IMPROVING THE MANAGEMENT OF SYSTEM DEVELOPMENT TO PRODUCE MORE AFFORDABLE MILITARY AVIONICS SYSTEMS

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ABSTRACT

This thesis aims to improve the management of system development to deliver more affordable systems. Improving affordability is investigated from the avionics supplier's perspective. An affordable system is defined as meeting customer needs for performance and lifecycle cost in an over-constrained program space where initial development budget, schedule, performance and lifecycle cost goals are not all achievable. In certain segments of the military avionics market, the nature of competition is changing from performance to affordability based. Firms that develop competitive advantage in delivering affordable systems can capture market share. This research is different than most literature published on affordability because it focuses on design innovation as opposed to product development and manufacturing efficiency through Lean, Six-Sigma or other techniques. Lean and Six-Sigma are necessary to improve system affordability but not sufficient to develop competitive advantage because they can be implemented by anyone on any system concept. Competitive advantage requires benefits from Lean and Six-Sigma <u>and</u> design innovations focused on affordability. Step function type improvements can be realized through system architecture and module design innovations that strike a better balance between lifecycle cost and performance.

Four areas are investigated: the nature of development focus during each design iteration, the role of requirements, managing lifecycle cost as a design requirement and effective integration of downstream knowledge into the design.

A model for developing requirements that strikes a better balance between performance and lifecycle cost is suggested – treating lifecycle cost as a design requirement and explicitly focusing on understanding the cost-performance trade space before developing requirements. A product development model is suggested – focusing on achieving lifecycle cost goals first and using iterations to grow performance can lead to lower cost solutions. Both the requirements development and product development models require leveraging prior knowledge, technology and capability. The requirements model requires high knowledge of system cost drivers and achievable performance. The product development model requires low technical risk allowing the team to focus on affordability first without running unacceptable levels of performance risk. Methods for increasing the effective integration of downstream knowledge are also discussed.

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I would like to thank two professors in particular who helped structure my thoughts and provided insights throughout the development of this thesis – my thesis advisor, Eric Rebentisch, and Kirk Bozdogan.

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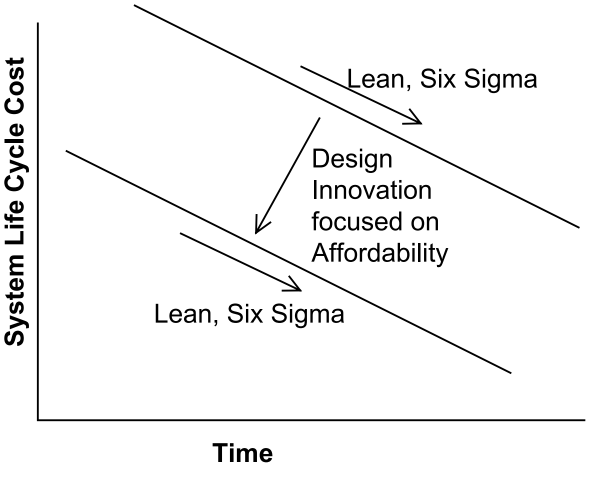
1.1 Executive Summary

Problem Statement

This thesis investigates improving military avionics system affordability from an avionics supplier's perspective. An affordable system is defined as one that meets the customer's needs for performance and lifecycle cost in a, typically, over-constrained program space – meaning development budget, schedule, performance and lifecycle cost requirements are not all achievable. Over-constrained programs are common in the military avionics industry for two reasons. First, the acquisition process favors over-constrained programs in competitive acquisitions. Avionics suppliers are paid by their customers to develop new systems so new business is awarded on the promise of future capability, not the demonstration of current capability. This process favors optimistic projections of future capability leading to over-constrained programs. Second, new system development is inherently costly, time consuming and uncertain. New development programs are always trying to stretch and optimize the system performance and lifecycle cost to provide significant improvements from legacy systems within the budget and schedule constraints. Uncertainty exists regarding the optimal balance of performance and cost. A valuable aspect of a development program is collaboration between customer and supplier to optimize performance and cost as the uncertainty is gradually reduced. The optimal performance and cost is often different than the program's original goals.

In certain military avionics market segments, the nature of competition is changing from performance based to affordability based. Firms that develop a competitive advantage in delivering affordable systems will capture market share in these segments. Significant research under the umbrellas of Lean and Six-Sigma has been focused on increasing the efficiency of product development, manufacturing and the extended supply chain to improve affordability. These techniques can generate incremental improvements that accumulate year after year and lead to significant benefits over time. These techniques alone are insufficient to develop competitive advantage because everyone can apply them to any system concept. Developing competitive advantage requires Lean and Six-Sigma efficiency and step function improvements from design innovations focused on affordability. These innovations involve system architecture and module design choices that strike a better balance between life cycle cost and performance. The objective of this thesis is to increase understanding of the factors that effect design innovations focused on affordability to identify engineering and management actions to be implemented during future development programs.

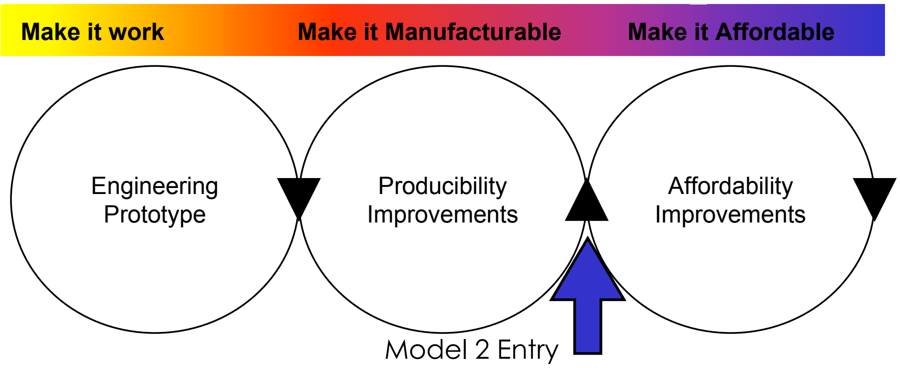


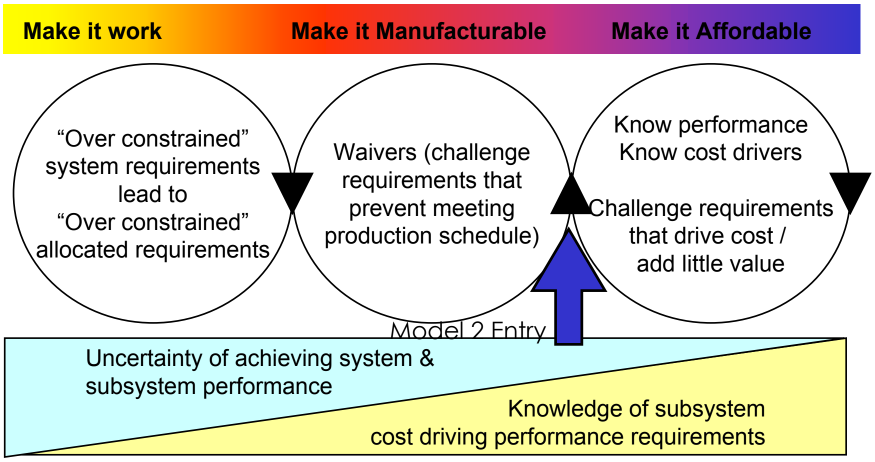
Originality Requirement

This research is different than most literature on affordability because it focuses on design innovation as opposed to product development and manufacturing efficiency through Lean or Six Sigma. This thesis extends the body of system design and management knowledge by explicitly exploring the impacts the program manager or chief engineer of an avionics system development program can have on system affordability. Four broad areas were researched: the nature of development focus during each design iteration, the role of performance requirements, treating cost as a design requirement and integrating downstream knowledge into the design process. The conclusions are based on case study investigations of seven military avionics development programs ranging from single module hardware programs with products that fit in the palm of your hand to large scale avionics systems involving hundreds of pounds of hardware and hundreds of thousands of lines of software code.

Content and Conclusion

All cases used an iterative development approach. The critical issue was each iteration's focus. Two models were identified. Model 1 is characterized as make it work, make it manufacturable then make it affordable. Model 2 develops the lowest cost system concept and uses development iterations to grow performance. Neither model is universally superior. Model 1 is appropriate under conditions of higher technical risk. Model 2 leads to lower cost products but can lead to performance failure if attempted without leveraging prior knowledge, technology and capability to reduce technical risk. Model 2 can be thought of as a subset of Model 1 entering the development process at a more mature stage.





In cases of low knowledge regarding performance and cost drivers, requirements typically drove high performance, high cost architectures. In cases of high knowledge of performance and cost drivers, requirements were challenged to achieve better value systems. Model 2 can again be viewed as a subset of Model 1 entering at a more mature state.

Cost has traditionally been considered a manufacturing or management requirement in the defense industry. Barriers exist to treating cost as a design requirement. There is often an engineering cultural bias against cost as a design requirement. The cost estimating tools are underdeveloped for use when they are needed most - in early stages of development. This suggests another reason why an affordability focus typically comes in latter design iterations when more knowledge of cost drivers exists. Although barriers exist, this research suggests more affordable products are developed when cost is managed using a system engineering approach of allocating cost goals throughout the system hierarchy and treating them like design requirements.

Integrated Product Teams provide the presence of downstream knowledge in the design process. Downstream knowledge takes the form of hardware engineers in the system design process or manufacturers in the hardware design process. Effective use of this knowledge is a classic problem of collaboration across boundaries where presence of knowledge is necessary but not sufficient. Mutual dependence, a clear goal and mutually accepted methods of assessing progress towards that goal greatly increase the effective use of downstream knowledge in system and product design. Mutual dependence can be established by treating cost as a design requirement – designers will need manufacturers' knowledge about cost to meet this design requirement. Cost analysis is the method for assessing progress provided it is credible to engineering and manufacturing stakeholders.

This thesis focuses on the underlying dynamics of a product development program and engineering and management execution issues that effect system affordability. A model for developing requirements that strike a better balance between performance and lifecycle cost is suggested – treating lifecycle cost as a design requirement and explicitly focusing on understanding the cost-performance space as a tool for developing more balanced requirements. A product development model is suggested – focusing on achieving lifecycle cost goals first and using iterations to grow performance can lead to affordability improvements. Both the requirements development and product development models require leveraging prior knowledge, technology and capability. The requirements model requires high knowledge regarding cost drivers and achievable performance. The product development model requires low technical risk allowing the team to focus on affordability first without running unacceptable levels of performance risk. Methods for increasing the effective integration of downstream knowledge are discussed.

1.2 Thesis Motivation - The Changing Nature of Competition for Military Avionics Firms

This thesis is motivated by the changing nature of competition for military avionics firms. The nature of competition has transitioned from performance to affordability. This section contains four main themes to illustrate this conclusion:

- The industry focus on affordability is here to stay
- This shift in focus is tangibly impacting behavior and decision making at the government and prime contractors. Military avionics firms that prosper in this era will develop a competitive advantage in delivering affordable systems.
- Affordable doesn't mean inexpensive. Affordable means better value, which encompasses both performance and cost.
- The primary leverage is in product design with secondary leverage in manufacturing and supply chain efficiency

The industry focus on affordability is here to stay

Norm Augustine, the former CEO and Chairman of Lockheed Martin, illustrated an alarming trend in his book, *Augustine's Laws*. If the tactical aircraft unit cost trend from the early 1900's through the 1980's continued on its historical trajectory, the entire United States defense budget will be able to afford only a single tactical aircraft by the year 2050. What's worse, the entire United States gross national product will be required to afford a single tactical aircraft by the year 2125 (figure 1.2.1).

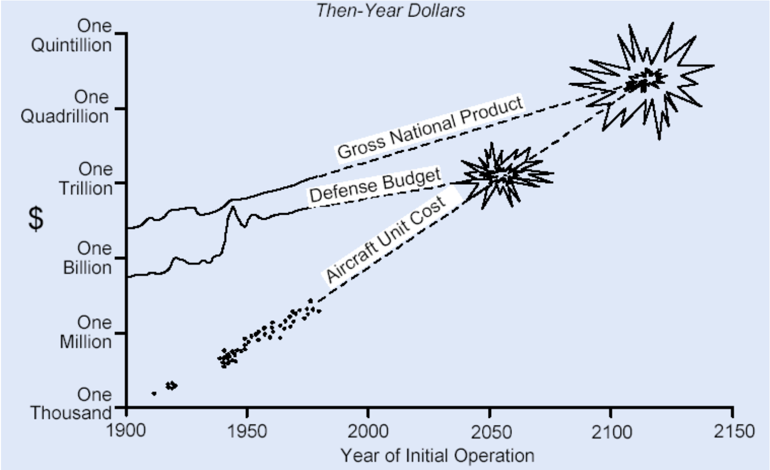


Figure 1.2.1 Trajectory of Aircraft costs, Defense Budget and GNP[1]

Of course, this is a satirical view of a very unlikely future. The United States will never spend its entire defense budget or its entire gross national product on a single aircraft. The point is that if the U.S. Aerospace Enterprise continues unchanged the entire defense department budget or gross national product would eventually be *required* to purchase a single tactical aircraft. This is a powerful argument that the increased focus on affordability is necessary in the aerospace industry.

On January 20, 1999, Dr. Jacques S. Gansler, the Undersecretary of Defense for Acquisition and Technology published a memo entitled, *Into the 21st Century - A*

Strategy for Affordability[2]. This memo has become to be known as the "Better, Faster, Cheaper" directive for the U.S. defense industry.

Dr. Gansler set three top-level goals with objective, verifiable measurements of success to focus the affordability initiative.

1. Field high-quality defense products quickly; support them responsively.
    - Reduce acquisition cycle time by 50% for all 1999 program starts
    - Reduce logistics response time by 50% by 2000 and 85% by 2005
    - Reduce repair cycle times by 10% by 2000 and 25% by 2001
2. Lower the total ownership cost of defense products.
    - Achieve unit cost and total ownership cost targets (that are 20-50% below historical norms) for 50% of systems in acquisition by 2000.
    - Reduce logistics support cost by 7% by 2000, 10% by 2001 and 20% by 2005.
3. Reduce the overhead cost of the acquisition and logistics infrastructure.
    - Reduce funding required by logistics infrastructure from 64% of Total Obligation Authority in 1997 to 62% by 2000, 60% by 2001 and 53% by 2005.

The importance of Dr. Gansler's memo over the long term remains to be seen. It is a sign that at the highest level's of the defense department, there is a recognition and demand for increased focus on affordability in system development, acquisition and field support.

James M. Utterback identified a trend of industry maturation and demonstrated it to be widely applicable in many different industries in his book, *Mastering the Dynamics of Innovation*[3]. Utterback's model contains three distinct phases in an industry's maturation: the fluid phase, transitional phase and specific phase.

The fluid phase is marked by frequent, major product changes with a small but increasing number of firms competing primarily on functional product performance. Market share fluctuates widely as fundamental product breakthroughs are relatively common until a dominant design is reached. A dominant design becomes the set of product features that define the essence of the product from that point forward. The dominant design for a tactical aircraft was reached many years ago (figure 1.2.2) and consists of a one or two seat cockpit, one or two jet engines, two forward wings, aft wings and aft horizontal stabilizers.

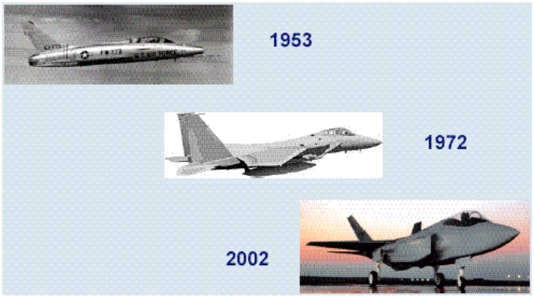


Figure 1.2.2 Dominant design in tactical aircraft is well established[4]

Once a dominant design is reached, the industry enters the transitional phase marked by industry consolidation creating a rapid decline in the number of competing firms, product innovation focusing on features instead of the fundamental architecture and competition transitioning towards product variation and ease of use. The transitional phase leads into the specific phase marked by very few firms competing on affordability with largely undifferentiated products and the primary industry innovation focused on affordability and process innovations. Figure 1.2.3 illustrates the transition from product innovation and performance focus to process innovation and affordability focus as an industry matures through the fluid, transitional and specific phases.

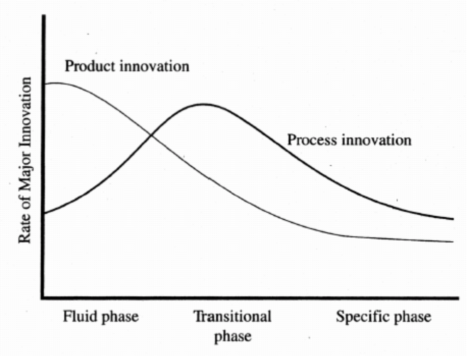


Figure 1.2.3 Utterback's model of industry maturation[5]

One clear mark of the transitional phases is industry consolidation. Far fewer firms remain in the industry during the specific phase than during the fluid phase and the transitional phase marks this, often painful, industry shake out (figure 1.2.4).

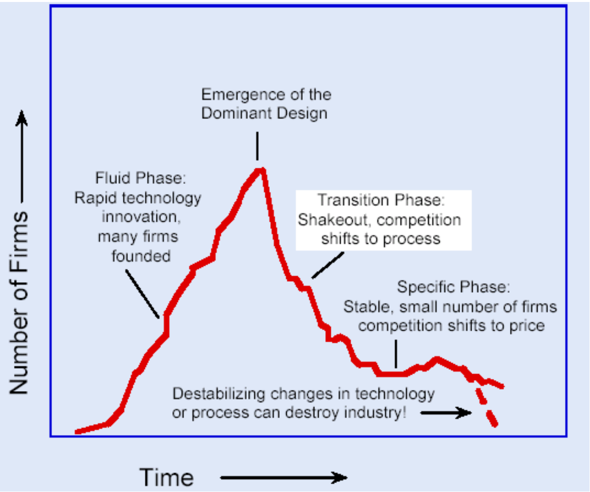


Figure 1.2.4 Typical pattern of number of competing firms through industry maturation[6]

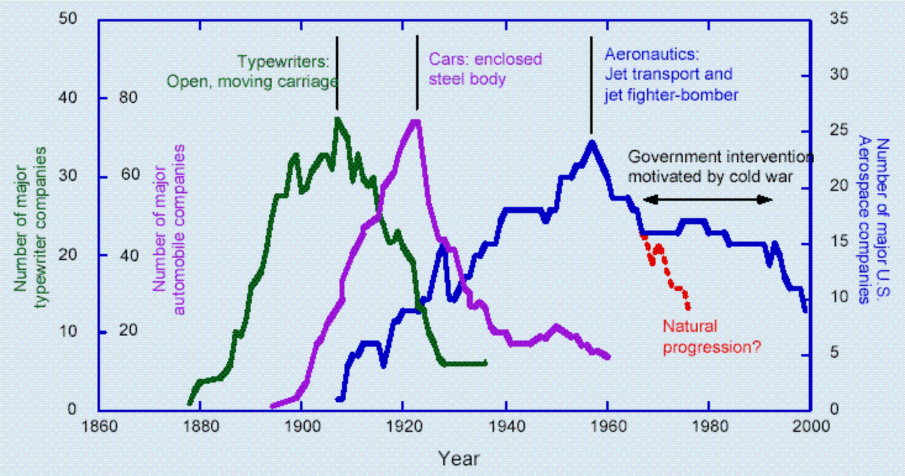


Figure 1.2.5 Utterback analysis of Typewriter, Automobile and Aeronautics Industries[7]

The aerospace industry is following this familiar and common pattern. Figure 1.2.5 shows the aerospace industry firm consolidation compared to similar consolidations in typewriters and cars.

Mr. Allen C. Haggerty, Vice President and General Manager (retired) of Military Aircraft and Missile Systems at The Boeing Company illustrated this transformation in the aerospace industry in his presentation entitled *New Directions in the Aeronautical Industry*[8]. The first piece of evidence is the reduction in product innovation from historical highs. He points out that federal investment in aerospace research and development in 2001 is 60% less than in 1991. Aerospace employment of research and development engineers and scientists is down 30% to 846,000 which is the lowest level on record. He shows that product innovation is slowing rapidly by showing the quantity of new air vehicle development programs during the typical engineer's career over the past several decades is dramatically shrinking (figure 1.2.6).

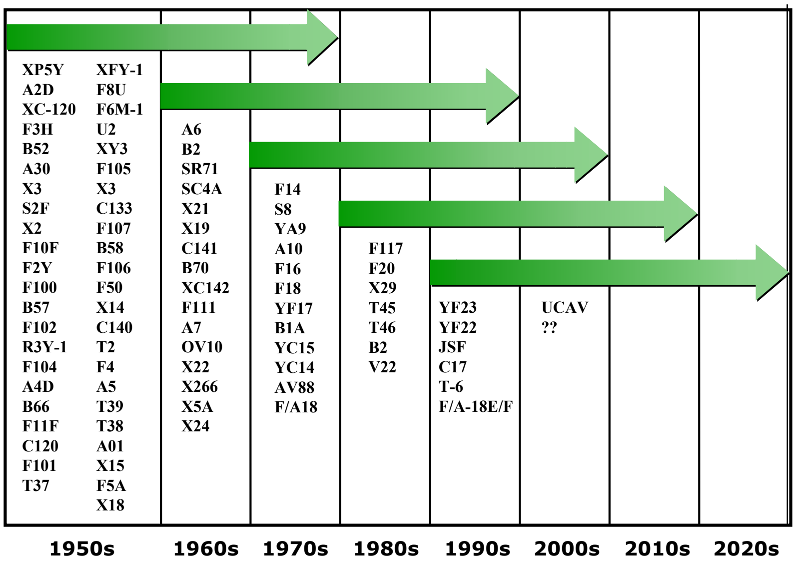


Figure 1.2.6 Quantity of new aircraft during an engineer's career is shrinking[9]

The second piece of evidence is the significant industry consolidation and reduction in the number of competing firms over the last half century as illustrated previously in figure 1.2.5 and by Mr. Haggerty in figure 1.2.7.

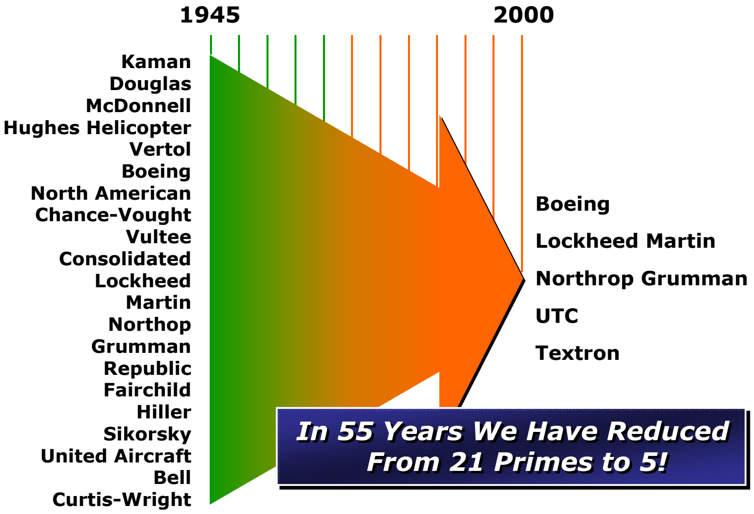


Figure 1.2.7 Consolidation suggests industry has entered the "specific phase"

Mr. Haggerty argues that "affordability is the key to delivering value to the military, NASA and commercial airlines" and that "weapon systems have value if they are delivered faster, better and cheaper."

In the book *Lean Enterprise Value*, a group of thirteen professors affiliated with MIT's Lean Aerospace Initiative summarize nicely the idea that this shift in priorities from performance to affordability is not likely a fad that will go away with the next presidential administration or Middle East flair up.

> "For much of its long history, the culture of best performance served the US Aerospace Enterprise well. In wartime - whether hot or cold - there are harsh penalties for falling behind in technology. But almost since the fall of the Berlin Wall, there has been a widespread recognition among industry thinkers and government policymakers that aerospace needs to shift from its performance driven culture, where cost is no object, to a focus on obtaining the maximum value for constrained dollars"[5]

Military avionics firms that prosper in this era will develop competitive advantage in delivering affordable systems

Now that we have established that the shift in focus from performance to affordability is likely here to stay in the defense aerospace industry, the question remains 'what does this mean to the military avionics firm?' Is this focus tangibly impacting the behavior and decision making at our customers - the government and prime contractors? Even if our customers are making decisions based more on affordability than performance at the highest levels of their organizations, will avionics receive sufficient top management attention to filter this shift in focus to avionics? Is there even industrial precedence that suggests operational advantage in delivering affordable products can translate into competitive advantage and increased market share?

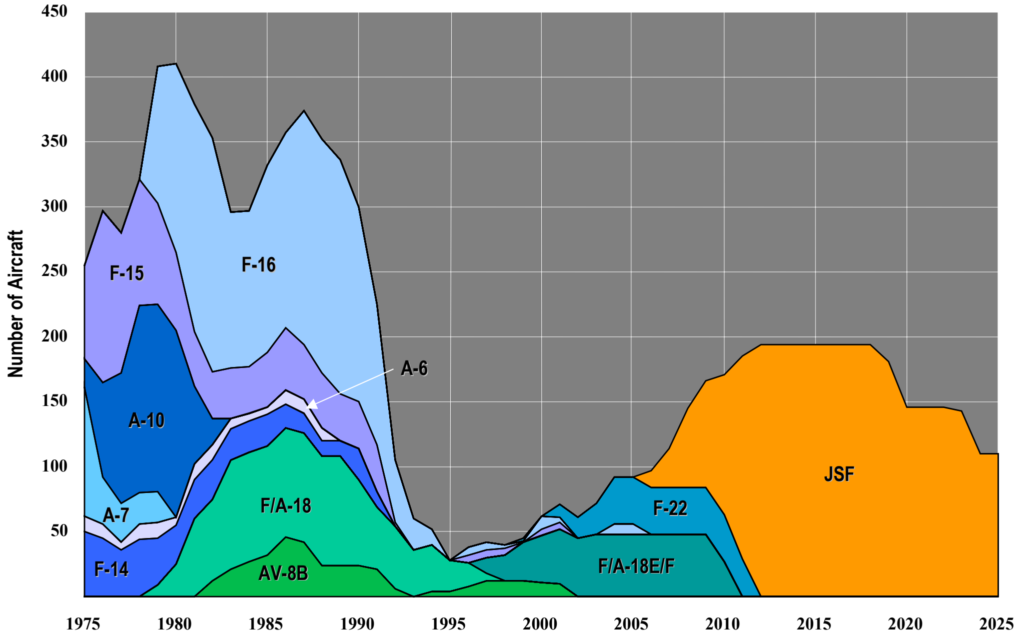


Figure 1.2.8 Annual procurement quantities of tactical aircraft[10]

The Joint Strike Fighter program is an excellent example of how the focus on affordability is changing behavior and decision making in the government. The Joint Strike Fighter program is potentially the most lucrative defense program in history with as much as $500 billion of business going to the winning team led by Lockheed Martin. According to Mr. Tom Burbage, Executive Vice President for JSF at Lockheed Martin, life cycle affordability is the top objectives of the program. The Joint Strike Fighter will replace the F-16, F-18, AV-8B (Harrier) and will be supplied to the United States, Britain and most likely a host of other NATO nations including Italy, the Netherlands, Turkey, Denmark and Norway. Primarily because of its affordability, the Joint Strike Fighter will become a transformational product - transforming all the U.S. services and their NATO partners and becoming the dominant manned fighter over the next several decades. In fact, the Joint Strike Fighter is practically the only new tactical air vehicle development program in the near future (figure 1.2.8).

Affordability is playing a bigger and bigger role in competitive decisions and the stakes are getting higher. Instead of having multiple new air vehicle development programs ongoing simultaneously with the different services, there is only one development program in the near future. This program is large enough that it can and will find suppliers that can deliver affordable avionics. Even the suppliers that win the development contract are not guaranteed the production contract. With three to six thousand aircraft planned in production and hundreds of billions of dollars at stake, the JSF program has the resources to replace an avionics supplier in production if they do not develop a capable, affordable system during the development program.

The JSF program illustrates that the government trend towards affordability but is the shift in focus tangibly impacting prime contractors? According to Mr. Haggerty, The Boeing Company has set aggressive goals and targets in becoming a more affordable aerospace company and is making impressive progress towards those targets (figure 1.2.9). The implication for the avionics supplier is that those who can help prime contractors, like The Boeing Company, achieve these strategic goals are more likely to win future business.

	Goal	2001 Status
– NRE development cost by	50%	48%
– NRE development cycle time by	50%	54%
– First unit (T1) cost by	66%	46%
– Design changes after release by	90%	90%
– First unit (T1) quality defects by	90%	In-Work
– Production recurring cost by	50%	39%
– Production recurring cycle time by	50%	In-Work
– Production recurring quality tags by	90%	65%
– Support (O&S) costs by	50%	25-40%

Figure 1.2.9 The Boeing Company's Affordability Goals and 2001 Status[11]

Is avionics likely to attract sufficient senior management attention to have the shift in focus effect avionics? The cost of avionics as a percentage of the total air vehicle cost has been steadily climbing over the past four decades and currently represents 25-35% of the cost of a new air vehicle (figure 1.2.10).

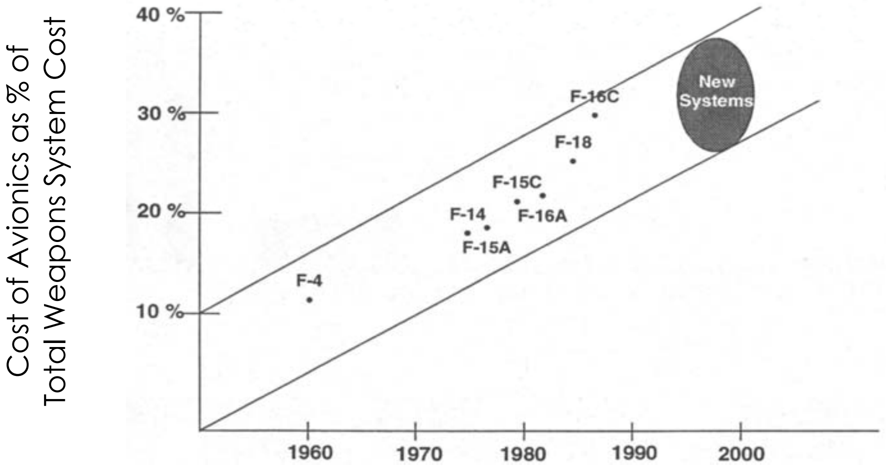


Figure 1.2.10 Cost of Avionics as a % of total air vehicle costs[12]

It seems hard to believe that the defense department and the aerospace prime contractors are going to shift their focus from performance to affordability and not impose this priority shift to 25-35% of their costs in the avionics suite.

Industrial precedence exists to suggest that military avionics firms that develop operational advantages in delivering affordable systems could exploit this for competitive advantage and increased market share. The automotive industry is a good example of this precedence. Figure 1.2.5 illustrates that aerospace and automotive industries have both been through a very similar pattern outlined by Utterback's model of industry maturation but the automotive industry experienced maturation several decades before aerospace.

In the book *The Machine that Changed the World*[13], the authors showed that large organizations designing complex products can significantly improve the affordability of their products and their organizations through design, production, distribution and management techniques that have today become known as a Lean Enterprise. Figures 1.2.11 and 1.2.12 illustrate the operational advantages the Japanese automotive firms, particularly Toyota, have developed over the competitors around the globe.

	GM Framingham	Toyota Takaoka
Gross Assembly Hours per Car	40.7	18.0
Adjusted Assembly Hours per Car	31.0	16.0
Assembly Defects per 100 Cars	130	45
Assembly Space per Car	8.1	4.8
Inventories of Parts (average)	2 weeks	2 hours

Note: Gross assembly hours per car are calculated by dividing total hours of effort in the plant by the total number of cars produced. "Adjusted assembly hours per car" incorporates the adjustments in standard activities and product attributes described in the next text. Defects per car were estimated from the J.D. Power Initial Quality Survey for 1987. Assembly space per car is square feet per vehicle per year, corrected for vehicle size. Inventories are a rough average for major parts.

Figure 1.2.11 Operational advantage in manufacturing

	Japanese Producers	American Producers	European Volume Producers	European Specialist Producers
Average engineering hours per new car (millions)	1.7	3.1	2.9	3.1
Average development time per new car (months)	46.2	60.4	57.3	59.9
Average ratio of shared parts	18%	38%	28%	30%
Supplier share of engineering	10-20%	30-50%	10-30%	
Ratio of delayed products	1 in 6	1 in 2	1 in 3	
Return to normal productivity after new model (months)	4	5	12	
Return to normal quality after new model (months)	1.4	11	12	

Figure 1.2.12 Operational advantages in designing the car[14]

The Japanese automotive companies directly leveraged these advantages in engineering and manufacturing affordability into competitive advantages and increased market share (figure 1.2.13).

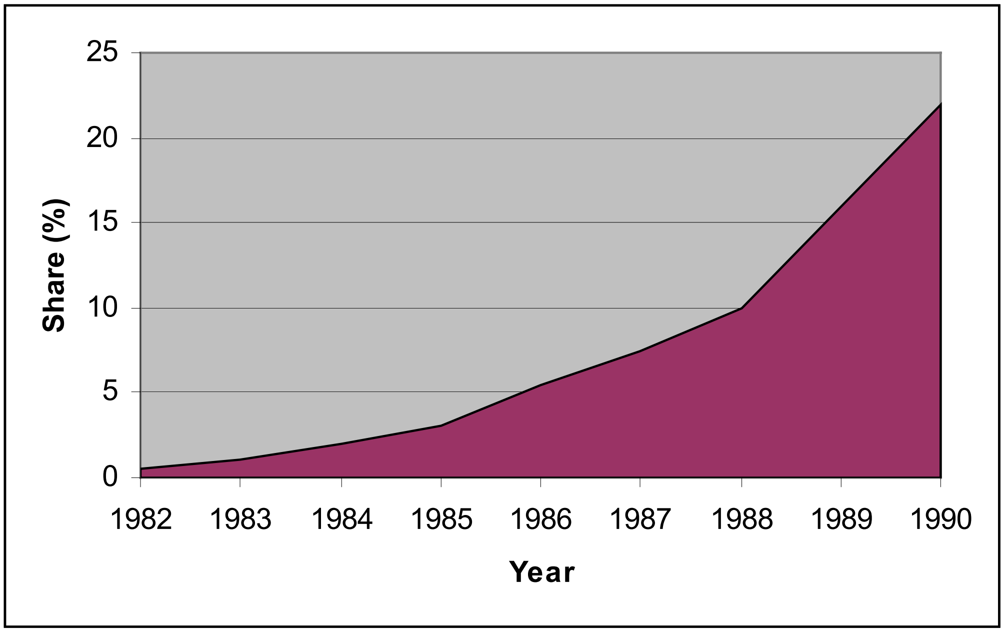


Figure 1.2.13 Increasing market share of Japanese automotive firms[15]

Note: 1990 is estimated based on production in the first three months.
Source: Calculated by the authors from Ward's Automotive Reports.

The story of *The Machine that Changed the World* is similar to what *could* happen in the military avionics industry. Affordability is becoming more valued by the United States defense department and the aerospace prime contractors. Study of other industries suggests that this trend will continue. If it does and if a company develops an edge against its competitors in developing affordable systems, similar market share changes among existing companies are likely.

Affordability means better value which encompasses both performance and cost

In the book *Lean Enterprise Value*, a group of professors in MIT's Lean Aerospace Initiative recognize that the typical approach firms take when industries enter the *specific* phase of the industry lifecycle is to focus purely on the cost side of affordability by striving to become more efficient. The authors' advocate an alternate approach for aerospace firms - focusing on increasing value. "Value *must* be the focus. It encompasses both 'performance', the dominant focus of the Cold War era, and affordability, the dominant focus since the Cold War"[5]. However, the authors recognize the challenge before the aerospace industry.

> "How does a set of industrial enterprises focused on high performance products to an annual market of $100 billion find business equilibrium as half of the industry becomes excess capacity in just a few years and affordability becomes paramount? How does an industry that has accommodated itself over decades to excelling in technology adapt to a new era in which efficiency of manufacturing and lifecycle support processes becomes dominant? Cultural monuments include a mindset that focuses on best technical performance to the detriment of other considerations, a systemic aversion to risk and disincentives to cost reductions."[16]

The authors' stress that increasing the value of aerospace products means balancing operational capability and cost over the product lifecycle which offers unique challenges for aerospace firms to be adaptable over the long lifecycles of their products.

> "It is not unusual to take five to ten years or more to develop an field a new aerospace product, which might then have a lifetime exceeding fifty years. Over such long periods, the external environment, available technology and market opportunities all change. This often results in radical changes in the way the end user will use the product, as well as in the needs of other stakeholders. Programs today must be flexible and adaptable, effectively integrating both mature and emerging technologies, anticipating and mitigating instabilities in funding and staffing, pioneering new business models and operating in a global context. Some programs, such as the F-16, succeed in this environment. Others do not. F-16 value has been sustained as much by its adaptability to changes in the global environment and customer requirements as by its drive for affordability. The F-16's success rate in open sales competitions is 67% over its lifetime, 75% in the 1990's and 100% from 1996 to 2000."

The primary leverage is in product design with secondary leverage in manufacturing and supply chain efficiency

Lean is getting significant attention throughout the aerospace industry because of the significant impacts it had on the automotive industry. Although Lean Thinking has been linked with value, most of the aerospace industry's focus in Lean has been on increasing the efficiency of product development and manufacturing throughout the supply chain. Figure 1.2.14 suggests that more leverage exists to reduce lifecycle costs in system and product design than in manufacturing.

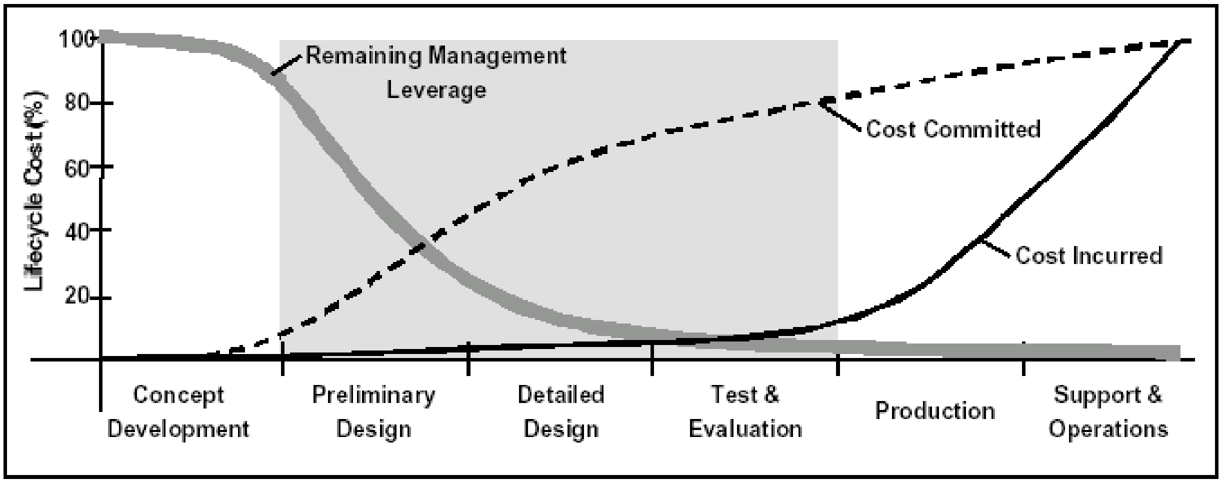


Figure 1.2.14 Lifecycle cost committed vs. incurred during a typical program[17]

The end of product development commits eighty percent of a product's lifecycle costs, even though only ten percent of the lifecycle costs are incurred. The end of concept development uses up more than eighty percent of management leverage on lifecycle cost. The primary leverage in reducing lifecycle costs lies in product design with secondary (but certainly not unimportant) leverage in manufacturing.

System design offers the most leverage in improving system affordability because it has the maximum influence on both lifecycle cost and performance capability over the product's lifecycle.

Closing remarks

The aerospace industry has shifted priorities from performance to affordability - balancing performance and cost. This shift is necessary and here to stay. Supporting evidence comes from several industry leaders. Utterback's framework demonstrates that this shift in priorities is a natural and common evolution of a maturing industry. Firms that prosper will adapt. Firms that do not adapt will likely perish or be reduced to niches in the industry.

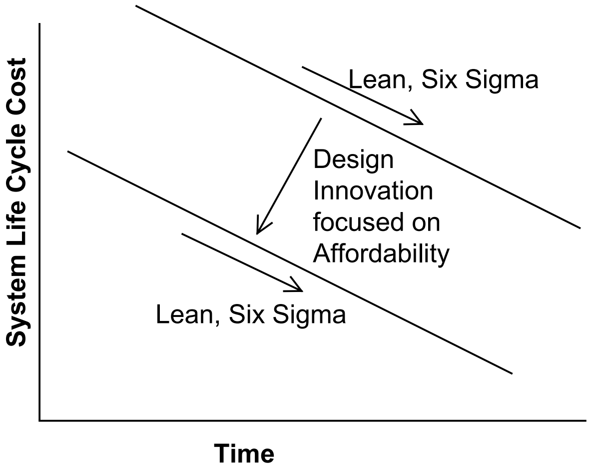
This change in priorities will impact avionics firms. Behavior and decision making at the government and prime contractors are showing tangible changes. The government has awarded JSF, the largest program in history, based fundamentally on affordability. There is evidence that The Boeing Company has set aggressive affordability targets and made significant progress towards meeting those targets. The F-16 business model suggests that avionics contains the most leverage to successfully adapt operational capability over the platform's lifecycle to changes in user needs.

The change will not be easy. There are significant cultural barriers to overcome. But, there is an opportunity for avionics firms that develop an operational advantage in delivering affordable products. The Japanese automakers are an example of firms that did develop such an operational advantage over their competitors and were able to translate that into increased market share.

MIT's Lean Aerospace Initiative is advocating that the focus on affordability should mean a focus on value - creatively balancing performance and cost. Based on this concept and the fact that 80% of a typical system's lifecycle costs are committed by the end of the development program, the most leverage for the avionics firm is to focus on system and product design.

1.3 Thesis Problem Statement and Research Objectives

This thesis investigates improving military avionics system affordability from an avionics supplier's perspective. In certain military avionics market segments, the nature of competition is changing from performance based to affordability based. Firms that develop a competitive advantage in delivering affordable systems will capture market share in these segments. Significant research under the umbrellas of Lean and Six-Sigma has been focused on increasing the efficiency of product development, manufacturing and the extended supply chain to improve affordability. These techniques can generate incremental improvements that accumulate year after year and lead to significant benefits over time. These techniques alone are insufficient to develop competitive advantage because everyone can apply them to any system concept. Developing competitive advantage requires Lean and Six-Sigma efficiency <u>and</u> step function improvements from design innovations focused on affordability. These innovations involve system architecture and module design choices that strike a better balance between life cycle cost and performance.



The objective of this thesis is to increase understanding of the factors that effect design innovations focused on affordability to identify engineering and management actions to be implemented during future development programs. The four broad areas for investigation are:

- The nature of development focus during each design iteration
- The role of requirements
- Managing lifecycle cost as a design requirement
- Effective integration of downstream knowledge into the design

In order to pursue a thesis rigorously with the goal of identifying practical methods to develop affordable military avionics systems, a rigorous definition of an affordable system is needed. Do we mean cheap on an absolute scale? Do we mean cheaper than our competitors? Do we mean better cost-performance value to our customers than our competitors? Do we mean meeting or exceeding the cost-performance value requirements and expectations of our customers?

To answer these questions, we need to ask why avionics firms want to develop affordable systems.

Is it lower cost? No. The defense industries' contracting structure provides a disincentive to lowering costs as a sole objective. Typically development contracts are cost plus and are followed by fixed price production contracts negotiated annually based on verifiable cost projections plus a negotiated profit. In both cases, the avionics firm's sales and profits are based on their costs - the more cost, the more sales and more profit. Conversely, on a given program lower costs lead to lower sales and lower profit. Low cost can not be the only objective for the avionics firm.

Is it competitive advantage? Yes. Avionics firms want to develop affordable systems because that is what their customers want. Much has been documented about the shift in the U.S. defense industry from demanding performance to demanding affordability or value. There are actually several types of cost. Today, the defense customer is demanding performance - Life Cycle Cost value. Life Cycle Cost (LCC) is the sum of the development costs, production acquisition costs and operations and support costs (repairs, spares, maintenance, training, etc). The desire to develop affordable systems is primarily a response to customer demand.

If the goal is competitive advantage, it is useful to briefly discuss how avionics firms compete. Avionics firms do not sell products, they sell perceived capability to develop products. Avionics firms are paid, typically in a cost reimbursable contract, to develop products for their customer. At this point, the customer is typically locked into the selected supplier for production because the switching costs to a different supplier are cost prohibitive. In general, avionics firms win new business when they win the development contract. When they compete for the development contract, they do not typically have a product, they have a concept of a product based on their capabilities developed on internal research and development, contract research and development and previous development programs. So, they are selling a concept and perceived future capability based on demonstrated past capability. To achieve the competitive advantage these firms seek, it is critical to demonstrate results in developing and delivering systems with high performance-LCC value.

Back to our series of questions regarding the definition of an affordable system.

Do we mean cheap on an absolute scale? No.

Do we mean cheaper than our competitors? No. Today's defense customer is not demanding cheap products, he is demanding costs with higher value. Just being cheaper than your competition is not necessarily a competitive advantage.

Do we mean better cost-performance value to our customers than our competitors? Do we mean meeting or exceeding the cost-performance value requirements and expectations of our customers? Yes. In practical terms it is difficult to directly compare the value of products because avionics firms don't typically develop directly competing products. They compete for the right to develop a product so only one product is ultimately developed leaving nothing to compare directly. The critical point to achieve competitive advantage is to develop a track record of developing systems that meet or exceed the customers performance requirements and Life Cycle Cost expectations. This track record becomes part of the demonstrated past capability that is the basis for competition on new business opportunities.

This leads to an objective of developing an industry reputation for delivering systems that meet the customer’s performance and lifecycle cost goals. Delivering what was promised hardly seems like a path for developing competitive advantage – it seems like a path for achieving parity with competitors. Don't all firms deliver what they promise most of the time? Wouldn't a firm striving for competitive advantage need to exceed the customer's goals for performance and life cycle cost? This leads to a fundamental dynamic in the defense industry somewhat unique from other industries. New business is awarded on the promise of future capability, not the demonstration of existing capability. Awarding new business on the promise of future capability typically leads to aggressive projections of future capability in order to win new business in highly competitive acquisitions. Aggressive projections can take the form of optimistic estimates in development cost, development schedule, system performance and/or system lifecycle cost. Since the contract is awarded to the firm that credibly projects the best capability, highly competitive acquisitions typically result in a over-constrained program space – meaning development budget, schedule, performance and lifecycle cost goals are not all achievable. Another dynamic that leads to initially over-constrained programs is the relatively high uncertainty regarding achievable performance and lifecycle cost before the development program begins. The high uncertainty means that the initial set of requirements may not strike the best balance between performance and lifecycle cost within budget and schedule constraints. An inherent and value-added aspect of a development program that has high initial uncertainty is collaboration between customer and supplier to optimize the requirements to achieve the best balance of performance and lifecycle cost. This is why meeting both performance and lifecycle cost goals can create competitive advantage on over-constrained programs. This also explains why over-constrained programs are common in the military avionics industry.

For this thesis, the definition of an affordable system is one that meets or exceeds the customers' goals for system performance and Life Cycle Cost in an over-constrained program space where development budget, schedule, performance and life cycle cost goals are not all achievable.

1.4 Research Overview and Summary of Thesis Contributions

This research involved case study investigations of seven military avionics development programs ranging in complexity from hardware development programs with products that fit in the palm of your hand to large system development programs involving hundreds of pounds of hardware and hundreds of thousands of lines of software code.

This thesis explicitly focuses on design innovation as a means to create step function improvements in system affordability. Although this focus is not unique, it does differ from much of the published literature on affordability that is focused on increasing productivity and efficiency in product development and manufacturing. This thesis explicitly focuses on affordability defined as meeting or exceeding the customer's goals for system performance and lifecycle cost – indicating increasing value is a more appropriate objective than lower cost. This view that affordability has a cost and a value component is an extension of the ideas published in *Lean Enterprise Value*[18], a book from MIT's Lean Aerospace Initiative. Although the findings are probably more generally applicable, this thesis investigates system affordability specifically for military avionics systems and specifically from the perspective of the avionics supplier. This is different from most published research on affordability focused on issues aimed at the government defense acquisition community or aerospace prime contractors. This thesis aims to contribute to the body of knowledge that can help Tier 1 military suppliers develop competitive advantage in delivering affordable systems to their prime contractor or government customers by making engineering and management changes in they way development programs are executed.

The thesis document is organized into five chapters or sections. This paragraph concludes chapter 1, which introduces the topic, problem statement and briefly summarizes the findings. Chapter 2 discusses topics published in the literature most relevant to the subject of system affordability and describes how the published literature shaped the direction of this research. Chapter 3 describes the research conducted for this thesis. Seven military avionics programs were researched by interviewing forty engineers and managers. Chapter 4 discusses the results and conclusions the author reaches from the research described in Chapter 3. Chapter 5 contains a brief summary and closing comments.

2 Literature Review

2.1 Literature Review Systemic Approach

A literature review was conducted to understand the issues facing the aerospace industry today relevant to developing more affordable military systems. The goal of this review was to serve as a launching pad into the case study research documented in section 3. The hypothesis of this literature review was that a lot can be learned both from specific insights people write *and* by determining the topics people write about. A systemic approach was taken to analyze a significant quantity of literature to determine what people write about. Seventy-five (75) documents were reviewed and the key points were summarized as critical issues or best practices. The seventy-five documents included 32 presentations, 17 masters and doctoral thesis, 26 white papers and published articles. There is a mix, but most of these documents represent practitioners experience as opposed to peer reviewed research. From these writings, 440 key points were categorized as critical issues or best practices. Critical issues were defined as important issues or challenges that must be overcome to improve the ability to develop affordable systems. Best practices were defined as innovative practices that serve as solutions to these types of issues. The following broad areas were defined and each of the 440 key points were categorized into one of the areas:

- Product system design (architecture, technology, requirements)
- Organizational issues (structure, learning, collaboration across boundaries)
- Program management and product design process
- Business model and incentives
- Tools, metrics and goals
- Culture
- Manufacturing
- Supply chain management
- LEAN enterprise

The hypothesis of this analysis of the literature is that people write about their critical issues (who would write about a trivial issue?). People write about their best practices when they are relevant - when they address one or more critical issues. So, understanding what people are writing about, not just what they are saying, will provide some insight into the critical issues facing the aerospace industry today. Of course, this approach is limited by what people do write about so will not highlight any new issues. Section 2.2 will summarize the results of this systemic analysis of what people write about. Section 2.3 will summarize key insights in the prominent broad areas.

2.2 Results of Literature Analysis

Figures 2.2.1 and 2.2.2 illustrate the percentage of the 440 key points that were categorized as best practices or critical issues. It also illustrates the percentage of the best practices and critical issues that were categorized within each of the nine broad areas (product system design, organization issues, program management and product design process, business model, tools, metrics and goals, culture, manufacturing system design, supply chain and LEAN enterprise processes). The average and weighted average percentages are calculated for each broad area. The average is simply the average of the percentage in the best practices and critical issues categories for each broad area. The weighted average weights the best practices and critical issues percentages by the quantity of lessons learned identified in each category. In other words, the best practice percentage is weighted more heavily than the critical issues percentage because more lessons learned were categorized as best practices.

	Best Practices	Critical Issues	Average	Weighted Average
Product System Design	28%	20%	24%	27%
Organizational issues	19%	20%	20%	19%
Program Management and Product Design Process	13%	28%	21%	16%
Business Model	7%	13%	10%	8%
Tools, Metrics and Goals	9%	5%	7%	9%
Culture	5%	9%	7%	6%
Manufacturing System Design	9%	1%	5%	8%
Supply Chain	4%	3%	3%	4%
LEAN enterprise processes	5%	0%	3%	4%
Total Lessons Learned Identified	365	75	440	440

Figure 2.2.1 Tabular Results of Literature Analysis

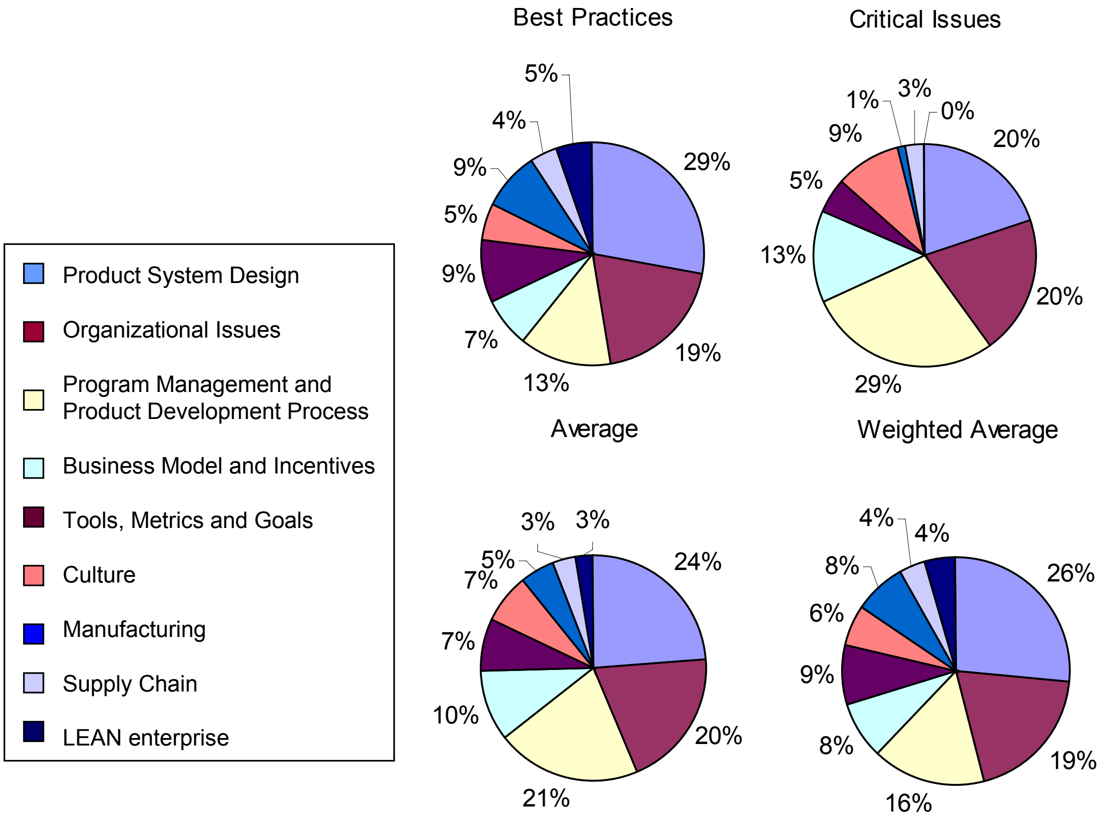


Figure 2.2.2 Graphical Results of Literature Analysis

A bibliography of the seventy-five pieces of literature used in this analysis is included for reference in Appendix A. The 440 summarized key points are included in Appendix B.

Applying the "80/20 rule", based on this analysis, the broad areas that people are primarily writing about are:

- Product system design
- Organizational issues
- Program management and product development process
- Business models and incentives

Figure 2.2.3 illustrates the percentage of key points that fell into these four broad areas.

	Best Practices	Critical Issues	Average	Weighted Average
Four "Primary" Broad Areas	68%	81%	75%	70%
Other "Secondary Broad Areas	32%	19%	25%	30%

Figure 2.2.3 Percentage of key points in "primary" and "secondary" broad areas

Depending upon which category is evaluated (best practices, critical issues, average or weighted average), approximately 70-80% of the key points from the 75 pieces of literature surveyed centered around product system design, organizational issues, program management/product development process or business model/incentives. These broad areas will be discussed in greater detail in section 2.3. The remaining broad areas (tools/metrics/goals, culture, manufacturing, supply chain and LEAN enterprise) will not be covered in any greater detail.

2.3 Discussion of Key Points

2.3.1 Product System Design

Product system design is discussed extensively in literature for several reasons because it is generally accepted that somewhere between 60-80% of a new system's lifecycle cost is determined by the product design (see figure 2.3.1)

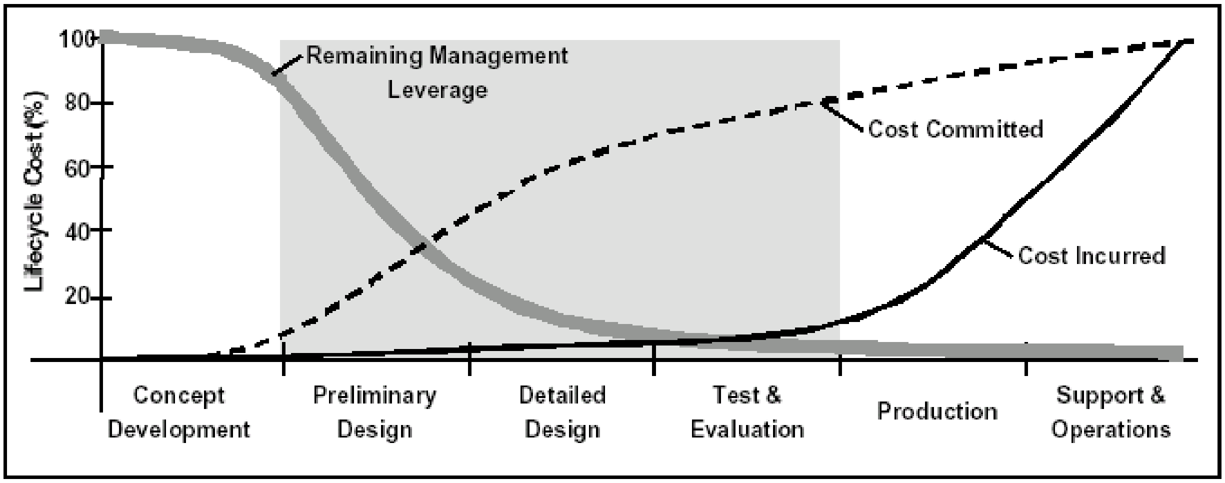


Figure 2.3.1 Lifecycle cost committed vs. incurred during a typical program[19]

The key points in the literature applicable to this thesis and related to system design and systems engineering are in the areas of requirements and commonality across systems. The specific key points for each of these areas will be covered in the following sections.

Requirements

The essential key points relative to requirements are:

- Performance requirements must be challenged at all levels to balance cost and performance
- Life Cycle Cost should be considered a design requirement

Mr. Michael Griffin, Executive Vice President and Chief Technology Officer of Orbital Science Corporation explains that "requirements must be challenged at all levels - both top down and derived requirements and further down the design process than usual."[20] "However, CAIV (Cost as an Independent Variable) does not grant cart blanche to change performance requirements. Operational requirements must be met. Methods of achieving operational requirements can be modified. The key is to define operational requirements not performance requirements."[21]

Mike Fortson, Director of Affordability for the Joint Strike Fighter program at Lockheed Martin, explains that the largest military program in history is embracing the idea that Lifecycle cost should be considered a design requirement and treated like other design requirements. "Lifecycle cost is a design requirement, flowed down to the lowest level IPT and suppliers and must be considered with other performance parameters. Lifecycle cost receives a monthly executive level review and is reported quarterly to the government."[22]

Commonality Across Systems

One of the strong arguments for modular system architecture with standard interfaces is that architecture and interfaces can be carried to the next platform or system. If the architecture and interfaces are common, then modules can now be reused across systems or platforms. This offers significant advantages in cost, development cycle time and risk. Cost benefits arise from production economies of scale across programs and dramatic benefits in maintenance costs from common replacement modules at customer depots. Development cycle time and risk benefits arise from reducing the scope of developing a new system - only the unique modules require development, the common modules are simply carried over from a legacy program. Common subsystems can be a method to "steal" an iteration or spiral during a development program.

Matthew Nuffort offers insight into both the benefits of commonality across platforms and some strategies to create commonality across platforms in his MIT master's thesis, *Managing Subsystem Commonality*[23].

Figure 2.3.2 illustrates the benefits possible from common subsystem strategies discovered in Nuffort's research. In addition to cost savings, Nuffort argues that subsystem commonality reduces development cycle time by taking advantage of design reuse.

Subsystem Acquisition Cost Savings From Commonality:
Fleet Installed Cost 10-35% savings
+ Initial Spares Cost 30-50% savings
+ Fleet Support Cost 50-75% savings
= Acquisition Costs Depends on cost structure

Annual Subsystem O&S Cost Savings From Commonality
Maintenance Labor 10-35% savings
+ Maintenance Material 10-25% savings
+ Spares Handling 30-50% savings
+ Operational support 50-75% savings
= O&S Costs Depends on cost structure

Figure 2.3.2 Potential benefits from subsystem commonality strategies

Nuffort also offers the following strategies for how to implement a common subsystem strategy.

Commonality Makes Sense at the Subsystem and SRU Level

- Commonality generally makes the most sense at the subsystem level, because it is at this level where the difference between the benefits and the costs of commonality is maximized. Subsystems are sufficiently complex and costly such that their commonality produces a significant cost advantage in all phases of the life cycle. At the same time, subsystem requirements often are at a low enough level to make it possible to effect commonality without compromising any particular system's requirements too much.

A Common Organization That Manages Across Platforms Has Many Advantages

- A common organization has the ability to keep track of the requirements of multiple platforms and recognize opportunities for cooperation. The common advocate, as an unbiased participant, also functions as a mediator between different platforms during such coordination to reconcile differences in requirements.

Contractors Should Focus on Modular and Open Architectures for System Sustainability

- To deal with electronic subsystems with high rates of technology turnover, contractors will need to work with common program offices to define and manage interface standards to guard against DMS and account for rapid changes in technology.

Commonality of subsystems across product families is also discussed in Meyer and Lehnerd's book, *The Power of Product Platforms. Building Value and Cost Leadership*[24]. Black and Decker experienced a reduction in manufacturing cost ranging from 40-70% on their basic circular saws, jigsaws, sanders and drills by implementing a product platform strategy. This strategy principally centered on common subassemblies or building blocks for their power tool line - common motors, batteries/power units, etc.

> "It avoided a piecemeal, single product focus. Instead management dealt with the power tool product line as a whole. It bridged the traditional divide between engineering and manufacturing with the result that both products and processes for creating them were simultaneously redesigned. Senior management adopted a long term horizon and made the initiative a top priority."

Boeing 777 offered an example of commonality of parts within the airplane (vs. across other airplanes). The 777 design provided more options and flexibility for customers while using significantly fewer unique parts and more common parts. The following benefits were cited:

- *Doors*. A typical aircraft passenger entry door has 1,400 parts, most being unique. In the seven doors on the 777, 95% of the parts are common to all doors.

- *Overhead bins*. In the past, overhead bins were unique to each airplane. The 777 has only three standard bin geometries. They are usable with any class of seating by simply changing the hinge points.

- *Seating*. Reconfiguring the seating in previous aircraft required a week of work. Thanks to the 777'snew modular "interfaces" between seats and the aircraft structure, seating can be reduced overnight"

Subsystem commonality across platforms offers advantages in affordability and development cycle time but there are some barriers to overcome. Programs are funded separately and costs tracked and managed very carefully to ensure that none of program A's funding is spent on program B. Firms that pursue this strategy will need to overcome these barriers and move from managing programs separately to more common organizational structures across programs. The avionics firm is generally limited to subsystems within their particular avionics system. More commonality would require prime contractors to standardize avionics interfaces like form factors, data bus structures and power supply voltages.

Closing Remarks

Focus on product system design is critical to developing affordable systems because 60-80% of a system's lifecycle costs is determined by the design. The literature in system design focuses in two areas:

- Requirements
- Subsystem commonality across systems or platforms

To develop an affordable system, firms should treat Life Cycle Cost as a design requirement and it should be traded, assessed and negotiated like other design requirements. This requires cost-performance trades to challenge performance requirements at all levels, and probably to a lower level in the design than has been typical in the industry. Performance requirements also need to allow design decisions to be made at the lowest level where the knowledge of the cost-performance tradeoffs is typically greatest. This requires specifying performance requirements and avoiding implementation requirements.

Subsystem commonality across platforms has been shown to produce dramatic benefits in affordability. 10-75% reductions in various categories of production and Operations and Support costs have been realized implementing subsystem commonality strategies. However, these strategies face challenges. The industry has focused on individual products and not product families. This focus is ingrained in the industry contracting structure. Prime contractor involvement is critical to increase subsystem commonality across platforms by standardizing critical system interfaces like form factor, power supply voltages and data bus structures.

Key Variables for Case Study Research

The role of requirements on system operational capability and lifecycle cost is well documented in the literature. However, the paradox is that during the requirements development phase, you have the greatest impact on performance and cost but you have the least knowledge of achievable performance and cost drivers. The high uncertainty regarding achievable performance diminishes the team's willingness to trade performance for cost. The low knowledge regarding cost drivers diminishes the team's ability to know where to challenge performance for the greatest impact on cost.

Key variables used in each case study will include:

- Is the technical customer at the next higher level of the system hierarchy willing to trade performance for cost?
- Do you have sufficient knowledge regarding achievable performance and cost drivers to effectively trade performance against cost during the requirements and architecture development phase?
- Does leveraging past programs and/or subsystem commonality across programs increase knowledge of achievable performance and cost drivers during the requirements and architecture development phase?

2.3.2 Organizational Issues

Organizational issues are discussed in the literature at great length. Some of the key areas in the literature relevant to managing system development programs to produce more affordable systems include:

- *Organizational structure.* Managing a system development program explicitly focused on affordability requires some structural organization changes. Managing for affordability is inherently a cross functional endeavor that crosses into practically all functional areas but it must be someone's responsibility to coordinate these functional areas on affordability issues.
- *Collaborating across boundaries.* As managing for affordability is inherently a cross-functional endeavor, collaborating across functional boundaries is a critical challenge to overcome. Some of the key boundaries to cross are those between systems engineering and the user, systems engineering and the detailed designers and the manufacturer.

Organizational Structure

In Jack Michael and William Wood's book, *Design to Cost*[25], the authors offer a method for organizing a development program to facilitate affordability management during system and product development. Figure 2.3.3 illustrates the structure.

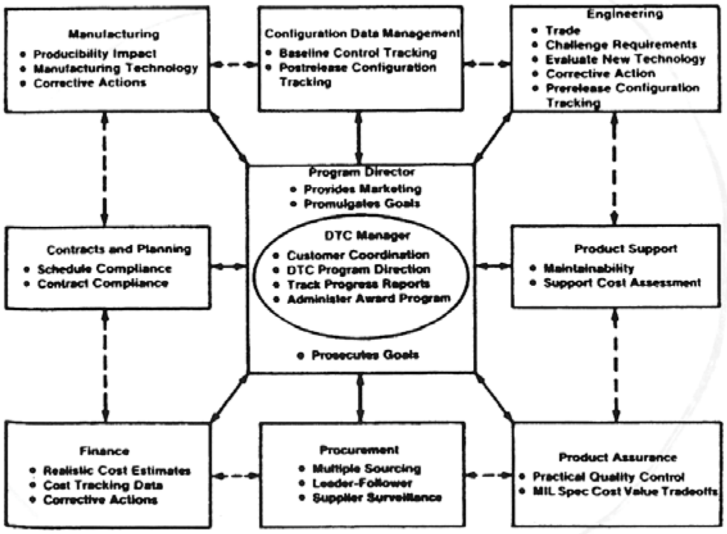


Figure 2.3.3 Organization structure, roles and responsibilities

> "In this organization, the "Design to Cost" manager reports directly to the program director to ensure independence. The tendency to appoint the manufacturing manager, or for that matter the engineering manager, can lead to conflicts of interest since the performance evaluation of these individuals is initially influenced largely by their functional departments, and frequently functional and program objectives are at odds with each other."

The functional managers shown in Figure 2.3.3 are those already on the program, fulfilling their respective line responsibilities, ensuring that design to cost is an integral part of their normal functions and avoiding the cost burden of additional staff.

The authors offer additional insights into the roles and responsibilities of the functional areas. The engineering, manufacturing and procurement organizations are included here as they dictate nearly all of the life cycle cost of a new product.

Engineering Organization
The actions and decisions of the engineering organization affect every other functional discipline so it takes the lead during design development. Engineering is responsible for making hardware design changes for improved producibility, reviewing costs of existing designs, challenging requirements, identifying and conducting trade studies and providing members to support the procurement and manufacturing organizations.

Manufacturing Organization
Aggressive participation of the manufacturing organization is required during the development phase. Manufacturing representatives should be IPT members and participate in the design and evaluation of the product. Manufacturing is responsible for make-or-buy plans, production plans and concepts that are consistent with cost goals (includes labor standards, capital, process development), recommend hardware design changes to improve producibilty and tracking and monitoring design changes against a baseline for cost impacts.

Procurement Organization
Typically, 40-60% of the cost of high technology products can be spent on procured items so the procurement organization is critical to meeting cost goals. Procurement is responsible to provide supplier cost history, support cost oriented trade studies and provide source selection data. Additionally, procurement should provide close liaison with suppliers of designed parts to make optimum use of advances in suppliers' technologies, provide supplier producibility inputs and recommendations on requirements changes and extend design-to-cost requirements and incentives to suppliers.

Collaboration Across Boundaries

Collaboration across boundaries simply means getting multiple individuals or groups from different organizations or different technical backgrounds to work together towards a common goal. Collaborating across functional organizations within a firm has long been an issue. The primary intent of Integrated Product Teams is to increase the effectiveness of collaborating across functional boundaries. The problem is getting harder as firms become less vertically integrated and the industry consolidates. As firms become less vertically integrated, a higher level of design collaboration is required across company boundaries. Collocation, one of the cornerstones or the IPT structure becomes more difficult or impossible. Alignment of goals, another of the IPT cornerstones, among firms is also more challenging. In today's consolidated defense industry, collaboration across firms becomes challenging as your supplier on one program is also a customer on another and a competitor on yet another. This can lead to misalignment of goals.

For effective collaboration across boundaries, three key elements are required:

- Mutual dependence
- Clearly defined goals
- Mutually accepted method(s) to define progress towards goals

William Blake's research in his MIT master's thesis, *Using System Dynamics to Understand Barriers to Cost Reduction*[26], focused on barriers the product development organization at an aerospace engine manufacturer was facing in improving their ability to develop affordable products. Blake identified two primary barriers.

- Time constraints in the product development process caused designers to skip "optional" tasks like IPT meetings and design for manufacturability and design to cost tasks
- Design engineers were not knowledgeable about cost

The aerospace engine manufacturer in this study had outsourced 80% of the content of its product so the critical boundary Blake studied was between the aerospace engine designer and the supplier manufacturer. He suggests involving suppliers earlier in the design process to provide knowledge about cost, removing barriers between suppliers and designers and finding ways to alleviate time pressure to allow the designers more time to focus on affordability as key improvement steps.

These sources and many others highlight the importance of breaking down barriers between groups to facilitate communication, alignment of goals to establish mutual dependence and mutually accepted methods for assessing progress towards goals. These methods must be timely, clear and credible to all parties. In the case of collaborating between designer and manufacturer over product cost, the method tends to be design to cost analysis performed by the manufacturer. If this cost analysis is not timely, clear and credible to the customer, management and design engineering it is less likely to be effective.

In David Hoult and Lawrence Meador's article, *Methods of Integrating Design and Cost Information to Achieve Enhanced Manufacturing Cost/Performance Trade-offs*[27], the authors' illustrate this point:

> “The Design/Cost Trades Task is typically time-constrained. This arises because in the development of complex products the IPPD team makes a design decision and immediately begins to realize its consequences. If the cost impact of the design decisions is not known immediately, costly rework arises when the consequences of the design decision must be cost-corrected. Thus, it happens that one of the metrics for *Database Commonality* is the time to roll-up cost estimates for the product. In the U.S. Aerospace industry, typical roll-up times were months, but the best in class rolled up costs daily. In the appliance industry, one leading firm has cost roll-up times measured in minutes instead of hours. In a *Wall Street Journal* article in 1995, a Chrysler representative was quoted as saying that cost roll up time of 24 hours was too slow.”

Paul Carlile and Eric Rebentisch discuss collaboration across boundaries explicitly in their white paper, *Into the Black Box: The Knowledge Transformation Cycle*[28]. The authors suggest that there are three challenges in collaborating across boundaries - novelty, dependence and specialization. Novelty indicates that the environment has changed so "old" ways of integrating knowledge may not apply. Novelty often spurs the need for active collaboration - new requirements require integrated solutions requiring collaboration of functional groups. Dependence means each group needs the other group to be successful (manufacturing has traditionally needed engineering knowledge to be successful, engineering only needs manufacturing/supplier knowledge to be successful if engineering success includes product affordability and producibility). The degree of specialization creates barriers to understanding. Specialization creates specialized language, tools and unspoken assumptions that are not common across other differently specialized groups. Specialization is in tension with dependence because functional groups often have desired outcomes that are at odds with each other. A key way to bridge these problems is to develop a common interface tool/language which abstracts each groups specialized knowledge sufficiently to both accurately represent the knowledge and effectively communicate it to the other party. Carlile and Rebentisch call these items "boundary objects".

> "Key in the development of an effective shared context is the representation of knowledge through the use of boundary objects. An effective boundary object establishes a shared language for representing knowledge, provides a concrete method for learning about differences and dependencies, and facilitates a process for transforming knowledge. Whether these boundary objects are mutually accepted methods, specific activities, or shareable artifacts, the key is that they not only facilitate representing knowledge but also its transformation. They also indicate the degree of inclusiveness of the process. Without the means of representing and applying one's knowledge in a cross-boundary setting (and by extension the ability to participate in future collaborations), some participants might withdraw from or even hamper the knowledge integration process. In a study we saw a clear example of how an up to date assembly drawing helped provide the means where both design engineers and the manufacturing engineer could represent their knowledge and transform the knowledge used to change the design of the product that accommodated both of their interests."

Rebentisch and Carlile also suggest another barrier to the aerospace industry in general is the concept that a good memory can lead to poor choices if the context or environment changes significantly. Certainly the aerospace environment has changes from performance focus to an affordability focus.

> "March asserted that for the most part "good memories make good choices". However, bad choices can also be made even from good memory if the circumstances surrounding the original development have changed. In such cases stored knowledge is no longer relevant when it is retrieved for re-use. This is a key point: when the context changes sufficiently (i.e. new requirements or some other form of novelty is introduced) between when knowledge is stored

> and retrieved, stored knowledge can be rendered less useful and its intended benefits can become harmful. Overall then, the degree of novelty introduced between knowledge storage and retrieval is a core knowledge integration challenge"

To recap, for effective collaboration across boundaries to occur, the following three key elements are required:

- Mutual dependence. The collaborating groups must need knowledge from each other for their own success.
- Clearly defined goals that define success.
- Mutually accepted method(s) to define progress towards goals

Closing Remarks

In the area of organizational issues, the key areas relevant to managing development programs to produce more affordable systems are in the areas of organizational structure and collaborating across boundaries.

One possible organizational structure was summarized that highlighted a new management position that could be called an Affordability or Design to Cost Manager responsible for coordinating the efforts of engineering, manufacturing, procurement, etc. with regards to issues effecting product affordability. This position would report to the program director, provide progress status to the entire team and serve as the customer focal point on issues effecting affordability. Of course, other organizational structures could be suitable but the key is that affordability management is inherently a cross-functional endeavor that requires some degree of centralized coordination.

Managing affordability is a cross-functional endeavor so collaboration across functional and organizational boundaries is critical to success. The systems engineers developing requirements for the avionics system must bridge the boundaries to the users to truly understand what is needed to effectively work cost-performance trades. The hardware design engineers and the manufacturers (either internal to the firm or at suppliers) must collaborate to ensure product manufacturability. A model appears in the literature that for effective collaborating between groups, three elements are essential:

- Mutual dependence
- Clearly defined goals
- Mutually accepted method(s) to define progress towards goals

Key Variables for Case Study Research

The traditional problem with integrating lifecycle cost into the design process has been on two fronts. First, who owns "design to cost"? Systems and design engineering have more influence on the lifecycle cost of a system but typically don't have the capability to perform cost analysis. Manufacturing typically has the capability to perform cost analysis but has less influence on the lifecycle cost of a system. Second, the tools for cost estimating are generally underdeveloped. Often, the cost estimating tools require a drawing and parts list, requiring the design to be nearly completed. These tools are not useful when you have the most influence on the system's lifecycle cost – at the early stages of development. The key variables in each case study will include:

- Is cost considered a design, manufacturing or management requirement?
- Are tools developed to assess cost during early stages of development?
- The organizational capability to perform cost analysis during the design

Collaborating across boundaries has always been a difficult issue in the defense industry. Integrated Product Team organizations and Integrated Product and Process Development methodologies have been implemented to bridge critical organizational boundaries. These concepts create the presence of knowledge from relevant stakeholder functions on one team and greatly reduce the difficulty of crossing these critical organizational boundaries. However, improvements can still be made in improving the effective integration of knowledge from the relevant stakeholder organizations. The classic example is integrating manufacturing knowledge into the hardware design to create a more producible design. The literature suggests a model for increasing the effectiveness of this knowledge integration (create mutual dependence, establish clear objectives and mutually accepted methods to assess progress towards objectives). Key variables used in each case study will include:

- Methods used to increase effectiveness of integrating "downstream" knowledge into the design process? (Particularly integrating manufacturing/supplier knowledge into design)
- Methods used to increase effectiveness of understanding the system performance trade space by crossing the avionics systems engineer – prime systems engineer – government acquisition/user boundaries?

2.3.3 Program Management and the Design Process

Karl Ulrich and Steven Eppinger articulate the traditional product development process in their book, *Product Design and Development*[29] (see figure 2.3.4).

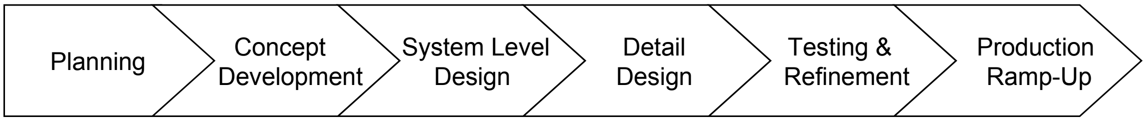


Figure 2.3.4 Traditional product development process

This process is representative of the traditional waterfall development process where the process steps are done, more or less, sequentially from left to right. The now popular spiral development process incorporates iterations into the design process and allows for some number of iterations in the detail design and testing & refinement steps of Ulrich and Eppinger's model.

This section will summarize two alternate theories on product development processes developed by Donald Reinertsen and James Highsmith. Both of these theories explicitly discuss the iterative nature of product development in somewhat different manners. The key conclusion about the product development process is that incremental maturation of product and process is key to developing an affordable system in the face of relatively high technical uncertainty.

Donald Reinertsen developed an intriguing framework on managing product development in his book, *Managing the Design Factory. A Product Developer's Toolkit*[30]. Reinertsen stresses the importance of designing the design process using three principles:

- Focus on making profits, not products
- Queuing theory provides insights to reduce product development cycle time
- Focus product development on generating new information

First, focus on making profits, not products. Define the profit drivers for the product, preferably define quantitative relationships between product features and profits. This makes sense in commercial endeavors but may produce undesired behavior in military endeavors because of financial incentive issues in Department of Defense contracting (see section 2.3.4). The critical issue is to develop a process for weighting various factors to enable making the inevitable tradeoffs between product performance and features, development budget, development schedule and production/support costs.

Second, focus on the product development process using queuing theory. The objective is to apply queuing theory to reduce cost and cycle time of the product development process. Generally this means controlling queues through increasing capacity, managing demand, reducing variability and using control systems.

Third, focus on generating new information in the design process. New information comes from experiments with uncertain outcomes. Successful and unsuccessful experiments generate valuable information. Maximum information generation occurs when you run a test that is equally likely to fail or succeed. This new information is critical and needs to be passed across the organization to avoid repeating old mistakes. Reducing cycle time per experiment or iteration is a key enabler to creating more new information because it allows more experimentation.

One good example is FPGAs vs. ASICs. The author suggests there are two schools of thought in product development – do it right the first time and do it right the last time.

> "The studies of integrated circuit design practices by Professor Stefan Thomke at Harvard, reported in his 1995 PhD thesis bear our these findings. When the cost of doing an iteration is high, such as in ASIC development, companies drive for high quality per pass and low iterations, averaging 1.5 iterations. In contrast, when iteration cost is low, in terms of dollars and time, such as they are with FPGAs, companies will gravitate to the multi-pass approach, averaging 13.9 iterations.
> On IC's of equivalent complexity the FPGA designers took an average of 8.45 man-months while the ASIC designers took an average of 19.24 man-months.

> There may be less difference between the two schools than might appear on the surface. Both approaches are trying to maximize overall economics, they are simply responding to difference economic drivers: when the cost of iteration is high, we should concentrate on first pass yields, when it is low we should concentrate on how quickly we can get through an iteration."

Reinertsen's second key point is to understand the interrelationships between organization, design process, product architecture and technology. Don't put organizational boundaries at underdefined system interfaces. Develop the architecture so many iterations are required within a subsystem but few are required across subsystems. Choose technologies that can reasonably be developed or understood during the time available.

> "The product architecture will create needs for more intense communication around the undefined interfaces within the design. The less well characterized the interface, the more likely we are to have questions about it. Thus, an architectural interface will act as a region of the design that requires heightened and accurate communications. This heightened communications cannot be achieved if we place such an interface at either an organizational boundary or a geographic boundary. Communications will be worst if we compound the problem by placing an undefined interface on top of both an organizational boundary and a geographic boundary. This suggests a powerful rule of thumb: *Never place an organizational or geographic boundary on top of a poorly characterized architectural interface."*

James Highsmith offers an innovative product development process called Adaptive Development in his book, *Adaptive Software Development. A Collaborative Approach to Managing Complex Systems*[31]. This method is developed specifically for software development projects but has applicability for any product development with high uncertainty. The model explicitly focuses on increasing knowledge through iterative development. The adaptive model is based on a view that the world is not deterministic. We have a high level objective but don't necessarily know the best end state to meet that objective so we'll iteratively increase our knowledge about what the best end state will be through iterations to guide us to the right solution. The adaptive model is based fundamentally on a speculate, collaborate, learn cycle of iterations. This compares to the waterfall model of plan, build, implement and the spiral model of plan, build, revise.

Success with the adaptive model involves the deployment of methods and tools that apply increasing rigor to the results, that is, the work state rather than the workflow. The workflow mindset is process oriented first and results oriented second. Workstate management reverses the order of importance."

Leading adaptive development projects requires a different approach than leading deterministic development projects. Leadership in adaptive projects is about setting directions, creating environments and letting results happen. Leadership in deterministic projects is about developing a plan and controlling deviations from that plan. In a deterministically planned project, deviations are viewed as mistakes to be corrected. In an adaptive project, deviations guide us toward the right solution. To lead adaptive projects, a key is developing a vision for the project and communicating to all team members. High level guidance is critical to focus development without micromanaging implementation details. However, low level detailed plans are too constrictive. This kind of management requires that every team member understand the team vision and priorities (performance, schedule, defects, costs, etc) for making the inevitable tradeoffs because these tradeoffs are made at lower levels in the team. What you're striving for is a specific goal, boundaries of behavior and wide latitude for implementation.

Highsmith's approach is developed for relatively small software development projects under high uncertainty in what users want. This approach seems very suitable for software projects where user needs uncertainty is high and iteration cycle time and cost is low. It is unclear how this process would scale up to large teams or to hardware centric systems where cycle time is much longer than for small software systems. However, there are some key features of Highsmith's process that seem applicable to any development process. The explicit focus on increasing knowledge and information through design iterations is consistent with Reinertsen. The focus on work state instead of work flow responds to long standing critics of earned value measurement systems that focus on deviations from a plan that work well when the plan is "right" but tend to lead to "wrong" plans because they make adapting the plan cumbersome. The key criticisms for large projects would be in scaling up the informal control mechanisms and relying on communication of high level vision to guide a large team.

Closing Remarks

Developing more affordable military avionics systems typically involves a significant amount of technical uncertainty from unproven technologies, product complexity and changing customer requirements. Iterative development has become the industry standard for developing products in the face of this uncertainty. The critical issue now becomes the nature of development focus during each iteration.

Key Variables for Case Study Research

The development methodology or process (waterfall, spiral, adaptive, etc.) sets the stage for how a new system will be developed. All of the leading development methodologies, except waterfall, favor an iterative or incremental development approach. The chief difference lies in the development focus of each iteration. Key variables used in each case study will include:

- Was an iterative development methodology used?
- If yes, number of iterations
- If yes, development focus during each iteration

2.3.4 Business Model and incentives

Aaron Kirtley summarized the business model and incentives issues that act as barriers to innovation and improved system affordability in the defense industry in his MIT master's thesis, *Fostering innovation across aerospace supplier networks*[32]. Kirtley's researched the F/A-22 program and focused on the avionics suppliers of Electronic Warfare and Radar systems and their subtier suppliers. His findings included the following excerpt:

"Contract structure and associated incentives have a significant impact on suppliers' motivation and willingness to innovate. However, very few F/A-22 contracts have employed target costing, profit sharing arrangements, or other incentive mechanisms. For many suppliers, the only incentive for innovation is avoiding program cancellation. This provides strong motivation for some suppliers with a major stake in the program, but less so for many others. Furthermore, without cost savings sharing arrangements, innovations that reduce suppliers' product costs tend to decrease their revenues and profits, thereby creating a disincentive for innovation.

The government's contracting approach with the prime contractor heavily influences the structure of contracts across the supplier network. It sets the tone for how supplier relationships are managed at lower tiers and determines the contractual terms and conditions that are flowed down the supply chain. Hence, the government has an important role to play in creating a contracting environment conducive to supplier innovation. The fixed-price, annually negotiated contracts used in the early production phase of the F/A-22 program have discouraged some suppliers from making long-term investments. This research suggests that the use of multi-year contracts and larger volume purchases would significantly reduce costs and incentivize greater innovation. Concurrency in design and production has made it difficult for suppliers to estimate yearly lot costs and has led to a continual stream of design changes that create process instability and schedule disturbances.

The government and companies should work to establish more creative incentive mechanisms that will reward suppliers for outstanding efforts. These might include the use of price commitment curves, under which the customer agrees to a fixed price for the supplier's product for several years in advance, after which time the price is renegotiated based on the customer's assessment of the supplier's new cost structure. Award-fee contracts offer another method of motivating supplier performance."

Figure 2.3.5 illustrates the benefits to both the supplier and customer of long term fixed price contracts. The supplier is financially incentivized to reduce costs because they reap the benefits during the current long-term contract. The customer is rewarded for the supplier's innovation by a lower cost during subsequent long-term contracts. In effect, long term fixed price contracting can be a very efficient method of cost savings sharing between the customer and supplier without the bureaucratic burdens associated with analyzing, proving and negotiating specific savings and sharing percentages common in other cost savings vehicles like Value Engineering Change Proposals (VECPs). Long term fixed price contracting also offers a more efficient method of approving projects that results in cost reduction because the approval decision lies at the supplier. In a VECP arrangement, the approval and funding for a cost reduction project comes from the customer. This can lead to long delays between when the idea is generated and when it is approved often frustrating the supplier's workforce where the ideas originate.

Key Variables for Case Study Research

The business model and incentives in the defense industry are primarily set by the government acquisition community and secondarily set by the prime contractors. The Tier 1 avionics suppliers have little influence over the industry business model and incentive structure. For the typical Tier 1 avionics supplier, the primary motivation to develop more affordable systems is market share. This manifests itself in two components – a "keep sold" component for existing contracts and a demonstration and marketing of proven successes for winning new contracts. Certainly, the incentives would be stronger if individual program financial incentives favored contractors who develop more affordable systems (and currently individual financial incentives tend to favor contractors who develop less affordable systems). As the Tier 1 avionics supplier has little influence over these financial incentives, no key variables for the thesis research will include incentives. This section is included to highlight the issue of financial incentives for the entire industry.

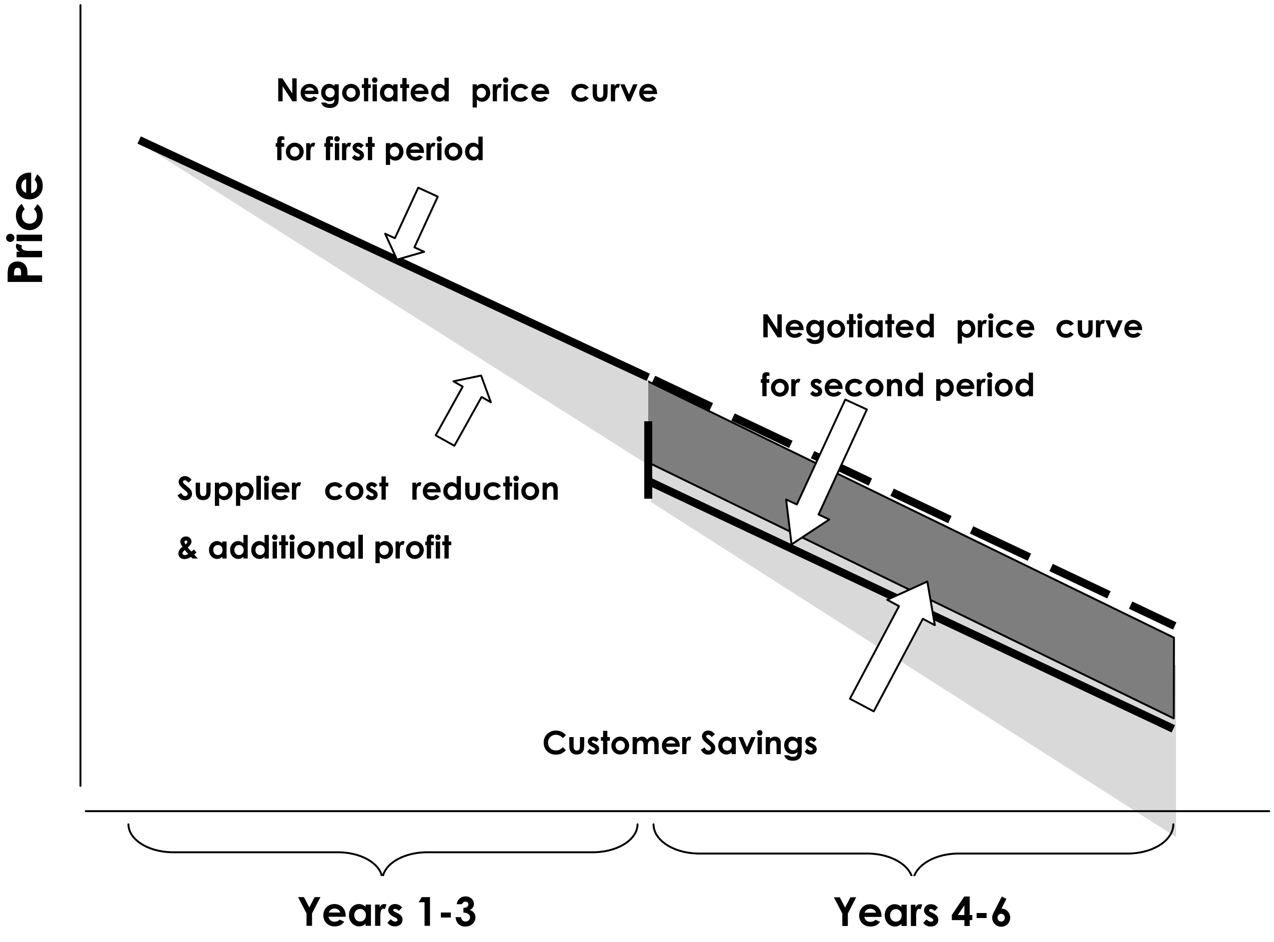


Figure 2.3.5 Benefits to customer and supplier of long term fixed price contracts

2.4 Summary of Literature Review Leading to Key Variables for Thesis Research

The development methodology or process (waterfall, spiral, adaptive, etc.) sets the stage for how a new system will be developed. All of the leading development methodologies, except waterfall, favor an iterative or incremental development approach. The chief difference lies in the development focus of each iteration. Key variables used in each case study will include:

- Was an iterative development methodology used?
- If yes, number of iterations
- If yes, development focus during each iteration

The role of requirements on performance and cost is well documented in the literature. The paradox is that early in the development process you have the most leverage but the least knowledge regarding achievable performance and cost drivers. The low knowledge regarding achievable performance diminishes the team's willingness to trade performance for cost. The low knowledge of cost drivers diminishes the team's ability to know where to challenge performance for the greatest impact on cost. Key variables used in each case study will include:

- Is the technical customer at the next higher level of the system hierarchy willing to trade performance for cost?
- Do you have the knowledge regarding achievable performance and cost drivers to effectively trade performance against cost during the requirements and architecture development phase?
- Does leveraging past programs and/or subsystem commonality across programs increase knowledge regarding achievable performance and cost drivers during the early phases of development?

The problem with integrating lifecycle cost into the design process has been on two fronts. First, who owns "design to cost"? Systems and design engineering have more influence on the lifecycle cost of a system but typically don't have the capability to perform cost analysis. Manufacturing has the capability to perform cost analysis but has less influence on the lifecycle cost of a system. Second, the tools for cost estimating are generally underdeveloped. Often, the cost estimating tools require a drawing and parts list which indicate the design is nearly complete. These tools are not useful when they are most needed – early in the development. The key variables in each case study will include:

- Is cost considered a design, manufacturing or management requirement?
- Are tools developed to assess cost during the architecture and requirements phase?
- The organizational capability to perform cost analysis during the design

Collaborating across boundaries has always been a difficult issue. Integrated Product Team organizations and Integrated Product and Process Development methodologies have been implemented to bridge organizational boundaries. These concepts create the presence of knowledge from relevant stakeholder functions on one team and greatly reduce the difficulty of crossing these organizational boundaries. However, improvements can still be made in improving the effective integration of knowledge from the relevant stakeholder organizations. The classic example is integrating manufacturing knowledge into the hardware design to create a more producible design. The literature suggests a model for increasing the effectiveness of this knowledge integration (create mutual dependence, establish clear objectives and mutually accepted methods to assess progress towards objectives). Key variables used in each case study will include:

- Methods used to increase effectiveness of integrating "downstream" knowledge into the design process? (Particularly integrating manufacturing/supplier knowledge into design)
- Methods used to increase effectiveness of understanding the system performance trade space by crossing the avionics systems engineer – prime systems engineer – government acquisition/user boundaries?

3 Case Study Research of Seven Military Avionics Programs

3.1 Research Focus and Approach

Seven avionics development programs at a single avionics company were researched by interviewing over forty engineers and managers. The programs ranged in size and complexity from single module hardware development programs with products that fit in the palm of your hand to large scale system development programs involving hundreds of pounds of hardware and hundreds of thousands of lines of software code. The intent of the case study research was to investigate four focus areas:

- The nature of development focus during each design iteration
- The role of requirements
- Managing lifecycle cost as a design requirement
- Effective integration of downstream knowledge to develop better designs

Interviews were used to collect the data. A cross section of functional disciplines were interviewed to develop an objective view of the program:

- Program management
- System engineering
- Hardware engineering
- Manufacturing engineering
- Company management
- Manufacturing factory management

Each interviewee was asked general questions regarding best practices developed and critical issues faced by their program relevant to delivering more affordable systems. A series of specific questions were asked probing at each of the four focus areas. See Appendix C for a copy of the questionnaire used for the interviews.

The seven programs selected have been disguised to protect sensitive data and will be referred to as Programs 1, 2, 3, 4, 5, 6 and 7.

Program 1 was a major system development program involving hundreds of pounds of hardware and hundreds of thousands of lines of software code. This program was selected because it is an interesting transitional program – focused almost entirely on performance at the beginning with a significant shift in focus to affordability almost a decade into the program. The case study illustrates how difficult it is for programs to switch focus but once they do, how dramatic improvements can be made. Program 2 is a subset of Program 1 - it dives into greater detail and illustrates the step function affordability improvements that can be made through design innovation when the program conditions support an affordability focus. These programs are covered in sections 3.2 and 3.3.

Programs 3 and 4 are less complex than Program 1 and cover single hardware modules that fit in the palm of your hand. Program 3 has been extremely successful in implementing Lean enterprise techniques and design innovations to make dramatic cost reductions while manufacturing over 10,000 modules. This program has become the company's model program for Lean manufacturing and affordability success. Program 4 experienced technical shortfalls in the transition from prototype to manufacturing resulting in contract termination by the customer. The interesting contrast is that the same group of people ran both programs. These programs are covered in section 3.4

Program 5 is a classically over-constrained program. This program had a highly competitive acquisition process that led to insufficient budget and schedule available to meet the performance requirements. Affordability was a major driver during the acquisition process. A low cost system that could be used on multiple platforms for multiple U.S. military services was proposed. A relatively high-risk system concept was proposed in order to meet the affordability goals. Once the program was awarded and execution began, the focus shifted to performance and schedule. At first flight, the system failed catastrophically. Several unplanned design iterations were required to develop a performance compliant system, which led to significant cost and schedule overruns. Program 5 is discussed in section 3.5.

Programs 6 and 7 are discussed jointly in section 3.6 because of the interesting contrast. Program 6 was a new product concept that entailed high performance risk. The customer was performance focused and requirements were very difficult to meet. Not surprisingly, this program developed a very high performance product at a very high cost. This program is considered unsuccessful because the cost is higher than the customer is willing to pay for the achieved performance so the production is in serious jeopardy. Program 7 leveraged the knowledge, technology and capability from Program 6 to work with their customer to shape the requirements to enable a low risk, low cost solution that met the needs of the user. Program 7 provides the same functionality as Program 6 at 4-5x less cost based developing more balanced requirements.

Figure 3.1.1 summarizes these seven programs and compares them along several metrics. The development manyears metric compares the number of manyears expended to develop the system. This metric and the system weight provide insight into the relative complexity of these systems. Development focus compares the top priority or focus of the development team. It is interesting to note that the development focus frequently changes in response to changing program environments. For example, Program 1 changed from a performance to an affordability focus in response to a similar focus change at their customer. The technical performance risk and the degree to which the team could leverage prior knowledge, technology and capability provide insight into the uncertainty of the program. Whether the team met the customer's needs for performance and lifecycle cost or not provides insight into the results of the development program.

Program	Development Manyears	Weight (lbs)	Development Focus	Technical Performance Risk	Leverage Prior Knowledge, Technology and Capability	Met Performance Needs	Meet Lifecycle Cost Needs
Program 1	4,000 - 6,000	650	Performance initially, transitioned to affordability	High	Low	Yes	No
Program 2	8 - 10	10	Affordability	Low	High	Yes	Yes
Program 3	60 - 80	4	Performance initially, transitioned to affordability	Medium	Medium	Yes	Yes
Program 4	15 - 25	4	Affordability initially, transitioned to performance	High	Low	No	?
Program 5	400 - 800	250	Affordability initially, transitioned to performance and schedule	High	Low	Yes	No
Program 6	200 - 400	75	Performance	High	Low	Yes	No
Program 7	200 - 400	75	Affordability	Medium	High	Yes	Yes

Figure 3.1.1 Comparison of Seven Military Avionics Program Researched

3.2 Program 1

3.2.1 Program history and summary

Program 1 is widely recognized for its superior performance. At the beginning of development, government customers and the prime contractors valued performance over all other elements of program value. Schedule was valued second, development budget third and life cycle cost was valued last on the list. These values shifted late in development and life cycle cost became a much more valued element of the program. This shift in values was a result of changes in the geopolitical environment and changes in defense budgets.

The top achievement of this program is revolutionary performance. Program 1 delivered the performance it promised with margin. The chief challenge this program continues to work to overcome is reacting to changes in customer priorities increasing the value of lifecycle cost. The program has made and is making significant strides in reducing the production costs of the product but more work remains to be done.

The avionics program investigated under Program 1 developed a sophisticated electronics system with several hundred pounds of electronics hardware and several hundred thousand lines of software code. This system was the most sophisticated and highest performance system of its type ever attempted. The avionics program mirrored the platform program – it delivered the revolutionary performance it promised with margin and is still working to react to changes in customer priorities increasing the value of lifecycle cost. Program 1 represents the most complex program researched for this thesis requiring four to six thousand man-years to complete development over more than a decade. The avionics supplier is making significant strides improving affordability through the following initiatives:

- Lean enterprise techniques
- Improving hardware producibility during product redesigns required by Diminishing Manufacturing Sources (parts obsolescence)
- Identifying and implementing opportunities for cost reduction through product or process improvement
- Implementing a system architecture innovation that exploits new technology unavailable when development began. Although the Program 1 avionics system researched represents only about 5% of the platform's cost, this innovation represents the largest cost reduction initiative on the platform.

The Lean enterprise techniques began with a primary focus on the factory floor and have expanded to include "white collar" processes. The focus has been on increasing the efficiency of transactional processes. Significant improvements have been made with the most dramatic improvements observed in factory performance and efficiency.

Diminishing Manufacturing Sources (DMS) is the program's term for parts obsolescence. The system was designed between 1991 and 1994 so it has 8-10 year old electronics component technology. With component lifecycles becoming shorter driven by the commercial electronics markets, today typical lifecycles for digital components are 3 years and 5-7 years for RF/analogue components. With over 3,000 components in the system, there are components becoming obsolete every year and some require product redesigns to accommodate the next generation component technology. The team has successfully turned this life cycle cost driver into a life cycle cost benefit by focusing the product redesigns on improving the producibilty and affordability of the hardware whenever it is redesigned for obsolete component technology. Typical benefits have been product yield improvements from below 50% to above 90% and production cost reductions of 10-30%.

The customer has made funding available to invest in cost reduction initiatives. The Program 1 avionics team has captured some of this funding through the demonstration and implementation of several innovative ideas to improve system affordability ranging from manufacturing process innovations to modular production innovations to system architecture innovations. Manufacturing process innovations have included automation of processes previously only possible manually. Modular product innovations have included module redesigns like Program 2 (see section 3.3). Architecture innovations have included simplifying the architecture by exploiting technology developments unavailable when Program 1 development began. This architectural innovation represents the single largest cost savings initiative on the platform.

The team has pursued funding made available by their customer but has also invested their own funds in product and process improvements. It is important to note that the team's motivation for improving affordability is not driven by tangible financial benefits. For each successful cost reduction initiative, the Program 1 team must invest current funds (that could otherwise be profit) to reduce future cost, which reduces future sales, cash flow and profit. The Net Present Value of each cost reduction initiative is a loss to the avionics supplier because all of the cash flows are negative. The future "benefits" are negative cash flows to the avionics supplier because all of the savings benefit the customer. The motivation for the avionics supplier is to keep the program sold and support their customer's needs which leads to improved customer relationships and creates advantages in competing for future business. For the avionics supplier, this is a powerful motivator because the prime contractor is their largest customer. The avionics supplier has a significant financial stake in the program, so helping to keep the program sold is a significant motivator.

This program was successful because it delivered what it set out to deliver – an order of magnitude leap in system performance. However, the team still has work to do to react to the customer's change in priorities placing higher value on affordability. The avoincs supplier is adapting to this change in customer priorities through an aggressive cost take out program that includes architecture level redesign, hardware module level redesign, manufacturing process improvements and LEAN implementation. This change demonstrates that defense firms can focus on affordability and develop significantly more affordable systems when that is what the customer wants.

3.2.2 Critical Issues Leading to Noteworthy Negative Outcomes

The most noteworthy negative outcome was that the production costs of the system were higher than the customer's goals. The program is now making significant strides to improve the system's affordability.

New technology: The team implemented several new materials to reduce weight that were expensive to implement and provided marginal improvements in weight. Many of these new technologies were removed to reduce cost. Several technical inventions were required, which drove the team to ignore affordability in a difficult struggle to get certain aspects of the system to function.

Insufficient design iterations, insufficient prototype manufacturing: The team did not build enough product to understand the problems and cost drivers. The team built one engineering prototype and then went directly to EMD manufacturing to build eleven systems. Once the team had built the eleven EMD systems, they better understood the cost drivers and what to fix but did not have remaining budget to solve the now known issues. The program was planned to be done 'right the first time' so funding was not planned for iterations.

Corner of the envelope requirements: A CAIV philosophy on requirements was not adopted until well after the Critical Design Review (CDR). The customer pushed for challenging requirements. Practically, the only acceptable reason to change a requirement was that meeting the requirement violated the laws of physics. Several interviewees indicated that the avionics supplier's engineers and managers never really figured out how to negotiate through the various stakeholders at the prime and the government to successfully pursue requirements changes based on "best value" or affordability considerations.

Design to Cost was not integrated with the design process: Design to cost analysis was conducted and reported every quarter during the early years of the program. Several lead engineers interviewed indicated they did not know that the analysis and reports were ever generated. Cost was not put in front of the systems engineers as a requirement. Eventually it was put in front of the hardware engineers but the effort was under-supported. Design to cost analysis and estimating support was not prevalent on the program so design engineers (who don't know how to estimate cost) had a requirement but no means to estimate compliance. This coupled with a performance focused program culture acted as barriers to integrating Design to Cost with Design. This issue is covered in greater detail in section 3.2.4.3.

Affordability was not valued at the beginning of EMD: Program 1 was focused on performance early in the program. Affordability was valued last behind performance, schedule and development budget. When an engineer said, I can save $X if you change my requirement from A to A', the answer was invariably "no". When an engineer said, I can save you $X if you give me $Y additional budget and Z additional months of schedule, the answer was invariably "no". This was intentional and entirely consistent with the customers' priorities.

Worst case engineering analysis: A lot of the design analysis used "worst case" instead of statistical techniques. For example, thermal analysis used to determine compliance with component junction temperature requirements assumed all components simultaneously drew maximum power during the maximum ambient and cooling temperature conditions. Not only is it unlikely for all components to simultaneously draw maximum power, it is physically impossible for many of them to do so under warmest temperature conditions (many of the components draw maximum power during cold temperatures). This kind of technical performance risk aversion lead to over-designing, increased complexity and increased costs.

3.2.3 Best Practices Leading to Noteworthy Positive Outcomes

The most noteworthy positive outcome was revolutionary system performance.

Structured engineering process: The program's director drove a very structured and rigorous engineering process into the team with well defined milestones and technical reviews. This was a culture change for the company as it was used to managing smaller programs with more free flowing engineering processes. Several interviewees credited the structured process with much of the program's success.

Integrated product teams: Program 1 was the companies' first large program to institutionalize IPT's. Not all IPT's were equally successful of course. Team dynamics and leadership played important roles in the relative success of the various IPT's. However, on the IPT's that really worked together well, the results were very impressive. One factory manager quoted that "the XYZ IPT was a very close knit cross functional team that developed high trust in each other and solid understanding of what each other needed to do and could do to make the product successful in the factory. The team was focused on a common goal to transition the product to the factory and systematically identified and resolved issues one at a time until the product could be manufactured in a production environment – a real success story."

Technical expertise: The Program 1 customer noted that the avionics team had developed the technical skills of their employees to exceptional levels. There were several "national experts" in their fields on the program team and the team seemed capable of solving "practically any technical problem" (given enough time and money of course).

Statistical Design Analysis: CpK analysis was used in pockets on the program – primarily in RF and microwave modules. This analysis technique uses statistics to analyze a design to predict specification yield (what percentage of the units built will meet the requirements). Tradeoffs were consciously made to trade margin and yield from one module to another to improve the system's robustness. There were noteworthy differences in the hardware that applied CpK and the hardware that did not apply CpK in terms of manufacturing yield and producibility.

Clear program priorities: The single, overarching priority of the program was clear to everyone on the program team – performance. This clarity of purpose lead to clear and consistent tradeoffs between performance, budget, schedule and affordability consistent with the top priority of the program and the customer. Performance was clearly the top priority from contract award through 1997 when CAIV began which ultimately lead to an increased value on affordability. The team's management effectively used very visible "rallying points" to focus the entire team around common objectives or goals.

3.2.4 Collaborating across critical functional or organizational boundaries

3.2.4.1 Understanding the system trade space

After the first year of the program, challenging requirements was pursued when a requirement could not be met. It was not a pursued to search for requirements that better optimized the balance between performance and cost.

Requirements closure was elusive. Entering the third production lot, the Program 1 team still has many unresolved requirements throughout the hierarchy of the system. In general, the hardware modules did not meet their requirements with sufficient margin to allow for production variability so virtually all modules required requirements relaxation in order to transition to production. However, these new relaxed requirements have not been incorporated into formal documentation of the program and remain in a state of some flux as the team finished system level verification and validation.

The Program 1 team lacked system simulation capability sufficient to understand the impacts of lower level requirement changes on the top-level system performance. This made arbitrating requirements changes at lower levels difficult. The company has recognized this shortfall and invested in the development of an end to end system model for use on future programs. The Program 1 avionics team and customer community also lacked simulation capability sufficient to understand the value of a particular performance level. For example, a heuristic was applied to weight reduction ideas – the program will spend $x per pound of weight reduction. These relationships were not developed for other performance levels. These questions are difficult to answer because they involve the loss of human life and enormous political costs of losing an aircraft.

The Program 1 team ran into difficulty developing consensus among the many stakeholders at the prime contractor and the government acquisition and user communities on requirements changes. Typically, it was difficult to find a "buck stops here" person who had the authority to arbitrate among the various stakeholders and make the final decision. Stakeholder consensus was elusive because the stakeholders for various performance attributes typically had no responsibility for cost or schedule and had little incentive to change performance requirements.

The system architecture was not very open or adaptable to new customer requirements. The digital control was implemented in Application Specific Integrated

Circuit (ASIC) technology which creates a "hard wired" system. ASIC respins were required to adapt to new requirements and take about a year to complete.

Where the Program 1 team was successful at understanding the customer's true needs, the common threads were developing a very close, working relationship with the customer at an engineering level and making the customer part of the team that developed the solution. This way, buy-in was developed along the way so final approval was much smoother. The open, engineering level relationship created trust that was critical to open and honest sharing of information.

3.2.4.2Subsystem and hardware design

The primary mechanism for integrating downstream manufacturing knowledge into the design process was through the IPT organizational structure. Manufacturing had representatives called producibility engineers on each IPT. These engineers were responsible for evaluating the product designs for producibility and production readiness. As performance was the driving force of the program, product producibility was given relatively low importance so these producibility engineers were not always involved in the decision process on equal footing with product engineers.

The producibility engineering role was to provide manufacturing insight into the design process. Several interviewees highlighted that producibility engineers who recently worked in the factory were the most effective because they were tightly integrated with the factory and highly knowledgeable about its capabilities.

The producibilty engineers were effective at raising issues and developing design alternatives that could have improved product producibility but many of those issues went unresolved and alternatives unimplemented. The producibility engineers were individual contributors who could raise issues and offer alternatives but couldn't set the culture of the organization or influence the priorities of the program. Today, the program is fully engaged in affordability and has had the opportunity to understand the cost drivers and producibility issues after building 30 systems through the first few production lots. In this environment, the producibility engineers are having a much more significant impact on cost reduction redesigns. Producibility engineers can be successful in the right environment but cannot overcome an environment that places low value on product producibility.

Suppliers were not well integrated into the design process. Arm's length relationships were established with little involvement of the design engineering community after the specifications were developed and contracts issued to the supplier. In most cases, the subcontract management fell to subcontracts administrators with insufficient technical support. This changed significantly when the "production of EMD assets" began and supplier issues got onto the program's critical path.

3.2.4.3 Life Cycle Cost feedback into the design

Life Cycle Cost includes development costs, production costs and operations and support costs. During the EMD program, Life Cycle Cost was not well integrated into the design process. Design to Unit Production Cost (DTUPC) was conducted during system and subsystem design but had varying levels of success at integration with and influence on the design process. Operations and support costs were estimated but not integrated with the design process. In general, the DTUPC analysis was not considered important until near the end of the program when the cost estimate was significantly higher than customer targets.

There were differing reports from interviewees related to whether cost targets were allocated to subsystems which indicates that cost targets did exist but were inconsistently and insufficiently communicated to the engineering team.

The early DTUPC work involved the Price-H tool which is an industry tool that uses parametric information about hardware designs to estimate production costs. For example, the analysis enters parametric information on size, weight, technology type, complexity, novelty, etc. The tool using that parametric information to estimate a production cost based on industry cost data. A quarterly report was generated and submitted to the customer during the early years of the program. However, this analysis was not well integrated with the design process. Several lead systems and hardware engineers indicated they were not even aware this analysis was going on and these reports were being submitted. This created a damaging underlying dynamic. The people doing the DTUPC reports were incentivized to show continuous improvement and the reports show a steady reduction in the DTUPC estimate over the early years of the program. The people doing product development (who determine what the cost will be) were not influenced or grounded by DTUPC requirements or analysis. The real cost steadily increased over the early years of the program as system complexity was added to meet the team's increasing understanding of the technical requirements. The estimated cost steadily decreased and the real cost steadily increased which led to a sizeable gap after a period of several years.

After CDR, the system and subsystem design was nearly complete, the Price-H model was abandoned and a "bottom's up" DTUPC estimating methodology was undertaken. This approach involved the manufacturing organization developing a cost estimate to build the design. This included:

- Industrial Engineering reviewing all the drawings and developing standards (number of hours it should take to build or test under ideal conditions)
- Manufacturing management developing performance factors (multiplier to the standards for how long it will take to build or test under expected conditions)
- Procurement soliciting quotes from suppliers

This method of analysis solved one of the issues with Price-H but created a new issue. This method was credible to the design community because it was a cost estimate of their design. The Price-H model was not credible to the design community because it was a parametric of their design – it couldn't tell you if part A was a better value than part B. The "bottom's up' analysis took 6 months to complete and it was updated only once per year. This method was better integrated into the design process. Some of the hardware engineers knew what their cost targets were and knew where they stood against those cost targets. No hardware engineers indicated that the cost estimates provided insight into what the cost drivers were which made it difficult to know what to change in the design. No hardware engineers indicated that there was a support group responsible for design to cost analysis that they felt they could go to run "what if" analysis of various design alternatives under consideration. The lack of agility of this estimating method led to frustration in both the manufacturing and engineering communities. The engineering communities voiced frustration because the estimating method couldn't run "what if" analysis and updates only came out once per year. The manufacturing community voiced frustration because it was impossible to keep up with the constant and relentless pace of engineering changes to the design. These frustrations point to the need for a credible and agile cost analysis method.

The avionics supplier today has created a "Design to Cost" organization responsible for performing design to cost analysis and running "what if" analysis of various design alternatives under consideration. This group is tightly integrated with the cost reduction design activities being pursued on Program 1. The hardware engineering community has voiced repeatedly that this is a welcome change that provides a valued service to the hardware design team. The team now knows where they stand against cost targets with much more frequent updates. It is believed that this is a major step towards "where they want to be" with respect to designing affordable systems and subsystems. The remaining area for improvement is that the Design to Cost analysis currently being conducted is still a periodic snapshot in time of where the design is compared to a target value. The hardware engineers provide a set of updates to the Design to Cost group who provides an updated estimate. Several engineers indicated "where we want to be" is more proactive with Design to Cost – not just periodic updates but Design to Cost driving the design through proactive identification of cost drivers and development of alternatives to lower the cost.

3.2.5 Summary

Program 1 was successful at delivering revolutionary system performance. The entire program, and this avionics system was no exception, was caught flat-footed by a change in government priorities increasing the value of affordability. The Program 1 team is now reacting to the change in priorities, motivated to keep the program sold and to strengthen relationships with their number one customer, the prime contractor. The team is implementing LEAN enterprise techniques to improve efficiency and is pursuing system and subsystem level product design changes. Even though the Program 1 avionics system represents only 5% of the platform's cost, the Program 1 team has the top cost reduction project on the entire platform and is changing the system architecture exploiting new technology unavailable when Program 1 development began. The avionics supplier is demonstrating they know how to design affordable systems and subsystems when that is what the customer wants.

Several lessons can be learned from Program 1. An IPT organizational structure is great for integrating manufacturing, reliability, maintainability and cost considerations into the design phases if and only if the program's leadership sets a culture that affordability and producibility is important. If the program's culture is driven purely by performance, the manufacturing, reliability and cost knowledge will be present but will influence decision making only when not in conflict with performance. Design to Cost analysis must be integrated into the design process and must have the following key attributes: (1) credible to the design community, (2) agile enough to keep pace with engineering changes and (3) proactive in highlighting cost drivers to drive alternatives to be considered. Personal relationships and open, objective engineering level communications are the key to successful requirements negotiations. Clear program priorities can rally a large team. The clear message that technical performance was most important led to revolutionary system performance.

3.3 Program 2

This section covers the Program 2, a subsystem cost reduction development program pursued as part of Program 1's increased focus on affordability and cost reduction. The section begins with an overview and summary of major outcomes of the program. Noteworthy positive and negative outcomes as identified by the Program 2 team are discussed along with the primary best practices and critical issues that contributed to these noteworthy outcomes. A more focused discussion of successful and unsuccessful practices in collaborating across functional and organizational boundaries rounds out the section.

3.3.1 Program history and summary

The Program 2 subsystem is part of the Program 1 system. The subsystem was designed during the EMD program with a focus on performance. The primary purpose of this redesign project was to reduce the cost of the Program 2 subsystem while maintaining the Program 1 system performance.

The development team met the performance and cost objectives for the program but required more development budget and schedule than planned. The team developed a low cost product architecture and selected a new technology because it offered significant benefits in product cost. The new technology came with specific performance risks. An iterative development program was planned to grow the product performance but one more iteration was required than was planned.

The Program 2 program manager reported directly to the Program 1 production program manager. The production program manager authorized the funds required to implement the project, selected the Program 2 program manager and monitored progress weekly throughout the development program. This manager's main motivation for authorizing this project was to reduce the cost of the Program 1 system. The Program 2 team also had to be aware of another primary stakeholder, the Program 1 EMD program manager. This person was ultimately responsible for the performance of the Program 1 system and served the role of the technical customer who accepted the performance of the redesigned Program 2 subsystem.

The Program 2 subsystem is a hardware only system consisting of complex radio frequency (RF) and digital electronics weighing approximately 10 lbs and requiring eight to ten man-years to complete development over a two year period of time. The cost drivers were:

- Very low manufacturing yield (5%) driven by too much component integration into a testable entity
- Too much variability in the manufacturing process driven by design required manual tuning or adjustment to RF circuits to bring the module within performance specification limits
- Exclusive use of expensive chip and wire technology

The team attacked these primary cost drivers and achieved the following primary benefits as a result:

- Partitioned the design for 95% manufacturing yield by reducing the level of component integration into a testable entity
- Outsourced some of the high variability, tuning intensive pieces of the design to a lower cost supplier
- Selected and implemented lower cost packaging technology used by the commercial industry for low frequency RF applications (printed wiring boards with packaged components instead of chip and wire technology).

The project was a relatively small, relatively low complexity project that met the customer's goals for performance and cost but required additional development budget and schedule to deliver these results.

3.3.2 Critical Issues Leading to Noteworthy Negative Outcomes

The team exceeded its development budget and schedule commitments to its management. The budget was exceeded by 20% and the schedule slipped by approximately 6 months which pushed the implementation of the new design from production lot 2 to lot 3. The following critical issues identified by the team were the primary contributors.

Not understanding design trade space: Failed to understand the design requirements and trade space. Miscommunication between the team and their technical customer led to a requirement non-compliance at Design Verification Review that the technical customer could not accept. This lead directly to cost and schedule overrun to grow the performance.

Parts obsolescence: A key MMIC amplifier went obsolete after CDR and it was too late to incorporate redesign into the program. An extended production buy was made so there was not direct impact to this effort but a subsequent redesign to address the obsolete amplifier will be required only 2-3 years after release of this design to production.

New Technology: Underestimated the risk of new technology leading to significant engineering rework and directly contributed to the requirement noncompliance. The team redesigned a traditional military microwave electronics design (unpackaged components wire bonded to ceramic substrates in a hermetic multichip module) using a more commercial design approach (plastic packaged components mounted directly to a printed circuit board in a non hermetic module).

3.3.3 Best Practices Leading to Noteworthy Positive Outcomes

The team met aggressive production cost reduction goals (reduce cost by 50%). The following best practices identified by the team were the primary contributors.

Program culture valued affordability: The program's primary goal was affordability. The program manager drove the focus on affordability. The team was very receptive to valuing affordability because they all had scars from transitioning some unproducible designs from development into production. This zeal also hurt the team as they pushed the design to achieve cost goals, which contributed to a performance issue.

Affordability considered a design requirement: An affordability requirement was set prior to design kick-off (AUPC = 50% current design). This requirement was a consideration in all design decisions.

Integration of cost feedback into the design process: Cost feedback was reviewed frequently during the conceptual design and technology selection process (kickoff through Preliminary Design Review). From PDR on, the focus switched to producibility and achieving the design performance needs.

Integration of producibility into the design process: An extremely zealous producibility engineer was a core team member of the program. She supervised the assembly of all prototypes and final units originating and collecting producibility improvement ideas from everyone who touched the product and drove the incorporation of those ideas into the next design iteration. Her enthusiasm and the group's value on affordability and producibility enabled almost all of the ideas to be incorporated.

Integration of suppliers into the program: The conceptual design decomposed the subsystem into 6 key modules. Integrated a very capable supplier to develop 3 of the modules. The supplier was funded to propose a solution for the entire subsystem. This experience gave the supplier greater insight into the entire product and enabled them to more effectively develop their pieces of the system. Weekly oversight by the subcontract management team (a very senior technical lead and subcontract manager) and collaborative design reviews really worked. The supplier was on time, on budget and their modules worked.

Iterative development process: The product development strategy was to build and test hardware early and often. The program consisted of two planned spirals and one unplanned spiral. The unplanned spiral was required to fix the late discovered requirements non-compliance. This approach allowed the team to identify issues with their approach, evaluate alternate solutions and implement the solutions in an iterative manner that significantly improved the quality of their product.

Architecture Innovations: The team developed a new subsystem architecture that dramatically reduced cost with no performance impact. The new architecture involved partitioning the subsystem into module and performing strategic make/buy decisions on each module. This allowed the team to dramatically increase the manufacturing yield by reducing the complexity in each testable module and outsource modules to firms offering competitive advantage in specific module types. The interfaces between the modules were given great consideration in the architecture. Performance adjustment would be needed to adjust the gain level once the modules were assembled together. Traditionally this adjustment is done within a module using delicate and costly ‘chip out and replace’ techniques for component changes. The team developed a coaxial attenuator that was part of the cable interconnects between the modules that could provide this gain adjustment. This dramatically reduced the time and cost of performing the adjustment.

<u>Successfully exploited a technology opportunity:</u> The team leveraged technology advances in digital circuit card technology to replace expensive multi-chip module technology for less expensive packaged surface mount circuit card technology for the low frequency RF circuitry.

3.3.4 Collaborating across critical functional or organizational boundaries

3.3.4.1 Understanding the system trade space

The technical customer for the Program 2 team was the Program 1 system engineering community. The systems engineering community included many stakeholders. There was a system engineering lead for each major function performed by the Program 1 system. Due to the integrated nature of the Program 1 system architecture, the Program 2 subsystem contributed to several major Program 1 functions so the Program 2 team had several technical customers. The systems engineering community assigned a point of contact ("Joe") to interface with the Program 2 team to ensure the new subsystem design would integrate into the larger system and arbitrate any requirements issues with the various systems engineering stakeholders. The Program 2 team interfaced directly with the various systems engineering stakeholders during major program milestones (mostly design reviews). Day to day collaboration was between the Program 2 team and Joe. With no company level organizational boundaries between the team and its technical customer, the communication was informal. This informality had pros and cons. It made the communications more frequent and completely focused on the technical issues. It also tended to be under-documented which opened the opportunity for miscommunications and misunderstandings.

The frequent collaboration led the design team to identify several aspects of the baseline design that no longer were needed by the Program 1 system. Specifically, 15 MMIC amplifiers and all the required supporting circuitry were eliminated from the design.

The late discovery of a requirements non-compliance based on miscommunication between the design team and the systems engineering community directly lead to an unplanned design spiral causing budget and schedule overruns. The design team thought they had agreement that the demonstrated performance was acceptable at CDR. The technical customer community could not accept the demonstrated performance and thought they had agreement from the design team to grow the performance.

The Program 2 team indicated that next time they would insist that critical agreements on requirements interpretations or changes be documented. Next time, the team would also insist upon more frequent interactions between the design team and all the stakeholders in the systems engineering community to allow the design team to understand the system's needs better and the systems engineering community to understand the Program 2 subsystem's needs better.

3.3.4.2Subsystem and hardware design

Manufacturing and suppliers were both effectively integrated into the design phase.

- *Producibility integrated into preliminary and detail design:* An extremely zealous producibility engineer was a core team member of the program. She supervised the assembly of all prototypes and final units originating and collected producibility improvement ideas from everyone who touched the product and drove the incorporation of those ideas into the next design iteration. Her enthusiasm and the group's value on affordability enabled almost all of the ideas to be incorporated. The key enablers were her zealous enthusiasm, the group's value on affordability and the design-build-test-design-build-test spiral development process. This last point cannot be overemphasized - having early hardware, putting it in various technicians and manufacturing engineers' hands to get improvement ideas and having additional planned design spirals to incorporate the ideas into the design was crucial. The producibility engineer was held responsible for bring producibility improvement ideas to the table. The design engineers were responsible for incorporating those ideas. It was difficult to determine how producible was producible enough? There was a cost requirement but the team didn't have any way to incorporate the producibility improvement ideas into the design to cost analysis because the analysis was at too high a level. This led to the inevitable question of how producible is producible enough when incorporation of producibility improvement ideas stresses the product's performance or the program's budget and schedule. This case highlights the need for quantifiable, verifiable requirements for producibility. One obvious solution is to link the producibility of the product with the cost of the product through closed loop design to cost analysis.

- *Suppliers integrated into the program:* A supplier made half of the criticl modules in the subsystem. The supplier was funded to provide a technical proposal for the entire subsystem in order to provide the team another perspective on architecture alternatives. This perspective helped the supplier develop their subassembly modules more effectively because they understood the needs of the subsystem and not just the needs of their modules. Weekly interaction between the supplier and the Program 2 subcontract management team helped keep the supplier integrated into the program. The supplier was given complete authority to design their modules within the requirements negotiated with the internal design team. They were monitored weekly but never directed to design something this way or that way. This worked. Clear requirements, clear accountability. Designs that worked, were on time and on budget.

3.3.4.3 Life Cycle Cost feedback into the design

There was great cost feedback into the design during the conceptual design. It was good in the preliminary design phase and did not exist during the detail design phase. The trailing off of cost feedback into the design was because the team had no way to tie producibility improvement ideas to the design to cost analysis because the analysis was done at a system level and broke down at the detail level. This may be adequate considering published literature indicates 80% of the cost is set by the conceptual design.

The cost estimating method used complexity factors to similar modules. This worked well because It can be done quickly, if you have an extensive enough database of cost history and similar modules - a new model developed in a day, iterations done in minutes or hours. This near real time feedback was critical to integrate cost feedback in the design. If it takes a week or two to do the cost analysis, it will always be a week or two behind the design and will be all but useless in influencing the design. Design decisions are made daily and the analysis needs to be able to keep up.

3.3.5 Summary

The Program 2 team was successful at delivering an affordable product. It met the customer's goals for performance and cost. Meeting both the performance and cost goals led to budget and schedule overruns in the development program. The team delivered an affordable product by focusing on affordability as a design requirement, integrated cost, producibility and supplier feedback into the design process and focused on risk reduction by using an iterative development process. The team ran into budget and schedule issues through miscommunications with their technical customers and not fully appreciating the risks of new technology.

Informality with the technical customer lead to richer discussions but increased the opportunity for miscommunication. Formality adds value for critical agreements while informality is best for communication. Producibility was effectively integrated into the design process through a very zealous individual and a team that placed a high value on affordability and producibility. Suppliers were effectively integrated into the design process by allocating clear technical and schedule requirements and maintaining weekly contact between the Program 2 subcontract management team and the key supplier. Cost was integrated into the design phases during the conceptual and preliminary design phase when it was most important in setting the subsystem costs. This program highlights that the current tool set for design to cost analysis makes it difficult to integrate cost feedback into the design process during the detail design phases.

3.4 Programs 3 and 4

3.4.1 Program history and summary

Programs 3 and 4 each consist of a single hardware module that fits in the palm of your hand. These programs are discussed together because they offer an interesting contrast. Program 3 has successfully produced over 10,000 modules and is known as the company's model program for success in Lean manufacturing and affordability. Program 4 was managed by the same team but was not successful. The contract was terminated as the team experienced difficulties in transitioning the product from prototype to manufacturing.

3.4.2 Critical Issues Leading to Noteworthy Negative Outcomes

The most noteworthy negative event was the contract termination of Program 4 .

The team was supplying the Program 3 product and another firm was supplying the Program 4 product. The other firm announced its intent to exit the business. The customer contracted two firms to develop a replacement design. Each firm was struggling to develop an affordable, performance compliant module. The customer turned to the Program 3 team and asked them to enter the competition based on their successful track record managing Program 3. All three firms were given the design documentation of the existing product design as a starting point. Affordability defined as meeting both performance and production cost requirements was the top priority in the competition. The team knew they were entering the competition later than their competitors and would need to "catch up" so they set an aggressive production cost target they felt would be substantially lower than their competitors and began work on a design concept.

The team reviewed the existing design, made assessments of which assemblies "worked" and should be reused and which assemblies offered the most area for improvement. These decisions set the product architecture – both the partitioning and subassembly interfaces. Once these architectural decisions were made, subassembly redesign began. The resulting concept offered relatively high technical risk to meeting performance requirements but offered a credible path to the aggressive production cost target. This concept centered around a small number of highly integrated and complex MMICs (an alternate approach would have been a larger number of less complex MMICs). These complex MMICs became the core of the new design and were marketed as the team's technical discriminator.

When the first 12 prototype MMICs were developed and demonstrated in a technology demonstration, the customer was thrilled because the demonstrated performance was superior to the other competitors. The customer was in serious jeopardy of interrupting production because of continuing problems at the team's competitors to supply compliant modules. The team accelerated the production MMIC fabrication and module design work and began building their first production product but ran into technical performance issues. As the team continued to struggle through these technical issues that prevented the design from replicating prototype performance, one of the competitors worked through their problems and began building compliant modules and delivering them on time. Eventually, the customer terminated the contract and continues to purchase the modules from the successful competitor today.

The critical issues that contributed to this outcome were as follows:

Took a technical risk and lost: The underlying cycle was as follows: striving for affordability led to a design concept with new, unproven technology which led to higher risk which led to a design that didn't work which led to program termination. The design centered around unproven MMIC technology. The "super MMIC" was demonstrated in a prototype but proved not ready for production. If the "super MMIC" concept had been technically successful, the production cost would have been significantly lower and the team would have had a good chance of winning the business. When you gamble, sometimes you win, sometimes you lose.

Underestimated technical risk: The team did not plan an iterative approach to maturing the module and MMIC technology over time. The team members interviewed believed strongly that with another iteration they could have "gotten there". The team was also slow in recognizing the MMIC risk because they had demonstrated the prototype MMICs and because they had marketed their MMIC ability as their key technical discriminator. This led to an unstated program team assumption that the "MMICs would work". So, no alternate path approach was taken that didn't rely on the new MMICs. Significant time was spent fixing the wrong problem before the team focused their energies on fixing the MMICs. However, the business environment was not conducive to cycle time required for this iterative approach because the competitor who showed up first with a functioning, affordable product would win and the team was a late entrant to the competition.

3.4.3 Best Practices Leading to Noteworthy Positive Outcomes

The most noteworthy positive outcome was the affordability and producibility of the Program 3 product.

The Program 3 product development included three design iterations. The first design iteration was focused on performance and several prototypes were produced. The second design iteration was called the Producibility Enhancement Program (PEP). The primary objective of the PEP was to make a production ready design from the prototype and transition the product into production. The PEP design had significant design issues transitioning to production but was able to achieve a manufacturing rate of 80 modules per month for about 1,100 modules.

A final design iteration was conducted called the Cost Reduction Program (CRP). The primary objective of the CRP design was to reduce the manufacturing cost and increase the production rate by almost 300% - from 80 modules per month to 220 modules per month. The CRP design was extremely successful with only one minor design issue that was resolved quickly. The design coupled with a very strong and successful implementation of Lean manufacturing lead to a 75% reduction in manufacturing hours required to assemble and test a module from the PEP design.

During the Cost Reduction Program, the team focused on all aspects of production to develop a more affordable product.

The best practices that led to this positive outcome were as follows:

Focused on all contributors to cost: The Cost Reduction Program focused on design issues, assembly process issues, implemented LEAN manufacturing methodologies and even reorganized the program team to reduce program management cost. The program team today does not believe there is an end to their improvement efforts – they continue to have Lean Kaizen events and drive out cost.

Iterative product and process development: The Program 3 product went through three major design iterations – the prototype design, the Producibility Enhancement Program (PEP) and the Cost Reduction Program (CRP). The first iteration focused on technical performance. The second iteration focused on producibility, transitioning to production and getting to production volumes. The third iteration focused on reducing parts count, simplifying functions and redesigning any cost driving design features identified when building the 1,100 units during PEP. This iterative design process led to a lot of experimentation, risk reduction and the final CRP design leveraged a known good design with known cost drivers from extensive data on 1,100 units manufactured. This made it easy to know what to change to reduce cost. The team's top priority was cost reduction. The team knew what the cost drivers were. They made design improvements, process improvements, focused on manufacturing flow (Lean), worked tightly with their suppliers to reduce supplier costs and worked tightly with their customer to challenge cost driving requirements.

Relative simplicity of product and high volume: The Program 3 product is a module about the size of your hand and team has built over 10,000 units. This is high volume for defense firms. The incredible success (90% reduction in cost and 75% reduction in touch labor) has been easy for employees, management and customers to see. The success and simplicity have combined to make this the company's model program for affordability and cost reduction.

3.4.4 Collaborating across critical functional or organizational boundaries

3.4.4.1 Understanding the system trade space

The Program 3 team developed the requirements specification for the CRP design iteration with full understanding and knowledge of the cost performance trade-offs and then negotiated with their customer for approval of the requirements specification. This was a very effective way to develop requirements that considered both performance and cost.

Program 4 was a different story. Program 3 was a sole source contract so there were no "fairness in competition" issues. Program 4 was a competition. The customer developed the requirements for all competitors. In a competitive environment, suppliers are less likely to push back on requirements for fear of appearing non-responsive to the customer's needs or technically inferior to their competitors. In a competitive environment, customers are less likely to change requirements once issued because they need to coordinate the changes with all competitors and they are hoping someone can develop an innovative solution that meets the requirements affordably.

3.4.4.2Subsystem and hardware design

Supplier integration was not a big driver because the components purchased were largely standard, off the shelf components. The critical driver was integrating manufacturing knowledge into the design process to be able to meet the very aggressive cost targets and production volume of over 10,000 modules. Producibility engineers were given the responsibility to integrate manufacturability into the design process. MANTECH funding was provided to the producibility engineering team to fund experiments to develop optimum design rules for automated assembly of millimeter wave modules. This funding spawned producibility improvements in the PEP design. Additional improvements materialized in the CRP design. The team had built 1,100 units and understood the cost drivers and could illicit ideas from dozens of people involved in building these 1,100 modules from assembly and test technicians to process engineers and factory managers. This unambiguous, fact based set of knowledge about the problem to be solved was invaluable to the CRP design.

3.4.4.3Life Cycle Cost feedback into the design

Life Cycle Cost consisted primarily of development and production costs. Little evidence was found suggesting production cost feedback into the design process until the CRP design. The team used a Design to Unit Production Cost (DTUPC) scorecard which set goals for all the subassemblies in the module and tracked progress towards those goals. These scorecards were very visible to the members of the team and decisions were made based on the analysis that tracked progress towards the goals in the scorecard. Several engineers indicated that this is a lot easier to do in a cost reduction iteration than the first iteration. Having a design with known performance and cost makes a big difference in understanding where tradeoffs can be made with minimal performance risk and maximum cost benefit.

3.4.5 Summary

These programs offer an interesting comparison of a successful and an unsuccessful program. Program 3 was very successful. The design met the customers needs for performance and affordability, has been profitable to the supplier and has become a model program for cost reduction and Lean manufacturing at the company. The primary enabler to this success was an iterative design process that focused first on getting the product to work, second on making it manufacturable to meet production schedules (PEP) and finally optimizing cost after gaining significant knowledge of the cost drivers (CRP). LEAN enterprise techniques were aggressively implemented and attacked the manufacturing flow, organizational structure and practically every production step in the process. All of this was supported by a close customer-supplier relationship and long term commitment to the supplier through sole source contracts with aggressive cost targets.

Program 4 followed a very different pattern. The customer-supplier relationships were "arms length" because of the nature of a competitive procurement. The team was a late entrant into the competition and did not have time for an iterative development approach. The technical approach taken was relatively high technical risk to meet the aggressive DTUPC targets. The result of relatively high technical risk without an iterative development process produced a design that had technical issues transitioning to production. The contract was terminated as the team was working through those technical issues because a competing firm developed a requirements compliant, affordable solution first.

3.5 Program 5

3.5.1 Program history and summary

This project was a medium sized avionics system development program. The development program required several hundred million dollars and several years to develop a complex system involving hundreds of pounds of electronics and hundreds of thousands of lines of software code.

The most noteworthy positive outcome was the eventual success in developing a very high performance system with order of magnitude improvement in system functionality. The most noteworthy negative outcome was significant cost and schedule overruns as several unplanned design iterations were required in order to meet the demanding performance requirements. Program 5 is a classic example of an over-constrained program with insufficient development funding and schedule to meet demanding performance requirements.

3.5.2 Critical Issues Leading to Noteworthy Negative Outcomes

The most noteworthy negative outcomes of Program 5 were severe technical problems that led to multiple unplanned design iterations that caused budget overruns and schedule delays. These led to program restructuring by the government acquisition customer, which has put the production program at risk of being cancelled. The plan does remain to upgrade the heritage system with the Program 5 system once testing and development is completed.

<u>Aggressive budget and schedule:</u> The Program 5 procurement competition was extremely competitive which led to aggressive budget estimates by all competitors. This negatively impacted the amount of risk reduction planned into the program. For example, no flight testing was planned until formal OPEVAL testing by the government. The Program 5 system was on the critical path for production authorization of a new fighter which created an aggressive schedule that was the top priority of the government customer and could not be changed without impacting the new fighter's production. An iterative development process focused on risk reduction was not pursued for the Program 5 development program. The funding only permitted a "success oriented" approach of one planned design iteration.

<u>High Technical Risk to be affordable:</u> Program 5 was aggressively marketed as an affordability enabling program for the government because of common hardware across multiple platforms across multiple U.S. military services. The program team "sold the program" based on the affordability of the product. The affordability driven marketing of the product essentially dictated certain design implementation approaches that were relatively high risk. This relatively high risk, coupled with only one planned design iteration led to a planned approach with a low probability of success.

<u>*Design Reviews lacked focus on affordability:*</u> Once the program was awarded, the focus shifted dramatically from affordability to performance and schedule. The customer would often tell the team to skip the affordability briefing to extend the technical dialogue in design review and Technical Interchange Meetings. This sent a powerful message to the team that affordability was no longer important.

<u>*No organizational capability to provide cost estimates to design team:*</u> For the manufacturing organization to perform the cost estimates using existing company practices, they needed drawings and parts lists – indicating the design was mostly complete. For engineering to perform the cost estimates, they tended to only focus on material costs and ignore factory labor costs. The major problem was that the analysis was not tied to the design process in a way that was meaningful to the design engineers.

3.5.3 Best Practices Leading to Noteworthy Positive Outcomes

The most noteworthy positive outcome of the program was a technically viable, common system design that could be used across several platforms.

<u>*Clear focus on technical excellence:*</u> The program took a relatively high technical risk in order to have a low cost approach and did not plan on an iterative design process to mitigate the risk through design evolution. This led to critical technical problems in system test that essentially eliminated all value from the product (these were not graceful performance degradations but catastrophic failures). Over time (a pretty long time), these issues were resolved leading to significant cost and schedule overruns. In the end, several design iteration were required but the system works and can be used across multiple platforms for multiple U.S military services (its not quite through all system testing but results to date are very positive).

3.5.4 Collaborating across critical functional or organizational boundaries

3.5.4.1 Understanding the system trade space

The particularly effective method of negotiating requirements and truly understanding the system trade space from the Program 5 team surrounded around three principles:

1) Develop personal relationships with key customer stakeholders
2) Involve the customer in developing the solution on controversial issues
3) Do the analysis for your customer if you can

Personal relationships were particularly valuable in a difficult program like Program 5. These relationships didn't necessarily translate into acceptance of requested requirements changes but did create an atmosphere where both sides trusted each other and believed their intentions were in the best interests of the program. This trust created a more open and honest dialogue, which is critical in resolving controversial issues. Involving the customer in developing solutions on particularly controversial issues was very effective. Nobody likes to give up something. Nobody likes to have do extra work in order to give something up. That is what suppliers ask of their customers when they request requirements changes that requires the customer to perform analysis to determine the impact of the requested change. If the supplier is capable of performing the analysis, doing so makes renegotiations easier because it doesn't require the customer to do work to justify giving something up.

3.5.4.2 Subsystem and hardware design

Program 5 was organized in an Integrated Product Team structure. The team had a producibility engineer involved in the program from very early on to bring manufacturing insight into the design. However, there were no hard metrics that defined how producible was producible enough? Suggested metrics from the team include first pass manufacturing yield and production related engineering change orders.

3.5.4.3 Life Cycle Cost feedback into the design

Several problems were identified in integrating life cycle cost into the design process:

- The process lacks rapid costing. Engineers seldom have access to cost information of their design until after the design is mostly completed and then they have to do a redesign to remove cost.
- Engineers should track and report parts count. This can be done rapidly, without the assistance of a cost analyst and is a good indicator of whether the cost is increasing or decreasing over time. The program director "discovered" one day that the parts count had more than doubled and had no prior indication of this tend.
- The design to cost / life cycle cost contract requirement is common but it is not viewed with high importance. Typically, a finance person works this with a logistics engineer. Design engineering needs to own this and take it seriously with cost estimating support from finance and manufacturing.
- The program director suggested programs need to appoint a Design to Cost or Affordability "Czar" who is respected technically and has downstream manufacturing experience. This person should report to the program director who needs to drive the importance of affordability into the entire team.

3.5.5 Summary

Program 5 was a very tough program. Severe technical issues caused significant budget and schedule overruns. After several unplanned design iterations to resolve these issues, the product works well and will provide a step function improvement in capability. The fundamental issue with Program 5 was taking a high technical risk approach in the system design and product development process (no iterations) under the banner of affordability. This high risk without appropriate risk reduction led to a planned approach with a low probability of success.

3.6 Programs 6 and 7

The products from these programs serve identical functions for different platforms. The products are very similar in functionality and design construction. The products were designed at similar times utilizing similar technology. However, 7 costs 4-5x less than 6.

Program 6 was a performance driven program. The customer pushed the requirements to the corner of the envelope. The customer was also extremely weight conscious and pushed the implementation of exotic composite materials in order to remove weight. The customer did not show interest in the production cost of the product so the supplier did not spend much energy on keeping track of the eventual production cost while the design was being developed. Towards the end of the development program, the customer finally asked what this product would cost and was shocked at the cost. The supplier was shocked at the cost. The program is now implementing cost reduction initiatives to reduce the cost of the product and it appears that the program's viability hinges on the successful implementation of cost reduction initiatives. If the cost does not get reduced, the program's survival is in jeopardy.

Program 7 was driven by value – a balance of performance and cost. It serves the same function as 6 but for a different platform. Program 7 started after Program 6 and leveraged lessons learned from Program 6. The supplier worked very closely with the customer and used CAIV techniques to present various cost-performance trade-offs in jointly developing the requirements specification. The result was a much lower risk design approach that produced about 80% of the performance of 6 at 20% of the cost. Program 7 is a very successful program and has entered full rate production. The customer is satisfied with the performance and has increased the production quantity. The program is profitable to the supplier.

The description of the research conducted on Programs 6 and 7 has been significantly abbreviated because they are classified programs to develop classified systems. They are included because there is an important takeaway. If you understand the cost-performance trade-offs and use that knowledge in developing requirements and system design it is possible to develop a product that produces 80% of the performance at 20% of the cost. (Or conversely, not understanding these tradeoffs can result in a product that costs 4-5x more cost for 20% more performance).

4 Discussion of Results and Conclusions

Each of the seven programs investigated offers results that provide deeper insight into engineering and management actions that can be taken by the avionics firm to improve system affordability. This section will briefly summarize each program. Then each of the four focus areas will be discussed in greater detail:

- The nature of development focus during design iterations
- The role of requirements
- Treating cost as a design requirement
- Integrating downstream knowledge into the design

4.1 Program Summaries

Program 1 successfully delivered a system that met demanding performance requirements and provided an order of magnitude leap in system capability compared to legacy systems. This lifecycle cost of this system was higher than the customer's goals. Program 1 delivered performance but not lifecycle cost. This program was caught by changes in the customer's goals – shifting focus from performance to affordability well after the program's Critical Design Review. The program today is shifting focus in concert with the customer's new priorities and is aggressively improving affordability through year after year incremental improvements using Lean techniques and step function improvements from architecture and module level design innovations.

Program 2 offers deeper insight into the step function improvements possible through module level design innovations. This program is a cost reduction design program implemented as part of Program 1's cost reduction initiative. The program redesigned a subsystem of the Program 1 system during the LRIP program. Architecture innovations at the subsystem level and a technology opportunity were implemented to reduce the production cost of the subsystem by 50%. The architecture innovation centered around how the subsystem was partitioned and how the pieces would interface with one another. The technology opportunity exploited advances in digital circuit card technology to replace more costly hermetic packaged chip and wire technology for RF circuitry. This program delivered both the performance and the lifecycle cost goals of the customer but required additional budget and schedule to do so (one unplanned design iteration was required to achieve performance goals).

Program 3 followed a traditional iterative development path of design it to work, make producibility improvements to meet production schedule then make affordability improvements to meet cost goals. This path was successful for the program. This program used both incremental improvements through Lean implementation and step function improvements to module design to meet the customer's performance and lifecycle cost goals.

Program 4 was a difficult program executed by the same group of engineers and managers as Program 3. The team entered the competition years after their competitors and took a high risk, high payoff design approach involving a "super MMIC" that if successful would have leapfrogged the competition in performance and lifecycle cost. As the team was entering the competition late, there was not time for planned design iterations to grow the product performance. The gamble was not successful. Difficulties in transitioning from prototype to manufacturing led to contract termination.

Program 5 was another difficult program. A highly competitive acquisition led to an over-constrained program. The budget and schedule were not adequate to achieve the required performance and lifecycle cost goals. The program was marketed on affordability – a low cost system that could be used on multiple platforms for multiple armed services to achieve greater economies of scale. Once the program was awarded, the focus shifted dramatically to schedule and performance. Schedule was the top driver because this program was on the critical path for Congressional authorization for production of a new fighter. Based on an extremely competitive acquisition process, the customer was unwilling to change performance requirements early in the program for fear of calling the integrity of the acquisition process into question. The over-constrained nature of the program forced the team into taking a high risk, high payoff approach with very little risk reduction or design iterations planned. Catastrophic performance failures occurred in system testing which required several unplanned design iterations leading to cost and schedule overruns. In the end, the system met most of the performance goals but did not meet the life cycle cost goals. The Program 5 production is somewhat in jeopardy based on the late schedule and higher costs.

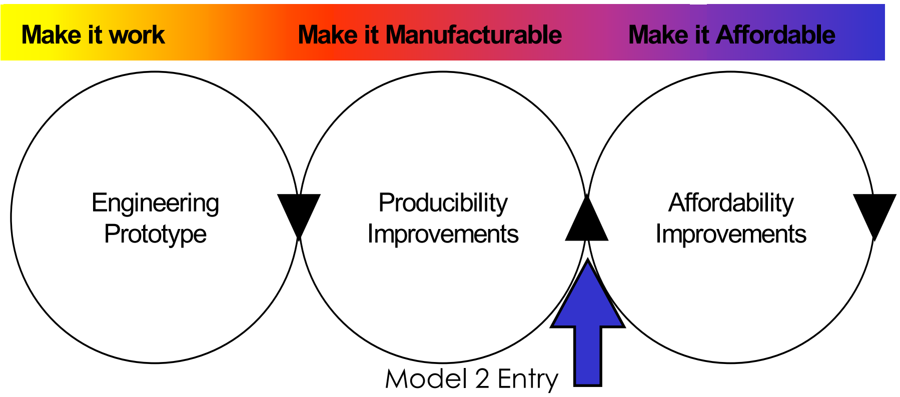
Program 6 and 7 offer an interesting contrast. Program 6 had low knowledge regarding achievable performance and cost drivers and a customer with high priority on performance and low priority on life cycle cost. This led to performance requirements that were technically very challenging. The team developed a system that met these requirements but at a very high cost. The production of Program 6 is in serious jeopardy because of the high cost. The cost required to achieve the last 10-20% of performance was more than the customer is willing to pay for that performance. Program 6 delivered performance but not lifecycle cost. Program 7 leveraged the knowledge from Program 6 about cost drivers and achievable performance. The team was able to credibly map out the trade space of performance and cost and work collaboratively with the customer to develop requirements. This process led to low risk requirements and a lifecycle cost 4-5x lower than Program 6. This program delivered both performance and lifecycle cost.

4.2 Overview of Conclusions

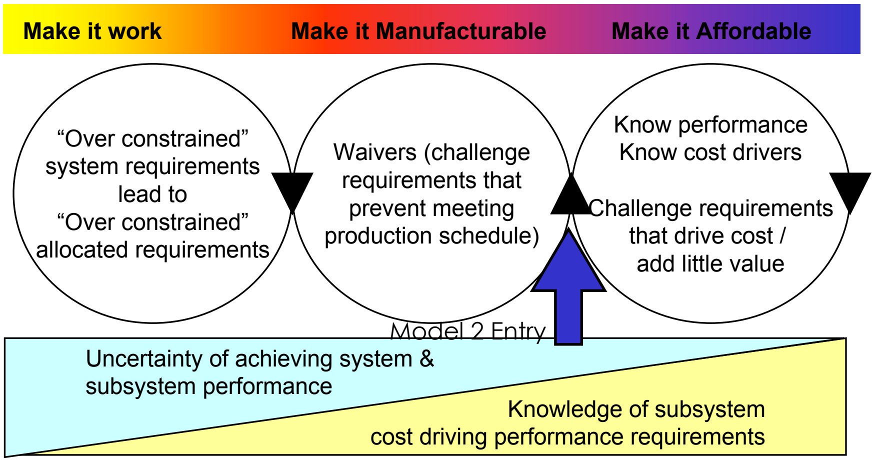
Four focus areas were investigated for their impact on delivering more affordable systems through these case studies. The focus areas are:

- Development methodology
- The role of requirements
- Treating cost as a design requirement
- Integrating downstream knowledge into the design

This section will briefly summarize the conclusions in each of these focus areas. More detailed discussion will follow.



All cases used an iterative development approach. The critical issue was the nature of development focus in each iteration. Two models were identified. Model 1 is characterized as make it work, make it manufacturable then make it affordable. Model 2 develops the lowest cost system concept and uses development iterations to grow performance. Neither model is universally superior. Model 1 is appropriate under conditions of higher technical risk. Model 2 leads to more affordable products but can lead to performance failures if attempted without leveraging prior knowledge, technology and capability. Model 2 can be thought of as a subset of Model 1 entering the development process at a more mature stage.



In cases of low knowledge regarding performance and cost drivers, requirements typically drove high performance, high cost architectures. In cases of high knowledge regarding performance and cost drivers, requirements were challenged to achieve better value systems. Model 2 can again be viewed as a subset of Model 1 entering at a more mature state.

Cost has traditionally been considered a manufacturing or management requirement in the defense industry. Barriers exist to treating cost as a design requirement. There is often an engineering cultural bias against cost as a design requirement. The cost estimating tools are underdeveloped for use when they are needed most - in early stages of development. This suggests another reason why an affordability focus typically comes in latter design iterations when more knowledge of cost drivers exists. Although barriers exist, the programs studied showed high correlation between development of more affordable products and costs being managed like a design requirement.

Integrated Product Teams provide the presence of downstream knowledge in the design process. Downstream knowledge takes the form of hardware engineers in the system design process or manufacturers in the hardware design process. Effective use of this knowledge is a problem of collaboration across boundaries where presence of knowledge is necessary but not sufficient. Mutual dependence, clear goals and mutually accepted methods of assessing progress towards those goals increase the effective use of downstream knowledge. Mutual dependence can be established by treating cost as a design requirement – designers will need manufacturers' knowledge about cost to meet this design requirement. Cost analysis is the method for assessing progress provided it is credible to engineering and manufacturing stakeholders.

The following sections will explore each of these four focus areas in greater detail.

4.3 Development Methodology

All programs evaluated used a iterative or spiral development approach. Some planned these iterations, others required unplanned iterations in order to meet performance or lifecycle cost goals. The critical issue identified through this research was the nature of development focus during each design iteration. Two models were observed. Mode 1 can be characterized as make it work, make it manufacturable then make it affordable. Mode 2 is characterized by developing the lowest cost architecture and using design iterations to grow performance. It isn't that one model is universally superior to the other at developing affordable systems – it's that each model is adapted for different conditions in the following areas: priority on cost vs. performance, technical risk – particularly the consequence of performance shortfalls and planned design iterations.

Program 1 and Program 3 were the examples of the Model 1 approach. Program 1 pursued four major design iterations. The first was described as a Design Verification prototype. One system was built and the sole objective of this iteration was to make the system work. The second iteration was called Engineering and Manufacturing Development. Eleven systems were built and the primary objective again was to get the system to work with a secondary objective of making producibility improvements and begin the transition from engineering to manufacturing. The third iteration was focused primarily on producibility improvements to help increase production rate. This iteration occurred during the first two LRIP lots. The fourth design iteration occurred in subsequent LRIP lots and is focused on affordability improvements. The Program 2 case is an example of the type of affordability improvements pursued during this design iteration. Program 3 pursued three design iterations. The first iteration was an Engineering Prototype, the second was called the Producibility Enhancement Program and the third called a Cost Reduction Program. The first iteration focused on getting the product to work. The second focused on producibility improvements to increase production rate. The third iteration focused on cost reduction. Figure 4.3.1 illustrates these iterations.

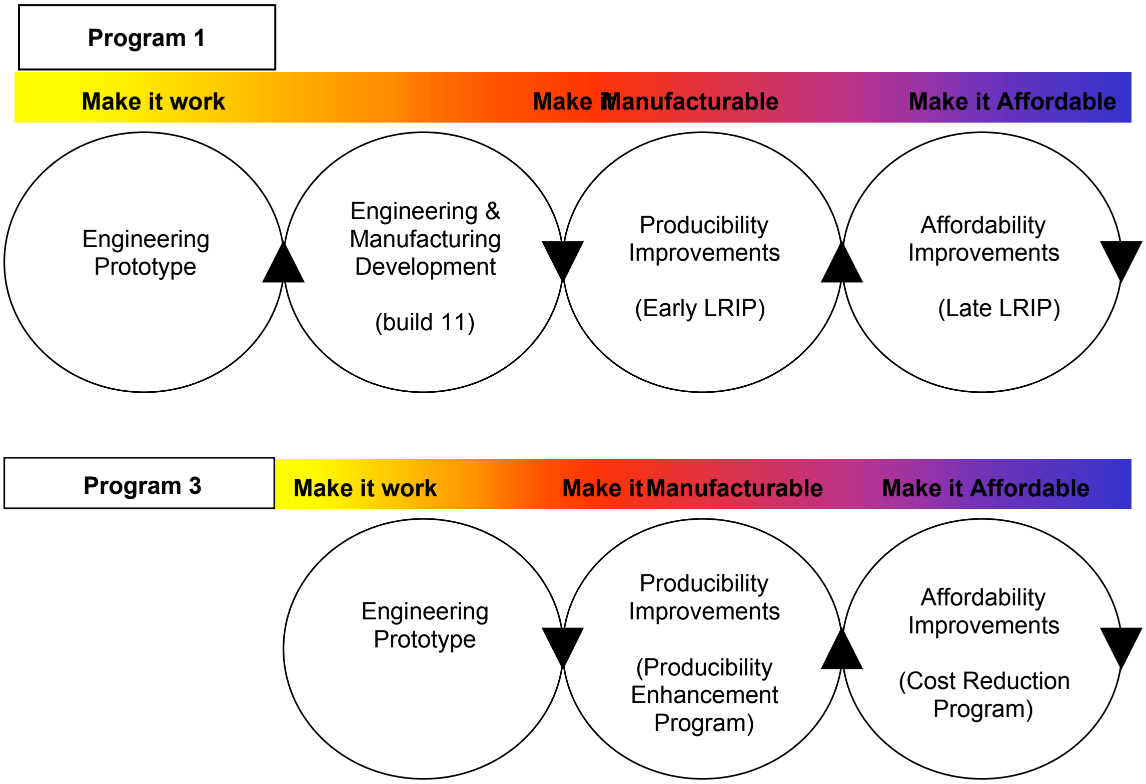


Figure 4.3.1 Model 1 Development Methodology

Make it work, make it producible, make it affordable

The make it work design iteration begins with high performance uncertainty stemming from new technologies or unproven architectures. Program 1 had both. This was the first large program to be primarily based upon Monolithic Microwave Integrated Circuit (MMIC) technology. The system architecture was completely new and embodied unprecedented and unproven levels of integration with the air vehicle and overall avionics suite. The Program 3 architecture was relatively well understood but it was one of the first production programs to use MMIC technology in the more challenging millimeter wave frequencies. Both programs had real doubts about the certainty of meeting the performance requirements. Both programs had performance driven customers indicating the performance shortfalls would carry significant consequences (perhaps contract termination). This lack of cost knowledge, coupled with high performance risk and customer focused primarily on performance lead to a performance focused first design iteration with little focus on lifecycle cost.

The state of knowledge and risk is significantly different in the make it manufacturable design iteration. Some number of systems have been manufactured so cost knowledge is more readily available and performance uncertainty is significantly reduced. At this time system performance has generally been established with some known shortfalls and plans underway to resolve these issues. Because of the novelty involved in the first design iteration, significant manufacturability and cost issues remain so transition to manufacturing is difficult and increasing production rate is behind plan. This design iteration is focused on improving producibility to enable increasing production rate.

The final design iteration is focused on making the product more affordable to get to customer cost targets and keep the program sold. Performance is well established, manufacturabilty is generally established – the program is back on production schedule or getting there. The primary motivator is keeping the program sold by demonstrating cost reductions. The team has very good knowledge of cost drivers because they have built a significant quantity. In some cases, enough time has passed from the first iteration to this final iteration to create technology opportunities. The Program 2 case highlighted a module level technology opportunity in exploiting developments in digital circuit card technology to lower the cost of RF circuits. The team is also exploiting a architecture level technology opportunity utilizing digital technology unavailable when Program 1 development began. Program 3 had built well over a thousand units before entering their Cost Reduction Program and made cost reductions through product design improvements and manufacturing process improvements.

The Model 2 development methodology is characterized by developing the lowest cost architecture or concept possible and using design iterations to grow system performance to meet performance goals. Program 2 provided an example. A low cost architecture was developed that changed how the subassembly was partitioned and how the pieces would interface with each other. The team exploited a technology opportunity by using advanced digital circuit card technologies for some of the RF circuitry leading to significantly reduced cost with only a slight penalty in performance. This technology opportunity created a performance risk in channel to channel isolation. The team grew the performance from 7dB short in the first iteration to 3 dB short in the second iteration and compliant during the final iteration. This approach increases development risk because it plans on growing performance. Planning on how much performance improvement is achievable in each iteration is uncertain. The team required one more iteration than planned to meet performance requirements, which led to a budget and schedule overrun. Program 7 provides another example of this approach with an interesting twist. Program 7 developed a low cost architecture (4-5x lower than Program 6) and was able to develop this system in one design iteration because of leveraging significant knowledge, technology and capability from Program 6. Program 7 leveraged little actual hardware and software from Program 6 but leveraged extensive knowledge.

Program 4 and Program 5 offer examples of unsuccessful attempts at developing products using the Model 2 approach. Both programs developed low cost system concepts. These programs were not leveraging significant prior knowledge, technology and capability so the low cost system concepts entailed significant performance risk. Both systems had catastrophic performance failures in initial testing. The failures were not graceful performance degradation but hard system failures leaving little value in the product for the customer until the shortfalls were resolved. Neither program planned risk reduction activities or design iterations to burn down the technical risk and grow system performance. The coupling of high technical risk, high consequence of failure and no planned design iterations or risk reduction activities put both of these programs on low probability of success paths. Both of these programs were over-constrained programs where the budget and schedule available was not adequate to meet the performance and lifecycle cost objectives. Program 5 was extremely competitive and the winning team had to promise a low budget, fast schedule approach in order to win. The Program 4 team was entering the competition several years after their competitors so the time for design iterations had already been used. This team needed to take a gamble in order to have any chance.

The programs that pursued a Model 2 approach had a 50% success rate. Program 2 and Program 7 were successful. Program 4 and Program 5 were unsuccessful. Model 2 does offer the potential to develop lower cost systems but it is not the right path in all cases. How does a program choose? Figure 4.3.2 illustrates a decision tree to determine whether Model 1 or Model 2 is best.

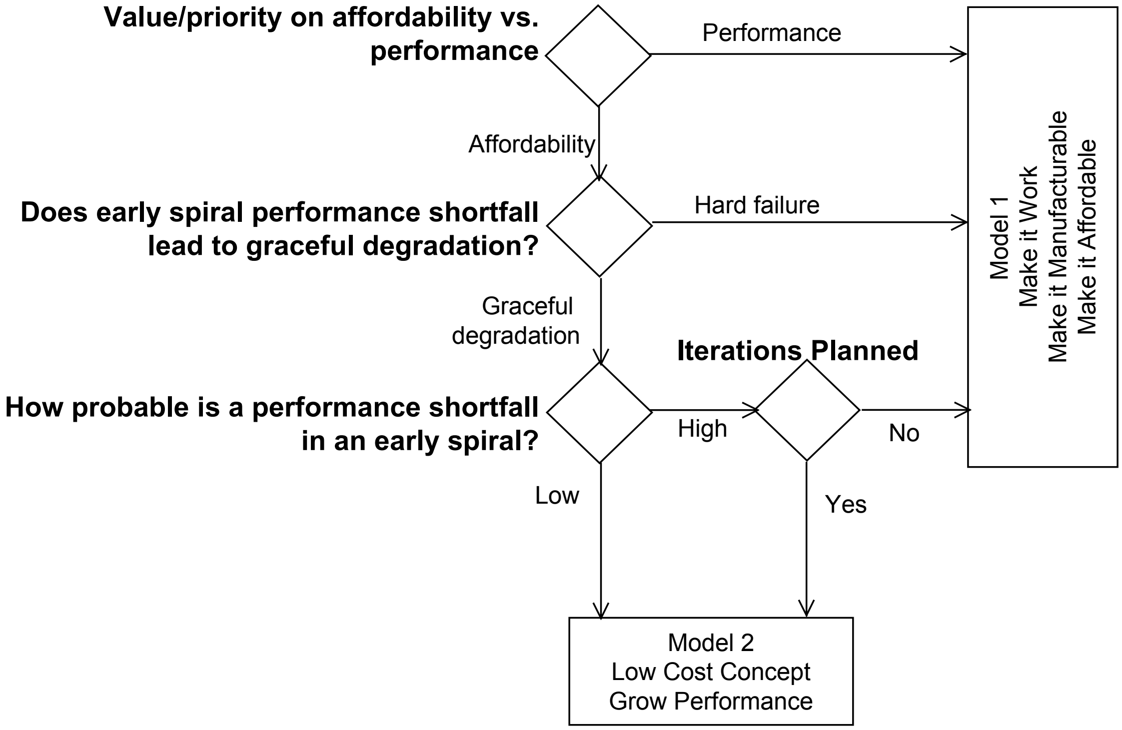


Figure 4.3.2 Decision model for decided between Model 1and Model 2.

This decision model takes into account the following variables or factors:

- Priority or value on affordability vs. performance
- Performance risk – particularly whether the consequence of having a performance shortfall leads to a hard failure or graceful degradation
- Consequence of performance shortfall “at the end” of the development – would the customer accept a product short in performance or require the supplier to keep working?
- Are design iterations planned?

If performance is the priority of the program, Model 1 is a better approach as it seeks to stretch performance as far as possible in the first iteration. If affordability is the priority of the program, a decision needs to be made between Model 1 and Model 2. Model 2 offers the potential for lower cost because it explicitly focuses on low cost during the first design iteration but offers higher performance risk because it plans on growing performance in subsequent iterations. The real variable to consider is performance risk. How likely is a performance shortfall to occur? What are the consequences of the types of performance shortfall that are most likely? If the answer is there is a high probability of a performance shortfall that leads to catastrophic or hard system failure, then Model 1 is a better approach because it minimizes the probability of performance shortfall. If there is a low probability of a performance shortfall and/or the likely consequences are graceful degradations that do not rob the product of all value from the customer's perspective, then Model 2 may be a better approach. You still have to ask yourself the question, what if I can't grow the performance? What are the consequences? If the consequences are catastrophic, planned design iterations are necessary to successfully pursue Model 2. Figure 4.3.3 illustrates this decision model for Program 1 and Program 3.

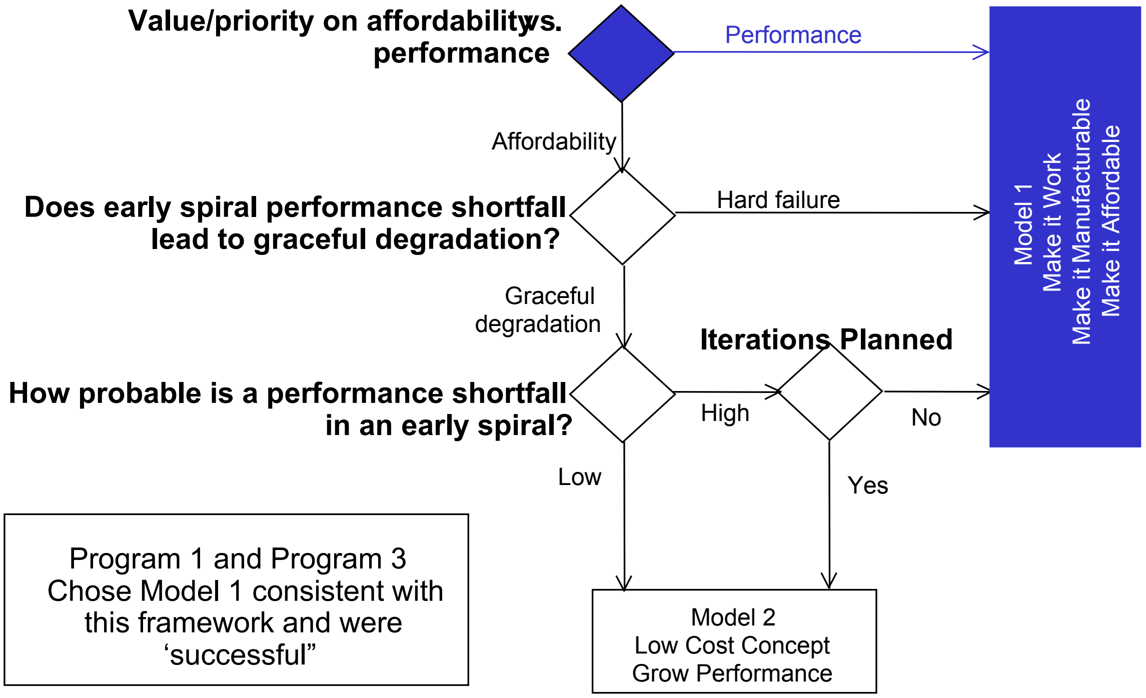


Figure 4.3.3 Decision model for Program 1 and Program 3

These programs pursued Model 1 consistent with this framework because both programs placed a higher value on performance than affordability at the outset of the programs. Figure 4.3.4 illustrates this decision model for Program 2 and Program 7.

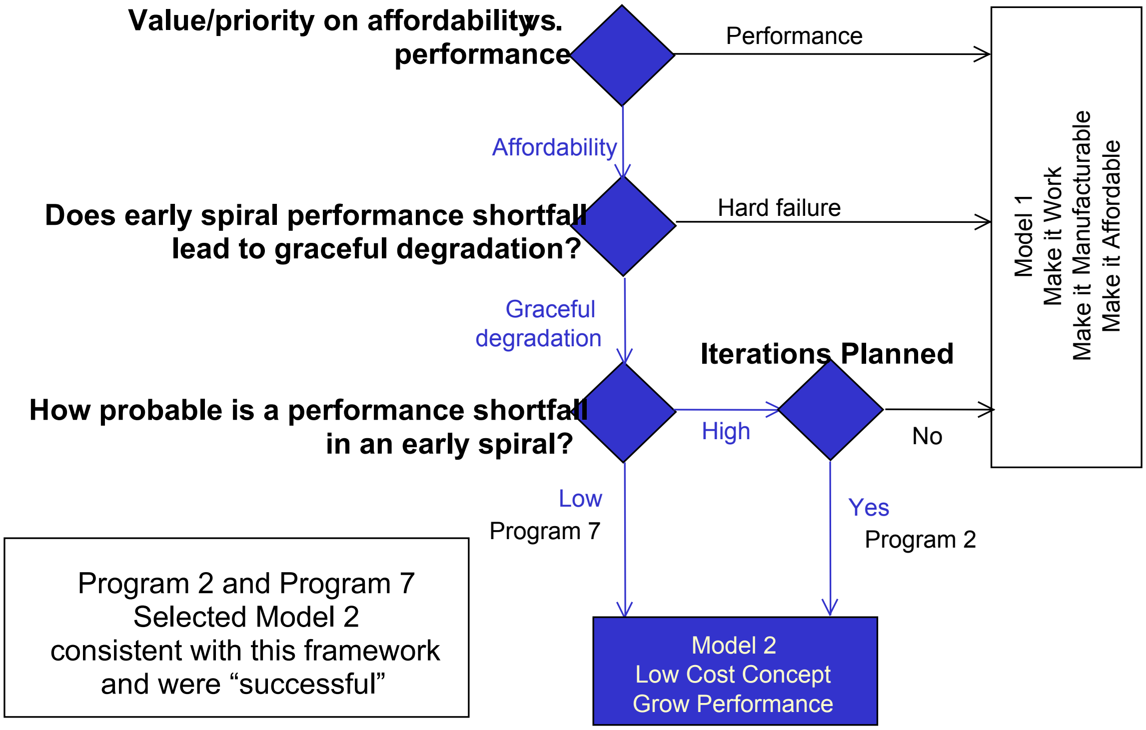


Figure 4.3.4 Decision model for Program 2 and Program 7

These programs successfully executed Model 2. Both programs leveraged significant knowledge, technology and capability from previous programs. Program 2 was a cost reduction redesign of a subsystem that had been in manufacturing for five years so a lot was known about the cost drivers and performance of the subsystem. A lot was also known about what performance was required by the next higher level system because that system was >90% through system verification and validation. The team selected some new technology that increased the probability of a performance shortfall but planned on design iterations to grow the performance. The consequence of the performance shortfall lead to graceful performance degradation and not a hard failure. Program 7 leveraged knowledge from Program 6 to understand the system cost drivers and achievable performance at a variety of cost points. This enabled the team to work collaboratively with their customer to develop a set of requirements that were low risk so the probability of having a performance shortfall was low and design iterations unnecessary. Figure 4.3.5 illustrates the decision model for Program 4 and Program 5.

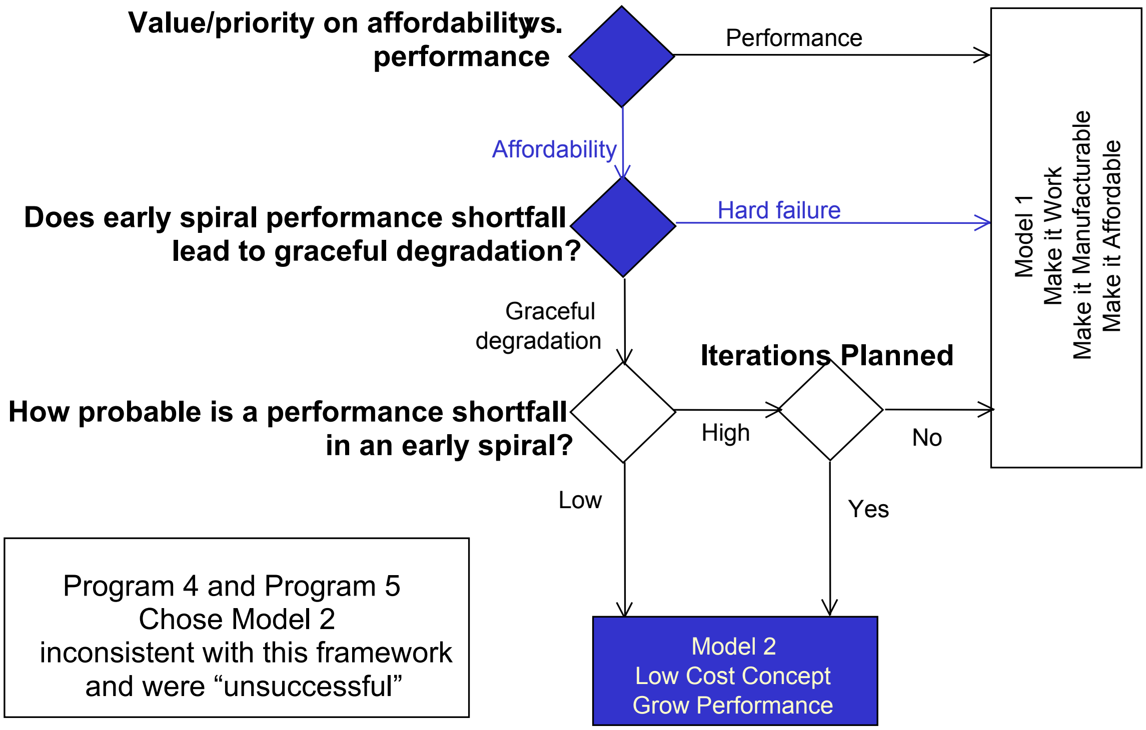


Figure 4.3.5 Decision model for Program 4 and Program 5

Both of these programs experienced catastrophic failures in their first design iteration. Program 5 had the staying power to complete several unplanned design iterations to finally achieve most of the performance requirements but at higher lifecycle cost. Program 4 did not have the staying power and the contract was terminated. Both of these programs took relatively high risk concepts in order to be lower cost and neither planned design iterations to grow the performance. These programs would have been better off taking a lower risk approach and growing affordability through subsequent iterations once they had a product that worked. With 20-20 hindsight, these programs would have been better off pursuing a Model 1 development approach. However, it is easy to see how program business dynamics drove these programs into high risk, high reward approaches.

These two development models appear fundamentally different. Model 1 focuses on performance early and uses design iterations to grow affordability. Model 2 focuses on affordability early and uses design iterations to grow performance. Model 2 can be viewed as a subset of Model 1, but entering the development process at a more mature stage. Figure 4.3.6 illustrates this point.

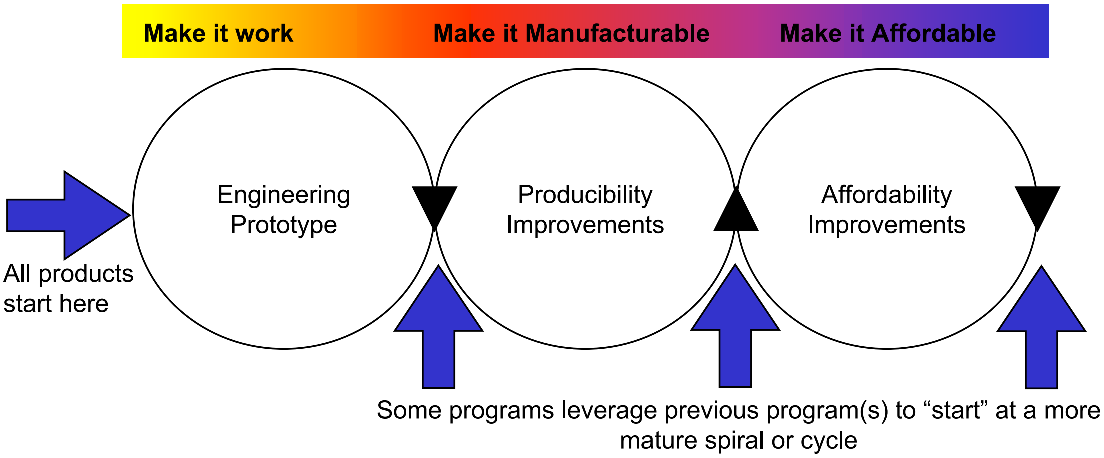


Figure 4.3.6 Model 2 viewed as a subset of Model 1 entering at a more mature stage

Model 2 can be viewed as a subset of a Model 1 approach but leveraging prior knowledge, technology and capability to change the program's risk. When trying to develop a truly new system the risks are largely unknown. When leveraging prior knowledge, technology and capability, the risks are largely known. Unknown risks tend to lead to unknown outcomes, and can generate catastrophic or "hard" failures. An example of a catastrophic failure is an airplane that doesn't fly. These types of failures can be deadly to development programs because they cause the system not to work. Thus, preventing additional testing to learn more about the system's capabilities and limitations. These types of failures also tend to eliminate all practical value of the product from the customer's perspective. Known risks tend to lead to uncertain outcomes within a range of known possibilities. When a team is leveraging prior knowledge, technology and capability, they can typically steer known risks to lead to graceful system degradation. An example of graceful degradation is an airplane that doesn't fly as fast, or as far, or as high as expected. These types of failures are far less deadly to development programs because they do not prevent the system from working – just not working as well as expected. These failures don't prevent further system testing used for risk reduction and increasing understanding of system capability and limitations. These failures do not rob the product from all practical value from the customer's perspective – in fact, systems with these types of failures are typically still significant performance improvements from heritage products.

In summary, Model 1 focuses on performance early and grows affordability. This model leads to lower performance risk but higher system lifecycle cost. Model 2 focuses on affordability early and grows performance. This model leads to higher performance risk but lower lifecycle costs. Model 2 is effective when leveraging prior knowledge, capability and technology to reduce performance risk below some threshold value where focusing on affordability first and growing performance does not lead to unacceptable risk levels. Of course, the threshold risk value for success using Model 2 is subjective and requires engineering and management judgement.

4.4 Role of Requirements

Much has been written suggesting that there is more influence on system lifecycle cost earlier in the design process than later. Figure 4.4.1 represents the idea that by the end of Preliminary Design, there is only 20% remaining management leverage in the system's lifecycle cost even though less than 5% of the lifecycle cost has been spent. In system concept and preliminary design, the primary activities are establishing system requirements, developing a system architecture and allocating requirements to the elements or modules of the system architecture. Requirements, at the system level and as allocated to elements or modules within the system, play a critical role in system affordability. Requirements that are too difficult to meet translate into higher development risk and uncertainty and lead to high performance, high cost systems. Requirements that are too easy to meet translate into low risk development programs and can lead to systems that are low cost but also have low value added capability. The art of establishing requirements is to find the right balance of performance and cost to find the best value. This is what is commonly referred to as "finding the knee of the curve" between cost and performance or finding the "80% technical solution" (see Figure 4.4.2).

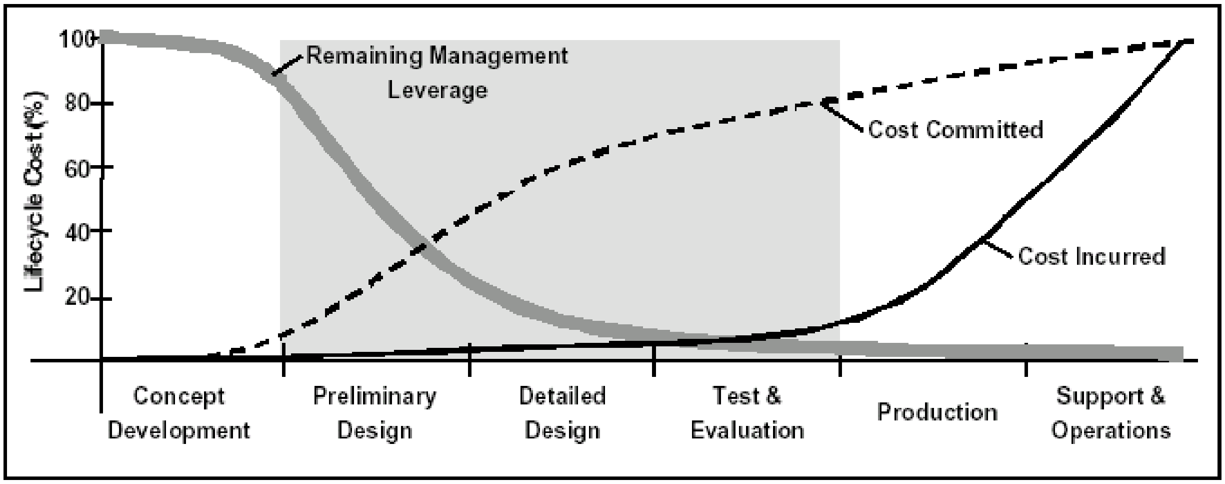


Figure 4.4.1 Lifecycle cost committed vs. incurred during a typical program[33]

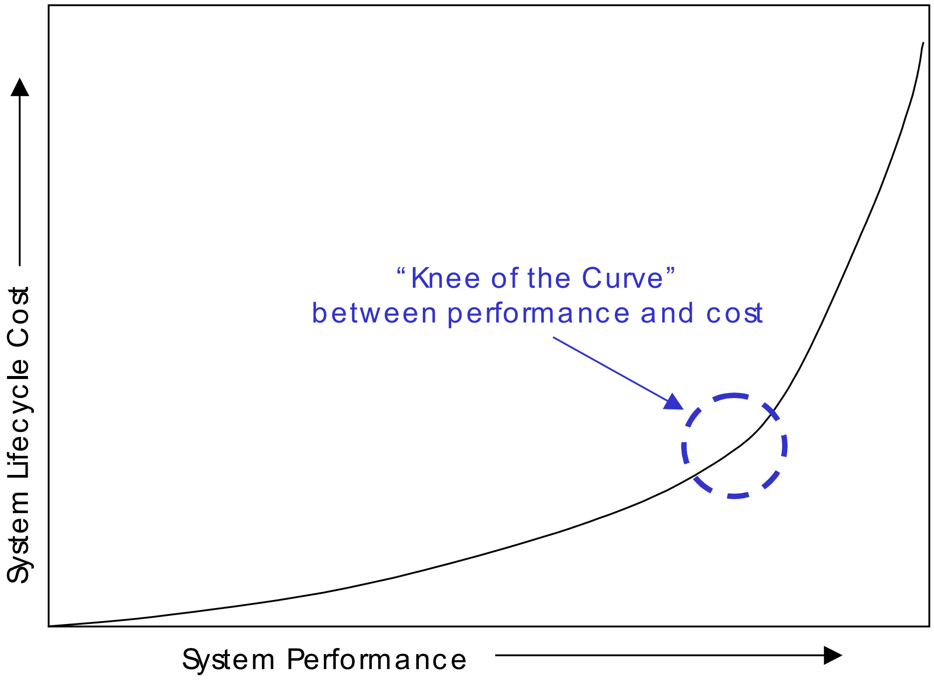


Figure 4.4.2 Typical relationship between cost and performance

Most engineers, managers and warfighters would agree that the best value set of requirements is near the knee of the curve between cost and performance. The critical issue is how to find this knee of the curve when you are establishing requirements. This is often difficult because the cost-performance trade space is largely unknown. Two patterns were observed in the case studies investigated – one leading to requirements further up the performance axis of the cost-performance curve and could be characterized as the "95% solution". A second pattern was observed that appeared closer to the knee of the curve or the "80% solution". Three factors appeared to be the difference between developing "95% requirements" and "80% requirements".

- Value or priority on performance vs. affordability
- Knowledge regarding achievable performance
- Knowledge regarding cost drivers

If a program placed a higher value or priority on performance, had a low knowledge of achievable performance and cost drivers, over-constrained performance requirements were developed (see Figure 4.4.3). This model correlates well with the Model 1 development approach.

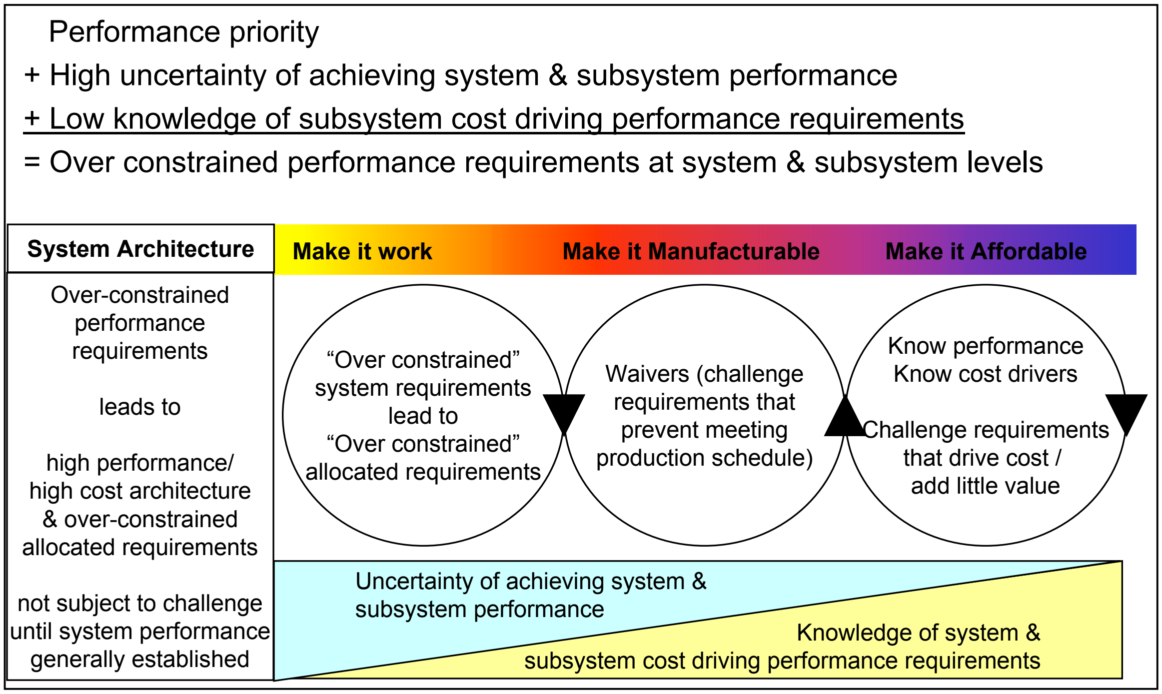
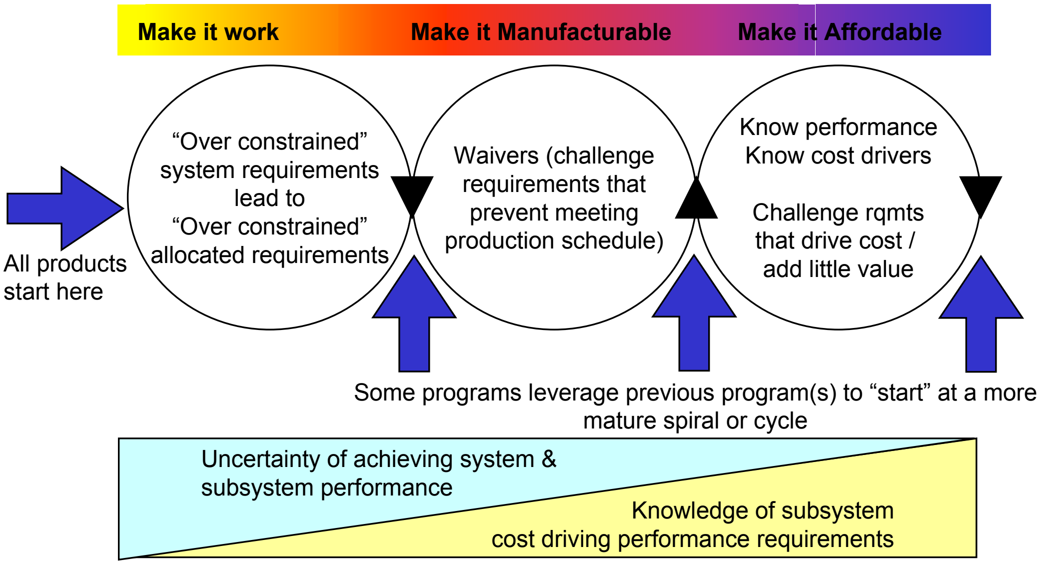


Figure 4.4.3 Underlying dynamics that lead to over-constrained requirements

When these underlying dynamics were observed, the over-constrained system level performance requirements lead to over-constrained allocated requirements to elements or modules in the system. This lead to a relatively high performance, high cost architecture and a relatively high risk development program. The requirements typically evolved over subsequent design iterations as the nature of the program's priorities naturally evolve towards affordability, the uncertainty of achieving system performance is reduced and the knowledge of system cost drivers is enhanced. Requirements work in the "make it manufacturable" design iteration is typically centered around requirements waivers, or challenging requirements that are preventing the program from increasing production rate. Requirements work in the "make it affordable" design iteration is typically more proactive. In this stage, the system has known performance and known cost drivers so requirements challenges explicitly challenge requirements that drive cost and/or add little value.

The first pattern was observed in Program 1, Program 3, and Program 6. Program 1 was performance driven in the requirements phase. Performance uncertainty was high and cost driver knowledge was low. Over-constrained system level requirements were allocated to modules with low probability of meeting the allocated requirements. The result was that most modules could only meet their allocated requirements in very controlled conditions in engineering labs and could not meet their requirements with the higher variability typical of a production environment. This led to a requirements waiver process when the hardware transitioned to manufacturing. Today the program is challenging requirements based on known performance and known cost drivers to improve the system's value. Late requirements changes are difficult to accommodate if the overall platform system architecture is highly integrated because of the extensive system testing required to validate changes. In 2002, the prime contractor reported that 40 times more cost savings have been booked on this program from cost reduction programs exploiting greater cost driver knowledge and technology opportunities than through requirements challenges. Program 3 followed the same pattern - difficult requirements for the engineering prototype, some waivers to enable getting to production rate during the Producibility Enhancement Program and challenging low value and cost driving requirements in the Cost Reduction Program. Program 6 showed a similar pattern. The program established "99.9% requirements" that led to a very high cost system. The system cost was so high, that when the performance and cost became known, the cost is higher than the customer is willing to pay so the production program is in jeopardy. The program today is challenging requirements to drive out cost to move closer to the knee of the curve. This program skipped the requirements waiver process to enable increasing production rate because this program has not gone into production because of its high cost.

The second pattern observed correlates well with Model 2. If a program valued affordability higher than performance, had high knowledge of achievable performance and cost drivers, the requirements typically struck a better balance between performance and lifecycle cost. Again, Model 2 can be viewed as a subset of Model 1 entering at a more mature phase when affordability is more valued, performance knowledge is higher and cost driver knowledge is higher (see Figure 4.4.4).



Model 2 starts at a more mature phase so it doesn't have the problem of high performance uncertainty and low cost knowledge at the start

Figure 4.4.4 Model 2 can be viewed as a subset of Model 1 at a more mature stage

Program 7 and Program 2 followed this pattern. Program 7 had high knowledge of the performance-cost trade space based on Program 6 and several other programs developing similar products. The uncertainty of achieving a given performance level was relatively low because it had been done before. The knowledge of cost driving performance requirements was relatively high because several similar products had been developed at different points along the cost-performance line. Leveraging this prior knowledge enabled the team to work collaboratively with their customer to develop a set of system requirements that led to a development program with relatively known performance and cost. The program transitioned into production and the customer has actually increased production volumes. Program 2 was a module level cost reduction redesign program of a subsystem to the Program 1 system that was in LRIP. About fifty Program 2 subsystems had been built before the team began. This gave the team known performance and known cost drivers before. The performance of the Program 1 system was also mostly known – having completed about 90% of system verification and validation testing. This enabled the team's technical customer to have high knowledge about what performance requirements added value to the next higher level system and which did not. This enabled the team to challenge low value requirements, which helped the team reduce the production cost by 50%.

Program 4 and Program 5 followed a Model 2 development approach but were generally viewed as unsuccessful programs. Program 5 required several unplanned design iterations in order to grow the performance into compliance after a catastrophic failure on the first, and only planned, design iteration. Program 4 was cancelled following catastrophic failure of the first, and only planned design iteration. The requirements model for the programs followed the same pattern as Program 1, Program 3 and Program 6. Low prior knowledge of achievable performance and cost drivers led to requirements that favored performance over affordability. But, the development approach initially favored affordability over performance. This represents a mismatched program – the difficult requirements and high technical performance risk did not match the development approach of a single iteration initially focused on affordability.

In summary, two patterns were observed in developing requirements with varying outcomes in balancing performance and cost that correlate well with the Model 1 and Model 2 development methodologies. When the program values performance, has low knowledge regarding achievable performance and cost drivers, the requirements tend to favor performance over cost-performance value. When the program values affordability, has high knowledge regarding achievable performance and cost drivers, the requirements tend to strike a better balance between performance and cost. The Model 2 dynamic can be viewed as a subset of the Model 1 dynamic entering at a more mature stage by leveraging prior knowledge, technology and capability to reduce performance uncertainty and increase cost driver knowledge. Programs that match the requirements and development approach tend to be successful. Programs that mismatch the requirements and development approach tend to be unsuccessful. The mismatched case is typically developing a system to meet Model 1 requirements with a Model 2 development approach and leads to a low probability of success program.

4.5 Lifecycle Cost as a Design Requirement

Traditionally in the defense industry, lifecycle cost has been considered a management or manufacturing requirement and not a design requirement. There are natural reasons for this. Development cost is considered a management requirement so why shouldn't lifecycle cost? The majority of lifecycle cost on a typical avionics program is spent in manufacturing – both in production and repairs and spares during operations and support. If manufacturing spends the majority of lifecycle cost, why shouldn't lifecycle cost be a manufacturing requirement? Lifecycle cost is inherently cross-functional with the outcome influenced by design, manufacturing and management. The prevalent argument for making lifecycle cost a design requirement is that the system design has the most influence on the outcome. Design has more influence than management practices or manufacturing efficiency. The case studies observed offer other reasons that suggest why lifecycle cost should be considered a design requirement.

When lifecycle cost is considered a manufacturing requirement, Design to Unit Production Cost (DTUPC) dominates the consideration of affordability during the development program. Operations and Support costs tend to take a lower priority because they are owned by a separate organization. The manufacturing organization does not design the system so the DTUPC effort tends to become decoupled from the design process. The manufacturing group generating DTUPC reports begins by working closing with the design organization to create a cost baseline. From this starting point, the estimating efforts tend to become decoupled from the design efforts. The group generating estimates is incentivized to show continuous improvement so the estimates get lower over time. If these estimates are not driving and constraining the design efforts, the design itself tends to increase in cost over time as design complexity is added as the team better understands the technical requirements and adds features to reduce risk of meeting those requirements. This leads to cost estimates decreasing over time while the real cost is increasing over time. This can lead to large gaps between the cost estimate and the actual cost on long development programs. It is not uncommon for estimates to diverge from real costs by 2x during a development program.

For this dynamic to occur, three things must happen. Manufacturing must own the lifecycle cost requirement, there must be a strong boundary between design and manufacturing and there must be high uncertainty in the cost estimating tools early in the design process. The uncertainty in the cost estimating tools is an important factor. If there isn't uncertainty in the cost estimating tools, this dynamic wouldn't occur – the cost estimating group can only credibly show decreasing cost estimates in the face of increasing real costs if there is real uncertainty in the cost estimating tools.

This dynamics was observed in Program 1. Design was considered a manufacturing requirement, there was a strong organizational boundary between design and manufacturing (this was the first large program at the company to use IPT's) and the technology was so new that there was a lot of uncertainty in the cost estimating tools early in the design. DTUPC reports were generated and submitted quarterly to the customer but several lead systems and hardware engineers indicated they were not aware these reports were even generated. This indicates decoupling between the DTUPC activity and the design activity. The DTUPC showed continuous improvement while the design added complexity over time leaving a gap between the estimate and the cost when the design entered LRIP.

When lifecycle cost is considered a management requirement, programs tend to develop relatively high risk, relatively low cost system concepts in order to win the development contract. Certain key affordability enablers of the system architecture are marketed heavily during the acquisition process as discriminators. These features of the architecture tend to become assumptions of the program team not subject to the same engineering scrutiny and risk reduction activities as other system design features. Examples of this were observed in the Program 4 "super MMIC" and in Program 5. This dynamic can lead to relatively high risk system design features without the appropriate level of risk reduction activities and planned design iterations to grow the system performance. This can lead to significant system failures in early system testing. The fate of the program then rests on its staying power and the patience of the customer because the program will experience budget and schedule overruns.

Solid arguments exist to treat lifecycle cost like a design requirement. A system engineering approach is recommended. Determine a set of system lifecycle cost requirements. Typically this is a Unit Production Cost to cover production aspects of lifecycle costs. Operations and Support Cost can be a requirement or the major cost drivers within the control of the avionics supplier can be requirements – Mean Time Between Failure (MTBF), Mean Time To Remove (MTTR), % fault detection and isolation and replacement cost. Decompose these system requirements and allocate to all of the modules within the system. Once the system level requirements are allocated to modules, they should be documented in engineering requirements documentation – typically the module specification. Methods should be standardized and agreed upon for assessing compliance to the affordability requirements as the design matures through design review gates and for verifying the module is compliant to the affordability requirements at the completion of the design. Assessing compliance as the design matures is through analysis. Assessing compliance when the design is complete is through combination of test and analysis. Production cost and MTBF typically experience a "learning curve" effect where costs decrease with production quantity and MTBF increases with quantity. The cost and reliability of development units can be measured and requirements compliance projected using historical "production learning curves" or "reliability growth curves". This is a classic system engineering approach to managing a design requirement. This only difference is that the design compliance cannot be measured without uncertainty at the completion of the design (like weight can) because learning curves or growth curves are required to project compliance from measured data available at the completion of design.

There are cultural and pragmatic issues associated with treating lifecycle cost as a design requirement instead of a manufacturing or management requirement. In many avionics firms this is a change and any change will experience resistance. There is often a cultural phenomenon that "engineers don't do cost" that is typically raised as the first barrier to treating lifecycle cost as a design requirement. Program 2, Program 7 and Program 3 Cost Reduction Program all treated cost as a design requirement so it can't be true that "engineers don't do cost". Engineers solve engineering problems. If the problem to be solved is to design a system that meets these performance requirements, that is what engineers will try to do. If the problem to be solved is to design a system that meets these performance requirements at this cost, that is what engineers will try to do. Making the engineering problem include a cost element required the program's management and customer to continue to highlight that cost was important. Lifecycle cost was reviewed at the management and customer level. Decisions were made regarding requirements and design approaches based on cost considerations. The team talked about it and reviewed it publicly. When affordability is not a priority on the program, meaning it does not impact customer and management decisions, the engineering community will not perceive that it is part of the problem to be solved and will generally ignore lifecycle cost.

In addition to these cultural barriers, there are pragmatic barriers. Engineering processes need to change. Affordability needs to become integrated into engineering plans and processes. It needs to be required in design trade studies in order to develop the knowledge of cost-performance tradeoffs necessary for decision making. Cost needs to be put into design requirements specifications as a pragmatic and symbolic gesture that it is indeed a design requirement. These are minor barriers that can be overcome by simply deciding to overcome them. The more significant barriers exist in the tools and methods to assess compliance to affordability goals during the design process and verifying compliance when the design is complete. The cost estimating tools that provide engineering insight are generally underdeveloped.

Traditionally manufacturing cost estimating tools required a parts list and drawing to estimate cost and could take a long time to develop a cost estimate. Program 1 required six months to update the system's cost estimate. The lead time was far too long to provide design insight because by the time the estimate came out the design had matured by six months and the estimate was not very relevant. The entry criteria for the analysis required parts lists and drawings – this means the design is practically complete and the ability to influence the design is almost exhausted. There is a great need for advances in credible, timely cost estimating tools that provide accurate estimates and engineering insight at the early stages of design – long before parts lists and drawings are generated.

The most effective method observed was parametric models based on cost history of similar products. This method was employed on Program 2 and Program 7. The inadequacy of cost estimating tools for programs in early stages of design highlights another reason why many programs pursue a Model 1 development approach – it simply isn't possible to create credible cost estimate information that provides real engineering insight before you've completed the first iteration and built prototypes.

In summary, there are compelling reasons to treat lifecycle cost like a design requirement. The system design determines as much as 80% of the system's lifecycle cost. Manufacturing and management ownership has led to undesirable dynamics. The cultural barrier that "engineers don't do cost" can be overcome by framing the engineering problem to include a cost component. Framing the problem to include cost requires frequent reviews and customer and management decisions based on cost considerations. The more difficult barrier is pragmatic – cost estimating tools that provide timely, credible estimates and engineering insight at early stages of the design are underdeveloped. Without engineering insight when there is engineering leverage, treating cost as a design requirement is not possible. The most effective cost estimating method observed was parametric models based on cost history from similar products.

4.6 Integrating Downstream Knowledge

Significant research has been conducted highlighting the advantages of integrating downstream knowledge into the design process. This comes in the form of hardware and software engineers in the system level design process or involving suppliers and manufacturers in the hardware design process. This approach had become institutionalized in IPT organizations and Concurrent Engineering or Integrated Product and Process Development (IPPD) processes. The goal is to concurrently develop product and process in order to improve the quality of both. The benefits of effectively integrating downstream knowledge into the design include more affordable and more manufacturable designs transitioned more smoothly to production. The idea of integrating downstream knowledge into the design has been at the forefront of product development organizations for over two decades. During this time, firms have greatly increased their ability to develop more affordable and more producible designs. The case studies investigated offer some insights into how firms can make further improvements.

The IPT organization is critical to effectively integrating downstream knowledge in the design because it creates the presence of downstream knowledge. The presence of this knowledge is the starting point for effectively using it. The program's underlying dynamics shaped by the development methodology pursued and the role of performance requirements have significant impacts on how effective teams are at using this downstream knowledge. Model 1 development programs with over-constrained requirements were less successful at integrating downstream knowledge than Model 2 development programs with requirements that struck a balance between cost and performance. Performance focused programs were less successful at integrating downstream knowledge than affordability focused programs. Programs that considered lifecycle cost a design requirement were more effective at integrating downstream knowledge than programs that considered lifecycle cost a manufacturing or management requirement.

In a Model 2 program, the top priority is affordability. The program is leveraging prior knowledge, technology and capability which changes key variables in a program:

- Knowledge of achievable performance is relatively high
- Knowledge of cost driving requirements is relatively high
- Cost is considered a design requirement
- Relevant downstream knowledge exists from prior programs

The first two variables have been discussed at length. The last two will be discussed here for their relevance in integrating downstream knowledge. Paul Carlile and Eric Rebentisch[34] suggest a model for increasing the effectiveness of knowledge integration across organizational or functional boundaries. This model suggests that effectiveness can be increased if the collaborating groups have three things:

- Mutual dependence
- A common, clear goal
- A mutually accepted method for assessing progress towards the goal

If cost is considered a design requirement, there is a clear goal. The design community depends upon manufacturing knowledge to assess compliance against the cost requirement and for ideas to improve the design's cost. Cost estimating tools become the mutually accepted method for assessing progress towards the goal. This points again to the importance of improvements in cost estimating tools that are credible to the design and manufacturing stakeholders at early phases of the design.

A typical Model 2 program leverages prior knowledge, technology and capability. This means the organization has done something like this before and therefore relevant downstream knowledge exists. On systems that are very different from the organization's prior experiences, relevant downstream knowledge may not exist.

In cases with these conditions, the underlying dynamics of the program are biased towards affordability. Downstream knowledge tends to be affordability focused so it is easier to integrate downstream knowledge because doing so supports the program's underlying dynamics. Program 2, the Program 3 Cost Reduction Program and Program 7 are examples where integration of downstream knowledge supported affordability focused programs and led to more affordable product designs.

If the program is performance focused and may not be leveraging significant prior knowledge, technology and capability, the key variables are reversed:

- Knowledge of achievable performance is relatively low
- Knowledge of cost driving requirements is relatively low
- Cost is considered a manufacturing or design requirement
- Relevant downstream knowledge may not exist from prior programs

In these cases, the program is performance focused. Integrating downstream knowledge is more difficult because it clashes with the program's underlying dynamics. This does not mean that integrating the downstream knowledge is ineffective, just less effective. In these cases, the design is changed to improve producibility under two conditions. One, if the design is physically impossible to manufacture. The second condition is when the producibility improvement does not conflict with other performance or programmatic requirements. In other words, when improving the design's producibility does not cause a requirement non-compliance or require more schedule or budget than planned.

5 Summary

In closing, four key variables were investigated by identifying repeating patterns in the seven case studies researched.

- Nature of development focus during design iterations
- Role of requirements
- Managing cost like a design requirement
- Effectively integrating downstream knowledge into the design

Two program aspects crossed into each of these four variables. Selecting an affordability focus and leveraging prior knowledge, technology and capability improved program's abilities to deliver more affordable systems. Conversely, selecting a performance focus and embarking into new technical territory inhibited program's abilities to deliver more affordable systems.

Choosing to be affordability focused is a relatively straightforward starting point for improving system affordability. Leveraging prior knowledge, technology and capability is critical for several reasons. It offers the potential to lower the development risk below a threshold where explicitly focusing on affordability first and using design iterations to grow performance can be pursued without unacceptable risk levels. It increases the knowledge of cost drivers and achievable performance, which are critical factors in establishing system requirements that strike a balance between cost and performance. It creates more relevant downstream knowledge, which can be a powerful source of ideas leading to innovations.

Recommendations for future research include increasing the effectiveness of leveraging prior knowledge, technology and capability in developing more affordable systems. Specifically, research aimed at improvements in understanding achievable system performance and cost drivers during the requirements and system architecture phase. System performance modeling, system cost modeling and knowledge management techniques would all be valuable. Future research in increasing the effectiveness of downstream manufacturing and supplier knowledge into the design process would be beneficial. Techniques to quantify producibility to be able to answer the question, how producible is producible enough could offer significant improvements by giving more engineering teeth to producibility during the design process.

This thesis focused on affordability from the perspective of a Tier 1 avionics supplier but there are a series of takeaways applicable to the defense prime contractors and government acquisition community that will serve as closing statements.

System performance requirements play a critical role in system affordability. They shape the program's technical performance risk, which impacts the system architecture and development approach. Demand that your suppliers push back on requirements with cost-performance trade studies and seek the "knee of the curve" between cost and performance.

Be careful about mismatched programs – meaning high-risk performance requirements (Model 1) and affordability focused (Model 2) and/or single iteration development approaches. If a mismatched program cannot be avoided, understand that this is a low probability of success path that warrants a fallback strategy.

The culture or focus of the development team plays a major role in affordability and is largely shaped by the contract's business model and the customer's culture and focus. If the customer uses traditional business models and reinforces performance as the priority, suppliers will be performance focused. Remember that traditional business models incentivize unaffordable behavior because lower costs lead directly to lower sales and profits. If the customer structures a business model that financially rewards affordability and reinforces affordability as the priority, suppliers will be affordability focused. Long term, fixed price production contracts are effective business models in production programs because the supplier keeps cost reductions in the current long term contract. Award fee programs with explicit financial rewards based on evidence of affordability can be effective business models for development programs.

APPENDIX A - BIBLIOGRAPHY FOR LITERATURE SURVEY

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4. Next Generation Transparency (NGT) Program presentation at DDR&E Affordability Task Force Conference by Robert E. Mccarty, AFRL/VACE, Oct 1, 1998.
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APPENDIX B - KEY POINTS SUMMARIZED FOR LITERATURE SURVEY

1. Space Systems Affordability presentation by Michael D. Griffin, Executive Vice President and Chief Technical Officer or Oribtal Sciences Corporation, Oct 26, 1999.
    - Keys to Affordability
        - Demanding External/Internal Cost/Schedule Constraints
            - You can't spend money you don't have
            - Time is money
            - Lean approach can be overdone – need to incorporate some margin
        - Flat Organization
            - One or, at most two steps between major projects and the corporate COO
        - Small, self-contained, capable project teams
            - Favors tight decision loops and cohesive execution
        - Control of technology insertion
            - New technology can clearly enable a paradigm shift in what is possible but should be used only when absolutely required with fallbacks if possible
            - Can't afford "science projects" on cost/schedule constrained projects
        - Commercial practices/systems/parts where appropriate
            - COTS software/hardware whenever possible
        - Requirements challenged at all levels
            - Top-level as well as derived
            - Farther down the design process than usual
        - Use of simple vs complex objectives
            - Quantitative objectives: ideally a single (scalar) performance function vs multivariate (weighted) performance metric
            - Qualitative goals: sharply defined specific vs generic goals
        - Architecture
            - International space station vs skylab
        - Stable customer requirements
2. "Methods of Integrating Design and Cost Information to Achieve Enhanced Manufacturing Cost/Performance Trade-offs" by David Hoult and C. Lawrence Meador.
    - "The Design/Cost Trades Task is typically time-constrained. This arises because in the development of complex products the IPPD team makes a design decision and immediately begins to realize its consequences. If the cost impact of the design decisions are not known immediately, costly rework arises when the consequences of the design decision must be cost-corrected. Thus, it happens that one of the metrics for *Database Commonality* is the time to roll-up cost estimates for the product. In the U.S. Aerospace industry, typical roll-up times were months [1], but the best in class rolled up costs daily. In the appliance industry, one leading firm has cost roll-up times measured in minutes instead of hours. In a *Wall Street Journal* article in 1995, a Chrysler representative was quoted as saying that cost roll up time of 24 hours was too slow.
    - [1] "Cost Awareness in Design: The Role of Data Commonality" by David Hoult and C. Lawrence Meador, Dennis Maresi and John Deyst. Presented at SAE #95MJA413 SAE International Congress and Exposition Feb 1996.

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    - 80% of product cost is committed by PDR
    - We have found no measurable differences between different sectors of the aerospace business (I.e. airframes, engines, avionics, etc) with regards to how they deal with cost in design.
    - Only 30% of aerospace companies have commonality between design and cost databases (not common is defined as being in a different place and not readily accessible by designers)

- Data indicates that with database commonality, cost-performance trades occur earlier in the process (some pretty good graphs on this) and more communication between design and manufacturing groups exists

4. Next Generation Transparency (NGT) Program presentation at DDR&E Affordability Task Force Conference by Robert E. Mccarty, AFRL/VACE, Oct 1, 1998.
    - Success story of developing lower cost manufacturing process and design for tactical fighter cockpit canopy
    - Save $100M, to be used on F-16, F/A-22, JSF.
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    - Longbow Example. 5 yr 9.25M, Objective: develop integrated product and proess deveopment to reduce the manufacturing costs of MMW transceivers in the 35-95 GHz frequency range. Examples – laser welding replaces solder, auto die attach/wire bonding, auto test/tune. Realized 30% cost reduction - $3,350 per missile for 11,900 missiles. Total savings $40M.
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    - Focus on "what skews the product development process towards performance? And how can the product development process be changed to focus on acquisition costs?'
    - Architecture of product development process (mechanisms, functional roles, organizational boundaries) inherently causes misalignment process and product goals.
    - Focuses on including manufacturability in design decisions. Barrier identified that 80% of manufacturing is outsourced so company boundaries stand between designer and knowledge of manufacturability.
    - System dynamics indicates 2 primary negative loops that impede cost reductions; (1) rework loop - time constraints causes designers to skip 'optional'

tasks like IPT meetings, DFM/DTC tasks and (2) productivity loop - designers not knowledgeable about cost.

- Policy (to fix problem) should have following characteristics: (1) product and process goals must be aligned, (2) simplicity relative to existing process and (3) easy to learn.
  - Benchmarking: related and unrelated industries. Rule based design and standard parts lists.
  - IPT phase gate process. Cross functional signoff required at phase gates or design reviews.
  - Increased supplier involvement in the design. Allow designers to talk directly with suppliers. Streamline red tape to involve suppliers.
  - Invest in design phase of product development process. Streamline the process to free up designer's time to perform DFM/DTC/IPT tasks.
  - Pilot project with primary or major goal 'knowledge gained'
- Traditional product development has emphasized schedule and performance. Realignment to include cost requires significant retooling of the process, training, incentives, etc.
- Interesting reference to Repenning work "Why good processes sometimes produce bad results: a formal model of self reinforcing dynamics in product development."
- Focus on three primary issues: (1) building knowledge, (2) communicating knowledge and (3) alleviating time pressues.
  - Building knowledge: benchmarking, employee rotation, outside review of the design process, rule based design, standard parts list
  - Communicating knowledge; involved suppliers in designers performance evaluations, phase gate system requiring supplier approval before moving to next level, take advantage of technology in communication practices, remove barriers between designers and suppliers
  - Alleviating time pressures: increase design staff size, (cost of design staff additions is very small to cost benefits in production cost)

8. The cost and cycle time implications of selected contractor and air force system program office management policies during the development phase of major aircraft acquisition programs. Sean Morgan. Advised by Wesley Harris, Jim Hines and Charlie Boppe. Research for LAI summary. May 1999.
   - High degree of interdependence between SPO and contractor program offices
   - Key policies in staffing, management reserve, process quality
   - "Several basic project management insights are found to underlie many SPO-contractor system behaviors including that: quality drives the level of rework experienced by a program, workforce capability is a prime contributor to project quality, and proper management of the workforce is critical for optimal program cost and schedule performance. Explorations of SPO-contractor system behaviors imply a link between a focus on schedule adherence and increased program cost and schedule slip, and they advise that … control of contractor and SPO workforce turnover, and that including realistic assessments of quality and productivity in early cost estimates are critical for their accuracy."
   - Good figure on boundaries, influences on SPO from warfighter, congress, pentagon, etc.

- System dynamics study with focus on 'the rework cycle" - includes a good figure description. Great graph showing average 'product quality' for aerospace, electronics systems, software, construction.
    - Rework is part of every program but is often unplanned or underplanned leading to cost/schedule overruns. Critical issue is the time lag between rework creation and rework discovery.
    - Quality drives rework. Need to continuously improve quality of the process and capability of the workforce
    - Workforce capability is a prime contributor to quality and productivity. Most serious problem in program ramp up, hiring binges in response to looming deadlines, episodes of high turnover
    - Proper workforce management is critical to effective capability. Extended periods of overtime (>50 hrs/wk) can result in real productivity decrease by 50%. When it becomes clear the schedule will be missed, take your lumps once and replan to a program that can be executed with 'normal' effort.
    - "Almost any action taken to force a program back on schedule will have negative implications on program cost'
    - Basically a classical tale of the rework cycle in project management system dynamics applied to SPO-Contractor PMO relationships.

9. Cycle time data. Unknown author.

- Interesting product development cycle time data for various industries

10. Differences in philosophy - Design to Cost vs Cost as an Independent Variable - New focus on total program costs doesn't mean scrap all previous methods to lower production costs. J. Gerald Land. March-April 1997. Program Management(?) magazine article.
    - One problem with DTC is incentives for the program manager. Difficult to trade off performance, schedule (measured here and now on his watch) for downstream costs in production and support (in the future and on someone else's watch typically)
    - 1995 Deputy Secretary of Defense "put in place a process for cost performance trades that permits day to day interaction between requirements and acquisition communities by adopting an Integrated Product and Process Development team approach within DoD." This became documented policy in March 1996 in DoD Reg 5000.2-R CAIV. Approach was to make cost an independent variable - not the dependent variable (one most likely to change to meet other requirements)
    - DTC - primary production costs, secondary O&S. Emphasis in policy statements: "identify cost (to include cost drivers) early in the lifecycle, keep costs within acceptable tolerances and design to average unit production costs". No actual process framework to make the tradeoffs between cost-schedule-performance.
    - CAIV moves cost focus from AUPC to TOC. Independent means fixed - vary the other variables (schedule, performance) to meet cost.
    - CAIV does not grant cart blanche to change performance requirements. Operational requirements must be met. However, methods of achieving operational requirements can be modified. Key is to define operational requirements not performance requirements.
    - Incentives are key in CAIV. Multiple sources, cost savings sharing with contractor.

11. F/A-22 LEAN - Lessons Learned and Challenges. Presentation to LAI. Unknown author. December 2000.
    - Good chart on affordability management process in a cost take out phase
    - Shows (I think) as of Sept 00, savings projected at $21B broken out in the following categories: multi year buy, JSF rates, product support, performance based contracts, material effeciencies, lean enterprise, DMS, PIPs. Shown for A/C and engine separately.
    - Best results on the shop floor but some results above the shop floor.
    - Key barrier - perception that purpose of LEAN is to eliminate jobs
    - Sanders EW Array Kaizen factory flow before and afters on a chart.
    - Good lessons learned and challenges from Sanders, TRW, Northrup Grummon
12. Into the 21st Century - a strategy for affordability. Dr Jacques Gansler. Undersecretary of Defense for Acquisition and Technology. January 20, 1999.
    - Chartered Defense Systems Affordability Council (DSAC) to guide implementation of "better faster cheaper"
    - Three goals
        - Field high quality defense products quickly; support them responsively
            - 50% reduction systems acquisition cycle time
            - Logistics response time from 36 days (current) to 18 days by 2000 and 5 days by 2005
            - Reduce repair cycle times by 10% (2000) and by 25% (2001) from 1997 baseline
        - Lower the total ownership cost of defense products
            - For systems in acquisition, surpass or achieve aggressive "CAIV" unit costs and TOC targets (which are 20-50% lower than historical averages) for at least 50% of programs by 2000.
            - For fielded systems, reduce logistics costs by 7% (2000), 10% (2001), 20% (2005) against 1997 baseline.
            - Move from cost based to price based acquisition process
        - Reduce the overhead costs of the acquisition and logistics infrastructure
13. Government remarks on acquisition cycle time. Presentation. Unknown author.
    - Interesting data on cycle time and cost for acquisition
    - Avg cost growth = 1.15 (<7 years), 1.32 (7-13 years), 1.42 (>14 years)
    - "We believe it is possible to cut this cycle in half"
    - Avg schedule slip = 22%
    - Avg cycle time by service shows air force programs most significant increase from 60 (early 70's) to 120 today
14. Analysis of Key Characteristic Methods and Enablers Used in Variation Risk Management. MIT MS Thesis in Mech Eng. Basak Ertan. Supervised by Anna Thornton. June 1998.
    - Variation Risk Management (basically same as VMM) discusses top down flowdown of Key Characteristics for system performance and bottoms up flowup of Key Characteristics for cost drivers
    - Proper KC identification critical. Requires robust development and review process. Yield calculations critical to assess design robustness.
    - KC identification, control, management in production is common. Linking to high level product performance goals not.
    - Heavyweight project teams best suited for KC / VRM

- Basically describes a Key Characteristic Maturity Model as a means to assess companies' success/maturity in implementing KC/VRM

15. S70A derivative helicopters. Presentation to LAI. Chris Holmes, Sikorsky. April 1998.
    - System architecture comments and issues with adapting S70A basic architecture for new military and commercial demands
    - Formed "Development Operations Teams" to oversee/coordinate functional organizations to look at the architecture and not just better subassemblies
16. Toward Lean Hardware/Software System Development: Evaluation of Selected Complex Electronic System Development Methodologies. LAI report. Alexander Hou. Feb 1995.
    - 30-40% of development and procurement costs of a new weapons system can be attributed to electronics hardware and software. Good figure on page 15.
    - Traditional development methods partition to hw/sw and develop separately despite tight coupling
    - System development longer than lifecycle of underlying electronics technologies
    - Evaluates several existing development methodologies
        - Rapid development process used to develop flight control software for DC-X
        - GritTech rapid development process
        - Ptolemy-supported hardware/software codesign
        - RASSP (Rapid prototyping of Application Specific Signal Processors)
        - Cleanroom software engineering
    - Software OFP lines of code in various a/c platform stats
    - Rates RASSP and Cleanroom engineering as the two best. Suggests combing the two would be better.
    - Toyota "set based design" emphasis on more prototyping, more experimenting before freezing requirements, supplying ambiguous requirements to suppliers and prototyping, getting feedback as a critical part of selecting requirements
17. LAI LEAN self assessment tool set. (several files including instructions and calculator)
18. The Lean Value Principle in Military Aerospace Product Development. Extracted from MIT Thesis. Robert Slack. July 1999.
    - 5 lean principles (based on Womack/Jones)
        - precisely specify value by specific product
        - identify the value stream
        - make value flow
        - let the customer pull value
        - pursue perfection
    - Are these principles applicable to product development?
    - Defines value for this study: Value is a measurement of the 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.
    - Some final diagrams depicting views on value.
    - Basically this is a discussion of value from the standpoint of the customer, shareholder, employee and other stakeholders.
19. Lifecycle Value Framework for Tactical Aircraft Product Development. April 2001. Ingrid Hallander, Alexis Stanke. Working paper.

- Maturity matrix based on practices and lessons learned of 3 a/c programs with 100 interviews. Purpose to "examine relative contributions in product development and determine factors that significantly promote abilities to consider and achieve lifecycle value"
  - Best Lifecycle Value (BLV) defined as "a system introduced at the right time and the right price offering best value in mission effectiveness, performance and affordability and retains these advantages though out its life"
  - Three cases: JAS 39 Gripen, F-18 E/F, F-16
  - JAS 39 Gripen: small, multi role fighter to replace the Viggen for the Swedish AF. Achieved 40% reduction over LCC from Viggen. As of writing in service for 7 years. Clean sheet of paper new design.
  - F-18 E/F: Upgrade program. 90% common avionics but radically different airframe from C/D. Program never rebaselined. Early program goals were met.
  - F-16. Lightweight 'no frills' ac. Then slow, evolutionary upgrade programs kept it small but continuously upgraded capability.
  - 6 themes developed as best practices or lessons learned
  - Holistic Perspective. Consideration of entire system and entire lifecycle. Essential to balance 'long term' demands like upgradability, maintenance, repair with 'short term' demands like low unit costs and performance. 57% id'd lack of visibility across lifecycle as a barrier.
    - Best Practices: systems engineering practices in product development, DFM&A, lessons learned databases, multiyear contracting, educated designers on maintainability and reliability, incorporate design recommendations from variety of lifecycle perspectives, incorporate flexibility, lifecycle issues into early systems architecture, acknowledge and plan for dynamic nature of lifecycle.
    - Lessons learned: coordinate design maturation and production planning to account for differences in subsystem and components
  - Organizational factors. IPTs and other organizational issues.
    - Best Practices: collocate product/people, align org structure to product WBS, establish multi disciplinary teams, use IPT structure to broaden functional responsibilities to develop flexible workforce, coordination meetings between leaders of different projects, specialization at core competency level, integration at system development level.
    - Lessons Learned: balance functional specialization and integration knowledge by shifting focus of support between functional and IPT orgs throughout development cycle as appropriate.
  - Tools and methods. Great tools, integration is the key
    - Best Practices: common CAD tool, eval design changes from ops perspective to reduce preventative maintenance, internet/web pages effective at information sharing, define common databases, tools, practices to be used throughout the value chain, risk management process, roadmap emerging technology to plan for technology insertion accordingly.
    - Lessons learned: increase commonality between modeling and analysis tools, integrate PDM and CM databases
  - Requirements and metrics. Setting, communicating, managing key factor in developing affordably timely systems

- Best Practices: metrics shared weekly, people empowered to make decision through rqmts flowdown creating RAA (responsibility, authority and accountability), EV 'perform the plan', incorporate plans for growth, upgradeability, technological development in design work, fixed development cost target focuses on near term development cost and shedule
    - Lessons learned: specs often not clearly written / adequately communcate requirements, use spec framework to establish actual goals, determine when its "good enough" and move on
- Enterprise relationships.
    - Best practices: require open/honest communication, encourage, reward asking for help, "hit by a bus" test - document your job so someone else can pick it up, utilize knowledge throughout enterprise regardless of source, share responsibility for decisions using a defined process, jointly establish design verification process, maintain organizational counterparts throughout the enterprise, create/maintain leadership alignment across enterprise, jointly establish targets for continuous improvement using structured process,
    - Lessons learned. Maintain visibility of enterprise relationships throughout levels of org to prevent suboptimization, incentivize behavior corresponding to targets, manage outsourced development work according to maturity, treat technical IP of all stakeholders with respect to build trust
- Leadership and management
    - Best practices. Create strategies, practices that can weather leadership transitions, maintain high expectations for success, emphasize maintaining credibility, clear roles for decision making, bring people together/facilitate/prevent strong personalities from taking over, support mentality (there to serve, not be served), training, push to evaluate the no growth (cost, weight) alternatives in terms of risk, proactive culture
    - Lessons Learned. Create buyin on budgets schedules, emphasize schedule, excellence under "normal" circumstances instead of hero in crisis,

20. Lean Implementation Considerations in Factory Operations of Low Volume / High Complexity Production Systems. LAI report #RP97-04-152. Authored by Shields, Kilpatrick, Pozsar, Ramirez-de-Arellano, Raynal, Quint, Schoonmaker. November 1997.
    - Model for lean implementation includes 4 phases: building a lean infrastructure, redesigning flow of products in the factory, revamping ops management, fostering process improvement
    - Building lean infrastructure steps: id business issues/goals, develop strategy, id current/needed skills, breakdown stovepipe mentality
    - Redesigning flow steps: distribute information, group products into families, design process layout, simulate flow, optimize flow and cell linkages, redefine/redeploy work tasks
    - Ops mgmt steps: cross train workers, realign incentives, reallocates support resources, implement pull
    - Critical factors: executive champion, degree of process ownership by those responsible for the product
    - Above are "most used steps" in case studies. Complete list of steps on p12
    - 12 case studies used to test the model mostly in the defense aerospace industry.

  - Paper focuses on the steps taken to implement factory lean compared to a theoretically correct sequence of steps. This paper does not draw correlations between steps taken and benefits received to verify theoretical model.

21. The LEAN Enterprise Model. Product from LAI.
    - Model developed by LAI to manage LEAN enterprise transformation
    - ID/optimize enterprise flow
    - Assure seamless information flow
    - Optimize capability and utilization of people
    - Make decisions at lowest possible level
    - Implement integrated product and process development
    - Develop relationships based on mutual trust and commitment
    - Continuously focus on the customer
    - Promote lean leadership at all levels
    - Maintain challenge of existing processes
    - Nurture a learning environment
    - Ensure process capability and maturation
    - Maximize stability in a changing environment
    - Offers metrics and enabling practices for each major theme listed above
22. F/A-22 War on Cost Update. March 26, 2002. Presentation. Handell.
    - Shows F/A-22 affordability process (really cost take out)
    - Shows 3 pillars - requirements, Lean enterprise, cost reduction investment strategy
    - Requirements - saved $40M production, $30M worth of ideas disapproved, unknown value withdrawn
    - PIP - 144 projects 2,747M savings, 150M investment, 18.2:1 ratio
      - LM Aero, Boeing Lean Rate Assembly Line
      - P&W WOC
      - BAE SYSTEMS 2C1, Carrier Elimination
      - TRW Backplane, IFFT, Conformal Coating Process
      - Raytheon Radar TR modules
23. Lean Effects on Aerospace Programs: Raytheon AMRAAM Case Study. March 27, 2002. Davidz. MIT LAI Presentation
    - Dropped cost from $1M to $250k in 7 years, doubled deliveries in 12 months, improved reliability to 3x requirement, mfg flow time decreased 71%, defects dropped 48%
    - Key enablers
    - Leadership: strong, involved enterprise leadership, great leadership at all levels, provide motivation and support for change, key to overcoming consolidation
    - People: extreme pride, enthusiasm, empowered at all levels, extensive use of IPTs
    - Govt relationship: once contractor cost reduced, govt cost drove missile cost, govt support office reduced from 300 to 60, TSPR, strong relationship
    - KEYS - strong leadership, emphasis on people, lean transformation and continuation, strong govt team relationship
24. Lean effects on aerospace programs: Atlas Case Study. March 27, 2002. Hitchings. MIT LAI Presentation
    - Atlas V - EELV - major purpose improved design for manufacturability, 1st launch May 02

  - 10,000 parts reduction, reduced supply chain failed inspections from 28-6%, increased payload by 2400 lbs, cut production cycle time in half (48-24 months), significant cost reduction
  - Enablers: leadership, communication, information flow, factory floor initiatives, lean from the government side
  - Major findings; leadership, coorporate visibility, LM21, people issues critical, employee value, supplier value, engage workforce in self reinforcing learning cycles, a significant fraction of supplier cost is determined by the customer's requirements and business practices

25. F-16 Lean journey 1992 - 2001. A decade of continual improvement. Dr Jerry Gannaway, F-16 Program Integrator. Alexis Stanke, MIT Researched. LAI presentation. March 27, 2002.

- 1991 company employment dropped 30k to 20k after A-12 cancellation
- Really interesting 10 year history of 6 manufacturing metrics: annual production rate, QARs/1000 earned hours, percent on time delivery of ac, percent USAF CFE price variance, zero defect ac, delta cpar performance
- Good comparison of mass to lean production chart
- Final Gannaway comments: quality better, technology continues to be infused, employees feel they have a future/purpose, suppliers are partners, cost/delivery under control
- Nearly constant price despite dramatic reduction in annual production rates
- Enablers: new leadership, metrics including goals, core competencies, IPT, pilot project success, IT tools, senior leadership commitment

26. Remarks to Science and Technology Affordability Conference. Oct 1, 1998. Raytheon COO Daniel Burnham
    - Excitement about technology advances / capability advances
    - Focus on Six Sigma to achieve affordability
    - Technology/processes - design of experiments, mistake proofing, design to cost, design for manufacturability, SPC, process mapping, etc
    - Leadership - direction, customer satisfaction surveying, organizational structure initiatives, metrics and tools, Process Capability Analysis Toolset (PCAT)
    - Theme is that affordability is a means to protect those who protect us by providing the most capable equipment possible within current budgetary constraints (is a "better" system that the government can't afford to purchase or can't afford to purchase in sufficient quantities to ensure that the men/women in harm's way have the new equipment).
27. DARPA funded simulation based design and advanced surface combatant programs. Presentation.
28. Affordability Considerations for the Joint/Future Transport Rotorcraft. Dr. Schrage. Georgia Tech.
    - Recommends an overarching affordability metric described as benefit or value to cost ratio (e.g. mission effectiveness / mission cost)
    - Affordability most influenced by requirements, concepts (design variables) and technologies
    - Uses lots of math, "Joint Probability Decision Modeling" techniques to mathematically evaluate alternatives
    - Recommends changes to DoD policy to focus on affordability
      - Rapid acquisition with demonstrated technology

- Time phased requirements and evolutionary development
    - Integration of acquisition and logistics
    - Interoperability
    - Cost as a requirement that drives design, procurement and support
    - Increased competition
  - "Requirements drive initial design studies, procurement decisions, and ultimately *operational effectiveness and cost*"
  - "However, it is often the case that design processes (and designers) overlook the impact of changes and/or ambiguity in requirements and fail to understand the relationships between requirements, technologies, and the design space"

29. Technology Transition for Affordability. A guide for S&T Program Managers. April 2001. DoD Deputy Under Secretary of Defense (Science and Technology) Delores Etter.
    - "the DoD must put into practice methods that lead to the best balance among a system's performance, life cycle costs and availability"
    - Identifies best practices for S&T program managers seeking to transition new technology into the acquisition community
        - Obtain management support to meet affordability goals
        - Implement IPPD
        - Develop and execute a training plan
        - Establish and track affordability metrics
        - Develop a transition strategy
        - Technology "marketing" best practices
            - Block improvement/upgrade
            - Fill unique military need
            - COTS
            - Mature technology "in time"
            - Customer buy in
            - Industry support
            - Application of open systems concept
            - Producibility
            - TOC
            - Spiral development
    - Lists activities undertaken by various government agencies to facilitate tech transition
30. Value Creation in the Product Development Process. MIT Thesis. December 2001. James Chase. Advised by Greitzer, McManus, Deyst, Velde.
    - Defines value as creating a desired product for the customer, continuing profit for the shareholders, lifetime satisfaction for the employee
    - Four principle elements of the framework - tasks, resources, environment, management
    - Figure 3.3 shows good view of the traditional cost commitment vs cost spent
    - Discusses three dimensional complexity in product development - product architecture, process architecture (WBS), organizational architecture
    - WBS evaluation of multiple programs
    - WBS of programs taking place in more "lean" environments showed MORE supporting tasks, primarily concerned with cost/schedule management than those taking place in more traditional environments

31. Supplier management practices on the Joint Direct Attack Munitions Program. MIT Thesis. Malee Lucas. June 1996. Advised by Hoult, Deyst, Neufville, Wachman.
    - Changes implemented by govt and prime contractor show progress in the general model for supplier relationships towards more collaborative, team oriented approach
    - Best practices: average unit production price metric, competitive acquisition, rolling evaluation and downselection process, stable multi year procurement, accelerated schedule, limited govt oversight, govt advocacy teams, open communications, contractor configuration control, limited project scope, establishment of "live or die" requirements, 20 yr warrantee, commercial practices, CAIV, cost-performance trades, streamlining standards, specs, "how tos", requirements, contractor incentives, pay for performance, contractor training, DFM/DFA and alternate dispute resolution
    - Describes 4 stages of approaches to supplier management - confrontational, arm's length, goal congruence, full partnership. Lots of discussions about costs/benefits of each stage
    - $68k unit cost, govt requested $40k, MacDac came up with $15k - saved $2B. Good table showing programmatic data including these costs on p62
    - specific examples about how they accomplished this - value engineering
32. World electronic warfare equipment markets. Market analysis conducted by Frost and Sullivan. 1998.
    - Overall growth rate 5.3% annual 98-05
    - 1998 EW market $4.78B, fighter/attach a/c EW $3.19B, other fixed wing EW 0.45B, rotary wing EW 0.74B, shipboard EW 0.15B, ground based EW 0.25B
    - Fighter / attack aircraft EW drivers - perceived threat to air force capabilities, proliferation of weapons of mass destruction, development of next generation fighter ac, proliferation of IR missiles, growing upgrade market. Restraints - decreasing platform counts, perceived air force superiority, limited air force capabilities
    - Historically EW 5% of airborne platform cost
    - Need for EW self protection depreciates in UCAVs - study views UCAVs as a major threat
    - P80 shows projected size of market, p81 shows percent of market in segments
    - P114 and on shows market forcast for EW on fighter aircraft - slightly neg growth until 2000, 5-8% growth 2000-2005 - US is only 20% of market
33. World Platform Self Protection. EW Markets. Market analysis conducted by Frost and Sullivan.
34. Kevin Reihl data take 1. R/Y/G metrics, COPQ, Baldridge Assessment.
    - We are almost never red on technical - reflects culture that given enough $/time all technical problems are solveable. Technical is the independent variable.
    - Successfully argued that goal of zero red programs is probably not the right objective - leads to too much risk aversion, what's the point of having a metric if you never fail (the bar isn't high enough if you always clear it)
    - Baldrige - need more leading metrics and sharing lessons learned across company
35. The role of product development metrics for making design decisions in the defense aerospace industry. MIT thesis. Todd Stout. Oct 1995. Advised by Hoult.

- 3 common problems - failure to focus on proper metrics and measurements of current activities, failure to maintain a significant historical database to facilitate corporate learning, use of a decision making process that often lacks the information necessary to make good decisions

36. Best Manufacturing Processes - LM GES Moorestown NJ. Oct 1995.
    - Producibility experts and design review
    - Defect and scrap reduction
    - Process improvement road map
    - Continuous acquisition and life cycle support systems engineering and laboratory
    - Design matrices
    - Integrated product development concept
    - Part obsolescence management
    - Rapid prototyping of electronics modules
    - Sys Eng requirements management and requirements analysis
37. Best Manufacturing Processes - ITT Industries. Fort Wayne, IN. April 1998.
    - Integrated product development process
    - Supplier integrated product development
    - Advanced manufacturing process development
    - Integrated management plan
    - Risk management process
    - Technology roadmap
    - Design review manual
    - Design to cost reduction planning
    - Robust system design process
    - Manufacturing for design initiative - proactively developing manufacturing capabilities to support future programs
38. Best Manufacturing Processes - Hamilton Sundstrand, Farmington CT. Oct 1993.
    - Design to cost information
    - Manufacturing technology insertion
    - Concurrent engineering
    - Design review for producibility
    - Design for manufacturability
39. Best Manufacturing Processes - LM NESSS Moorestown NJ. Aug 2001
    - Cost estimate process
    - Lean and six sigma
    - Technology roadmapping
    - Transition to production process
40. Best Manufacturing Processes - Lockheed Martin Electronics and Missiles. Orlando. April 1995.
    - Key characteristics and variability reduction
    - Design for assembly process
41. Best Manufacturing Processes - Lockheed Martin Tactical Aircraft Systems. FW Texas. Aug 95.
    - Cost assessment - dedicated cost team
    - Lean enterprise
    - F/A-22 Variability Reduction
    - Supplier integrated product development

42. Robustness in Product Design. Don Clausing. Presentaion. Oct 1998.
    - Advocated robust design instead of build/test/fix approach to problems
    - Requires culture change (hard)
    - Requires metrics to be enforced (first pass mfg yield)
43. Cycle time reduction using design structure matrixes. Tyson Browning. Nov 1997. Presentation
    - Good last chart on typical schedule risk drivers
44. Product Development Team. Prod Development Schedule reduction. John Deyst. Nov 1997
    - Good metrics on DoD avg development times compared to some commercial standards
    - Includes 6 steps to faster cycle time (constantly improve work processes, know what adds value, flat, multifunctional team based org, pursue process development as avidly as product or service development, establish stretch goals and publicly measure, create environment which stimulates/rewards continuous learning/action
45. Toyota, Termites and Zero Risk System Development. Allen Ward. Presentation. Nov 1997.
    - Great chart (12) on difference between "Newton's intellectual universe" where we manage programs today vs. real physical universe that Toyota recognizes in its PDP

– All is knowable	nothing is completely knowable
– If we knew enough, we could predict all	its all probabilistic anyway
– Variation is minor problem dealt with later	tiny input changes - big output changes
– Put smartest guys in charge, all obey	logic is unpredictable, most thing too complex for computation

    - Compares set based to point bases system design (p 22)
46. Product development team effectiveness. Oct 95. Gerald Susman. LAI white paper.
    - Follow up to study that concluded 50/50 power balance functional/program best for high risk projects and heavy shift to program best for low risk projects
    - Team leaders of successful projects form good relationships with functional managers who have different backgrounds and responsibilities than they do
    - Team leaders of successful projects focus more energy on resolving technical/production issues with functional managers than resolving priority/resource issues
47. Managing subsystem commonality. Eric Rebentisch. April 2001.
    - Good charts (17,18) showing savings estimates of having common LRUs across platforms or systems
48. JSF presentation. Burbage
    - 5 principles
    - strategic focus on affordability
    - advanced evms, subcontractor management
    - 10 anchor points
    - understand rework phenomenon
    - create environment for success
    - onboarding
    - wizards

49. EELV Case Study Lean Implementation. Col Robert Saxer. Dec 00.
- Explanation of Lean implementation on EELV from acquisition, PD, mfg points of view
- Major success story
- EELV was an evolution from pervious rocket

50. JDAM Lean lessons learned.
51. Darlene Druyun keynote speech to LAI. Dec 2001.
52. BAE SYSTEMS COPQ "Why do programs go red? How do they return to green?"
53. Avionics Life Cycle Forcasting Model. Stephen Czerwonka. June 2000. Advised by Rosenfield, Deyst, Hagwood.
    - Exec summary of thesis (need to find thesis).
    - Statistical model to predict lifecycle of avionics components based on reliability, sustainability and economics
    - Forecasting ability of the model is high only when there is little variation in the measurement data sets and it increases as components approach the end of their life
54. JSF - Collaborative Design for Affordability. Mike Fortson, Mar 26, 2002. Presentation to LAI.
    - Stringent air system requirements
    - Engineering impact on cost
    - Life cycle cost requirements
    - Collaborative design for best value
    - Meeting life cycle cost requirements
    - Majority of cost of our products is driven by the way we design them. 70% of LCC based on design, 20% material, 5% labor, 5% burden rates. I think he means influence on the cost not the cost itself
    - DTLCC allocations, Collaborative "best value" designs, affordability initiatives & harvest savings
    - LCC is a design requirement
    - Good example in inlet duct construction trade study
55. Value Creation through Integration. Fostering innovation across aerospace supplier networks. Presentation to LAI. Aaron Kirtley. Jan 2002.
    - Investigated issues/barriers to innovation for affordability across supplier networks
    - Focused on F/A-22 avionics, included research conducted at BAE for EW and some major BAE suppliers
    - Focus on ways to increase communication
    - Support suppliers through shared/joint investments (PIP program highlighted as step in the right direction but not large enough in face of magnitude of problem)
    - Increase contractual incentives (recognized that aside from good will with customer and keeping programs from getting canceled, suppliers often have negative incentive to reduce cost/improve)
    - Reduce program uncertainty
    - Train suppliers where appropriate
    - Provide insight into future technology needs/roadmaps
56. Case study of LEAN implementation - F-18 E/F. Presentation.
57. JSF Manufacturing System Design highlights. Presentation.
58. New directions in the aeronautical industry. Allen Haggerty. VP/GM (retired) military aircraft and missile systems, Boeing. April 2001. Presentation.
    - Industry is shrinking (21 to 5 primes, fewer people)

- Fewer new platform starts, more derivatives - less interesting for engineers
  - "affordability is the key to delivering value to the customer"
  - 80% of product's cost is determined by the engineering design
  - chart 26 has good comprehensive set of targets for affordability at the enterprise level

59. Value creation in the product development process. Jim Chase. Presentation based on his thesis. Jan 2002.
    - WBS review and study, interviews on time allocation
    - Trying to determine how much of product development contributes to value, how much is waste - concludes that 86% of tasks contribute to a definition of value that he has developed
    - Interesting finding - there is a 3 to 1 ratio of time spent communicating vs. time spent working in isolation. Conclusion is that investment should be in more efficient communications methods / tools instead of improving work processes
    - Chase thesis is #30.
60. F/A-22 research on developing a "Product Delivery System" or manufacturing system. Steve Hendricks. Presentation
    - PDS based on Suh's axiomatic design principles
    - Rigorously defines requirements and solution space and maps two together from very high level down to detail level
    - Evaluates goodness of achievements of all the requirements elements
61. Manufacturing System Design. Shields. Presentation
    - More than the factory floor
    - Strategy driven, not product driven
    - No one size fits all
    - Best results when interacting with design, suppliers, marketing
    - Manufacturing is a competitive weapon in a maturing product industry
62. New applications for technical performance measurement in program risk mitigation. Unknown author or date
    - paper on integrating TPM and EVMS into a predictive diagnostics tool for program managers to see problems in front of them instead of behind them
63. 3D Concurrent Engineering - Clockspeed based principles for product, process and supply chain development. Charles Fine. May 1998. Presentation and Jan 2001 presentation.
    - Aircraft development has three clockspeeds - airframe (slow), engines (med) and electronics (fast). Currently ac firms operate at airframe clockspeeds, in the future they will need to operate at electronics clockspeeds
    - Vertical industry structure with integrated product architectures
    - Horizontal industry structure with modular product architectures
    - Argues that supply chain design is a core competency

Two files longer one has some practical frameworks for doing supply chain design

64. Doing The right things. John Horton. Lockheed Martin. Presentation.
    - Good charts (11-15) on management vs leadership including "the 12 dimensions of leadership"
    - Shows a graduating maturity level of those you lead/manage and how leaders respond differently to different people (situational leadership)
    - Team building charts
    - Keys to followership

- Eight key elements of high performance work systems
  - Motivating people
  - Management is doing things right, leadership is doing the right things

65. Fostering innovation across aerospace supplier networks. Aaron Kirtley. MIT thesis. Advised by Kirk Bozdogan. June 2002.
    - Review of F/A-22, F-16, JSF platoforms - technology, architecture, supply chain issues at high level
    - Review of F/A-22 EW, Radar and four key suppliers for each at a detailed level
    - Great chart (p26) showing avionics as a percentage of A/C costs increasing over time
    - Indicates F/A-22's integrated avionics suite architecture caused the DMS problem to be significantly higher than it would have been with a more federated approach
    - Lessons learned
      - Emphasis on affordability
      - JSF 28-38M vs 80M F/A-22
      - Good technology performance at reasonable price vs. best technology available
      - Widen design margins
    - Good graphic (p56) on incentives of long term contracting (supplier keeps cost savings as profit in period 1, gives them to customer in period 2)
    - Has titanium as an EW innovation (says it saves weight…) has conversion to PHEMT as an innovation, digital receiver, automated diagnostics
    - Specified lessons learned - design tradeoffs made at higher levels and little to no margin specifications flowed down - practically dictating technical approach
    - Modular vs integrated system architecture;
    - Includes questionaires used in research
66. Organizing for Product Development. Thomas Allen. Dec 2001.
    - Propose 4 parameters that determine appropriate org structure for R, D, Eng organization
    - Compares functional , project, matrix orgnizations
67. Product Realization in the Defense Aerospace Industry. March 27, 2002. Mandy Vaughn, 2nd LT, USAF. LAI presentation
    - Chart on Augustine's law that by 2050 average unit cost of single a/c will equal GNP
    - Utterback's innovation models - good example of aerospace vs auto vs typewriter
    - Fine's 3D CE
    - Lead to manufacturing system design framework
68. Framework for achieving best lifecycle value. Alexis Stanke. April 11, 2001 presentation
69. Modeling and Analyzing Cost, Schedule, and Performance in complex system product development. MIT Doctoral Thesis. Tyson Browning. Dec 1998. Advised by Eppinger, Deyst, Whitney.
    - Explores iteration in the aircraft design process
    - A causal framework for risk drivers in complex system product development
    - DSM based systems engineering, organization planning, schedule management
    - Shows relation to the LEM

70. Best practices in user needs / requirements generation. Joe Wirthlin. MIT SDM Thesis. Advised by Rebentisch. Jan 2000.
    - Covers process space from id of initial need/perceived need to product/development program launch
    - Case study approach - 8 commercial orgs, 8 military orgs and US AF
71. The effective use of process capability databases for design. Thesis MIT. Melissa Tate. Jun 1999. Advised by Anna Thorton.

Process capability databases are critical design tools but noone uses them

72. Challenges in the better, faster, cheaper era of aeronautical design, engineering and manufacturing. White paper. Murman, Walton, Rebentisch. Sept 2000.
    - Aeronautical industry reached dominant design and into the specific phase focused on incremental product improvement, especially for quality and productivitiy, process technology and technological innovations that offer superior substitutes
    - Shows graph of increasing development time for military systems over past 4 decades
    - Has aerospace company Utterback chart
    - Fig 5 best chart so far showing LCC committed vs incurred by PDP phasex
    - Good summary of a lot of LAI research work
73. Lean Aerospace Initiative Implementation Workshop; implementing cross functional teams in an IPPD environment. Joel Gershenfeld. 1998.
    - No one size fits all best approach to IPTs
    - IPPD contexts vary along 5 dimensions - customers, products, IPTs, suppliers and time.
    - Implementation of IPTs in IPPD environment is not a one time event - it must be revisited, adjusted as programs move from one phase to the next or when other significant changes occur
    - Lean requires IPTs. Its not that IPTs are better at implementing Lean, they are required.
    - Implementing IPTs requires fundamental changes in flow of information, authority, rewards, and other enabling systems
    - Rockwell lessons learned
        - Practices are a continuum w/o start/stops
        - Accept variation reduction as a way to do business.
        - Joint ownership of process by everyone is critical.
        - Expect resistance; lead your way through it.
        - Clearly defined roles and responsibilities are essential.
        - Corrective action to feedback is critical.
        - High robustness leads to lower costs when processes create accountability for results.
    - Northrup Grummon lessons learned
        - Maintain constant communication at all times.
        - Don’t second-guess technical experts.
        - Vigorously resist requirements creep.
        - Gain customer agreement with program management approach and technical goals.
        - Have design decision authority resident within the IPT.
        - Streamline procurement practices.

- Use rewards and recognitions to build team spirit and to give IPT members "bragging rights."
  - F/A-22 lessons learned
    - IPT philosophy takes leadership commitment from the top.
    - Need to constantly work on improving team communication/integration: the "I" in IPT stands for integrated, not independent.
    - Training to function as a team is paramount.
    - IPT managers must have authority over personnel and budget resources.
    - An integrated network of communications/software tools is mandatory.
    - Set team goals and objectives, and then track them!
    - IPT leadership should become a mainstream discipline/function and a viable management career path.

74. A partitioning method for helicopter avionics systems with a focus on life cycle cost. Leon Silva. MIT SDM thesis. Jan 01. Rebentisch advisor.
75. A framework for achieving best lifecycle value in product development. Alexis Stanke. MIT Thesis. June 01. Advised by Murman.
    - Complete details of thesis summarized in other shorter works listed above.

APPENDIX C – RESEARCH QUESTIONNAIRE

Interview Questions *(All comments are non-attributable)*: Please comment on experience gained from your involvement with a specific program. Some questions may not be applicable to all individuals.

General questions about critical issues and best practices
Objective: Identify critical issues and best practices in developing affordable military avionics systems

1. Explain program history in terms of delivering an affordable product that met performance needs on budget and on schedule.
2. What were the most noteworthy positive outcomes of the program?
3. Please provide examples of what you would consider best practices that enabled the program to deliver such noteworthy positive outcomes?
4. What were the most noteworthy negative outcomes of the program?
5. What were the top 5 critical issues that hindered the program's ability to deliver an affordable product?

Questions about the nature of development focus during design iterations
Objective: Identify differences in the nature of development focus during design iterations of a spiral or iterative development process and draw a correlation between the nature of development focus and program positive outcomes.

1. Did your program pursue an iterative development process? Was it planned?
2. What was the nature of development focus during each design iteration? (Examples – affordability focused, performance focused, budget focused, schedule focused, etc)

Questions about collaboration across organizational and functional boundaries
Objective: Identify critical issues and best practices specifically in design collaboration across organizational and functional boundaries. Focus is in three areas: (1) how to you get systems engineers to truly understand the system design trade space by working more closely with the prime, government acquisition and user communities. (2) how to get hardware/software knowledge to improve the requirements process and how to get producibility/supplier knowledge to improve the design process and (3) how to get cost feedback into the design by bridging the gap between the design and cost communities.

Understanding the role of requirements. How can better understanding of the cost-performance trade space lead to more affordability systems? How can a better understanding of the cost-performance trade space be developed?

1. What did your program do to try to understand the system trade space (i.e. not just what's in the spec but what the customer really needs and values)? What processes or methods used were particularly effective? Ineffective? Why?
2. Provide examples of how a <u>lack</u> of understanding of the true system trade space hindered the program's ability to deliver an affordable product.
3. Provide examples of insights into the true system trade space enabled the program to deliver a more affordable product.

Integrating downstream knowledge into the design process : Systems - software - hardware - manufacturing/supplier

1. How was ‘downstream’ knowledge brought upstream in the design process? (how were HW/SW engineering brought into the system design phase, how were manufacturing/suppliers brought into the hardware design phase?)
2. What responsibility/accountability/authority was given to manufacturing/supplier in the design phases? To HW/SM engineers in the system design phases?

Cost feedback into design: Design community - cost community

1. What problems existed in incorporating cost feedback into the design process?
2. What techniques worked well in incorporating cost feedback into the design?
3. Was affordability considered a design requirement, a management requirement or a manufacturing requirement?

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[3] Mastering the Dynamics of Innovation by James M. Utterback published in 1994 by Harvard Business School in Boston, Massachusetts.

[4] Product Realization in the Defense Aerospace Industry presentation to Lean Aerospace Initiative by Mandy Vaughn on March 27, 2002.

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[9] Intellectual Capital White Paper for The California Engineering Foundation, 12/07/99 by Hernandez, C.

[10] JSF - A Winning Environment presentation by Tom Burbage.

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[14] Product Development in the World Auto Industry by Kim B. Clark, Takahiro Fulimoto and W. Bruce Chew, Brooking Papers on Economic Activity, No. 3, 1987. Organizations for Effective Product Development by Takahiro Fulimoto, PhD Thesis, Harvard Business School, 1989, Tables 7.1, 7.4, 7.8. As adopted by Womack, Roos and Jones in The Machine that Changed the World

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[23] Managing Subsystem Commonality by Matthew Nuffort, MIT Thesis, February 2001.

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