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CHALLENGES IN THE BETTER, FASTER, CHEAPER ERA OF AERONAUTICAL DESIGN, ENGINEERING AND MANUFACTURING

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Abstract

"Better, Faster, Cheaper" (BFC) emerged in the 1990s as a new paradigm for aerospace products. In this paper, we examine some of the underlying reasons for BFC and offer some thoughts to help frame the thinking and action of aerospace industry professionals in this new era. Examination of literature on industrial innovation indicates that aeronautical products have evolved to a "dominant design" and entered the "specific phase" of their product life cycle. Innovation in this phase centers on: incremental product improvement, especially for productivity and quality; process technology; technological innovations that offer superior substitutes. The first two of these are aligned with BFC objectives.

The concepts of "value" and "best lifecycle value" are introduced as conceptual frameworks. Value is offered as a metric for BFC. Risk management is intimately tied to achieving value and needs to be integrated into aeronautical processes. The process technology area is addressed by considering "lean" practices for design, engineering and manufacturing. Illustrative results of process improvements from the seven-year Lean Aerospace Initiative research program at MIT indicate opportunities to achieve BFC. Concluding remarks offer some challenges to industry, government and academics in aeronautical design, engineering and manufacturing.

1 Introduction

Starting in the 1990s, the aerospace field was challenged to produce products and systems Better, Faster, Cheaper. This new paradigm is a considerable change from the mantra of Higher, Faster, Farther that had been the driving force behind aerospace products and systems for many years. What are the reasons for this changing paradigm? Is it a short term fad or a systemic change? How can aerospace engineers adjust their thinking and actions to respond to this challenge? What actions should industry, academia and government take to address the Better, Faster, Cheaper challenge for aeronautical engineering?

In this paper, we will examine some underlying reasons for this change and offer some thoughts to help frame the thinking and action of aeronautical engineers in this new era. Our views are based upon a decade of strategic thinking and action at MIT and more particularly upon a research project called the Lean Aerospace Initiative (LAI) that has been underway at MIT for seven years.

2 Better, Faster, Cheaper

The 1990s opened with the end of the Cold War, a 45-year period of history characterized by technologically sophisticated superpowers dominating the world's geopolitical forces. By the 1990s, most active aerospace professionals had been educated and had practiced their profession during the Cold War years. Sustained government investments were made in aerospace research, development and technology to assure that the technological capability of the country was superior to the enemy's capability. These investments had impact on both military systems and commercial products. The resulting achievements of aerospace engineers were truly remarkable: e.g. jet propulsion, supersonic flight, one-day commercial air service anywhere on the globe, instantaneous global communications and surveillance, human space travel and return to earth, deep space exploration, and on and on.

By and large, the dominant emphasis during the Cold War was on the performance of systems rather than on time or cost to develop and sustain the systems. By the 1990s, metrics related to cost and schedule of aerospace systems were troubling. With an industry facing reduced government investment and global competition in both commercial and military markets, the need for improvement was evident to all enterprise leaders. The call was for systems to be developed Better, Faster, Cheaper - or some permutation of these three adjectives (which interestingly are not modifying any noun). The Administrator of NASA, Dan Goldin, introduced these words to aerospace in 1992, and many others have echoed them in the intervening years.

2.1 Trends in cost and development time

Perhaps the first person to call national attention to the fateful trend of increasing costs for aircraft was Norm Augustine [1]. His plot (which he first introduced in the late 1960s) of the unit cost of US tactical aircraft versus years showed an extrapolated crossing of the cost of a single aircraft with the total DoD budget in the middle of the 21st century. Although there has been considerable attention given to reducing the cost of new tactical aircraft, it has proven difficult to realize. "Augustine's Crossing" remains a major concern.

McNutt reported in 1999 [2] that the time required to develop all major DoD systems, including aircraft, increased by 80% in the thirty years from 1965 to 1994 as shown in Figure 1.

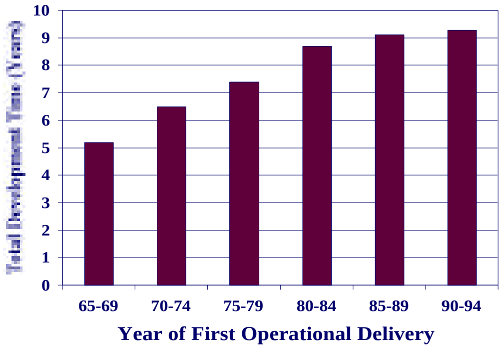

Figure 1 - Development time for major US DoD systems from 1965 - 1994. McNutt[2].

McNutt also reported a correlation between the cost and the time of development for such systems. Although there is considerable scatter in the data, the best curve fit indicates cost increases with the *fourth power* of the development time. Clearly development time is a major variable to consider.

One might argue that the root cause for these time increases is growing system complexity. However, development time for commercial systems of comparable complexity has been reduced during this same period. For example, the Boeing 777 was developed and fielded from 1990-1995[1]. Beyond complexity, other likely causes include a wide variety of inefficiencies in acquisition, design, engineering and manufacturing practices and processes for aeronautical systems.

At a subsystem level, Menendez [3] looked at methods to improve development cost and time of embedded software in aerospace systems. Figure 2 show the trends for embedded software costs in all US DoD systems. Such data is difficult to isolate, and specific information for just aeronautical systems isn't known to the authors. However, these trends indicate that

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[1] Today's New Economy investor expectations would require that time to develop the 777 in this decade would need to be halved.

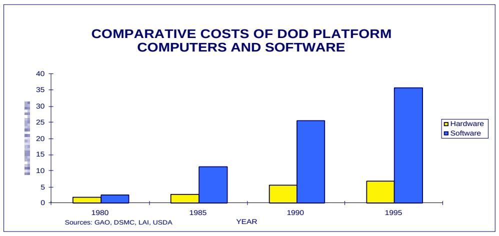

Figure 2 - Cost trends for embedded software and hardware in US DoD systems. Menendez [3].

without major improvement in software engineering and development, information intensive aerospace systems could become unaffordable. As Augustine noted [1], software provides the perfect opportunity to increase the cost of aircraft without an increase in weight!

2.2 Industry evolution and innovation

The forecasted market for commercial aircraft is \$1.2-1.3 trillion dollars in the next 20 years for jet transports carrying 100 or more passengers. The market for military aircraft has diminished in the post-Cold War period, but is still substantial in modernization alone. The dynamics of changing markets and fewer new systems have led to considerable industry consolidation that could have long term effects on the aeronautical profession. With fewer new programs, engineers will have limited opportunities to participate in the conceiving, designing, building, and fielding of new aircraft. The dramatic change in this situation from the beginning of the Cold War to the present is shown in Figure 3, prepared by Hernandez [4] from Reference [5], which shows the number of US military aircraft new starts by decade with an overlay for a typical 40 year aeronautical engineer's career. For commercial systems, the only new US jet transport aircraft of the 1990s was the Boeing 777. Outside these two major markets there are opportunities for rotorcraft and aircraft for regional transportation, business travel and personal use, as well as specialty missions. Even in these markets, derivative aircraft are more likely than brand new designs.

Indeed, the most likely products of the future will be derivatives and evolutionary configurations rather than new concepts.

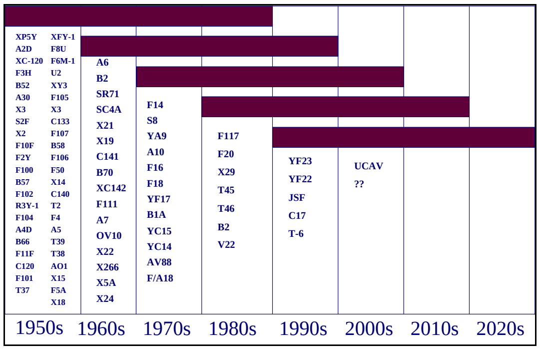

Figure 3 - New US military aircraft programs by decade and career lengths of a typical engineer. Hernandez [4].

An indicator of the evolving industry dynamics is the number of major US aerospace companies as shown in Figure 4, which includes all aerospace products, not just aircraft. From 1908 to about 1959, with the exception of the depression years, more companies entered the field than exited. From 1959 to the present the trends are the opposite. There was a steep decline from 1960 to 1969, followed by a long plateau from 1969 to 1992. The post Cold-War mergers and acquisitions left a vastly different industrial base at the end of the decade. Similar dynamics have influenced the European industries, but with time shifted effects. The first wave of consolidation at the national level started earlier, and the current period of international consolidations lagged due to the more complex political considerations.

The shape of the Figure 4 curve follows a classic pattern of product evolution exhibited by many industries producing assembled products, as studied and reported by Utterback [6]. In the early years of a new product, the *fluid phase*, the basic product features are evolving and many startup companies enter the field. At some point, a dominant design emerges when the basic product features become established and a

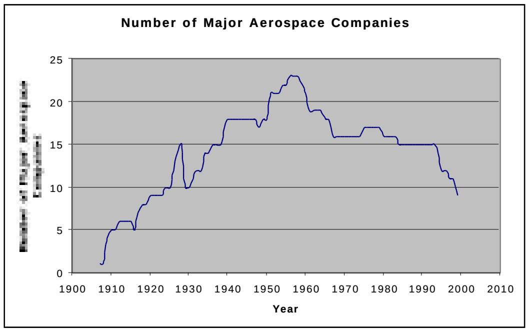

Figure 4 - Evolution of the number of US aerospace companies[2].

transitional phase is entered. Many factors come into play to establish the dominant design including technology, infrastructure, customer expectations, individual entrepreneurs, etc. At this point, more companies start to leave than enter the field. Innovation starts to switch from product to process technologies, i.e. to design, development, manufacturing innovation. As the *specific phase* is reached, significant changes in product features are unlikely.

Aeronautical engineering is deeply into the *specific phase*. It is important to understand the characteristics that are typical of this phase of industrial innovation. These are listed in Table 1 excerpted from Utterback [6]. In the specific phase, innovation opportunities exist for:

- Incremental product technologies, to improve product productivity and quality
- Process technology
- Technological innovations that present superior product substitutes

These characteristics, largely developed from non-aerospace industries, are very representative of the current thinking of our industry - Better, Faster, Cheaper. It is characteristic of many industries. One can surmise that the only reason the aeronautical industry didn't enter this phase sooner was the influence of the Cold War. Indeed, the long plateau from 1969-1992 in Figure 4 was largely sustained through government investment in aerospace and the industrial base for political reasons. Had market forces been at play, as they were in the commercial aircraft sector, the field likely would have started Better, Faster, Cheaper years earlier.

Table 1 - Significant characteristics of the Specific Phase of industrial innovation [6].

Attribute	Characteristics
Innovation	Incremental for product and with cumulative improvements in productivity and quality.
Source of Innovation	Often suppliers
Products	Mostly undifferentiated, standard products
Production processes	Efficient, capital intensive, and rigid; cost of change high
R & D	Focus on incremental product technologies; emphasis on process technology
Equipment	Special-purpose, mostly automatic, with labor focused on tending and monitoring equipment
Plant	Large-scale, highly specific to particular products
Cost of process change	High
Competitors	Few; classic oligopoly with stable market shares
Basis of competition	Price
Organizational control	Structure, rules, goods
Vulnerabilities of industry leaders	To technological innovations that present superior product substitutes.

It is noted that history shows the source of innovation in the specific phase is suppliers. Often suppliers are smaller, more nimble organizations who accept the greater risk accompanying innovation .

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[2] This chart was prepared based information in Weiss, S and Amir, A. The Aerospace Industry. *Encyclopedia Britannica*, 1999

For the *specific phase*, Utterback points out the significant challenge for a radically new product designs to enter the market. Infrastructure, patterns of user expectations and preferences, and the amortized investment in existing products all are major barriers to radical product innovation. Certainly this is borne out with attempts such as the recent High Speed Civil Transport (HSCT) program in the US. The newest aeronautical product, the Airbus A3XX, has an estimated development cost of US$12Billion and has a high degree of financial risk [7]. Yet the A3XX is not really a radical design. Perhaps the new Blended Wing Body (BWB) configuration for large air transport [8] will be successful in entering the market. For military systems, Uninhabited Combat Air Vehicles (UCAVs) are one example of new innovation in aeronautics. However, one should not underestimate the significant obstacles that need to be surmounted before either of these replaces the current dominant designs.

There is always the possibility that totally new innovations, say in information technology, will make air travel and military airpower obsolete, totally changing the innovation dynamics. On the other hand, these may increase the demand for aeronautical products. More likely opportunities lie in exploiting information technology at the system level to enable expanded markets and services for air transportation. There is always the possibility that some total new threat, technology or market opportunity will appear, opening the window for innovation. Stealth technology, coupled with Cold War priorities represents just such an innovation in the 70s and 80s. Only time will tell about such future possibilities.

More promising opportunities for innovation in the predictable future lie in incremental upgrades to improve product quality and productivity (Better), reduce product cost (Cheaper), and respond to market or threat demand more quickly (Faster). For aircraft, these would include improved safety and environmental impact. In fact, this is borne out by current commercial and military programs such as derivatives in Airbus and Boeing products, the F/A-18 E/F program, and C-130J. Brand new starts such as the F-22, A3XX face significant financial challenges. Incremental upgrades, however, offer significant opportunities for innovation, particularly in information technology at both the aircraft subsystem level and the air transportation infrastructure level.

From a process point of view, there are major opportunities for innovation. By and large, improvements to design, development and manufacturing were given lower priority during the Cold War than were improvements to performance. The same can be said of improvements to product support for fielded systems. The military and civil space sectors had a strong "front end" focus on innovation, emphasizing superior performance metrics representative of a fluid phase of product development. The commercial aircraft sector adjusted sooner to the dynamics of the specific phase due to market forces. But as an industry, aeronautics is way behind most others that have entered the *specific phase* such as automobiles and copiers.

It should be cautioned that Utterback's study spans the years that the mass production paradigm dominated industry. The book notes the relatively recent innovations of "flexible manufacturing" system developed by Japanese automakers, popularly know as "lean", and the "mass customization" system based upon platform architectures with many variants to meet customer needs (e.g. the Sony Walkman type of product). He speculates that "Flexible manufacturing and the strategy of mass customization seem to offer an escape hatch from the innovation dead end of the specific phase." but follows with "However, flexible manufacturing and mass customization may also be the trap resulting in products with little commercial potential and in unwanted product variety." Lean techniques squarely address the characteristics shown in Table 1 for the attributes of production processes, equipment, plant and cost of change.

2.3 Challenge of Better, Faster, Cheaper

To summarize this section, let us reflect on the challenges the aeronautical profession faces in the Better, Faster, Cheaper era. First, it needs to be recognized that aeronautics is in the *specific phase* of innovation. History shows that opportunities for innovation are in incremental product features that improve productivity and quality, in process technology, and are more likely to occur in the supplier base. Although there is always the possibility of new product concepts offering superior substitutes, the days of markets driven solely on performance are long gone for the aeronautical industry. It remains to be seen whether the new industrial paradigms of lean will change the fundamentals of innovation dynamics of the past century.

3 Value

"Value" is a word that is common in the business literature and vernacular, and even in some quarters of engineering. It is certainly common to each of us individually. Over the past few years, LAI research has found that "value" provides a useful framework for engineering in the Better, Faster, Cheaper (BFC) era. In fact, it will be shown that BFC can be recast as a value metric. The authors are not experts in value, but have a growing awareness of the literature and concepts, including the field of Value Engineering that was an outgrowth of WWII propulsion engineers.

Slack [9] studied value, particularly as it applies to Product Development and proposed the following definition:

> *"Value is a measure of worth of a specific product or service by a customer, and is a function of (1) the product's usefulness in satisfying a customer need, (2) the relative importance of the need being satisfied, (3) the availability of the product relative to when it is needed and (4) the cost of ownership to the customer."*

The specific definition of value is situational dependent and depends on the customer. Its attributes can be related to more familiar terms. (1) and (2) relate to performance and map to "Better". (3) has to do with the timing of the product availability and maps to "Faster" in the current aerospace era. Finally, (4) relates to cost and maps to "Cheaper" in the BFC triad.

3.1 Best Lifecycle Value

The concept of value can be extended to the still emerging concept of Best Lifecycle Value (BLV), with a candidate definition:

> *"A system offering best life-cycle value is defined as a system introduced at the right time and right price which delivers best value in mission effectiveness, performance, affordability and sustainability, and retains these advantages throughout its life."*

The emphasis of this extended definition is to consider the total lifecycle, which is central to aerospace systems that have long lifetimes and considerable lifecycle operational costs. Research is currently underway to develop a framework for BLV. Best Lifecycle Value can elevate the thinking of aeronautical engineers beyond "Higher, Faster, Farther" or "Better, Faster, Cheaper" to an abstraction that embraces both and provides a framework for future challenges.

3.2 Elements of Value

From the above discussion, it is apparent that value is a multidimensional attribute, and the definition in the aeronautical context is still emerging. One might assume a functional relationship as:

$$Value = \frac{f_p(performance)}{f_c(\cos t)\cdot\ f_t(time)}.$$

Improved performance (Better), lower cost (Cheaper), and shorter times (Faster) generally lead to increased value. This definition of value is a variant on the one used by Value Engineers who don't include the time function. The functional relationships need to be defined by the customer for each product or system. These relationships would comprise specific metrics with weightings to indicate customer utility functions and normalizations for consistency. Some examples of elements that might be in these value metrics are given for illustration. These are not exhaustive, but illustrate the large number of possible factors that might enter a value analysis.

Performance function, f_p

- Vehicle performance (range-payload, speed, maneuver parameters)
- Combat performance (lethality, survivability, store capability)
- Ilities (Quality, reliability, maintainability, upgradability)
- System compatibility (ATC, airport infrastructure, mission management)
- Environmental (Noise, emissions, total environmental impact)

Cost function, f_c

- Development costs
- Production costs, fixed and recurring
- Operation costs
- Upgrade/conversion costs
- Support costs
- Disposal costs
- Opportunity Costs
- Cost of ownership

Time function, f_t

- Acquisition response time [2], or lead time
  - Recognition time to develop customer needs
  - Initiation time to put program in place
  - Product development cycle time
- Order to ship time
  - Lead time
  - Production cycle time
- Availability - right time at right place

Focussing on multidimensional value helps break out of one-dimensional thinking. In the Cold War years aeronautics focussed mostly on performance, and in the 90s it has focussed mainly on cost. The challenge is to balance the elements of value, which are generally recognized as the three dimensions of project/product engineering: cost, schedule, performance/quality. Considerable research needs to be done on value, including: how it is defined; how it is measured; and tools to utilize value in aeronautical design, engineering, and manufacturing.

3.3 Risk

However value is defined, it is likely only known to some degree of certainty at any point in time. This relates directly to risk and risk management, another area of fruitful research in the Better, Faster, Cheaper era. In the early years of the Cold War, customers were willing to take considerable risk as national security was seriously threatened. By the mid 60s, the tolerance for risk started to diminish due to public accountability both for fiscal reasons and the consumer rights movements. Now society is very risk-averse for fields like aeronautics. In a modern aeronautical program, a single significant failure can doom the entire program, particularly if it is not managed well. So this elevates the need for better methodologies and tools for risk management.

Risk and value are intimately interrelated, as the quality of the value metric is related to the probability of certainty of its representation. At the beginning of product development, there is great uncertainty and hence the risk can be significant. As design and development proceed, followed by transition to production and eventually production, risk needs to be managed, reduced, and mitigated. Opportunities for research exist in risk management as well as improved knowledge surrounding underlying technologies and processes. One effective risk management strategy is evolutionary development leading to derivative and upgrade systems and products.

The current values of customers favor such programs.

3.4 Achieving Best Lifecycle Value

As a better understanding of value evolves, what approaches and tools will be used for improving best lifecycle value in future aeronautical systems? One can only give some general guidelines at this point, as there is still considerable work to be done.

It becomes immediately clear that holistic or systems thinking and approaches are absolutely necessary when dealing with value. This turns out to be much more challenging than one might think. During most of the past two generations, emphasis has been placed on specialization and on deep understanding of disciplines underlying aeronautical engineering. The same is true of our approach to education and to much of our recognition and incentive systems.

Disciplinary depth and expertise is extremely important for systems as complex as aerospace products. But without being embedded in a systems or holistic framework, there is a strong tendency towards sub-optimization with consequent diminished value to the customer. Having a focus and definition of value helps to overcome a narrow-minded investment strategy, both at the personal and enterprise level.

An article on holistic systems engineering by Fredriksson[10] provides an excellent example of such approaches as applied to the JAS 39 Gripen program. One example from this article, which has appeared earlier [11] is shown in Figure 5. Experience from many programs indicate that the ability to influence the lifecycle costs of a product or system is greatest in its earliest stages, and rapidly diminishes as detailed design is executed. This indicates the importance of developing methods and tools to incorporate all life-cycle attributes into early stages of design. This is another fruitful area of aeronautical research. For example, modeling and simulation can play an important role here, but so can simple practices such as capturing "lessons learned" from earlier programs.

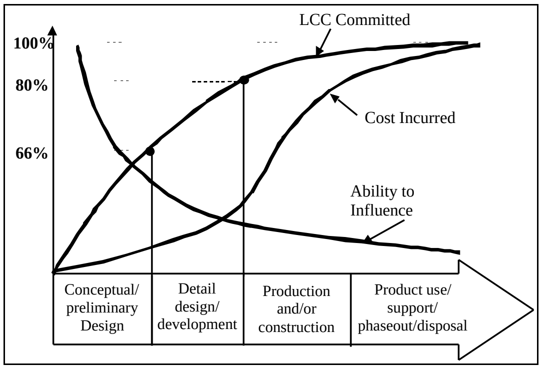

Figure 5 - Life cycle cost committed, cost incurred and ability to influence life cycle cost throughout the product/project life cycle Fabrycky [10].

Another approach to improving best lifecycle value is to focus directly on value creation through the application of lean practices and principles. Let us turn to this topic, noting that the relationship of lean to system engineering has been considered by Warmkessel [12] and is another area of emerging understanding.

4 Lean

In a seminal book in 1990, Womack, Jones and Roos [13] of MIT's International Motor Vehicle Program (IMVP) identified a new industrial paradigm they called "Lean", emerging from the Japanese automobile producers, in particular Toyota. Lean production is replacing mass production throughout many industries, including aerospace - an industry that has been characterized prior to 1990 as a craft production system with a mass production mentality. Lean is focussed on two meta principles: (1) waste minimization and (2) responsiveness to change. Or stated in other words, focusing on adding value and flexibility. Lean is responsible in large part for the recovery of the US automotive industry from the desperate situation of the 1970s. Applications to other industries, including aerospace, are illustrated in the 1996 book by Womack and Jones [14]. This latter work has a stronger focus on value than *The Machine that Changed the World*, and introduces the important tool of value stream mapping. Lean originated as a manufacturing system for large volume, low to moderate complexity products and much of the research and application outside of aerospace remains in this arena.

In late 1992, MIT was contacted by the Aeronautical Systems Center of the US Air Force to explore the application of lean to defense aircraft. This led to the formation of a research consortium called the Lean Aerospace Initiative (LAI) comprised of US industry, government, labor and academic participants [15]. The consortium includes over two dozen industry members, a dozen government members and two labor unions. Objectives of LAI include expanding the understanding and implementation of lean principles to all phases of product creation - from early concept development to delivery - and to an industry characterized by low volume, high complexity products. Aircraft, avionics, missiles, launch systems, and spacecraft are all considered. A major emphasis is to characterize the fundamentals of best lifecycle value.

LAI has completed or has ongoing numerous studies related to acquisition, product development, manufacturing systems, supplier networks, organizations and people, and test and space operations. More information about LAI as well as research reports can be found at http://wed.mit.edu/lean. A companion program called the Lean Sustainment Initiative is focused on lean principles for maintenance and operation of aircraft systems. LAI also has cooperative agreements with two international programs: the UK LAI involving Warwick, Bath, Cranfield and Nottingham Universities; and the Lean Aircraft Research Program at University of Linköping in Sweden.

Lean is process oriented and addresses directly the need for process improvement in the aerospace industry in the Better, Faster, Cheaper era. Although it is not "rocket science", it could be characterized as "rocket making science". It represents a new way of thinking about organizing and executing tasks and activities to achieve project and organizational goals through adding value by eliminating wasteful practices. Although research and implementation of LAI findings has been underway for over seven years, it is still relatively early in the lean era and there are still many methods and tools to develop for improving the design, engineering and manufacturing phases of aerospace products. It is far too early to know how Lean will alter the Utterback model of industrial innovation highlighted in Section 2.2. Hopefully it will eliminate the legacies of mass production. If this can be achieved, an industry might be better positioned to overcome barriers to innovation.

4.1 The Lean Enterprise Model

One outcome of the LAI is the codification of lean principles and practices at the enterprise level in the Lean Enterprise Model (LEM). A top level view of the LEM is shown in Figure 6. It is comprised of enterprise principles and metrics that characterize the top level objectives of a lean enterprise. The heart of the LEM consists of 12 overarching practices identified by LAI researchers. These are broadly applicable, and are supported by more actionable and specific enabling and supporting practices. The LEM is implemented in a web based tool supported by benchmarking and

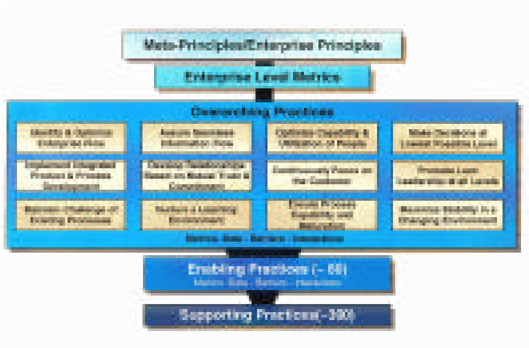

Figure 6 - Top level architecture of the Lean Enterprise Model. Weiss, et al [15]. For more detail, refer to http://web.mit.edu/lean

other data identifying metrics, enablers and barriers to implement lean.

4.2 Lean findings and implementation

Impressive progress has been made in development and manufacturing of aerospace systems with the application of lean over the last decade. A list of examples contributed by LAI members in late 1998 [16] is given in the appendix. A few specific examples are included to illustrate findings and application at sub system levels. A big challenge is to optimize the mix of sub process improvements to achieve system level, or bottom line, improvements. A particularly stellar example in this regard is the C-17 program that has taken $100M of cost out of *each* aircraft, partly due to implementation of lean practices.

Figure 7 shows the cumulative results of applying a number of lean practices to design and production of a forward fuselage section. Compared to an earlier product, the application of lean led to an effective learning curve shift of 9 units and a 48% reduction in labor hours once learning was stabilized.

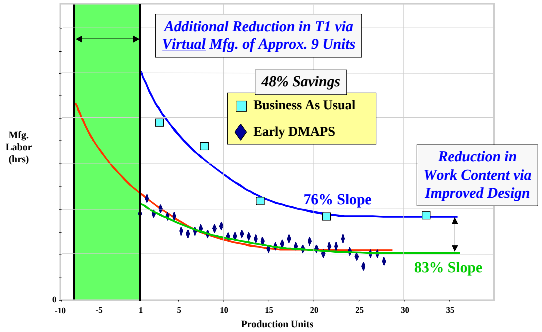

Figure 7 - Impact of lean practices on manufacturing labor hours versus production units for a forward fuselage section.[3]

Figure 8 shows the impact of applying value stream mapping and single piece flow concepts from lean manufacturing to the process of approving drawing releases for an aircraft program. The number of signatures required was reduced by 63%, the rework of release engineering was reduced from 66% to 3%, and total cycle time for drawing releases was reduced by 73%. The improved process had considerably better predictability with major reduction in the standard deviation in the time taken for drawing releases.

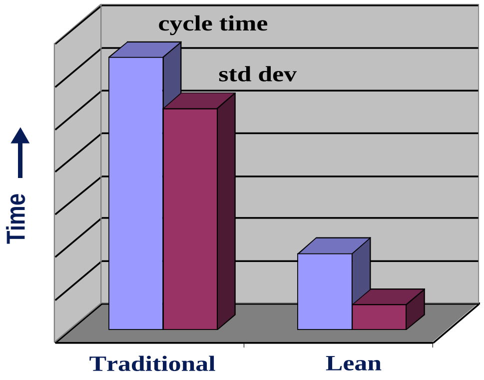

Figure 8 - Improvement in time for drawing release time and predictability by application of lean practices.[4]

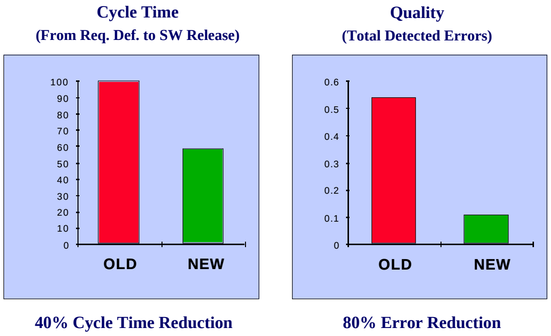

Figure 9 - Reduction in product development time and coding errors using automatic code generation tools (NEW) versus manual coding (OLD) for a mission critical engine controller. Menendez [3].

The use of "software factory" tools for mission critical embedded software applications was

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[3] Presented by John Coyle of the Boeing Company at LAI Executive Board meeting, June 1, 2000. Assistance of Peggy Holly is appreciated.

[4] Courtesy of Karen Albrecht of Lockheed Martin Co.

identified as a lean practice by Menendez [3] in several case studies. Figure 9 shows the reduction in product development time and improvement in quality using automatic code generation tools for an engine controller.

For a more extensive military aircraft avionics upgrade effort, Ippolito and Murman [17] applied Value Stream Mapping approaches [14] to identify the total cost and time factors. Figure 10 shows that a 62-month period was required for the upgrade effort - an excessively long time for the end user to benefit from a new capability. In terms of cost, only a small fraction, about 6%, was attributable to actual code development. Much greater costs were associated with flight testing and incorporation of other systems related to the software upgrade. Thus improvements are needed across the program phases, not just in code development. Currently the US Air Force is applying lean practices to avionics upgrade efforts to significantly reduce the time required from that shown in Figure 10.

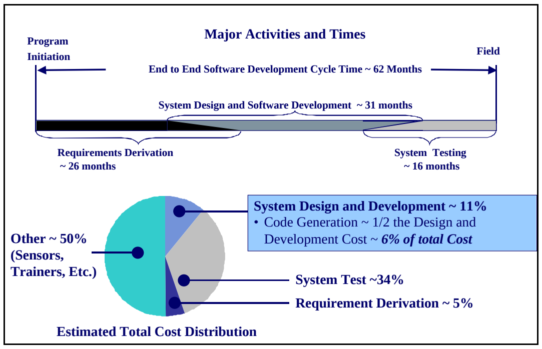

Figure 10 - Analysis of time and cost for a military aircraft avionics upgrade. Ippolito and Murman [16].

One improvement in manufacturing technology is the use of "determinant assembly" with self location of parts. This eliminates special tooling needed to locate parts before they can be assembled. The improved manufacturing techniques that support determinant assembly also significantly improve product quality. Figure 11 from a study by Hoppes [18] shows the reduction in assembly hours, tooling, shims and quality defects with the use of determinant assembly. Such techniques are now being incorporated in a number of aircraft assemblies.

Category	Old Paradigm	New Paradigm
Hard tools	28	0
Soft tools	2/part #	1/part #
Major assembly steps	10	5
Assembly hrs	100%	47%
Process capability	$C_{pk}<1$ (3.0σ)	$C_{pk}>1.5$ (4.5σ)
Number of shims	18	0
Quality (nonconformances/part)	.3 (> 1000)	.7 (<20) *

* Early results with improving trend

Figure 11 - Comparison of metrics for "old" paradigm where tooling was used for locating parts and the "new" paradigm with self locating parts using determinant assembly for aircraft floor beams. Hoppes [17].

Enabling technologies for determinant assembly include Statistical Process Control (SPC) for assuring that manufacturing processes (hole drilling, milling, etc.) are within known tolerances, and Key Characteristics (KC). KCs are used to identify the most critical design variables that must be held within tolerance for the final assembled product to meet user expectations. Figure 12 from Thornton [19] illustrates how top level KCs flow down to sub assembly and process parameters. With the millions of parts in aircraft, this is not a trivial matter. Tools and techniques for effective KC implementation are currently under development.

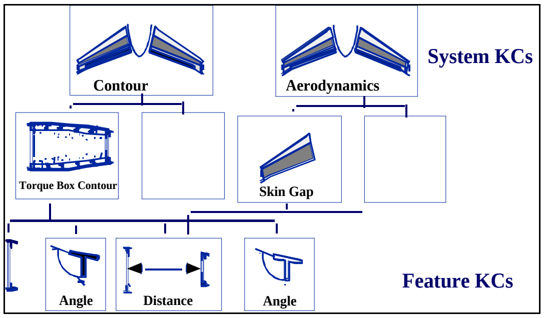

Figure 12 - Schematic illustrating how Key Characteristics at the system level needed to meet design requirements flow down to sub assembly and component levels (and eventually process parameters). Thornton [18].

The final example illustrates a powerful risk management method developed by Browning [20] using Design Structure Matrices. The approach affords a probabilistic estimate during development of the most likely system level performance, cost and schedule, based upon inputs from individual tasks. The complexity of aeronautical systems with hundreds of integrated product teams and thousands of tasks precludes realistic outcome predictions without the use of powerful mathematical models such as these. Figure 13 illustrates the probabilistic prediction of cost and schedule outcomes for a proposed UCAV project. The two most likely end states using the proposed program plan did not satisfy the needed schedule, but did meet the required cost. With the DSM tool, a reordering of tasks was identified which slightly increased the cost but dramatically decreased the schedule by eliminating an iterative design process late in the design cycle. Without the DSM tool, the visibility of this option was poor.

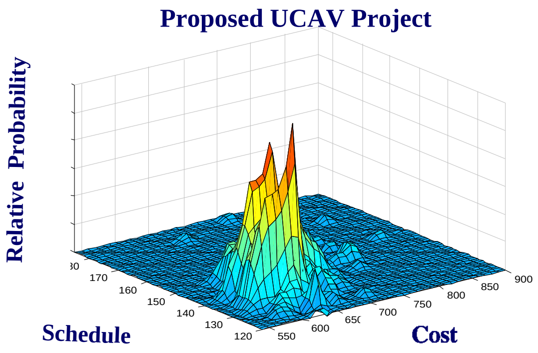

Figure 13 - Predicted most likely cost and schedule end states for a UCAV project using a probabilistic risk prediction method. Browning [19].

4.3 Leaning towards the future

The Lean paradigm for aerospace is just a decade old, and many aspects need to be understood, discovered and implemented. Already the research has led to two major findings:

1. For Lean to have major benefits, it must be implemented across the entire enterprise. This includes all functions such as product development, manufacturing, supply chain management, business functions, and product support. Only a portion of the total costs of an aerospace system is in manufacturing. With high product development and support costs, major impacts on total product development time and costs cannot be realized by implementing lean only in manufacturing. Lean has to become a way of thinking across the total enterprise.

2. The principles of the LEM can be implemented in at least two different ways, with significantly different expected end states. One way is narrowly focused on waste elimination - cutting costs, cutting labor, eliminating capability not needed for short term gain, etc. This path leads to an end state with little capability for future opportunities. The other path focuses on adding value, using lean to eliminate waste and free up resources to invest in future capability. This path envisions a future where aerospace organizations are nimble, able to respond to future opportunities with creative solutions incorporating advanced concepts. Perhaps this will enable innovation by lowering entry costs.

At this point in time, the path for the future is uncertain. There has been more implementation of Lean following the first option as aerospace enterprises struggled in the 1990s to lower costs. The value based approach of the second option is clearly preferable for the long term. Whether industry and government choose this path remains to be seen. There are plenty of opportunities for aeronautical professionals to engage and contribute to this fundamental change sweeping the field.

5 Challenges for Aeronautical Design, Engineering and Manufacturing

With the Cold War over for a decade, with numerous mergers and acquisitions changing the industrial base, with global competition, and with uncertain challenges for the future, aeronautical design, engineering and manufacturing face many challenges. To the authors it is evident that the value systems that so impacted the field during the long Cold War period are obsolete. Today's values favor Better, Faster, Cheaper rather than Higher, Faster, Farther. Yet many of the individuals and institutions in the aeronautical fields were shaped by the Cold War values. The field faces a significant challenge to align personal and institutional values with the societal values of the 21st century.

Viewing the aeronautical field through the historical lens of other industries, it is now in the *specific phase* of Utterback's model of industrial innovation with well established dominant designs. This phase is characterized by opportunities for innovation in:

- Incremental product technologies, to improve product productivity and quality
- Process technology
- Technological innovations that present superior product substitutes.

Let us briefly revisit each of these in the light of the discussion in the paper.

Incremental product technologies, to improve product productivity and quality - Although the opportunities for radical configurations and concepts may be limited, there are significant opportunities in this category. But to develop effective technologies, methods and tools, aeronautical engineers need to truly understand value to the customer and what enables its achievement. Traditional areas such as aerodynamics, propulsion, and structures can contribute, but not by following a "big bang" approach. Perhaps the greatest opportunities for incremental product improvement lie in the information technology area. New flight systems, ATC systems, passenger systems, scheduling systems, and so forth all can offer benefits, if value is clearly understood. Opportunities in incremental improvements focused on product quality and productivity, including safety and environmental aspects, should not be undervalued.

Process technology - This is an area ripe for innovation. The Cold War investment strategy favored product improvement, and specifically engineering science based approaches, over process improvement. As a result, the aerospace field lags other areas in process innovation. Lean represents one major approach. There are many dimensions to Lean and only a few have briefly been addressed in this paper. The important aspect to realize is that process improvements are not based upon Newton's Laws and other familiar roots of aerospace engineering. Aerospace engineers need to adjust their thinking to encompass broader foundations that underlay design, engineering and manufacturing processes.

Technological innovations that present superior product substitutes - This is the "high ground" of innovation, so warm to the hearts of aerospace engineers. But Utterback's work suggests this is also the most unlikely area for real market penetration—at least in aeronautics. Perhaps new concepts like Blended Wing Body and Uninhabited Combat Air Vehicles will enter service. One needs to recognize the significant odds against challenges to the dominant design that emerged 40 years ago, more or less, from within aeronautical engineering. On the other hand, it should be asked if some new technology will provide a superior substitute to aircraft and make air travel obsolete. Some suggest that the emerging global information infrastructure will reduce the need to travel. This would defy historical trends that travel increases with communication. But the radical innovations that mark the decline of incumbent technologies seldom come from within the industry they are challenging. A worst-case scenario might combine elements of a new entrant technology, such as internet-enabled telepresence, coinciding with factors such as an economic recession, the flexibility-limiting high fixed-cost structure in the aerospace industry, fuel price shocks, taxes on carbon emissions, or demographic/generational changes in travel behavior. None of them alone would be enough to significantly threaten the demand for aircraft.

But combinations of them could erode the market enough that the investment in aeronautical innovation required to sustain the technology base and the supporting infrastructure is no longer economically attractive. A key lesson from studies of the dynamics of innovation is that over time, firms in technologically mature industries become increasingly vulnerable to threats from new entrants. Long-lived incumbent firms are masters at adaptation to changing environment and assimilation of new technologies. Nevertheless, the authors foresee that at least in the near term, aircraft and aeronautics will remain central to national security and the movement of people and goods in the New Economy.

The aeronautical field and its stakeholders face, significant challenges in the Better, Faster, Cheaper era. The field is in an era of systemic change. This is not a minor perturbation that will pass by with the next election. It behooves us to look forward and create an exciting future, not to look back and wish we were in the past. For some of us, this is frightening. But for others, it is a time of opportunity. As we approach these changes, the authors suggest a firm understanding of best lifecycle value is central to our actions. This requires a holistic systems approach and a value based implementation of lean practices.

Industry is challenged to deliver best lifecycle value to commercial and military customers in a global market. Lean provides a framework, but only a total enterprise approach focused on adding value will succeed. This is indeed a daunting challenge.

Government is challenged to adjust acquisition and R&D policies and investments to meet present and future needs. During the Cold War, government policies were designed to "pull performance" from the industrial base and research infrastructure. Cost-plus contracting was well suited for this. But these old paradigms were not designed for today’s needs. Today, government must strive to "pull value" from industry, and support R & D in areas with the greatest future potential.

Academia is challenged to take a more holistic and systems view to education and research. The engineers of the present and the future must be system thinkers in addition to disciplinarians. Our department at MIT has wrestled with these changes for a decade and has made significant commitments and investments to this end [21]. It has decided to educate engineers within the full context of engineering - conceiving, designing, implementing and operating aerospace vehicles and systems. And it is investing heavily in the information aspects of aerospace.

6 Conclusions

Better, Faster, Cheaper is rooted in Post Cold War values of society and the fundamental dynamics of industrial innovation as aircraft reach the *specific phase* of their product lifecycle. Opportunities exist for innovation in incremental product improvements, particularly for quality and productivity - including safety and environmental impact. Significant opportunities exist for design, engineering and manufacturing process improvements based upon Lean practices. Focussing on achieving *best lifecycle value* using a holistic systems engineering approach and lean practices provides a framework for future actions.

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of the Lean Aerospace Initiative, the US Air Force, the sponsoring companies and organizations (individually or as a group), or MIT. The latter is absolved from any remaining errors or shortcomings for which the authors take full responsibility.

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Appendix - Quantitative Savings Cited by LAI Consortium Members due to Lean -1998

Complete Products

- Product order to delivery time reduced from 24 to 10 months with 15% annual price reduction and performance exceeding goals for a munitions product
- 50% fewer cycle days for lightweight airframe product
- Production hours under budget by 11% for EMD and 16% for LRIP for major airframe product
- 50% reduction in cycle time for production and launch of commercial launch vehicle
- For a major aircraft system, production rate doubled with same workforce, repair and rework reduced by 88%, last 30 units delivered to field early.

Major Components or Sub-assemblies

- Horizontal stabilizer reductions of 20% in weight, 90% in parts, 81% in fasteners, 70% in tools, and 50% in cost
- Horizontal tail reductions of 61% in parts and tools, 48% in design cycle time, 38% in design hours, 50% in assembly, 62% in defects
- Engine pylon reductions of 10% in cycle time, 10% in labor hours, 89% in people travel with all safety issues eliminated and 5S score improved by 58%
- Nose installation reductions of 60% in cycle time, 85% in set-up time, 77% in people travel distance and with increase in productivity of 60% and elimination of 2 safety issues
- Landing gear pods reduction of 32% in cycle time, 17% in set-up time, 16% in lead time, 42% in people travel distance, 83% in product travel distance with 32% increase in productivity

Production Operations

- Enterprise-wide 35% improvement in productivity
- After 1 year of Kaizen workshops, average improvement of 27% in productivity and reductions of 50% in inventory, 25% in floor space, 50% in lead-times with significant improvement in quality and reductions in set-up time
- After several Kaizen workshops, reductions of 47% in cycle time, 31% in inventory, 34% in floor space, with 100% improvement in throughput in certain areas
- HPWO led to reductions of 28% in scrap, 20% in rework, 60% in cycle time
- Kaizen workshops led to reductions of 47-71% in labor hours, 76-92% in travel distance, 54-80% in setup time, 65-81% in floor space and 20-97% in cycle time for certain production operations
- Reductions of 51% in space, 79% in travel distance, 80% of work in progress, 36% in direct labor, 50% in defects, 66% in capital equipment requirements, 80% in through-put time
- Reduction from several thousands to 420 defects per million opportunities
- 50/60/70% reductions in implementing critical processes are being proposed and achieved on several major space related products
- Selected demonstration projects for new aircraft program documented reductions of 67% in manufacturing cycle time, 80% in inventory and 60% in cycle time variations.
- Kaizen workshop with supplier led to reductions of 28% in unit cost, 70% in floor space, 98% in work in progress, 95% in distance traveled, 38% in cycle time
- Just-in-time delivery of titanium billet reduced inventory by $8-10M, lead time by 50%, suppliers to 2 from 31

Product Development

- Pilot efforts in improved information flow between engineering and manufacturing resulted in cost reductions of approximately 30% in engineering, 15% in manufacturing with a 25% reduction in overall cycle time
- IPPD led to reductions in hours of 80% for design, 50% for NC programming, 50% for inspection and 67% for fabrication of flying testbed
- For prototype development, 1/3 less time for 90% drawing release milestone