low rate initial production for a long period of time, but this production occurs in the manufacturing system that will take the product up to full rate. Also, products in engineering and manufacturing development phases are produced at low rates, but again, in the planned rate manufacturing system.

The other change made on the framework was the wording in the strategy formulation body. The original framework has the three levels in the strategy formulation body labeled "Stakeholders, Executive Management, Middle Management [Business Unit]". Based upon use of this framework in the case studies and feedback received from various sites, this is changed in the recent version to read "Stakeholders, Corporate Level, Business Unit". This change in labeling made the different levels in the strategy formulation body more understandable and universal.

Perhaps the most drastic change in the manufacturing system design framework is not evident on the framework itself and this is the change in intended scope of the Product Strategy. When the framework was first derived, the product strategy was intended to describe the unified strategy of all the component functions with regards to a single product. Through the course of the more recent research activities, this has changed to become not just the product strategy for a single product but for a family or a collection of products. This is the incorporation of the enterprise level focus that was outlined as a determinant of performance that became evident as more case studies were explored.

An example of this is the 737 Next Generation. In the early versions of this framework, the product strategy for 737NG would include the reorientation of the airplanes on the line and making the final assembly line move. But in the new interpretation of product strategy, this would mean that all commercial airliners will be produced on moving assembly lines while mixing the all the narrow body or all the wide body jets. Another example of this is the product strategy used by Lockheed Martin on the Atlas V. A product strategy from the original framework would have been to try and kit the parts for the Atlas V, use kanban squares and organized, preventative tool replenishment for the new booster. But the enterprise level perspective of the product strategy expands this to include using kanban squares for all the Atlas boosters and sharing the tool replenishment organization across the complete booster family. This is a substantially different view of the same portion of the framework and it is the greatest shift in interpretation this framework has experienced through this research.

Through the initial framework development and this subsequent research, no new classifications of tools were added. Instead, specific examples of tools or methods to enable the execution of each phase were observed. For example, the integrated design tool, DMAPS, that was used on F/A-18 E/F EFF is an example of an analytical and simulation tool.

8.4 Research Summary

The first goal of this research project was to understand current manufacturing system design processes in use in the aerospace industry. This was accomplished through searching the available literature for tools and methods to assist in the manufacturing system design process in addition to both real-time and retrospective case studies to observe actual manufacturing system design processes. The next goal for this project was to propose a model of the manufacturing system design process and test it. The model proposed was the Manufacturing System Design Framework that has been highlighted throughout this thesis. This framework was validated by comparing the actual manufacturing system design processes followed in the case studies to the process proposed by the framework. The final goal of this research was to establish any key characteristics or relationships of the manufacturing system design process that can aide aerospace firms in their manufacturing system design processes. These key characteristics emerged from the framework validation data and revealed that breadth, strategy, status of manufacturing, co-location, customer involvement and an enterprise perspective were commonalties of the effective manufacturing systems.

The main goal of this research was to test the Manufacturing System Design Framework to see if it was an adequate model of the manufacturing system design process. But it was found that the collection of determinants of performance separated the case studies that could produce their products in the allotted resources with those that could not. The research simply aimed to see if the framework was valid and it ended up with a set of determinants of performance that could help a future manufacturing system design process in an aerospace firm.

In summary, the cases that were able to produce their products in the planned resources were the cases that integrated across the different functions to produce a more effective system and a product that could be produced. These cases also treated manufacturing as an element of their competitive skill set and drove the manufacturing function in the same strategic direction as the rest of the company. These cases also co-located the product designers with the manufacturing, or integration, functions and made efforts to involve the customer in the role that manufacturing played in helping to delivery a high quality product on-time and on-budget. Finally, a handful of the cases showed an enterprise level perspective and applied the strategies beyond just a single program or product. These cases are creating a strategically designed manufacturing system and family of products that will help them in future business.

This research did much more than just validate the Manufacturing System Design Framework. This research sheds light on determinants of performance that aerospace firms can use to change how they do business in the future to assist in the realization of the aircraft and spacecraft the will support our nation in the future.

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Appendix A: Research Plan

Manufacturing Systems Team Project

Title: Design of Complex Manufacturing Systems and Verification of Manufacturing Design Framework on Assembly Operations

Motivation: The ultimate goal of this research is to develop a method to design an appropriate manufacturing system for enterprises in the aerospace industry. There are many factors that make this industry unique. We are interested in providing consortium members information about what type of manufacturing system design is possible given their manufacturing environment. Previous research has developed a framework describing the manufacturing system design environment. The purpose of the current project is to test the framework in aerospace assembly operations and contribute to the development of the manufacturing system design guidelines.

Key Questions: The key questions this research addresses are:

- How are manufacturing systems integrated with the overall enterprise strategy?
- What are the requirements/considerations/constraints which most influence manufacturing system design?
- What are the current frameworks or methods used in the design process throughout industry?
- What are the emergent key characteristics for manufacturing system design?

Research Design: This research has three stages. The first stage, now completed, was to understand those influences that affect the design of the manufacturing system. The second stage was the development of a framework for manufacturing system design. This effort was a team effort developed through literature and team ideas. The final stage is to determine the validity of the framework and outline any emergent key characteristics. Various active manufacturing systems currently under development are being treated as case studies. The case studies are being conducted in real time, or retrospectively, across the industry. The sectors included in this research are airframe, electronic and space (satellites and launch vehicles). By studying the design methodologies in use and the comparison to the previously developed framework, we hope to develop guidelines for manufacturing system design.

Staffing: This research will be a team effort among Tim Gutowski, Stan Gershwin and Tom Shields with the assistance of graduate student Mandy Vaughn. Mandy Vaughn will apply the previously developed framework in assembly operations of the aerospace industry. Dr. Stan Gershwin will be the thesis advisor for Mandy Vaughn. Tom Shields will be the designated thesis reader.

Timetable: During academic year 2000-2001 the framework was developed. During academic year 2001-2002 the case studies will be conducted and reported.

Expected Products: The framework was discussed at the Manufacturing Systems Team Meeting February 2001. Verification of framework and manufacturing system design guidelines were presented at March 2002 Plenary Conference.

Appendix B: Case Study Interview Log

Research was carried out at the various case study sites from June 2000 through August 2001. This was followed by a final round of structured interviews using the framework evaluation tool to determine the degree of framework congruence between the manufacturing system design process used at each case study and the process proposed by the framework. This table is a log of all the site visits and interviews conducted through this research.

Table 6: Case Study Interview Log

Site Visited	Date of Visit	# of Interviews Conducted
Preliminary Research Visits		
GEAE Rutland, VT	14-Jun-00	4
Boeing – Seattle, WA (F-22)	17-Jul-00	9
Boeing – Seattle, WA (737NG)	18-Jul-00	14
Northrop Grumman, El Segundo, CA	19-Jul-00	10
Boeing – Huntington Beach, CA	20-Jul-00	8
Boeing – Decatur, AL	25-Jul-00	2
Lockheed Martin – Marietta, GA	26-Jul-00	7
TOTAL	7	**54**
Case Study Visits		
Boeing – St. Louis, MO	21-Sep-00	5
Northrop Grumman – Baltimore, MD	12-Oct-00	7
Northrop Grumman – Baltimore, MD	19-Oct-00	7
Northrop Grumman – Baltimore, MD	16-Nov-00	6
Lockheed Martin – Sunnyvale, CA (A2100)	30-Nov-00	6
Lockheed Martin – Sunnyvale, CA (A2100)	15-Dec-00	5
Lockheed Martin – Sunnyvale, CA (A2100, AEHF)	10-Jan-01	2
Boeing – St. Louis, MO	11/12-Jan-01	18
Boeing – Seattle, WA (F-22)	18-Jan-01	3
Boeing – Seattle, WA (737NG)	19-Jan-01	4
Boeing – Decatur, AL	29-Jan-01	9
Northrop Grumman – Baltimore, MD	5-Feb-01	9
Rockwell Collins – Melbourne, FL	16-Feb-01	3
Boeing – Seattle, WA (F-22)	26-Mar-01	16
Lockheed Martin – Denver, CO	30/31-May-01	12
TRW – Redondo Beach, CA	16/17/18-Jul-01	10
EELV SPO, LA AFB	19-Jul-01	1
Motorola – Chandler, AZ	26-Jul-01	1
Boeing – Decatur, AL	2-Aug-01	8

Lockheed Martin – Fort Worth, TX (F-16, F-22, JSF)	13/14/15/16-Aug-01	31
Lockheed Martin – Sunnyvale, CA	28-Aug-01	2
Boeing – St. Louis, CA	29-Aug-01	7
Boeing – Al Haggerty, Cambridge, MA	13-Sep-01	1
TOTAL	**23**	**173**
Framework Validation Interviews		
Rockwell Collins – Melbourne, FL	6-Nov-01	1
Lockheed Martin – Fort Worth, TX (JSF)	6-Nov-01	1
TRW – Redondo Beach, CA	6-Nov-01	1
Lockheed Martin – Sunnyvale, CA (A2100)	7-Nov-01	1
Motorola – Chandler, AZ	7-Nov-01	1
Boeing – St. Louis, MO	8-Nov-01	1
Lockheed Martin – Fort Worth (F-22)	8-Nov-01	1
Northrop Grumman – Baltimore, MD	9-Nov-01	1
Boeing – Decatur, AL	13-Nov-01	1
Lockheed Martin – Fort Worth, TX (F-16)	13-Nov-01	1
Lockheed Martin – Denver, CO	15-Nov-01	1
Boeing – Seattle, WA (F-22)	19-Dec-01	1
Boeing – Seattle, WA (737NG)	19-Dec-01	1
TOTAL	**--**	**13**
GRAND TOTALS	**30**	**240**

Appendix C: Manufacturing System Design Inputs

This description of the manufacturing system design inputs is from P. Fernandes, *A Framework for A Strategy Driven Manufacturing System Design in an Aerospace Environment – Design Beyond the Factory Floor.*

Extensive literature search was conducted to explore any previous work done in this area. Experience of the team members and result of past LAI research was also used to develop a list of factors that were thought to have influence on manufacturing systems. To solidify this list of factors, 9 different factories from different sectors of aerospace industry were visited and Individuals who had any exposure to manufacturing system design (from decision authority to detailed component level design) were interviewed. The audience included plant managers, manufacturing engineers, industrial engineers, Lean champions, Lean consultants, shop floor managers and shop floor employees. All in all, more than 100 people were interviewed during these visits. The list of all factors obtained from all of the sources above is given in Table 1. The factors listed will be defined and explored further after some initial categorization and elimination. It should be noted that all of the considerations mentioned are listed here to show the number and variety of factors that were discovered. It will be shown later that there are hierarchies and cause and effect relationships in these factors. For example, the "stakeholder satisfaction" effectively represents "corporate strategy" since corporate strategy most often is built to satisfy stakeholders. Similar relationships exist between many of these factors, which will be used to reduce the list to a manageable level.

Table 7: Considerations in Manufacturing System Design

Stakeholder Satisfaction	Product Complexity
Corporate Strategy	Process Capability
Make-buy/Outsourcing Strategy	Type of Organization
New Product Introduction Strategy	Worker Knowledge/skill
Market Uncertainty	Investment
Geopolitical Considerations	Time to first part
Offset Requirements	Affordability/Cost
Environmental/Government Regulations	Customer Price (Target Price)
Product/Program Nature	Product Quality
Product Volume	Resources Available
Product Mix	Existing Resources
Product Design	Performance Goals
Frequency of changes	Management Culture
Payback Period	Product Life Expectancy
	Level of Product Maturity
	Response to change

Even though all of the factors that are mentioned in Table 7 are valid, not all of them affect the manufacturing system design directly. This list of factors can be reduced to a manageable level by retaining only the factors that directly affect manufacturing system design. For example, the offset requirements might change the location of a plant but does not necessarily change the design of the plant itself. Similarly, careful investments and efficient manufacturing processes achieve affordability. The core input is the investment and not affordability. Based on this thinking the above list was reduced to the following factors:

- Market Uncertainty
- Product Volume
- Product Mix
- Frequency of Changes
- Complexity
- Process Capability
- Worker Skill
- Type of organization
- *Time to first part (a constraint)*
- *Investment (a constraint)*
- *Available/Existing Resources (a constraint)*

Market Uncertainty

Market uncertainty is defined here as the demand fluctuations for product including both short-term random variability and long-term step/cyclical variability.

Measure: Demand +/- X per time unit

Market uncertainty is a major concern in aerospace business environment. As discussed in the introductory chapters, both commercial and military branches experience unique patterns of demand fluctuations. Commercial aircraft manufacturers, for example, experience a cyclical demand profile, where the ups and downs can be predicted fairly well. In the military branch, the demand profile can be best described as step-wise stable. The demand is stable for a certain period then drops unexpectedly and remains there for an unexpected period of time. Other sectors within aerospace industry might experience similar fluctuations or variations of these demand profiles. These demand fluctuations are by no means limited to the final product integrators. The suppliers at all levels also experience these fluctuations, sometimes with even larger amplitudes. A manufacturing system should be designed to take these variations into account.

The demand uncertainty affects manufacturing operation by creating over capacity or under capacity in the system. In the case of over capacity, the demand has fallen significantly and the manufacturer is paying for the unused and idle resources. In the case of an under capacity, the manufacturer is unable to supply the market demand causing customer dissatisfaction. In both cases, the corporation's bottom line is being affected adversely. It is always difficult to have the exact capacity needed at all times since the demand itself is uncertain. In aircraft manufacturing, since the manufacturer incurs a charge for late deliveries, the manufacturers might prefer over capacity than under capacity. In military environment, there is a higher chance of budget cuts than budget increases. Hence there is a higher chance of order quantity reductions leading to leaving manufacturers with over capacity.

To cope with uncertain demand, the manufacturers tend to build buffers (inventory) in the system. In the commercial side this can be purchasing material during troughs to lock in low costs. In the military branch where the government pays cost in most of the programs, due to the possibility of budget cuts in the future, the manufacturers buy all materials needed to produce the entire order at once. They hold inventory and start producing products as needed.[310] Therefore, the uncertainty in demand creates the need for buffers in the system

Market uncertainty also affects factory design as far as the worker skill is concerned. Aerospace industry is known for frequent layoffs, which are closely correlated with demand cycles. Frequent layoffs can cause a manufacturer to lose skilled workers. Subsequent hiring to build capacity will require training to build up the lost skill set. The time needed to build the skill might be longer than the available time. The solution to this would be to design a factory that requires the lowest set of skills.

Moreover, the knowledge of market uncertainty affects investment in factory improvement initiatives. The executive interviews also showed that the very possibility of a down turn in demand or budget cuts (military) can create a risk-averse behavior among manufacturers.

Production Volume

The number of products to be manufactured over a time period.

Measure: Total production volume per time unit

Production volume is one of the most important considerations in manufacturing system design. The maximum volume that can be produced determines the plant capacity. In fact, market uncertainty and production volume are tightly coupled. The market demand determines the actual current production volume of the facility, which might not be the maximum volume the facility can output. Since the demand fluctuates over time, having a predetermined maximum volume leads to the facility operating with over capacity or under capacity. The maximum production volume can not be changed quickly without financial expenditure. As mentioned above, operating with both over and under capacity will lead to financial consequences. Therefore, careful analysis should be done prior to selecting a maximum plant capacity. It is also crucial that management is aware of the actual plant capacity so that they may not over sell leading to missed or late deliveries.

Selecting a maximum production volume determines most of the factory physical design. It affects the floor space needed, machine selection, machine layout, factory control system, number of shifts, number of workers, ability to meet or not meet market demand, unit cost and operating cost of the plant. Because of this wide effect of volume on factory design, many researchers in the past have used volume as one of the two factors to describe the entire manufacturing system.

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[310] Wang, A., *Design and Analysis of Production Systems in Aircraft Assembly*

Product Mix

The number of different products to be manufactured.

Measure: Number of different products manufactured

As the definition shows, this factor allows the designer to build in product flexibility or product variety in the manufacturing system. From a market need satisfaction and resource use point of view, it is important that a manufacturing system be able to produce various versions of a product or entirely different products in the same factory. In the aerospace business, especially, there is a possibility that each product could be one of a kind. In this case, it is crucial that the factory be designed to accommodate this level of flexibility.

Product Mix and Production Volume are closely related since having a large product mix would reduce the volume produced per part. These two variables alone can determine the factory design and hence most of the 2-D manufacturing system maps use Volume and variety as the two factors to specify a manufacturing system. For example, if a corporation desires very high product mix and high product volume, the charts show that currently there is no system available that meets this need. On the other hand, a Flexible manufacturing system can provide a high product mix and low volume. Historically, this has been done using departmental layouts where similar processes such as milling, turning, grinding, etc. were organized in one area and all the products that needed these services went through these departments. Lean manufacturing principles advocate product–oriented layouts as compared process-oriented layouts.

It is important that the designers build in product mix flexibility during the design if the corporate strategy includes rapid product introductions. Also, factory life cycles are typically longer than product life cycles and even if new product introductions are not part of the strategy, the factory most likely will see entirely new products introduced in its lifetime.

Frequency of Changes

The anticipated possible set and types of changes that will affect the production facility.

Measure: Number of engineering changes per time period

The changes here refer only to engineering design changes that affect the factory operations. The manufacturing process changes that might occur without engineering changes will be dealt with later. It should also be noted that there is possibility that an engineering change might not affect the factory floor. A software change in avionics suite would be an example of this type of change.

It is impossible to foresee all the changes that might be introduced to the product in the future. To make that happen the system will have to be infinitely flexible and the designers will have to make tradeoffs in other areas. One can, however, anticipate certain types and sets of changes based on past experience and the product maturity. Changes can be grouped by types such as software related, structure related, assembly sequence related, etc. Likewise, within these types, a decision can be made towards the extent of change that should be anticipated and designed in. It should be stressed that these changes are only anticipated and they might not materialize. Thus, having this flexibility might not necessarily enhance the system performance (in terms of response time) but it surely will not worsen it. Since there is some monetary costs involved in designing flexibility in the system, care should be taken deciding on the level of flexibility to accommodate. Note that the frequency of changes is also important. The effect on system performance will be minimal if there were only a couple of changes over a period of a year compared to couple of changes introduced every week.

Frequent design changes are a common characteristic of both commercial and defense sectors of the aerospace industry. In the commercial arena, this can happen in two different ways. First, the design changes can occur due to, the more common, lack of design/product maturity. Second, the changes might be an effect of the corporate strategy. Some aircraft manufacturers have a strategy to offer fully customized aircraft to their customers to increase customer satisfaction. This is an example of the direct effect of corporate strategy on manufacturing. While these customizations mostly affect the interior of the aircraft and might not require major design changes, they do introduce constant variations in the manufacturing process and require the system to be able handle this disturbance smoothly. In the military sector, the changes can be introduced by the manufacturer for various reasons or required by the customer. These changes can be major design changes. As the customer realizes the needs for better performance, maintenance or uses for the aircraft, the manufacturer will be required to make the necessary changes to the aircraft. The changes can be structural or upgrades to existing systems and can occur as the aircraft is being manufactured. Traditionally, aircraft manufacturers have dealt with this variability by introducing the changes in blocks. That is, all the changes will be catalogued and introduced at the next block (a certain number of aircraft) of aircraft deliveries. The system nature of manufacturing operation is evident here where both corporate strategy and engineering divisions have strong influences on manufacturing performance and operation.

Complexity

Measures: Number of parts, number of process steps, size of the CAD file needed to describe the part, size of the part, time needed to finish the task efficiently, number of subsystems involved, etc.

The word complexity mainly is used to describe the level of difficulty associated with fabricating or assembling a part. Complexity is a difficult subject to describe in a manufacturing context since it can represent the product complexity, fabrication process complexity, assembly complexity, the complexity of the entire manufacturing system itself, and a combination of the above. Therefore, a definition is not provided here for this factor. Here, the effect of a complex product or part on the manufacturing system design is described. After much discussion, it was agreed that the level of complexity is affected by the available process capability (here capability is used in the sense of being able fabricate a part of given specifications). That is, if the part or product to be fabricated or assembled is perceived to be complex by human standards and if a machine is available to perform the task, then as far as the human effort is concerned, the complexity of the operation is reduced significantly. Therefore, the complexity of the manufacturing system as a whole depends on the available process capability.

The complexity of the manufacturing system design task can be understood at two levels. One can think of complexity in terms of the operations performed on a part between any two points (or processes) in a factory. This can be called the delta complexity. When a part comes to a work area (it might be worked on before or it could be a raw material), what matters the most as far as the system design is concerned are the operations that will be performed between these two points. The designers will have to design machines, process steps and verification methods for the operation needed in this area. If certain process technology, say a five axis milling machine, is not available, then the process design exercise itself becomes a complex effort. This is because the designers will have to invent methods to manufacture the complex product some how (if product design change is not an option). The second way is to abstract delta complexity idea to the entire factory level. That is, to consider number and types of operations needed to manufacture the whole part or product from its entry in to and the exit from the factory. Designers have to design the entire system to perform all the needed operations on the part or product. If the product is complex and appropriate process technology is not available, the product most probably will be decomposed to a manageable level of complexity where the existing process can be used. A very high level of decomposition requires more subsystems, process steps, workers, machines, inspections, assembly steps and a robust control system, which leads to a complex manufacturing system and a complicated manufacturing system design effort.

It can be concluded that the complexity of the product itself increases the complexity of the manufacturing system design effort if appropriate process capability (or process technology) is not available, which in turn increases the complexity of the system itself.

Process Capability

Generalized technological ability to repeatedly make something with minimal intervention.

Measure: First time yield rate and/or Rework rate

This factor describes the quality of the manufacturing processes seen by the company itself. A low process capability would mean high rate of scrap or rework depending on the manufacturing stage. This variable does not explicitly describe the external product quality – the quality seen by the customer. Since rework is allowed, it is assumed that the desired external quality is delivered at the expense of scrap and rework. Therefore, high process capability would achieve a desired external quality at a much lower cost to the company. The process capability is affected by machine process capability, worker skill level, and the capability of the fabrication process (casting, forming, etc.).

Tight tolerances and complex geometry are typical characteristics of aerospace products. The factory floor processes have to be designed to produce these products repeatedly. At the component fabrication level, the process capability refers to machine's capability to repeatedly produce a part to the exact specifications. If the part has a complex geometry, process capability refers to the ability of the machine or group of machines to fabricate the required geometry. Any non-conformance at this stage would most probably result in scrap. At the assembly stage, a low process capability would indicate gaps, mismatched holes, part deformities, etc. Almost all of the cases will result in rework. Due to the size of aerospace products, the process capability at the assembly stage tends to be low. Especially in airframe manufacture, the aluminum components tend to expand and contract depending on the factory temperature, making it difficult to align predrilled holes and body frame edges. These situations are typically remedied using shims or various types.

Process capability and system complexity are closely related. As discussed above, the complexity of the system increases if the process technology to fabricate a complex product/part does not exist since the system has to be designed to fabricate this part in multiple steps. Having the process technology such as the five axis milling machine, for example, will reduce scrap, and the number of machines, operations, workers and time needed to perform the operation. In electronic fabrication, for example, the complexity can often be measured by the size of the part. The smaller the chip, the more difficult it is to fabricate it perfectly every time. However, if a machine is available which can fabricate this part to the required quality then that particular chip does not add to the complexity of the system. The machine itself might be complex but that does not make the system complex. Therefore, availability of capable process technology can greatly reduce the complexity of a manufacturing system.

The existence of the above challenges requires considerations at the manufacturing system design stage to compensate for them. Process capability is the factor that needs to be well understood so that appropriate processes and remedies for non-conformance can be developed.

Type of Organization

This factor describes the level of innovativeness supported on the factory floor.

The lean manufacturing initiatives have shown the benefits and needs of using employee's knowledge to continuously improve machines, processes, and the overall work procedures in general. Since most of the companies are investing lean initiatives and encouraging employee participation in process improvements, it can be assumed that the future workforce will be more empowered to making improvement suggestions than the current workforce. The manufacturing system should be designed to take this into account. Just as the frequency of changes factor discussed earlier dealt with engineering changes that affected the factory floor, this factor deals with the process changes that affect the factory floor. A highly innovative workforce, one that strives to improve the work environment continuously will introduce changes on the factory floor frequently. Machines, layouts and level of automation should be chosen carefully since many changes can be expected in a highly innovative work environment. The designers will have to considering the level of employee innovativeness and failure tolerance of management during job design. A risk-averse management would prefer freezing the design and not allowing the employees to tinker with the process and a risk-positive management would prefer a very flexible system that accepts changes continuously.

Worker Skill Level

Overall skill level of both factory management and hourly workforce available to the factory

Measure: Skill level available in the geographic area

The available employee skill level determines the level of detail necessary in work statements, type of system, quality of the work performed (scrap rate) and the level of automation. Certain manufacturing systems such as a job shop or a craft production system requires a very high skill level compared to a transfer line, which hardly requires any human skills. It can be seen that if the system requires a high level of skill level, the system itself is relatively simple (craft production system). On the other hand, if the required skill is low, the system itself becomes a complex system (transfer line, FMS) The best example of utilizing a very low skill level to produce a complex product is Henry Ford's assembly line. Ford and his engineers designed the factory to make use of the low skill level (hence, cheap labor) by inventing the assembly line, which in itself was a complex system in those days. Therefore, the available skill level also determines the level of automation. The transfer line was a successor of the assembly line. The main point being made here is that the skill level is a very important determinant of the characteristics of a system. These characteristics can be the required real estate, process capability of the machines, number of supervisors, number of inspections and the inclusion of robotics and computers.

Investment

Amount of financial resources required for the manufacturing system design activity, floor space, personnel training and all equipment required for the operation of the factory.

Measure: Dollar amount spent

Investment is treated as a constraint in the manufacturing system design process. It is assumed that this factor limits the choices available to the designer based on cost of implementation, payback period and time needed for the system development. It should be noted that this is the investment for the manufacturing system design and not the product design. Figure 14, below, shows the effect of this constraint combined with the time needed to implement the system. The green blocks are various designs requiring different investment and time. The investment constraint filters out any designs outside the feasible region. There might be some negotiation to adjust the constraint boundaries.

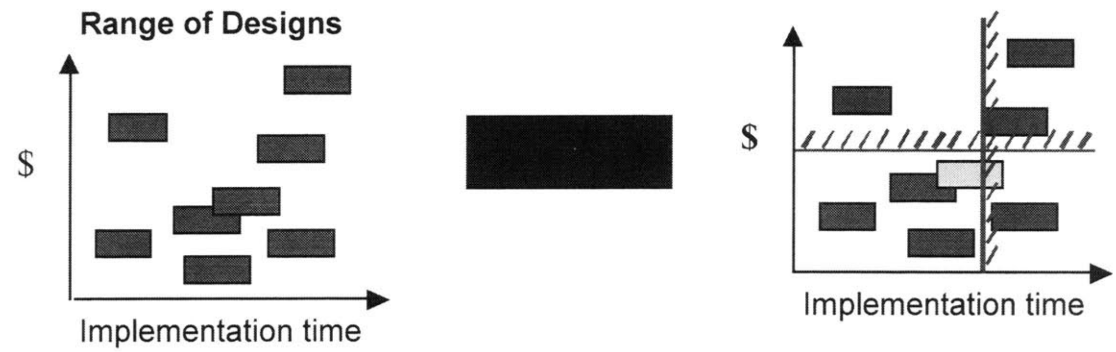

Figure 72: Schematic of Investment versus Time and Feasible Design Regions

This is the factor that indirectly represents affordability and lifetime cost of the product. Since manufacturing cost includes the capital investment that went into building the capability, the product price will reflect a part of this investment. Moreover, the way the factory is designed to operate directly affects the actual cost of the product. Thus, the initial investment and operating procedures have a strong effect of product affordability and the life time cost of the product.

Time to first part

Length of time allotted from start of manufacturing system design to the full rate production of the first part.

Measure: Time required from initial system design efforts reaching full rate production

This is the second major constraint on the system design process. As can be seen in Figure 16, this filter eliminates any designs that take longer to implement than some acceptable time period. It is often difficult to determine the implementation time and time to reach full rate production at design stage for manufacturing systems. The decision typically is based on experience. The design that is chosen is not guaranteed to be fully operational when the market demand is high. Traditionally, the plant at the current state is used to meet market demand and simultaneously brought up to full rate. Nevertheless, time needed to have the desired full rate capability is an important factor in the design process.

Available/Existing Resources

The available resources are a very broad category, which simply describes what resources (financial, technological, human skill level, time etc.) are available to the designers. The existing resources are the resources already purchased prior to the design, the designers did not have a say in the purchase of these factors. This typically affects the most in a brownfield environment where the existing system resources such as the machines, factory control system, fabrication processes, people and culture are the remnants of the past system. While these are resources from a financial point of view, they typically are constraints to the design effort since the system will have to be designed to accommodate these items. These can significantly restrict a designer's freedom and hence the performance of the new system.

Appendix D: Framework Evaluation Tool

The validation activity of the Manufacturing System Design Framework led to the creation of the framework evaluation tool. This tool was developed to structure the process of determining how closely the manufacturing system design process proposed by the framework matched the processes used in the case studies. How closely the two processes matched became the "framework congruence" value (also affectionately known as "waterfallness" and "niagratude" to the research team members). Since the use of this tool provided a structured guide for conducting the interview, it helps battle the possibility of bias introduced by the interviewer. This tool ensured that the same questions and scoring criteria were used for each site.

It was mentioned in the description of the research design in Chapter 5, but it is important to emphasize again – this tool was developed to evaluate the framework. This tool aimed to compare the process in the Manufacturing System Design Framework with processes used in the real world to determine the validity of the framework. This is not an evaluation of the processes used by the case studies.

D.1 Framework Evaluation Tool Development

Through the early stages of developing the evaluation tool, it was determined that there were three main things to capture. These were:

- Phase Presence
- Timing of Phase
- Breadth in Phase

Phase presence is determining whether or not each phase on the Manufacturing System Design Framework was present in the actual process used by the case study. The next element was that if the phase was present, to determine what the timing of the phase was. Did it match the timing proposed by the framework or was it different? Finally, the interaction between the other functional areas during the execution of that phase, the breadth, was to be captured.

Detailed tool development was structured by going through each phase of the framework and determining a way to capture each of these three items for that phase. This led to the general structure of the tool. The tool first asks general questions to determine the context of the manufacturing system design process. Then the tool goes through each phase of the framework and follows roughly the same form. Each phase starts with a general question that can determine phase presence. This was then followed by additional more specific questions that would help an interviewee if they had difficulties on the more general question and would also determine how explicitly the phase was present. If the phase was present, it would be followed by a question that would determine the timing of the phase, then another exploring the involvement between different functional areas to determine the breadth in the execution of the phase.

D.2 Data Collection for the Evaluation Tool

During the development of the evaluation tool, it was decided to perform the initial round of interviews at the Business Unit level of the framework. This allowed a complete set of data to be obtained quickly. Each interview in this initial round would be conducted with people that had the same perspective of the manufacturing system design process. It is desirable to follow this research effort with additional data collection with this, or a similar, tool with people from multiple levels and multiple functions in the organization. But this more in-depth data collection is beyond the scope of this study.

D.3 The Framework Evaluation Tool

This is the complete Framework Evaluation Tool. Each section is a phase on the framework, followed by questions to determine phase presence, timing and breadth. The numbers in parentheses at the end of the line are the scores for each possible answer.

System Status
- Are you going through a system design or re-design process currently?
- If the system is being re-designed, why? What is (or was) the impetus for change?

Strategy Formulation Body
- Do you have a corporate strategy with regards to this product?
    - What is the corporate strategy?

Product Strategy
- Do you have a manufacturing strategy?
    - Does the manufacturing strategy fit into the corporate strategy?
    - Phase presence:
        - How well does the manufacturing strategy fit in with the corporate strategy (the enterprise, other products)?
            - Strategy fits really well (5)
            - Strategy kind of fits (3)
            - Doesn't fit (0)
    - Breadth:
        - What functions were represented on the design team?
            - Manufacturing engineering? (1)
                - Were they happy with the outcome? (1)
                - Did they have veto power over the design? (1)
            - Tooling? (1)
                - Were they happy with the outcome? (1)
                - Did they have veto power over the design? (1)
            - Production operations? (1)
                - Were they happy with the outcome? (1)
                - Did they have veto power over the design? (1)
            - Suppliers (or their representatives?) (1)
                - Were they happy with the outcome? (1)
                - Did they have veto power over the design? (1)

        - Program management? (1)
            - Were they happy with the outcome? (1)
            - Did they have veto power over the design? (1)
    - Timing:
        - When did you integrate with suppliers?
            - Before having direction from the business unit (4)
            - Concept development (3)
            - During preliminary design (2)
            - After preliminary design (1)
    - When did you integrate with manufacturing?
            - Before having direction from the business unit (4)
            - Concept development (3)
            - During preliminary design (2)
            - After preliminary design (1)

<u>Requirements/Considerations/Constraints</u>

- What was important to your manufacturing system design? What were your requirements, considerations and constraints?
    - Did you think about:
        - Production volume?
        - Mixing this product with other products?
        - How you would incorporate changes to the product?
        - Complexity of the product?
        - Capability of the system and its processes?
        - Type of organization?
        - Skill level available?
        - The amount of time you had to get the system up and running?
        - Available investment for the system?

    - Phase presence:
        - (almost)All of the inputs were considered (5)
        - Approx. half of the inputs were considered (4)
        - 2-3 of the inputs were considered (3)
        - 1-2 of the inputs were considered (2)
        - None of the inputs was considered (0)
    - Timing:
        - You mentioned ____ as being important to the system design – when did you consider _____?
            - All considered before selecting/designing the manufacturing system (5)
            - Most considered before selecting/designing the manufacturing system (4)
            - A few (2-3) considered before selecting/designing the manufacturing system (3)
            - 1-2 things drive the design effort and were considered before selecting/designing the manufacturing system. (2)

        - None of the considerations were thought of before selecting/designing the manufacturing system (0)
- Breadth:
    - Did they engage other functional areas of the organization while determining the requirements, considerations and constraints? (Did they exercise the different levers of the organization in this process? Miltenburg)
        - Human Resources
        - Suppliers
        - Production planning and control
        - Manufacturing
        - Facilities
        - Engineering
            - All 6 levers (5)
            - 4-5 levers (4)
            - 2-3 levers (3)
            - Only 1 lever (2)
            - None (0)

- What was the goal of the manufacturing system design? (Some examples: on time delivery, Flexibility, Cost reduction, Lead time reduction, Reduced part travel, Ergonomic improvements)
    - Timing:
        - When were these goals determined?
            - Before selecting/designing the manufacturing system (5)
            - After selecting/designing the manufacturing system (0)

<u>Manufacturing System Design/Selection</u>

- What did you use to assist in the manufacturing system design?
    - Did you use:
        - Frameworks (like Miltenburg)?
        - Maps (like Black)?
        - Cooperative decision making (like 3P)?
        - Simulation tools?

    - Phase presence:
        - Follow an established, structured process (5)
        - Had some guidelines to help the process (3)
        - No process at all – just picked a solution (0)
    - Timing:
        - You mentioned you used _____ to help with the design of the manufacturing system. When did you utilize this tool?
        - After all the requirements had been defined (5)
        - Repeatedly as the requirements were becoming more defined (5)
        - Jumped to a conclusion and just used this as a check (3)
        - No tools were used (0)
    - Breadth:

    - How mature was the product design when you began to design your manufacturing system?
        - Mature (>90% design complete) (1)
        - Nearly complete (approx. 80% of design complete) (2)
        - Halfway there! (approx. 50% of design complete) (3)
        - Still early in the design phase (about 30% of design complete) (4)
        - Very early in the design phase (5)
- How was the interaction between the suppliers and the system considered?
    - Did you think about:
        - Synchronization with suppliers? (1)
        - Point-of-use delivery? (1)
        - Parts presentation to the floor? (1)
        - Order mechanism? (1)
        - Shipping containers? (1)

Implement (pilot)/Evaluation

- What did you do to try out your manufacturing system design concepts?
    - Did you use:
        - Mock-ups?
        - Moonshine shop?
        - Pathfinders?
        - Rapid prototyping?
        - Simulations?

    - Phase Presence:
        - Extensive piloting was done (5)
        - Some type of piloting was done (3)
        - No piloting was done (0)
    - Timing:
        - You mentioned you used _____, when did you use ____?
            - Pilots were used early in the selection process to test out some different concepts for the resulting system design. (2)
            - Subsequent to the system design selection decision to aid in details process layout. (2)
            - Piloting only occurred after the low rate production had started to tweak the system on the floor. (1)
            - Piloting was not a part of the manufacturing system design process (0)
    - Timing (follow up):
        - The pilot programs were used closer to the product design phase. (3)
        - The pilot programs were used closer to the rate production phase. (1)
    - Breadth:
        - Did the process development work feedback into the product design?
            - Certainly – the two were linked (5)
            - Only for really major issues (4)
            - Once or twice (2)
            - No – the processes were made to fit the design (0)

<u>Modification</u>

- When you are at rate production (of any rate!) how do you foster continuous improvement? What process (if any) do you use?
    - Kaizen events?
    - 3P?
    - 5S?
    - Value stream mapping?
    - 6 sigma?

    - Phase presence:
        - Continuous improvement is an integral part of the work on the manufacturing system (5)
        - Continuous improvement is fairly common through the system (4)
        - Continuous improvement occurs sporadically through the system (2)
        - Continuous improvement doesn't really occur (0)
    - Timing:
        - Continuous improvement occurs (at least) during rate production (5)
        - Continuous improvement does not occur during rate production (0)
    - Breadth:
        - Who participates in the improvement activities?
            - Manufacturing engineering? (1)
                - Do they contribute? (1)
            - Tooling? (1)
                - Do they contribute? (1)
            - Production Operations? (1)
                - Do they contribute? (1)
            - Suppliers? (1)
                - Do they contribute? (1)
            - Program management (1)
                - Do they contribute? (1)
    - What are your objectives for improvement events?
        - High level – revisit overall goals of the system (5)
        - Low level – go after the low hanging fruit on the floor (1)
    - Are their improvement efforts conducted in other functional areas?
        - Engineering?
        - Suppliers?
        - Contracting?
            - Improvement efforts span all other functions beyond the factory floor. (5)
            - Improvement efforts occur in some other functions beyond the factory floor (3)
            - Improvement efforts only occur on the factory floor (0)

D.4 Scoring

To score the results from the tool, simply go through each section (one section corresponds to one phase on the framework) and total up the points. This following list outlines the break down of points for each section and then for each goal of determining phase presence, timing and breadth:

Detailed Scoring (Maximums):

- Product Strategy (28)
- Requirements/Considerations/Constraints (20)
- Manufacturing System Design/Selection (20)
- Implement/Evaluate (15)
- Modification (30)

After determining a score for each section, the product strategy, implement/evaluate and modification section scores must be normalized. This was done to give each section a total of 20 points and balanced the scoring between each section. Since this is the first validation activity for this framework, it was decided to make every section equal weight. Also, since this was the first use of this tool without any *a priori* notion of one phase being more important than another, all the phases were given equal weight of a maximum of 20 points for a maximum total score of 100.

The total framework congruence value is found totaling the sections normalized to a 20 point maximum:

*(Product Strategy Raw Score / 28) * 20 = Product Strategy Section Score*
*(Implement Raw Score / 15) * 20 = Implement Section Score*
*(Modification Loop Raw Score / 30) *20 = Modification Loop Section Score*

Total Framework Congruence Value = Sum of all Section Scores

The construction of the tool also allows the individual scores of phase presence, timing and breadth to be brought out and normalized individually.

3231- 52