A HOLISTIC APPROACH TO MANUFACTURING SYSTEM DESIGN IN THE DEFENSE AEROSPACE INDUSTRY

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Keywords: *manufacturing system design, systems engineering, production systems, lean manufacturing, assembly operations, system integration*

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. 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 paper outlines the generation and validation of a framework to guide this manufacturing system design process.

1 Introduction

The aerospace industry can justifiably be proud of its many accomplishments in both the commercial and military sectors. Yet, the environment and the industry itself are changing.

The aerospace industry customers are demanding specific capabilities rather than specific platforms and in the post cold war era cost and affordability are more prominent. It is not now the heyday of the industry where innovative ideas sparked a new company and major air vehicle technology jumps occurred in rapid succession. Now the industry is more mature, it has recognized design solutions in a number of areas. Sure there is rapid technology insertion for electronic equipment and information fusion that keeps the industry vital and exciting. However, the rate of major product technology innovation is slowing.

This general phenomena was observed by Abernathy and Utterback [1] whose model states that the rate of product (industry, product or product class) innovation and process (means by which products are produced) innovation vary over the history of an industry. At some point the rate of process innovation overtakes the rate of product innovation (called the dominant design by Utterback). At this point there are generally accepted solutions by customers that win marketplace allegiance and to which competitors must now conform. It is also the point where production processes, equipment, materials and the plants themselves experience rapid changes as the designs become more stable and competition shifts more to cost.

We argue that in many ways the aerospace industry has reached this point. We see generally accepted airliner and tactical aircraft designs. Certainly there are many areas of product innovation still in progress but major platform designs change little in a gross sense. Where this is true, process innovation should have emphasis over product innovation.

However, we see a lag to this realization in the aerospace industry. Many companies view themselves as entities with core competencies in design or system integration. Manufacturing and manufacturing strategy does not play as significant a role as the engineering function or platform strategy. The result is that heritage equipment, facilities and mindsets drive the manufacturing system design. The industry has matured and the customers are demanding affordability. These two dynamics demand a change in outlook.

Using Utterback's analysis the product design alone is less of a discriminating factor for competitive success therefore design efforts should ensure producibility and manufacturing inputs should carry more weight. In more mature technologies, process technology development yields the most benefits. Therefore there should be some process for continual introduction of new processing capabilities and organizational elements to champion process developments.

We propose a holistic manufacturing system design framework that will ensure that these considerations are integral in the product development process.

2 Manufacturing System Design 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. [2] 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.

The following figure is the Manufacturing System Design Framework. [For more information on the development of this framework, please see reference 3.]

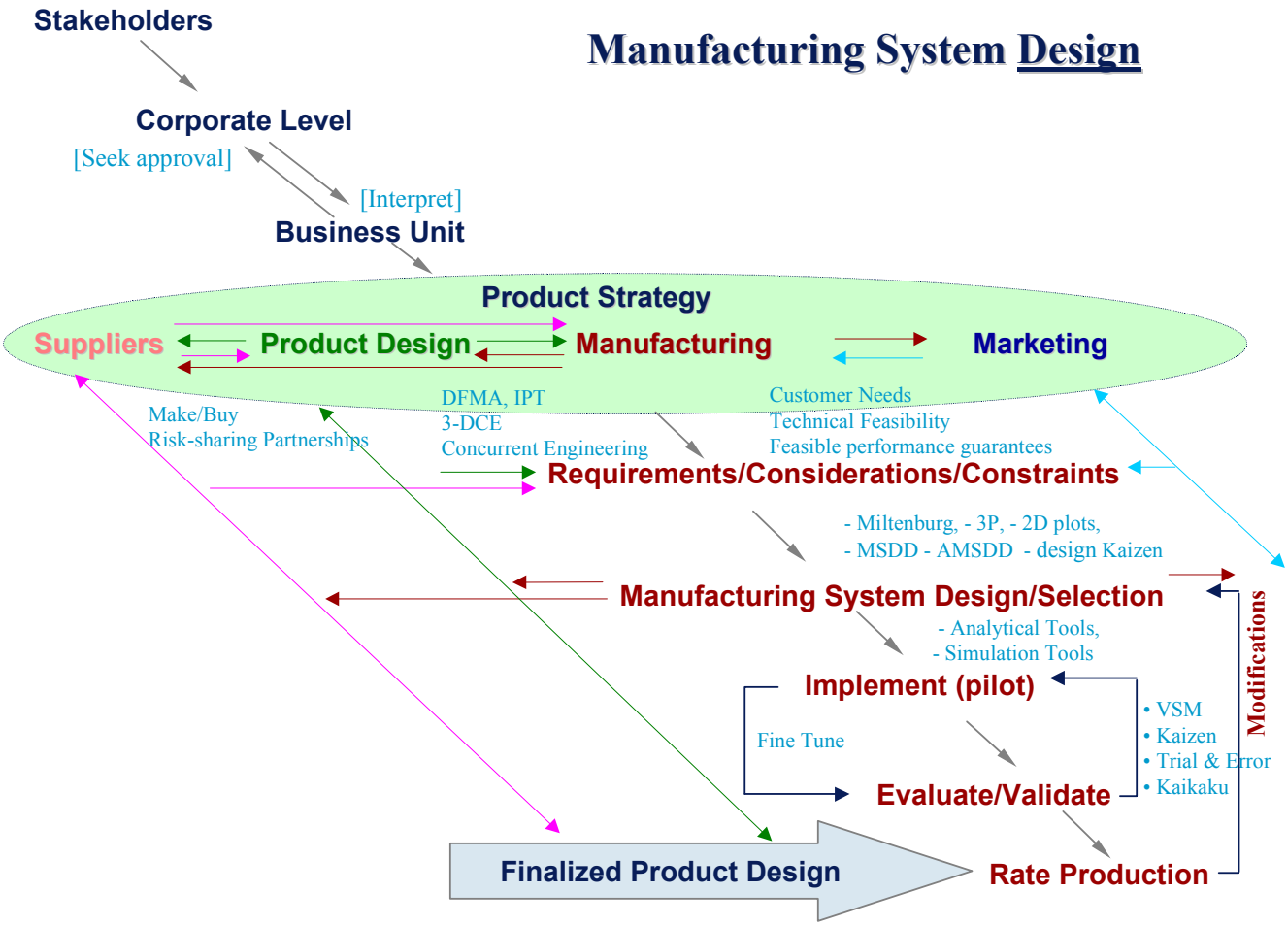

Figure 1: Manufacturing System Design Framework [4, Used with permission.]

2.1 Framework Description

The framework is comprised of a series of phases which represent the major design activities through the complete manufacturing system design process. This section steps through each phase of the framework.

2.2.1 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. [5] 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. [6, 7]

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 out 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.

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-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. [8] The product strategy is an attempt to address the importance of these interactions.

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. [9]

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. [2] This leads to the design of the manufacturing structure.

2.2.2 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 the “Requirements” phase. 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. [5]

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

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.

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.

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.

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.

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. [10]

2.3 Key Insights from the Framework

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 experience and previous research so the remainder of this research attempts to validate the framework.

3 Research Design

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.

3.1 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.

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. [3] 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.

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.

3.2 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.

3.3 Performance Metric

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.

4 Data Analysis

Following the data collection, the framework congruence scores were compared with the actual/planned performance measure to see if there was a relationship between the two. In addition to the framework validation analysis, similarities and differences between different groups that emerged were determined.

4.1 Framework Validation

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.

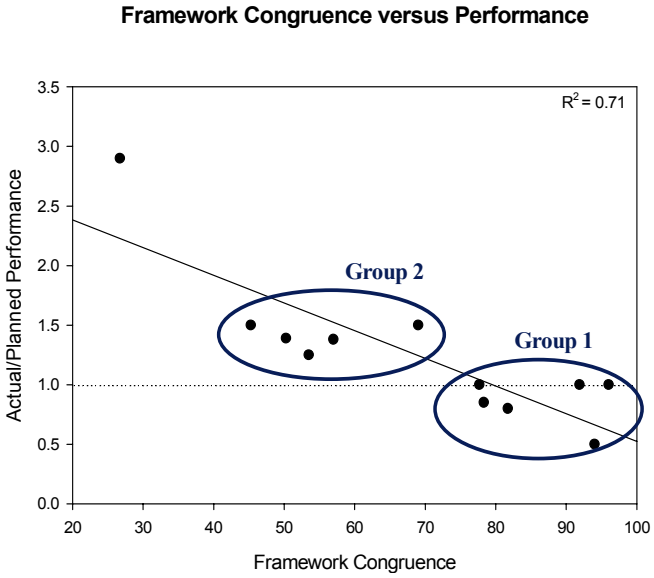

Figure 2: Framework congruence versus performance [4, Used with permission]

The original data did more than just show a relationship between following a process like the framework outlines and system performance. Just from looking at the data there appeared to be 2 different groups which are marked on the graph in Figure 2.

An independent t-test performed and showed the difference between the groups is statistically significant at a confidence level of 95%. This difference allowed us to look at these groups to try and determine why there was a difference.

4.2 Determinants of Performance

In addition to the breadth issue found in the numerical analysis, qualitative reviews of the cases in each group led to the discovery of a set of commonalties in the cases making up group 1. This section outlines each determinant of performance that was observed.

4.2.1 Functional Breadth in Phase

The numerical analysis of breadth in phase being a difference between the cases in group 1 versus the cases in group 1 can be supported by observations made at the case study sites. Only the breadth portion of the total framework congruence score remained statistically significant.

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.

4.2.2 Strategy Presence

The determinant 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.

4.2.3 Production Volume Independence

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. It was the quality of the manufacturing system design that had the most impact on system performance.

4.2.4 Customer Involvement

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.

4.2.5 Organizational Structure

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.

4.2.6 Enterprise Perspective

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.

5 Conclusions

With the maturity of the aerospace industry and a customer focus on affordability, competitive advantage can be achieved with an emphasis on excellence in manufacturing. Yet, manufacturing strategy is either absent or subservient to platform strategies.

To link manufacturing strategy to enterprise strategy and help in the actual design of the manufacturing operation, the Lean Aerospace Initiative developed a Manufacturing System Design Framework. This research aimed to validate this framework but it did more. It identified a number of key determinants for a successful holistic manufacturing system design.

Most counterintuitive among the findings was that manufacturing system performance was more closely related to how the system was designed than to production volume. In many executive offices lack of product volume or rate serves as an excuse to accept high manufacturing costs. What this research showed was that a focus on an effective manufacturing system design that integrated needs across a broad functional base was the most important contributor to system performance success independent of volume. Therefore, the low volumes experienced in the aerospace industry should not justify a production penalty just because of low numbers of products ordered.

For enterprise success aerospace products must be affordable, conform to the highest quality standards, perform as or better than envisioned, and be produced on time. In addition, the enterprise must be flexible to support not only system upgrades but flexible in terms of volume and product variety. The manufacturing system must meet each of these requirements. It can only do this if the manufacturing strategy is a key player in the enterprise strategy (particularly so in those cases where the technology is mature). For manufacturing to be successful it must have coequal status with other functions such as engineering and procurement. As this research shows the best results are realized by interacting with engineering, suppliers and marketing at *all* stages of the manufacturing system design.

Finally, this research has broadened our perspective as well. We have seen that an enterprise approach considering all products or product lines in the manufacturing system design yields higher performing manufacturing systems.

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