EVIDENCE OF LEAN ENGINEERING IN AIRCRAFT PROGRAMS

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Abstract

Over the past decade, the aerospace industry has adopted Lean, Six Sigma, and related productivity improvement approaches to increase the quality, shorten the delivery times, and reduce the costs of their products across all life cycle functions. Engineering is a particularly high leverage area for applying lean thinking as 60-80% of the life cycle costs are locked up by up-front engineering decisions.

Based on nine case studies done by MIT students, this paper will illustrate that the elements of Lean Engineering have been used successfully in various ways in many programs for over fifty years. Many of the elements are tried and true practices of good aircraft engineering, while some are more recent additions. The main challenge of Lean Engineering lies in utilizing the various elements in an integrated holistic approach. Not all programs have achieved this state.

1 Introduction

The impact of the Lean movement on manufacturing processes has been, depending on the industry, from strong to revolutionary [1,2]. In the last 10 years, the aerospace industry has seen dramatic benefits from the application of lean principles not only from manufacturing and supply chain management but to engineering where key decisions dictate as much as 80% of the downstream unit costs of aerospace products [3]. Research conducted by the Lean Aerospace Initiative has led to a Lean Engineering Framework [4] consisting of 3 main areas: (1) Creating the right products, with (2) effective life cycle and enterprise integration, and (3) using efficient engineering processes.

Over the last 65+ years there have been a series of very successful military and commercial aircraft programs that have used specific elements of Lean Engineering. While the individual principles come from the field of practice and are not revolutionary, very few programs rigorously applied all the principles and therefore did not capture all the customer value / benefit potentially available. The program management challenge is to establish the organizational framework, leadership model, and discipline to comprehensively apply these key lean engineering principles during the development program.

A review of 9 programs (B-52, B-777, DC-9, F-111, F/A-117, F-14, F-16, Citation X, G-IV) drawn from detailed case studies conducted by graduate students at the Massachusetts Institute of Technology during the period 2000-2005 are used to illustrate the above findings [5]. These case studies represent retrospective analysis of the aircraft designs, and were not selected to focus on lean engineering aspects. Each of the three main areas of Lean Engineering is illustrated using findings from the case studies. The paper concludes with a summary how each of these programs did or did not utilize all the major elements of Lean Engineering.

2 Creating the Right Products

Of the three areas of Lean Engineering, by far the most important is “Creating the right product” with the features the customer and end user require, and with an architecture that allows the design to evolve with upgrades and derivatives to meet customer needs.

2.1 B-52 Stratofortress: An Enduring Product Architecture [6]

Perhaps the best example of the right product with enduring value is the B-52 (Fig. 1), arguably the best bomber ever developed. Conceived in 1946 to provide large, long-range bomb delivery, the B-52 first flew in March, 1952 after extensive iterations between Boeing and the USAF Strategic Air Command. Requirements for speed as well as 10,000 mile range with significant payload led to the adoption of 35-degree swept wings and other innovations including bicycle landing gear, folding vertical tail for hangar storage, completely movable horizontal tail for pitch control (the 1st application to a bomber), and a braking parachute.

Continuous design improvements including new offensive and defensive electronics, new weapons such as ALCM, Harpoon anti-ship missile, CALCM, JDAM, Advanced Cruise Missiles, etc. kept the various B-52 models (from the original B-52A model to the venerable B-52H) at the forefront of both nuclear and conventional bomber capability of the U.S. Key design drivers included simplicity of systems leading to high reliability, ease of maintenance through "quick-change" features, reduction in fire hazards for improved safety, good pilot visibility, and a rugged fuselage structure. Later, B-52s with new turbofan engines were able to increase payload from 43,000 lbs to 70,000 lbs while increasing combat radius from 3310 nm to 4510 nm for the B-52H. The remaining B-52s are expected to remain on active duty through 2037 for a useful life of 85 years in operation, yet the "mission capable" rate of 80% for the B-52 compares well with the 50% for the B-1 and 35% for the B-2 bomber based on 1998 data.

This performance bodes well for the continuous value provided by this workhorse product that has surpassed all its stakeholders' expectations. Unquestionably, getting "the design requirements right" at the outset of the program contributed significantly to the viability of the B-52 family of aircraft and its product architecture which has supported many upgrades and set the design for generations of jet transports.

2.2 F-16 Fighting Falcon: Getting the Requirements Right [7]

From inception in 1972, over 4000 F-16 fighter aircraft (Fig. 2) have been delivered to the U.S. Air Force and 23 foreign governments. The F-16 has won numerous awards for performance and manufacturing excellence and is noted for having an impressive 71-0 air combat record. The program emerged from the USAF Light-weight Fighter Competition in the early 70s in direct response to poor combat ratios of other fighter aircraft in Vietnam and a desire to return to "prototyping" as a procurement concept as a result of very unsatisfactory results with DoD's Total Package Procurement concept used on the C-5A and F-111 (see Sec. 2.3). General Dynamics (now Lockheed Martin) focused their design on a "smart blend" of advanced technologies and proven equipment for improved reliability. The

Fig.1. B-52 Stratofortress (Source :www.AviationExplorer.com).

Fig.2. F-16 Fighting Falcon (Source: www. public.andrews.amc.af.mil/jsoh/display_usaf.html).

aircraft with its innumerable upgrades to engines, avionics and weapons is expected to be in USAF service until the year 2020.

It was clear that, with the ongoing threat in Europe, an agile, highly maneuverable, high thrust-to-weight ratio fighter with low wing loading was required to win in a "cat fight / fur ball" type of aerial conflict. GD made the design decision to use a single engine, relaxed static stability, fly-by-wire fighter based on Energy Maneuver Theory advocated strongly by Major John Boyd and Tom Christy, U.S. DoD. To achieve lighter weight, there was extensive use of composites and only essential avionics were used. It was GD's objective to make the F-16 a "pilot's aircraft" with a high visibility cockpit featuring a "frame-less canopy" and the first use of an integrated heads-up display. In addition, the F-16 was the first aircraft to use "HOTAS" (hands on throttle and stick) integrated flight controls / weapon system / targeting system.

The aircraft was modified to perform a variety of missions including air defense, night precision attack, and the suppression of enemy air defenses. It was delivered "on-schedule" and was the first aircraft in more than 40 years to cost less than its predecessors! Designed with inherent high reliability, high "operational readiness" through simplicity of systems, modular construction for low manufacturing and maintenance costs, ease of battle damage repair, and an "open architecture" for modular upgrades of critical avionics systems to keep the aircraft combat competitive, the F-16 has had remarkable operational and marketing success.

Truly, achieving the right balance of original design requirements, affordability, and providing for eventual growth in mission requirements were critical to the USAF customer and resulted in a long production run that is still in progress today.

2.3 F-111 Aardvark: Not Getting the Requirements Right [8]

Few aircraft developments have been as controversial as the F-111 (Fig. 3), known as the "TFX" during the design competition between Boeing and General Dynamics / Grumman Aircraft. It was one of the largest, most expensive developments of its time during the Cold War. The acquisition strategy driven by then Secretary of Defense Robert MacNamara was for "Systems Analyses / Cost-effectiveness" and with it, the decision to save $1 billion by developing a "common" aircraft for the U.S. Air Force and U.S. Navy. The requirements included fighter, bomber, and attack missions, flying at tree-top level at supersonic speeds with nuclear weapons while having the inherent capability to take-off from aircraft carrier decks and short fields carrying significant payloads over long distances.

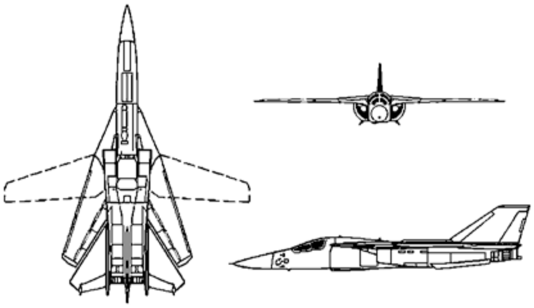

Fig. 3. F-111 Aardvark (Source: http://en.wikipedia.org/wiki/General_Dynamics_F-111).

To accomplish this broad array of requirements, General Dynamics and Grumman, the winners of the competition, had to incorporate many innovative design features including a "swing-wing", after-burning turbo-fan engines, and a revolutionary avionics package highlighted by terrain-following radar. The F-111 proved to be highly capable in the attack mission, but due to its weight / lack of maneuverability, fell short in air-to-air missions and was never used in that capacity. Secretary of Defense MacNamara underestimated the political and bureaucratic forces of the Pentagon (USAF, USN) and Congress and the Navy ultimately withdrew from the program in 1968 to pursue the F-14 Tomcat (see Sec. 2.4).

There is no question that the contrasting requirements of the Air Force and Navy were daunting and challenged the best technology of the era. The difficulty of capturing all these top-level requirements in a joint-service aircraft with "high commonality" to achieve affordability caused a protracted source-selection with four separate "competitions" between September 1961 and November 1962. GD / Grumman was selected as the prime contractor but the "forced requirements" by DoD led to compromises between the USAF and Navy, leading to eventual friction and withdrawal of the Navy. The final designed aircraft had 84% common parts between the two versions and had the potential to achieve economies of scale, greater production efficiencies, and large savings in logistics / spares / training for reduced life cycle costs. In actuality, with the withdrawal of the Navy production quantities, the aircraft cost *twice as much* as originally forecasted.

The F-111 suffered from frequent requirement changes from both services resulting in the USAF aircraft being both heavy and over-designed and the Navy withdrawing altogether[1]. What is clear is that the first principle of Lean Engineering – "Creating the right product" up-front – is key to a successful aircraft program and not getting this right can have disastrous consequences.

2.4 F-14 Tomcat: Meeting the Life cycle Needs of the "Real" Customer [9]

Grumman Aircraft, even during their partnership with General Dynamics on the F-111, were "listening" to the U.S. Navy, the "real customer" for the carrier-based version of the TFX. Their engineers created with company funds Preliminary Design 303E and a full-scale mock-up that reflected the needs of the people who would use the aircraft – the pilots, Radar Intercept Officers, mechanics, hangar deck crews. For example, 80% of the avionics equipment was accessible without the need of workstands and "remove time" was reduced via "quick release" disconnects and release mounts.

Grumman Aircraft was awarded the development contract in 1969. Because the MiG-25 Foxbat and MiG-23 Flogger fighters were operational in 1967, Grumman proposed a development schedule of only 51 months to meet the urgent requirements of DoD and the Navy. The resulting aircraft had twin TF-30 after-burning turbofan engines (for over-water operations) and carrier compatibility features with a tandem cockpit. Its variable-sweep wings permitted optimum performance over a wide range of flight conditions. The F-14 was capable of Mach 2.4 dash speed and the ability to land on carrier decks. Its advance radar could track 24 separate targets.

Rigorous specifications for empty weight, landing speed, acceleration, approach speed, maintainability, reliability, etc. were reinforced with severe financial penalties for non-performance (e.g. $450,000 for every maintenance hour that exceeded the MMH / Flight Hour Target in order to minimize operating / sustainment costs over the life of the aircraft). Weight was reduced through use of innovative pallets for the modular missiles and bombs. The engines were "podded" for easy maintenance and upgradability.

The combination of speed, advanced radar, and long-range weapons made the F-14 (Fig. 4) the most capable long-range interceptor in the world at the time of introduction. Performance of the aircraft was more than the Navy asked for, leading to a very pleased customer! The total life cycle advantages and capabilities in the final F-14 design convinced the Navy that they had made the right decision in dropping out of the F-111 program. A total of 637 F-14As were built with more F-14Bs and Ds manufactured in

Fig. 4. F-14 Tomcat (Source: U.S. Navy photo by PHAN P. McDaniel).

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[1] One wonders if the current Joint Strike Fighter (F-35) with its very ambitious goals of 3 separate but common configurations (STOVL, CTOL, and CV) could suffer the same fate as the F-111 with its unit price increasing and production quantities decreasing.

later years. They are still operational today. But the lack of product improvements has led to unacceptably high maintenance costs and their eventual replacement with the F/A-18E/F.

3 Product Life cycle and Enterprise Integration

The product value chain shown in Fig. 5 depicts the role of key stakeholders in delivering the value expected by the end customer. The value chain is the set of all the stakeholders that are linked together in the value stream (the linked activities that produce the product.)

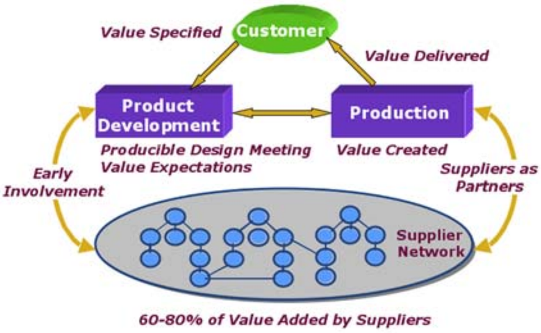

Fig. 5. Product Value Chain [4].

During product development, engineers must design products that are producible and meet the customer's value expectations for price, performance, quality, and schedule. To accomplish this, engineering must work closely with the customer, manufacturing, and suppliers (who can typically create 60-80% of the value). In today's industry this is accomplished with multifunctional Integrated Product Teams (IPTs) which can include relevant engineering disciplines, suppliers, manufacturing, test, maintenance, and logistics personnel.

Systems engineering is the process used to develop the top-level architecture necessary to flow down customer requirements to a set of specifications used for designing sub-systems and components needed for the overall design. Designing for the required product performance, reliability, unit cost, maintainability, life-cycle cost, and supportability is often called "Design for X". Efficiently handling all these requirements without letting them fall through the cracks is a difficult job. Carrying out good systems engineering is a necessary component of integrating Lean Engineering into the value stream.

Other important tools of Lean Engineering used to achieve best life cycle designs include:

- Design for Manufacturing / Assembly (DFMA)
- Solids Based Design
- Common Parts / Specifications / Design Re-use (hardware and software)
- Variability Reduction / Dimensional Management
- Production Simulation

A key enabler of Lean Engineering is the integrated design tools available with modern networked computer systems. These tools have evolved rapidly in recent years and have had dramatic impact on reducing product development time and improving quality.

3.1 DC-9: Effective Life cycle Engineering [10]

The Douglas Aircraft DC-9 (Fig. 6), with its derivatives MD-80, MD-90, and B-717, is the third most widely sold commercial jet transport ever developed. Design emphasis on a simple structure, two aft-mounted engines, a two-crew cockpit, and heavy emphasis on reliability, accessibility, and ease of maintenance to reduce airlines direct operating costs were fundamental to the sales success of the aircraft. The extensive use of common parts with a focus on lowering the total parts count (known today as DFMA) improved reliability and lowered manufacturing cost. Selecting components with proven reliability for the

Fig. 6. DC-9 Commercial Transport (Source: http://en.wikipedia.org/wiki/DC-9).

design and using low corrosion structure enabled the DC-9 to achieve 99% dispatch reliability, well ahead of the competition at the time.

The significant reduction in parts of the DC-9 as shown in Table 1 improved the reliability since the probability of a system failure was less with fewer parts. Fewer parts also reduced the design man-hours, the manufacturing engineering cost, reduced tooling / fabrication / inspection, assembly costs and weight. The design emphasis on the use of "common parts / specifications" permitted ease of maintenance and reduced the logistics requirements for spare parts.

Table 1: Number of Functional Components [10]

Aircraft	DC-8	727	DC-9
Air systems	138	86	73
Hydraulics	238	276	204
Fuel System	117	75	39
Electrical Power	33	32	25
Control Surfaces	38	72	28

The DC-9 design philosophy of "Keep it Simple / Keep it Safe" affected all aspects of the aircraft. For example, designers were directed to make the aircraft maintainable with mechanics wearing "cold weather gloves". Because the DC-9 was simple as well as safe, and had high reliability and ease of maintenance, the operating economics of the aircraft were very attractive to domestic and foreign airlines. After more than 45 years in service, many of the world's airlines are still operating efficiently with their rugged, dependable DC-9s and derivative aircraft.

3.2 The B- 777: Integrated Engineering - Manufacturing Systems Pay Off [11]

Seeking to achieve a decisive competitive advantage over the A-330 / A-340 and the MD-11, Boeing conceived the largest twin-engine aircraft ever built (Fig. 7). GE, Pratt & Whitney, and Rolls Royce all developed new engines at their own expense, with 50% greater thrust than existing engines (approximately 90,000 lbs vs. 60,000 lbs). For FAA/JAA certification, the aircraft had to be able to function on one engine and achieve Extended Range Twin-Jet Operations (ETOPS), overcoming the marketing perception that long over-water flights on twin engines was less safe than operating with 3 or 4 engines. ETOPS had to be certified at entry into service which had never been done before. With these formidable challenges, Boeing utilized the most advanced design / manufacturing systems ever applied to a new aircraft development.

Fig. 7. B-777 (Source:NASA).

The CATIA 3-D design tool was used by 238 "Design–Build Teams" or DBTs consisting of engineers, tooling, manufacturing, logistics, key suppliers, and airline customer personnel in a philosophy of "Working Together". Each DBT was authorized and accountable to fully design and develop a major hardware or software element of the 777 aircraft. Digital mock-ups derived from CATIA were used to improve designer manufacturing coordination and the development of factory operations sequence planning. Suppliers provided their technical data to Boeing Engineering also using 3-D CATIA solids for integration into the total aircraft design. A large investment in a giant system known as DCAC/MRM for "Define & Control Airplane Configuration Manufacturing Resource Management" was first developed and utilized on the 777 by Boeing to maintain configuration management of the various airline models of the 777 and to efficiently interface the factory with the "build-to-model" data from the engineering release system.

For the very first time at Boeing, no hardware mock-ups were required on the 777.

The productivity of these advanced systems was realized with a 90% reduction in Engineering Change Requests to finished engineering, a 50% reduction in release cycle-time, a 90% reduction in material re-work, and a 5-fold improvement in assembly tolerances for fuselages. The beneficial comparison on variability reduction / dimensional management on the 777 vs. the 747 can be seen in Table 2. In addition, the power of 3-D solids enabled Boeing to dramatically reduce the number of expensive tools required on the program, thus saving millions of dollars in development cost.

Table 2 Benefits of variability reduction for floor beams for two commercial aircraft [4]

	747	777
Assembly strategy	**Tooling**	**Toolless**
Hard tools	**28**	**0**
Soft tools	**2/part #**	**1/part #**
Major assembly steps	**10**	**5**
Assembly hrs	**100%**	**47%**
Process capability, C_{pk}	**<1 (3.0σ)**	**>1.5 (4.5σ)**
Number of shims	**18**	**0**

3.3 Gulfstream G-IV: Integrating Customers & Suppliers for Program Effectiveness [12]

The Gulfstream IV was conceived as a twin-turbofan executive transport to replace the G-III using new Rolls Royce Tay low-noise turbofan engines and being the first commercial aircraft certified with an all-glass cockpit. The aircraft also featured a stretched fuselage, and an aerodynamically and structurally improved wing with greater fuel capacity for increased range. With a range of 4100 miles the G-IV could fly U.S. to Europe but also had economical performance for short ranges as well. Launched in 1983 to compete with the Dassault Falcon 900 and Canadair Challenger 601, the G-IV was designed to protect Gulfstream's 60-80% market share of high-end long range business jets.

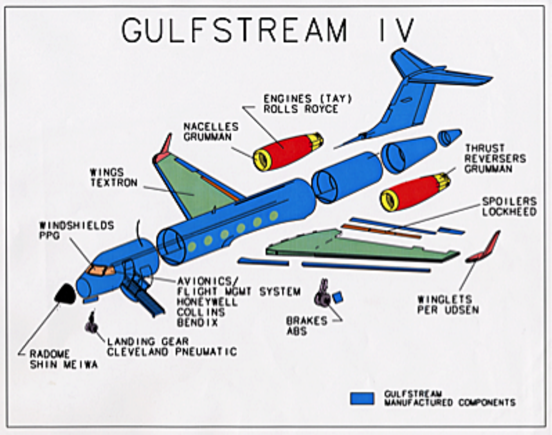

Fig. 8. Gulfstream Supply Chain Members (Source: Gulfstream).

Critical to this strategy was developing "long-term partnering agreements" with key suppliers shown in Fig. 8, e.g., Rolls Royce for the Tay engine; Honeywell for the glass cockpit; Cleveland Pneumatic for landing gear. In total, 70% of the G-IV value came from the supply chain providing maximum use of proven, reliable G-III subsystem components in the hydraulic, electrical, ECS, and flight control systems (adjusted for stretched fuselage). The significant design reuse from legacy Gulfstream products enabled the short four years product development time.

In redesigning the high performance wing, Gulfstream utilized the Lean Engineering principle of DFMA by reducing parts count by 30% in the wing internal structure. Not only did this save design, tooling, fabrication, and assembly costs, but it also saved 870 lbs of airframe empty weight, while the new design provided 5% more aerodynamic performance.

Extended enterprise integration was achieved by emphasizing outstanding "Gulfstream Customer Service" (in order to maintain brand loyalty and capture repeat sales) through a strategy of extending the maintenance "service intervals" on critical fuselage and subsystem components by being the first business jet to utilize the FAA's new MSG-3 (Maintenance Steering Group 3) methodology. All suppliers, airplane operators, and FAA maintenance personnel cooperated with Gulfstream's initiative to apply MSG-3 and achieve 50% savings in scheduled maintenance man-hour costs and aircraft down-time. This permitted the G-IV to allow operators to operate world-wide with minimal support. Gulfstream committed to send spare parts and technical support personnel to AOG aircraft (airplane on ground) anywhere in the world. The result of this enterprise-wide effort, combining the prime contractor, several tiers of suppliers, customer aircraft operators, and the FAA regulators, was an outstanding dispatch reliability of 99.96%.

4 Using Efficient Engineering Processes

Although the engineering profession has made huge strides in improving throughput and quality of design and development activities, studies indicate that there is "waste" in the typical processes used in the design of recent aircraft. As can be seen from Fig. 9a, a survey by McManus [13] indicates the fraction of "real value added" in the accomplishment of a typical engineer's time charged to a project might be as low as one-third. This does not imply engineers purposely do "non-value added" work, but that the processes being used cause undue and wasteful time waiting for information, waiting for results from tests, translating information into different computer analysis formats and other tasks that may be required but are really not adding value to the end product. Figure 9b shows that a typical task on a project spends more time waiting for work to be done than having value added work be accomplished. Improvement in basic engineering processes to remove non-value added time is the third important area of lean engineering.

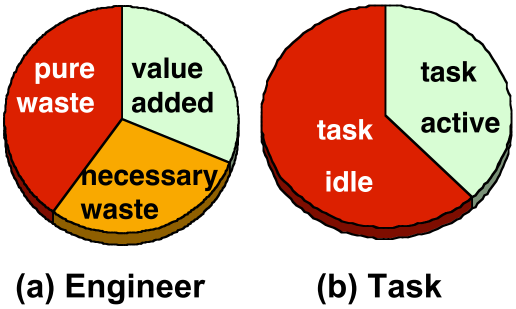

Fig. 9. Non-value added time for engineering time and task time [13].

Fig. 10. F-117A Nighthawk (Source: www. public.andrews.amc.af.mil/jsoh/display_usaf.html).

4.1 The F-117A Nighthawk: The Lean Engineering Legacy of Kelly Johnson [14]

Perhaps the most important aircraft technology breakthrough following the B-47/B-52 swept wing was Low Observable (LO) techniques introduced in the 1980s. The unconventional, but now familiar, F-117A geometry (Fig. 10) epitomizes stealth aircraft. Developed under top secret classification, the F-117A aircraft represents both the presence and absence of lean engineering elements.

In 1978 following the DARPA-funded Have Blue subscale prototype demonstrator, the USAF awarded the Lockheed Aeronautical Development Company, aka "Skunk Works", a contract to develop what became the F-117A. The two domineering requirements were low observability and schedule. The classified nature of the program with emphasis on LO performance both enabled and prohibited certain lean engineering practices. In the former category fell close working relationships with the customer with a focus on customer value, and design reuse and commonality. In the latter fell supplier integration and design for maintainability and reliability. The F-117A program exemplifies the benefits of design reuse. To meet the tight schedule and keep the program footprint small, virtually any existing system or component that could be used was used. Some noteworthy examples are the F-16 fly-by wire system, the F/A-18 GE F104 engine, the F-15 air data computer, and modified F-16 control surface actuators.

But perhaps the best lean engineering practices represented by the F-117A stem from the famous 14 rules of Kelly Johnson [15]. Recognized as an early embodiment of some lean thinking principles [2], these rules ruthlessly focused on process efficiency. Teams were kept small and focused on value added activities. Communication was clear and timely. In the F-117A program, engineering personnel spent about 1/3 of each day working with manufacturing. The result of applying Kelly's rules was a short 4-year development time from program launch to first flight for an aircraft that was utilizing leading edge technology.

4.2 The Citation X: Efficient Engineering Processes Makes the Fastest Business Jet [16]

The Citation X (Fig. 11) started in late 1990, was designed with a competitive edge to be the fastest business jet, and only second to the Concorde as the fastest commercial aircraft. Using supercritical airfoil, Rolls Royce-Allison high by-pass turbofan engines for fuel efficiency and low noise, an area-ruled fuselage for low drag, 37-degree wing swept wings with a low wing to increase fuel volume, and a highly integrated Honeywell Primus 2000 glass cockpit flight director system, the Citation X design was aimed to dominate the medium to large business jet market with pre-emptive transcontinental range and speed.

Fig. 11. CitationX (Source: oea.larc.nasa.gov/ PAIS/Concept2Reality/graphics/fig046.jpg

Cessna utilized the most modern and efficient engineering processes available including the use of Integrated Design Teams, focus on the end customer via Total Quality Management, 3-D solid CATIA design system, computational fluid dynamics for wing and fuselage design, and a high degree of "design re-use" for reduced engineering, manufacturing costs, and improved reliability. The prototypes were made with production tools for maximum commonality and to minimize technical, schedule and cost risk.

Other key lean principles used by Cessna on the Citation X included:

- Decisions made at the lowest level
- Design for "simplicity"
- Lean manufacturing
- Treating suppliers as "partners"
- Co-locating all Citation Team "X" employees to shorten communication lines
- No more than 25% new employees
- Customer Advisory Council to assist in key design decisions and avoid engineering changes.

The Citation X was designed from the start with the lowest possible acquisition cost and lowest possible operating cost for their customers. Cessna's use of efficient engineering tools went a long way in accomplishing that objective for this very successful aircraft that is used by numerous *Fortune 1000* business customers and fractional ownership companies.

5 Summing Up the Elements of Lean Engineering

Recalling the opening words in this paper, the elements of lean engineering emerge from practice. As such, they should be familiar to seasoned aeronautical engineers. A frequent reaction from readers and audiences is "what's new about lean engineering?" As the short accounts of nine familiar programs illustrate, the basic principles are tried and true and frequently utilized. However applying all or most of the principles is not as frequently observed. The

Table 3. Lean Engineering practices observed in the case studies. √ = observed. x = partially observed.

Lean Engineering Element	B-52	F-16	F-111	F-14	DC-9	B-777	G-IV	F-117A	C-X
Focus on customer value	√	√		√	√	√	√	√	√
Architected for upgrade/derivatives	√	√		√	√	√	x		
Effective trade studies, prototypes	√	√		√	x	x	**x**	x	
Effective requirements management	√	√		√	√	√	√	√	√
Realistic business case or need	√	√		√	√	√	√	x	√
Multifunctional design teams		√		x	√	√		√	√
Integrated design tools						√			√
Supplier integration		√			√	√	√		√
Design for manufacturing/assembly			x	x	√	√	x	√	√
Design for maintainability/reliability		√	√	√	√	√	x		√
Design reuse, commonality		√	x	x	√		√	√	x
Quality focus in engineering						√			√
Effective system engineering		x	x	x	√	x	x	x	
Production simulation						√			
Engineering process efficiency				x	x	x		√	**x**
Open, honest communication	√			√	√	√		√	√
Effective cost management	√	√					**x**	√	
Effective schedule management	√	√		√	√	√	√	√	
Effective risk management	x	√		x	x	√	√	√	x
Program launch-first delivery (yrs)	6	4	4.5	3.75	3.6	5.5	4	4	4.5

purpose of this paper is to point out that the basic principles of lean thinking are quite applicable to aircraft engineering and should be used on future programs to achieve superior results.

The matrix in Table 3 illustrates the application of a list of lean engineering practices across the nine case study aircraft programs. There is considerable judgmental choice in filling out this matrix, and it should only be used as an indicator of lean engineering, not a rigorous assessment of any program. A number of practices were observed on the majority of the programs, while others were infrequently observed in the case studies. In five programs more than half of these lean engineering principles were observed: F-16, DC-9, B-777, F-117A, and Citation X.

6 Conclusions

Modern military and commercial aircraft are subject to increasingly demanding performance and cost requirements from customers, regulators, and society at large in order to produce a competitive product. These requirements are being met through added system functionality enabled by modern technology, but the resulting complexity and interdependency of the systems in modern aircraft has necessitated rigorous application of systems engineering / lean engineering principles to achieve products providing best life cycle value to the customers and end users. The basic lean engineering principles are not complicated, and are frequently observed in past programs. The major challenge is for program leadership to have the discipline to adopt a majority of them in an integrated program approach.

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