Opportunities for Lean Thinking in Aircraft Flight Testing and Evaluation

by

Carmen E. Carreras

B.S. in Mechanical Engineering (2000)

Carnegie Mellon University

Submitted to the Department of Aeronautics and Astronautics Engineering
in Partial Fulfillment of the Requirements for the Degree of
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Signature of Author..
Department of Aeronautics and Astronautics
May 10, 2002

Certified by..
Dr. Earll Murman
Ford Professor Engineering
Department of Aeronautics and Astronautics

Accepted by..
Wallace E. Vander Velde
Chair, Graduate Committee
Department of Aeronautics and Astronautics

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ABSTRACT

The application of Lean principles and practices has been shown to help aerospace companies reduce waste and maximize value to help meet the changing demands of the market. The most visible area of influence has been manufacturing, where great strides have been made in cost and cycle time reduction. Recently, the flight testing community has been faced with similar challenges. This paper investigates whether Lean principles can be applied to aircraft flight testing and evaluation to help meet these goals. Specific objectives are to identify opportunities for the implementation of Lean thinking and establish a framework for structured implementation of Lean principles and practices.

This study focuses on seven aircraft programs: 737-NG, 767-400, Hawker Horizon, F-22, F/A-18E/F, C-130J, and the T-6A. The programs are analyzed from a programmatic viewpoint to identify where lean practices are currently being used and how lean thinking could further improve the overall flight testing process. Additionally, a detailed examination is performed on the day-to-day activities to identify the daily sources of waste and their impact on the program. The detailed analysis focuses on flutter testing as a surrogate for the entire testing program. A total of 90 flights were analyzed.

Data collected from the case studies fits well into the value-creation framework established in *Lean Enterprise Value*. Each of the phases of the framework – value identification, value proposition, and value delivery – are discussed as they relate to flight testing. Many examples of the application of lean principles and practices as well as opportunities for implementation are presented in the value delivery phase. Opportunities were identified in: coordination of the systems engineering value stream, coordination with other test aircraft and necessary support functions, and management of the daily test operations.

This preliminary study indicates that Lean thinking can be applied to flight testing. The guiding principles of well-run testing programs paralleled those of Lean. Additionally, there are many instances where Lean thinking would provide an opportunity to eliminate waste and improve efficiency.

Thesis Supervisor: Earll Murman
Title: Ford Professor of Engineering

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LIST OF ACRONYMS

AFFTC	Air Force Flight Test Center
AFOTEC	Air Force Operational Test and Evaluation Center
ASC	Aeronautical Systems Center
BTP	Build-To-Package
CTF	Combined Test Force
COTS	Commercial-Off-The-Shelf
DER	Designated Engineering Representatives
DTC	U.S. Army Developmental Test Command
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FTE	Flight Test Engineer
GVT	Ground Vibration Test
IMVP	International Motor Vehicle Program
IOC	Initial Operational Capability
IPT	Integrated Product Team
ITT	Integrated Test Team
JPATS	Joint Primary Aircraft Training System
LAI	Lean Aircraft Initiative, formerly Lean Aerospace Initiative
LEM	Lean Enterprise Model
MILSPEC	Military Product Specifications
MIT	Massachusetts Institute of Technology
MOU	Memorandum of Understanding
NAWCAD	Naval Air Warfare Center Aircraft Division
SAR	Search and Rescue
SFTE	Society of Flight Test Engineers
T&E	Testing and Evaluation
TIA	Type Inspection Authorization
TM	Telemetry

Chapter 1. Introduction

1.1. Evolution of Lean Thinking

Lean, doing more with less, originated in automobile manufacturing in Japan in the 1950s. The word "lean" was introduced in the United States in 1990 by Womack, Jones, and Roos in *The Machine that Changed the World*[1]. The book discusses the origins and fundamentals of lean production and the techniques that it employs to surmount the weaknesses of the conventional mass production approach. The principles of lean production include: teamwork, communication, efficient use of resources and elimination of waste, and continuous improvement (Womack 1990).

In mid-1992, Lt. Gen. Thomas R. Ferguson, Jr. – the Commander of the Air Force's Aeronautical Systems Center (ASC), the acquisition center for all aircraft systems for the United States Air Force – read *The Machine that Changed the World.* Curious whether the principles presented in the book could help counteract the rising costs of military aircraft, General Ferguson engaged one of the authors in an exploratory study. Preliminary results indicated that lean production could be applied to aircraft, but techniques would have to be tailored for the unique challenges of aircraft manufacturing. The Lean Aircraft Initiative (LAI)[2], a consortium between MIT, major US aerospace

[1] This book was based on a study conducted by the International Motor Vehicle Program (IMVP) at the Massachusetts Institute of Technology
[2] The Lean Aircraft Initiative was later renamed the Lean Aerospace Initiative to include the spacecraft sector. For more information see http://lean.mit.edu

companies, the United States Air Force, other federal agencies, and labor, was established to explore this further (Murman 2002).

By 1996, lean was elevated off of the factory floor and presented as a product development strategy by Womack and Jones in their second book, *Lean Thinking*. The book presents guiding principles for *how* to apply lean concepts to other industries.

Figure 1-1 Five Principles of Lean Thinking

1. Precisely specify value in terms of a specific product.
2. Identify the value stream for each product and eliminate wasteful activities.
3. Make value flow without interruptions.
4. Let the customer pull value from the producer.
5. Pursue perfection.

Source: Lean Thinking (Womack, 1996)

Around the same time, LAI developed the Lean Enterprise Model (LEM) as a "hypothetical model of a generic lean enterprise" (Murman 2002). The principles and practices presented in the LEM outline *what* a lean enterprise should look like. Of the twelve overarching practices, half of them represent human-oriented practices, the other half, process-oriented practices.

Figure 1-2 Overarching Practices of the Lean Enterprise Model

Human-oriented Practices	Process-oriented Practices
• Promote lean leadership at all levels	• Assure seamless information flow
• Relationships based on mutual trust and commitment	• Implement integrated product and process development (IPPD)
• Make decisions at lowest appropriate level	• Ensure process capability and maturation
• Optimize capability and utilization of people	• Maintain challenges to existing processes
• Continuously focus on the customer	• Identify and optimize enterprise flow
• Nurture a learning environment	• Maintain stability in changing environment

Source: Lean Enterprise Value (Murman, 2002)

In the spring of 2002, the research staff of the Lean Aerospace Initiative published the book *Lean Enterprise Value*, which emphasized the role of lean at the enterprise level. In the book, lean is redefined as "eliminating waste with the goal of creating value" and a framework for implementing lean at the enterprise level is presented (Murman 2002). This value-creation framework has three phases: Value Identification, Value Proposition, and Value Delivery. Each will be discussed in more detail in subsequent chapters.

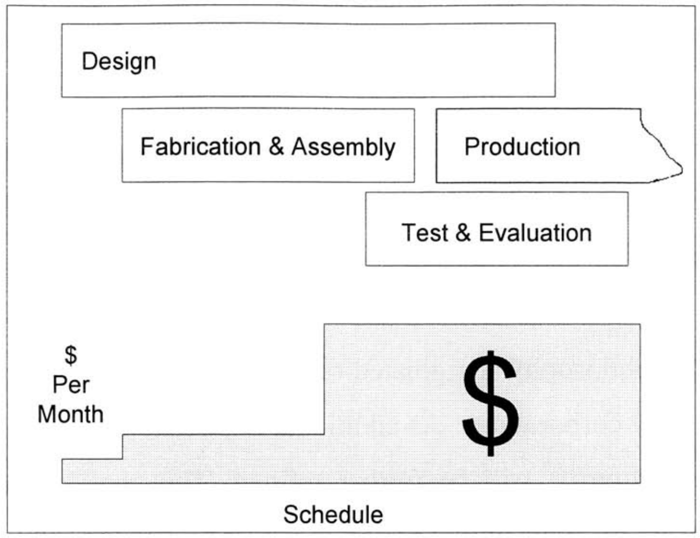
Lean is an evolving philosophy. Originated on the factory floor, lean has emerged as a core strategy for many corporations. As additional applications of lean thinking continue to be realized, its definition will be further refined. This thesis aims to continue the exploration of new applications of this powerful paradigm.

1.2. Motivation and Objectives

The testing and evaluation of new aircraft (T&E), or aircraft upgrades, can be a long and costly process. As seen in Figure 1-3, T&E is the most expensive phase of an aircraft development program. One of the case studies estimated that the costs of modern military aircraft test and evaluation programs can range from $1.3 – 5.6 Billion, with flight testing and evaluation, hereafter referred to as flight testing, as the largest component, as seen in Figure 1-4. Commercial programs cited estimates of $10,000 per flight hour and $30,000 per day. Much of the cost of testing is associated with the "standing army" of engineers needed to analyze data and implement design changes generated by test results.

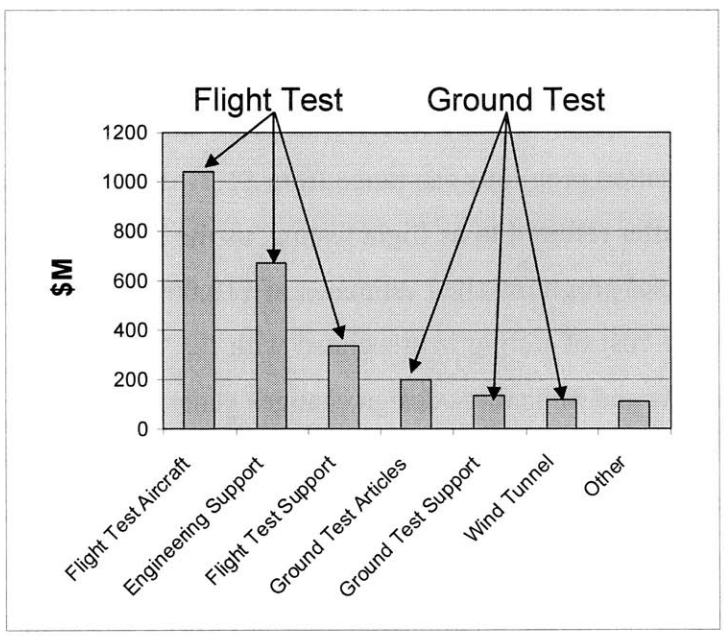
Over the years significant effort has been put forth to modernize test facilities – specifically with regards to data processing and handling of test articles – to minimize cycle time and cut down on test costs. Significant modeling and simulation capabilities have also been developed and integrated into the test and evaluation process, thereby improving the effectiveness of specific tests. Despite these efforts, T&E continues to be an area needing process improvements as aircraft systems become more complex, customers expect reduced costs and shorter development times, and the political consequence of failure increases.

Figure 1-3 Notional Costs of the Stages of Aircraft Development



Source: Presentation by Allen Haggerty to the Defense Science Board (23 February 1999)

Figure 1-4 Estimated Test & Evaluation Costs for Military Aircraft



The objectives of this research are to assess whether the principles of lean thinking apply to aircraft flight testing and to establish a framework for structured implementation of Lean principles and practices. The study examines flight testing on both a program level and on an operational level. It is the first LAI study to address aircraft testing and evaluation and aims to lay the groundwork for future research. This thesis is also the first to be based on the value-creation framework. It is the hopes of the author that flight testers and managers will be able to relate to the material presented and be inspired to become lean advocates in their organization.

1.3. Prior LAI Research Studies

Although this thesis is the first LAI research to investigate aircraft testing, a previous thesis addressed satellite testing. Annalisa Weigel in her thesis, *Spacecraft System-Level Integration and Test Discrepancies*, found that about a third of the discrepancies in satellite testing were attributable to problems with the test equipment. There have also been studies on the sources of delays and anomalies in the operation of satellites. David Steare in his thesis, *Space Launch Operations and Capacity Modeling*, found that the majority of launch delays were due to range crew rest requirements, a factor outside of the control of the launch customer. David Ferris in his thesis, *Characterization of Operator-Reported Discrepancies in Unmanned On-Orbit Space Systems,* discovered that the majority of on-orbit anomalies were unrelated to the spacecraft, but were instead due to the operational infrastructure on the ground. The results generated by these studies motivated the question: Are the majority of delays associated with aircraft testing unrelated to the aircraft itself?

1.4. Overview of Thesis

Chapter 2 discusses the research approach used for the study as well as some background information on the case studies and the data gathered. Chapter 3 explains the value-creation framework and how the value identification and value proposition phases apply to flight testing. The value delivery phase is addressed in Chapters 4 and 5. The first focuses on the effects of upstream activities and multiple test aircraft, the second on flight test operations. Chapter 6 presents the conclusions and recommendations of the study.

Chapter 2. Approach and Background

This chapter provides the reader with an overview of the approach used for the study as well as some background information. It begins with a discussion of the research methodology, how the study was conducted and why the approach was chosen. This is followed by a description of each of the aircraft studied. The chapter concludes with an introduction to the phenomenon of flutter, the subject matter of the data gathered.

2.1. Research Methodology

One of the first steps of a research project is to determine the appropriate research strategy. Robson suggests that strategies for "real world research" should be chosen based upon the purpose of the inquiry, of which there exist three primary classifications: exploratory, descriptive, and explanatory (1993). Exploratory research is performed to "find out what is happening" and seek new insights into the situation. Descriptive research portrays "an accurate profile of persons, events, or situations", and usually requires extensive previous knowledge of the situation. Explanatory research seeks to explain a situation, usually by developing causal relationships. Traditionally, exploratory research is conducted through case studies, descriptive through surveys, and explanatory through experiments, although all of the strategies can be used for any of the three purposes. The goals of this research clearly marked it as an exploratory study, thus the traditional case study approach was used.

A case study allows for the "development of detailed, intensive knowledge about a single 'case', or of a small number of 'cases'" (Robson 1993). It involves studying a case in its context through a variety of data collection techniques such as observation, interviews, and documentary analysis. Six case studies were chosen for this research, comprising eleven different aircraft. Each study required two site visits: the first introductory, the second data-gathering. Introductory visits generally lasted half a day and included the author and advisor. Their purpose was to familiarize the organization with LAI, allow the researchers to become acquainted with the organization and facilities, discuss the research goals, and assess the availability of data and resources to support the study. Data-gathering visits lasted between one and four days and were attended only by the author. The format of these visits varied by site, but the time was generally split between interviews and gathering quantitative data. A total of 22 days were spent onsite: 12 data-gathering, 7 introductory, and 3 additional background visits.

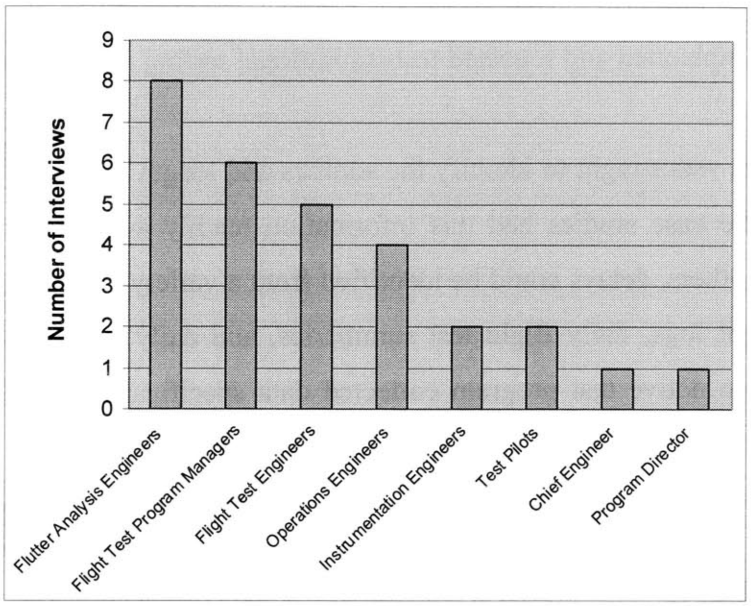
Case Study Selection Criteria

The case studies were chosen to meet some general requirements. Being an exploratory study, it was desirable to select a range of programs that covered the spectrum of flight test. Since testing is strongly influenced by the regulations of the oversight agency, it was decided that the study should include each of the certification sources: military, commercial, and commercial-off-the-shelf (COTS). Two aircraft from each category were chosen to allow for a better understanding of the issues associated with each arrangement. An additional consideration in choosing the case studies was recency. It was important to study recent and/or on-going programs because of the availability of personnel and data. Test personnel frequently transfer between programs, thus the more recent the program, the greater the chance of locating the individuals who worked on it. Similarly, the detailed data sought by this study is often not archived for very long. Furthermore, recent test programs are likely to have used the most up to date practices. A final consideration was the type of aircraft. Testing strategies vary based on the size of the aircraft. Large aircraft often carry the test team aboard during tests whereas smaller aircraft must telemeter all of their data or rely on onboard data tapes. A range of different aircraft from large passenger jets to military fighters to small aircraft were chosen to assess the influence of the different testing approaches.

Data Collection

As discussed previously, data-gathering visits involved interviews and gathering quantitative data. Interviewees were selected based on their position in the flight test organization. An attempt was made to speak with at least one individual in every key position in the test program, including: Chief Engineers, Program Directors, Flight Test Program Managers, Analysis Engineers, Operations Engineers, Flight Test Engineers, Instrumentation Engineers, and Test Pilots. A total of 29 interviews were conducted per the breakdown shown in Figure 2-1.

Figure 2-1 Number of Interviews per Position



Interviews were arranged by the point-of-contact at each site. For short visits this was done prior to arrival, on longer visits interviews were arranged upon arrival. Whenever possible, an interview form with the guiding questions was sent to the interviewees prior to the visit to allow them time to prepare. All interviews were conducted with protocols approved by MIT's Committee on the Use of Humans as Experimental Subjects. The interview sought information on both the testing program as a whole and on the day-to-day operations. The following questions were asked:

- Looking back at the flight testing program, what was done particularly well to allow the testing program/day-to-day activities to progress smoothly?
- What were the major barriers in the program/on a day-to-day basis that impeded progress/caused delays?
- Where do you see opportunities in flight testing for process improvement to eliminate waste?
- Which, if any, of the following were prevalent in the program? What impact did they have on the program and on a day-to-day basis?
    - Cancelled tests (an entire day of testing lost)
    - Testing delays (the start of testing delayed or a delay in the test sequence during flight)
    - Unplanned and repeated tests (additional testing added to plan)

Quantitative data was sought to identify the sources and length of delays on a day-to-day basis. One of the case studies had this information readily available in a summarized version, for the others, delays could be identified from a variety of sources including: test cards, daily flight logs, daily flight test summaries, and daily pilot reports. One of the programs with an active test program collected data specifically for this study using a delay tracking sheet created by the author, available in appendix A. Data on a total of 90 flights was gathered, ranging from nine to twenty-four flights per case study.

Data Analysis

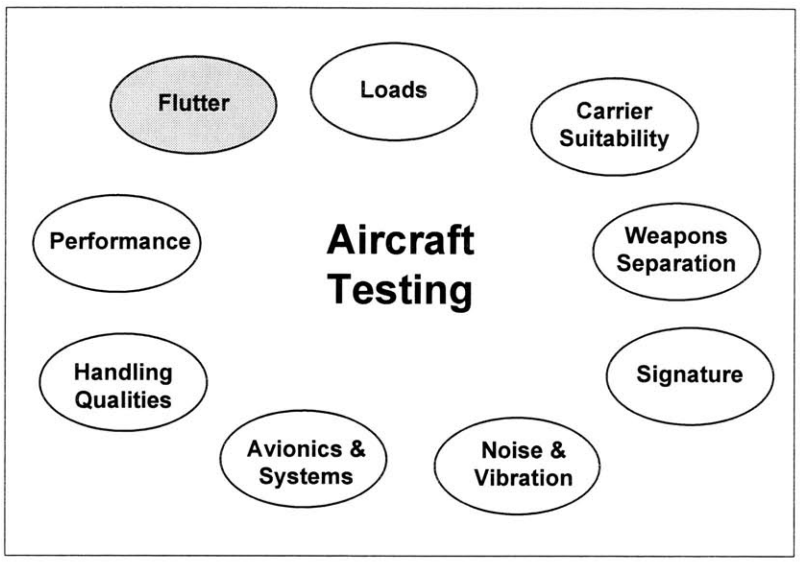
The qualitative information gathered from the interviews was grouped under the principles of lean thinking presented by Womack and Jones (1996) and the practices of the Lean Enterprise Model (Murman 2002), both given in Chapter 1. Within these groupings, the data was further divided into two categories: instances where lean thinking was applied and instances where lean thinking could apply.

Quantitative data analysis began with carefully sifting through the large amount of information gathered from each site to identify the sources and length of delays. The data was then summarized in either pie charts or Pareto charts, depending on the level of detail. Since the amount of raw data required to assess delays was so great, only a limited number of flights were analyzed and a statistical analysis could not be performed. Additionally, the inconsistency of the available data between sites did not allow for aggregation of data.

Flutter Testing as a Surrogate

The flight testing of new aircraft is a complex process that involves many different tests spanning a variety of disciplines. Common types of tests are shown in Figure 2-2. Since this study spanned only nine months, it was decided to concentrate on one of these areas as a surrogate for the entire flight test program. This helped to focus the data collection efforts.

Figure 2-2 Common Types of Flight Testing



Flutter testing was chosen for several reasons. First, it is performed on both commercial and military aircraft in much the same way. This minimizes the differences between cases and widens the target audience for the study. It is also a non-controversial area with well-established techniques. Although there are some new technologies being developed, the technological platform is relatively stable. For further efficiencies in testing, the processes must be improved. This makes it a good candidate for a lean analysis. Finally, flutter was an area initially unfamiliar to the author, so it presented an excellent learning opportunity.

2.2. Case Studies

As mentioned previously, eleven aircraft programs were studied: 737-NG (-600, -700, -700IGW, -800), 767-400, Hawker Horizon, F-22 Raptor, F/A-18E/F Super Hornet, C-130J and J-30 Hercules, and the T-6A Texan II. This section includes a brief discussion of each of the aircraft. For key facts on each aircraft, see appendix B.

737-NG and 767-400

The 737 is a twin-jet airliner. The original 737 first flew on April 9, 1967. In 1991, the Boeing Company asked more than 30 airlines to help define an improved series of aircraft. Of this study was born the 737-"Next-Generation" series. Approximately 1,602 737-NG aircraft are currently in service, not including the business jet variant (Jane's 2001).

The 767 is a wide-bodied airliner. The original 767 first flew September 26, 1981. The 767-400 is a stretched version of the -300, offering a 10-15% increase in passenger accommodation. It includes many new features, several of which are based off of the 777 (Jane's 2001). Approximately 48 767-400 aircraft are currently in service.

Boeing performs flutter testing with only the pilot and copilot onboard. All of the data is collected on data tapes and critical data is telemetered down to a ground station at Boeing Field, where the test team monitors the flight. The test team flies aboard the aircraft for most other tests.

Hawker Horizon

The Hawker Horizon is a twin engine "super mid-sized" business jet developed by Raytheon Aircraft. Being the first 14 CFR Part 25[3] aircraft built by Raytheon, it is the largest airplane they have ever made. Testing began in August of 2001, and it is anticipated to enter service in the fall of 2003.

Raytheon Aircraft performs all of their tests on the Horizon with a pilot, copilot, and a flight test engineer (FTE) onboard. The data from the flight is collected on data tapes which are reviewed by the analysis engineers after landing. The FTE monitors data collection during the flight to ensure data quality.

F-22 Raptor

The F-22 is the United States Air Force's replacement for the F-15C Eagle. It is an advanced tactical fighter capable of air-to-air and air-to-ground attacks. The program began in 1981 with the issue of request for information. In October of 1986, the Air Force announced selection of demonstration/validation phase contracts to Lockheed and Northrop. Lockheed, partnered with General Dynamics and Boeing, was announced as the winner on August 2, 1991. Flight testing began on September 7, 1997 (Jane's 2001). The aircraft is scheduled to complete developmental flight testing in April of 2003, with initial operational capability (IOC) in December of 2005.

Since the F-22 seats only one person, the test team must remain on the ground. All of the flight test data is recorded by onboard data tapes and critical data is telemetered to the control room where the flight test team monitors the flights.

F/A-18E/F Super Hornet

The F/A-18E/F is a multi-role fighter for the Navy. It was proposed in 1991 following the cancellation of A-12 as a replacement for the aging F/A-18A/B and C/D fleet and other United States Navy/ Marine Corps aircraft. The E/F is an upgraded version of the C/D model. It employs the same avionics, but has an all-new airframe. It is 25% larger, has a 40% increase in unrefueled range, a 25% increase in payload, three times greater bring-back ordinance, and five times greater survivability. Approximately 140 F/A-18E/F aircraft have been procured (Jane's 2001).

Like the F-22, the F/A-18E/F accommodates only the flight crew, thus the test team must monitor the flight from the ground. All of the flight test data is recorded by onboard data tapes and critical data is telemetered to the control room.

[3] A transport category aircraft

C-130-J and C-130-J-30 Hercules

The C-130J and J-30 are tactical transport and multi-mission aircraft for the United States Air Force and other military customers. The original C-130 first flew on August 23, 1954. Development of the next-generation version (-J and -J-30) was privately funded by Lockheed Martin and began in 1991. The J version is dimensionally similar to the preceding H version but incorporates new equipment and features, most notably, more efficient propellers and lighter engines. The J-30 is a stretched version of the J. The fuselage is 15 feet longer, offering between a 31 and 50% increase in capacity. Approximately 111 C-130J aircraft and its variants (EC-130J, KC-130J, and WC-130J) have been procured (Jane's 2001).

Flutter tests were performed on the C-130J with a pilot, copilot, and a flight test engineer (FTE) onboard. All of the flutter flight test data was recorded by onboard data tapes while critical data was telemetered to the control room where the flight test team monitored the flights.

T-6A Texan II

The T-6A is a turboprop trainer, based on the Swiss Pilatus PC-9. In 1990 Beech (now Raytheon) and Pilatus formed a partnership to compete in the USAF/USN Joint Primary Aircraft Training System (JPATS) competition. They were announced as the winners on June 22, 1995. Approximately 25 T-6A aircraft are currently in service, with a total of 109 aircraft ordered as of June 2000 (Jane's 2001).

The T-6A would generally fly developmental tests with a Raytheon pilot in the front seat and a military pilot in the back seat. When one of those pilots was not available or if non-pilot tasks such as hand-recording data were required, a flight test engineer would ride in the back seat. Data was telemetered only for high risks tests such as flutter and some spin tests. The majority of the tests rely solely on data recorded on onboard tapes which were analyzed after the flight.

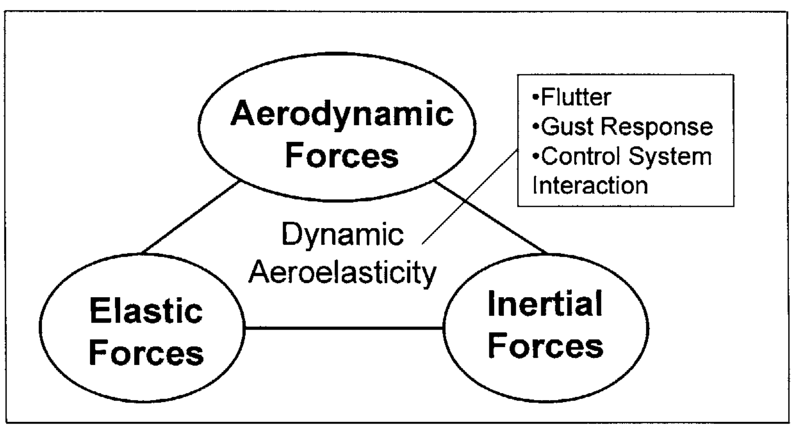
2.3. *Introduction to Flutter*

As discussed previously, flutter testing was used as a surrogate for the entire flight test program. For readers unfamiliar with flutter, this section provides a brief explanation of the phenomenon as well as an introduction to the development of the analysis and the various testing methodologies. Dowell et al. provide a more complete treatment of this phenomenon (1995).

Explanation of the Phenomenon

Since aircraft are light, they deform considerably under load. These deformations alter the aerodynamic forces, which in turn alter the deformations. This interacting process may lead to flutter, a self-excited, often destructive, oscillation wherein energy is absorbed from the airstream. Flutter is considered a type of dynamic aeroelasticity because it embraces all of the aspects of aeroelasticity: aerodynamic, elastic, and inertial forces (Figure 2-3). Flutter can occur on any aerodynamic surface including the wings and the control surfaces. In general, it must be either completely eliminated from the design or prevented from occurring with the flight envelope (Garrick 1981).

Figure 2-3 Collar's Aeroelastic Triangle

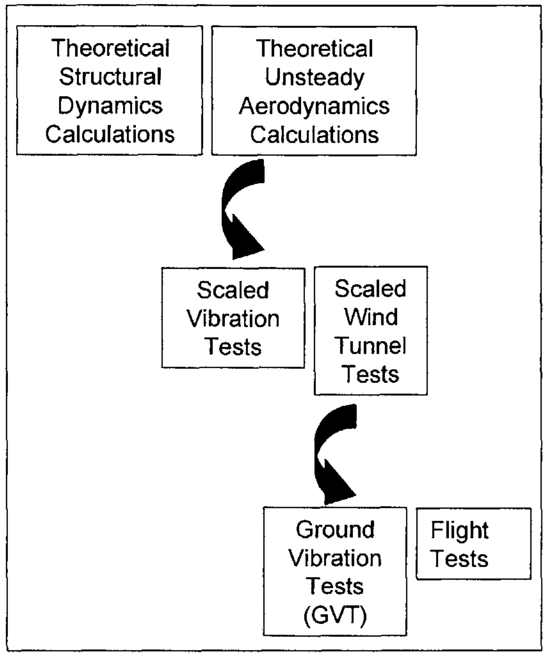


Source: Journal of Royal Aeronautical Society (1947)

Development of the Flutter Analysis

Flutter analysis is the determination of damping characteristics, and dynamic bending and torsion frequencies from the static bending and torsion frequencies and the aerodynamic loads. There exist three basic steps in the flutter analysis of a new aircraft, each with increasing complexity: theoretical analysis, scaled experiments, and full scale tests (Figure 2-4).

Figure 2-4 Flutter Development Flowchart



The flutter engineers are initially provided with a simplified mass and stiffness model of the aircraft from other structural engineers. This model is used to perform theoretical structural dynamics, which generate first approximations of the static bending and torsion frequencies. They are also provided with a reduced aerodynamic model upon which they perform unsteady aerodynamics calculations to approximate the aerodynamic loads. This is used to generate the first approximation of damping characteristics and dynamic frequencies.

Next, vibration tests are performed on a scaled mass model to generate a more accurate approximation of the static bending and torsion frequencies. The second approximations of the aerodynamic loads are measured on the model in the wind tunnel. This data is used to update the flutter calculations.

The final tests are performed on the actual aircraft. First, a ground vibration test (GVT) is completed to measure the actual static bending and torsion frequencies of the aircraft.

These values are used to update the flutter model and to refine the predicted flutter parameters. Finally, the aircraft is tested in flight to verify the predictions.

Flight Test Methodologies

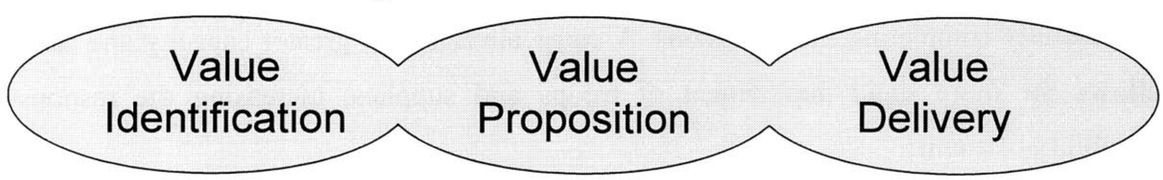
To test the flutter characteristics of an aircraft in flight, the aircraft is flown at different speeds, vibrated, and the damping characteristics measured. Tests begin at relatively slow airspeeds where confidence is high that the aircraft will not flutter. As the measured damping matches the predicted results, the airspeed is gradually increased. This is known as expanding the envelope. The aircraft is never intentionally flown to the predicted flutter speed.

Aircraft with fly-by-wire capability are installed with a flutter excitation system that, when initiated by the pilot, takes command of the control surfaces. It deflects the surfaces at various rates to excite the different frequencies of the aircraft. Aircraft with cable-linked control surfaces must use an external excitation system for vibration. Some programs detonate small explosives on the tip of the wing, others fashion more controllable excitation devices. Onboard accelerometers measure the rate of damping. Some examples of flutter excitation system controllers from the aircraft studied are available in appendix C.

Chapter 3. The Value-Creation Framework

The value-creation framework is presented in *Lean Enterprise Value* as a guideline for organizations seeking to create value for all of their stakeholders (Murman 2002). The three-phase framework is iterative in nature and has at its heart the concept of "doing the right job as well as doing the job right". The first phase, value identification, involves identifying the stakeholders and their value expectations. The needs of the key stakeholders are brought together in the value proposition phase. The goal of executing these two phases is to identify "the right job". The third phase, value delivery, focuses on "doing the job right". This chapter will focus on the first two phases of this value framework; the following two chapters will focus on the third phase.

Figure 3-1 Value-Creation Framework



Source: Lean Enterprise Value (Murman, 2002)

3.1. Value Identification

Customer Value

What is value? Although the specific meaning of value depends on the context, it generally involves a measure of function (i.e. performance, quality …), a measure of cost, and a measure of timeliness (Murman 2002). Womack and Jones assert that value must be defined by the ultimate customer in terms of a specific product (Womack 1996). The final product of a flight test program is a proven aircraft ready for production. The ultimate customers, or end users, and the immediate customers that represent them vary as shown in Figure 3-2, depending upon whether it is a military or commercial unit.

Figure 3-2 End-users and Immediate Customers of Aircraft

Type of Program	End-Users	Immediate Customers
Military Aircraft	Pilots, Mission Commanders, & Maintainers	Program Offices
Commercial Aircraft	Pilots, Passengers, & Maintenance Personnel	Airline Companies

In a military program, the end-users are the war-fighters: the pilots, mission commanders, and maintainers. During the development program, the interests of these groups are represented by the immediate customer, the program office. During peacetime, pilots value most the safety of their aircraft. The pilot's lives depend on proper functionality of the aircraft and egress system, thus a safe aircraft is their greatest concern. In wartime, performance, namely lethality and survivability, become more important. A fighter/attack aircraft with strong performance characteristics allows the pilots to be faster, more maneuverable, and less vulnerable to attack than the enemy, increasing the probability of successfully completing their missions. A cargo aircraft with greater capacity and range allows for more rapid deployment of troops and supplies, increasing the response capability of a unit.

The mission commander would certainly cite performance and safety as high value characteristics, but would include availability both in terms of the number of aircraft assigned to the unit and the number of those ready when needed. The lower the unit cost of the aircraft, the more that can be deployed. Similarly, the sooner the capability is delivered, the sooner the effectiveness of the troops can be increased. Finally, the more reliable the aircraft, the more likely it is to be available when needed.

The end-users of a commercial aircraft are the pilots, passengers, and maintenance personnel. Their interests are represented by the immediate customer, the airline companies. The commercial pilots' and passengers' definition of value includes the same factors as the military pilots, safety and utility, but weighs even higher on the first. Similarly, the airline companies focus on the same factors as the mission commander: cost and schedule. An airline company's goal is to make money, and thereby satisfy its shareholders. It makes good economic sense to fly safe airplanes, with strong performance specifications, low unit acquisition cost, and low direct operating costs. It is also important for aircraft deliveries to be timely, to allow airlines to react to the fluctuations in travel demand.

Customer Value*: Delivery of an aircraft on schedule, within budget, and with full confidence in its safety, performance, and reliability characteristics.*

Oversight Agency Value

Although the flight test group is responsible to the end-users, they must also answer to an additional "customer": the oversight agency, also known as the certification agency. There are three different ways in which an airplane can gain certification. The two traditional avenues in the United States are through either the civilian agency, the Federal Aviation Administration (FAA), or through the military. The Naval Air Warfare Center Aircraft Division (NAWCAD) at Patuxent River NAS oversees Navy military developmental testing, the Air Force Flight Test Center (AFFTC) at Edwards AFB oversees Air Force developmental testing, and the U.S. Army Developmental Test Command (DTC) at Fort Hood oversees Army developmental testing. Operational testing is overseen by the Air Force Operational Test and Evaluation Center (AFOTEC), the Naval Air Test and Evaluation Squadron NINE (VX-9), and the U.S. Army Operational Test Command. The military oversight groups are under separate command structures from the program offices to prevent biasing. The third arrangement, known as Commercial-off-the-Shelf (COTS), is a combination of the first two. In a COTS program, the contractor of a military aircraft undertakes a certification program with the FAA to ensure that the basic airframe meets their approval. Once the aircraft receives its FAA airworthiness certification, additional testing is performed under the oversight of the military group to verify that all of the military-specific requirements are met.

Technical specialists in the oversight agencies are responsible for ensuring that the aircraft meets all safety specifications as laid out in the Federal Aviation Regulations (FAR) or the military equivalent[4], and that the testing program is performed in a safe manner. The military agencies have the additional task of ensuring that the aircraft is technically and operationally capable. Both the military and civilian oversight groups are protected from cost and schedule pressures, allowing them to make decisions that are best for the safety and performance of the aircraft.

Commercial Programs

A commercial test program begins with developmental testing. The purpose of this testing is to ensure that the aircraft performs as designed. Since this is the first time that the aircraft is flown completely integrated, in its actual operating environment, it is not uncommon for problems to arise. The design team works closely with the test team to fix any deficiencies that are found.

Certification testing, also known as Type Inspection Authorization (TIA) testing, can begin as soon as the developmental testing of some aspect of the aircraft, such as flutter characteristics, is complete. Certification testing is not as thorough as developmental testing, targeting only critical test points. As a precautionary measure, companies generally perform a dry-run of every TIA test to make sure that it will pass. "Never show something to the FAA if you don't already know what the answer is", was one tester's impression of the process. For certification tests that FAA pilots fly personally, this pre-TIA testing is actually required. The FAA wants to be sure that the aircraft is safe for their pilots to fly.

[4] Formally the Military Product Specifications (MILSPEC), now performance-based requirements (more details follow on page 36)

By the time a test point is performed in a certification test, it has already been flown in the pre-TIA tests. Recognizing the expense to the companies, the FAA has devised ways to try to cut down on costs. One such initiative is the assignment of Designated Engineering Representatives (DER), a title that can be earned by both engineers and pilots employed by an aircraft manufacturer. Regulations require that every certification test must be witnessed by an FAA official. Sometimes the FAA will delegate this authority to a DER. If a DER participates in a pre-TIA test and deems the results adequate, they recommend to the FAA approval of the test results and a formal TIA test is often not required. The level of direct participation on certification flights depends on the class of aircraft, the degree of importance and risk, and the desires of the FAA.

Military Programs

The testing philosophies of the United States Air Force have evolved over time. In the 1950s, "phase testing" prevailed. Aircraft were tested in "eight distinct and sequential phases, each performed by different organizations and frequently at different locations" (Lucero 1994). These programs were costly, time-consuming, and often resulted in expensive retrofits.

In an attempt to solve these problems, a three-phase approach was introduced in the late 1950s. First, the contractor would perform developmental testing at their own facilities to ensure that the aircraft met the design requirements. Next the Air Force would repeat the developmental testing at their facilities with their own pilots, to verify the contractor's results. Finally, the Air Force would perform operational testing to ensure that the aircraft met the operational requirements. Although this new approach was an improvement over the original, late input from the operational testers still generated costly retrofits.

In 1972, the Air Force once again restructured testing to establish the process in use today. To cut down on rework, the separate contractor and military developmental testing phases were collapsed into one. Additionally, operational testing was combined with developmental testing to ensure some input before major production decisions and minimize the need for retrofits. A Combined Test Force (CTF) was established at the Air Force Flight Test Center (AFFTC) at Edwards AFB, California to accomplish the combined testing efforts. The basis of the CTF concept is collocation of an integrated team comprised of contractor and government developmental testers as well as operational testers (Lucero 1994).

The Navy and Army recently began using a similar approach to testing, under a different name: an Integrated Test Team (ITT). The words of one tester describe well the benefits of an integrated team.

> *"The ITT approach meant that there were customer [Navy] and contractor members side by side during testing, thus eliminating a great degree of "status" reporting. We also had periodic review of results with the customer, to assess future (planned) testing based on what had been learned to date. This resulted in some configurations being eliminated or substituted to provide the most efficient program in the shortest possible time"*

Commercial-off-the-Shelf Programs

The Commercial-off-the-Shelf (COTS) approach to testing is a product of the acquisition reform movement to reduce the development costs of new military products. In a COTS program, the military does not fund the development or design process of the aircraft; they only pay for the final product. There are both benefits and drawbacks associated with this approach.

Besides monetary savings, one of the main benefits of some of the COTS programs is that testing is performed at the contractor's facilities, provided military safety protocol is followed. This allows the test team to remain close to the design group, facilitating any required design changes. An additional benefit is quick completion of test reports. A test program is officially over when the final report is complete. Military test bases tend to be understaffed and their personnel overloaded. Since report-writing is a low priority, it often takes a considerable amount of time for reports to be completed. In a COTS program, this is not a problem because timely delivery of a complete report is one of the contract requirements.

Prior to acquisition reform, the requirements for all military aircraft were defined in rigid specifications and standards known as Military Product Specifications (MILSPEC). One of the reform concepts dictated a transition away from these regulations to a focus on performance-based requirements and commercial standards (Lucero 1995). This allows for minimization of some unnecessary testing because only the test requirements that are pertinent to the aircraft are imposed by the military oversight group.

Although the COTS approach enjoys many benefits, it exposes the program to all of the drawbacks of the commercial testing process. The duplicate testing associated with certification becomes an immediate source of waste and the program may be subjected to unnecessary requirements that pertain only to commercial aircraft.

The nature of the COTS arrangement also allows for multiple independent customers, each of whom may bring with them additional test requirements. One of the programs studied had to repeat many tests with various customer pilots, a situation would never arise in strictly military or commercial program.

As the final authority on most technical issues, the individuals in the military and civilian oversight groups have the power to require contractors to continue testing until they are fully convinced that the aircraft meets all requirements. They often feel personally responsible for the safety and performance of the aircraft and thus tend to be conservative and risk-adverse.

Oversight Agency Value*: A minimal risk testing program that ensures that the aircraft is fully compliant with the safety and performance requirements.*

Additional Stakeholders

According to Womack and Jones, once customer value is clearly defined, the producer, in this case the test team, should focus next on creating this value (Womack 1996). In other words, testers should strive to conduct a minimal risk program that is completed on schedule, within budget, and with full confidence in the safety and performance characteristics of the aircraft. While emerging lean thinking agrees with this strategy, it goes one step further and maintains that the values of *all* of the stakeholders must be considered (Murman 2002). The remaining stakeholders in a flight test program are the flight testers and program management.

The flight test team is made up of a variety of individuals: flight test managers, operations engineers, flight test engineers, test conductors, analysis engineers, instrumentation engineers, test pilots, and maintenance personnel. They have chosen to work in flight test because they enjoy the unique challenges of an experimental environment. They understand, and even thrive on, the technical surprises and rigorous pace, but are resentful of micromanagement, instability caused by poor planning, and inadequate support and equipment.

> ***Test Team Value:*** *A well-planned and stable program with timely access to adequate support equipment and personnel*

Management is ultimately accountable to the shareholders. During the testing program they focus on factors that directly affect the bottom line: cost and schedule. Military contractors aim to achieve the full bonus in cost-plus contracts by completing the program within the prescribed margins. Commercial contractors seek to maximize profitability by minimizing costs.

> ***Management Value:*** *Completion of a test program with the aircraft meeting all technical specifications within the prescribed time and budget.*

3.2. Value Proposition

Accommodating the values of the customers, the oversight agency, the test team, and management, is a delicate juggling act. It is a tough equilibrium to establish, but one which is crucial for deriving the full benefits of lean thinking. Although it may be tempting to sacrifice the values of one of the stakeholders in order to satisfy the others, examples from the programs studied show the importance of accommodating the values of all of the stakeholders.

Figure 3-3 Value Definitions

Customer: *Delivery of an aircraft on schedule, within budget, and with full confidence in its safety, performance, and reliability characteristics*
Oversight Agency: *A minimal risk testing program that ensures that the aircraft is fully compliant with the safety and performance requirements.*
Test Team: *A well-planned and stable program with timely access to adequate support equipment and personnel*
Management: *Completion of a test program with the aircraft meeting all technical specifications within the prescribed time and budget.*

Customer value ultimately defines the cost and schedule of a testing program. The performance requirements set by the customer dictate the testing requirements. For instance, the maximum speed of an aircraft sets the upper limit of flutter testing, which determines the number of flutter test points. During the testing program, customer value is driven through the management team.

Oversight agency value is never compromised and can thus be an unbalancing force. The flutter specialists in the oversight agency of one of the cases studied were extremely risk averse. Their unwillingness to accept reasonable, managed risk forced a greater number of tests than the test team felt was necessary. The additional test requirements increased the cost of the program and frustrated the test team.

In the face of other pressures, test team value often yields. Testers are often overworked and underappreciated in an effort to meet unrealistic schedule deadlines to satisfy their customers. An extreme example of the potentially devastating consequences of this neglect is the highly publicized engineering strike at Boeing in the spring of 2000. Frustrated with the way they were being treated, the employees went on strike. The company's testing program was stalled while new contracts were negotiated. A workforce on the picket line cannot apply lean principles!

Although difficult, accommodating the values of all of the stakeholders is not an impossible goal. The method recommend by the value framework is through a value proposition. The goal of this phase is "to structure value streams based on the stakeholders' value propositions so that people, groups, and enterprises will contribute their efforts or resources to the value streams in those ways from which they, in turn, derive value" (Murman 2002). One of the programs studied did just that in the drafting of their Memorandum of Understanding (MOU). This document, written very early in the program (before the critical design review), established guidelines on how the test program was to be run and explicitly laid out the roles of each of the stakeholders. Agreements between the prime contractor and the FAA in terms of an approved test plan, or between the contractor and the government agency, are very beneficial to establishing the value framework for the key stakeholders.

The success of the test program can be attributed to the creation of the MOU. The overseers understood how their decisions impacted the test team; likewise, the test team could appreciate the rationale for requirements imposed by the oversight agency. The close interaction between the contractor's test team and the overseers also encouraged management to be trusting of the test team and work together with them to eliminate barriers instead of scrutinizing and micromanaging their actions.

3.3. Conclusions

The value identification and value proposition phases are important parts of incorporating lean thinking into any organization. Together, they allow for an understanding of what the "right job" should be. In flight testing, this is the set of tests, test procedures, and required approvals that will satisfy the values of all of the stakeholders. It is important to establish this early in the development program, before the beginning of flight testing, to ensure that the value delivery phase is producing the proper product. If lean principles are applied only to the value delivery phase, the organization runs the risk of becoming very efficient at performing tests that do not satisfy all of the stakeholders thereby sub-optimizing the implementation of lean thinking. The greatest waste of all is optimizing a task that does not have to be done at all!

Chapter 4. Value Delivery: Upstream Activities and Multiple Test Aircraft

Value delivery is the phase of the value-creation framework with which flight testers are most familiar. It includes all of the activities directly involved with the planning and executing of flight tests. There are three main factors that affect the efficiency of value delivery: upstream activities in the systems engineering process, multiple test aircraft, and the daily flight test operations. This chapter will discuss how lean thinking can be applied to the first two; the next chapter will focus on the third.

4.1. Upstream Activities

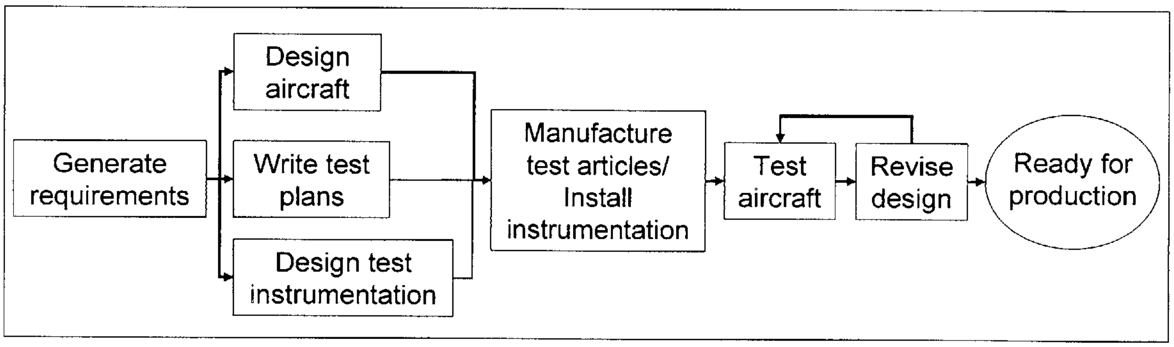
The term "value stream" was introduced by Womack and Jones in *Lean Thinking* with the following meaning:

> *"The set of all the specific actions required to bring a specific product through the three critical management tasks of any business: the problem-solving task running from concept through detailed design and engineering to production launch, the information management task running from order-taking through detailed scheduling to delivery, and the physical transformation task proceeding raw materials to a finished product in the hands of a customer."* (1996)

A proposed definition for flight testing is: the end-to-end set of all tests, modeling and simulations, and related processes and interactions, which are executed to reduce the risk of not achieving the end goal of delivering an aircraft to the customer which meets the end user's expectations.

As the final step in the systems engineering value stream, flight testing is often greatly influenced by the activities that precede it. This section briefly describes the major elements of the value stream, for readers unfamiliar with the process, and then discusses the influence that each element can have on flight testing. In conclusion, a lean thinking solution is presented to the problem of upstream activities affecting downstream activities.

Figure 4-1 The System Engineering Value Stream



The first step in the development of a new aircraft is the generation of requirements. The Systems Engineering Requirement Document includes design specifications and establishes how they will be verified. For example, in the case of flutter, the document may prescribe that the aircraft will not flutter within a particular speed envelope and that this will be verified by analysis, ground test, and flight test. Common sources of requirements are the Federal Aviation Regulations (FAR) and performance-based requirements. The requirement document also includes precise definitions of the content of each of these activities. For flutter this would likely state that flight testing will be performed using inputs from an external excitation system.

As soon as the requirements are established, the design group can begin working on the detailed design and the test group can start on the test plans. Once the design is mature, assembly of the first test article commences. During assembly, embedded test instrumentation should be installed in the aircraft and then calibrated. Upon completion, the flight test program is initiated. Results from tests can often generate design changes which must be incorporated and retested before the aircraft is ready for production.

Requirements Generation

Many of the problems seen in of one of the cases studied can be traced to a lack of timely requirements. The testing program actually started before the requirements document was even complete! Since requirements generation is a crucial initial step in the product development value stream, this could have been disastrous. Fortunately, many of the airframe test team leaders had experience from other programs that allowed them to draft test plans without the detailed guidelines. The avionics group was not as lucky and struggled throughout the program.

Another case-study presents an excellent counter-example. Many of the testers on this program cited delivery of a complete requirements document prior to the start of testing as a key enabler to their smooth program. One of the instrumentation engineers interviewed gave a specific example: "We knew which stores were going to be used, so we could begin installing instrumentation early [in the program]." Waiting for instrumentation to be installed was never a source of delays during testing.

Test Planning

Although the airframe group in the aforementioned example was able to overcome the requirements barrier, the lack of complete certification test plans was a major impediment. Since there was no official agreement on specific tests, the overseers were able to freely change the test requirements. This directly affected the flutter testing.

The flutter group had been working closely with the oversight agency to establish a testing plan. All of the prerequisite testing had been completed and preparations for the final tests were in place. During the morning brief for the final test, the oversight group announced that it had changed its mind and the test should be performed differently. All the test plans had to be reworked and testing was delayed.

Test planning within the organization can also cause tremendous problems. Poor or incomplete upfront planning on one of the case studies created havoc throughout the flight testing program. Management erroneously adopted the task list as the master schedule. There were no built in down days for weather, maintenance, or test anomalies, so the program was always behind schedule without any hope of recovery. Program personnel worked eighty-plus hour weeks in an effort to avoid falling too far behind. Much of this chaos and instability could have been prevented with a more realistic test plan.

Aircraft Design

According to the product development value stream, the initial design of an aircraft should be completed before the start of testing. When this is not the case, problems ensue. One of the programs studied was plagued with so many late design changes that the first aircraft bore little resemblance to the production aircraft. Many features could not be tested on this initial aircraft, limiting its usefulness. Furthermore, the design engineers were so busy completing the initial design that they were unable to properly support the design changes being generated by the test program.

Poor integration with the oversight agency was one of the sources of these late design changes. One tester gave his impression of the aircraft design process: "design, show the FAA, redesign". Low staffing levels at the FAA limited the amount of attention they could devote to contractors during the design phase, forcing discrepancies to be caught later on in the program when they had a larger impact.

Manufacturing of Test Articles

It is easy to see the impact that manufacturing has on flight test because of its proximity in the value stream. "If the aircraft is delivered late, the [flight test] program is always behind schedule" commented one tester. Late delivery of test articles was a major problem on many of the programs studied. Furthermore, when the aircraft finally arrived, they were often incomplete and/or missing instrumentation. Programs that received their test aircraft on time were able to complete their planned test program on schedule.

Common sense would suggest that the completion date be pushed back by the length of the startup delay; however, flight test is rarely given an extension. Pressure from upper management to complete the program on time forces flight test to try to make up for the cumulative delays in the value stream. In one of the cases studied, flight test received the test aircraft six months late. It took them two months to get the aircraft ready for first flight. The test program was given a one month extension! A tester on another program divulged his planning scheme to compensate for late deliveries: "We plan on working seven days per week for the first two months, six days a week for the next two, and five days a week thereafter".

Although this study did not focus on manufacturing, a cursory investigation found some interesting reasons for late completion of test articles. One interviewee cited the following reasons for manufacturing delays: (1) parts arriving late from suppliers, (2) parts being lost on the premises, and (3) FAA conformity paperwork (a necessity for certification testing) being lost in transit. Another interviewee identified engineering definitions being delivered late, incorrect, or incomplete to the suppliers or internal parts fabrication as a common cause of test article delays. Problems such as these can be virtually eliminated with proper implementation of lean thinking.

A cursory investigation into the causes of incomplete test articles also proved interesting. One of the programs studied exhibited a failed attempt at systems thinking. Initially the company had planned to install test instrumentation while the aircraft was being assembled. This allows for easier access to hard-to-reach areas and eliminates the need to open up the airframe after it is completed. Unfortunately, a tight assembly schedule forced this idea aside. Each manufacturing cell was being judged on how well they met their completion date. Although concurrent instrumentation installation would have saved the program time in the long run, the time spent during the assembly process would have put the cells behind schedule and under tremendous scrutiny by management.

All of the activities in the systems engineering value stream can adversely impact the flight test program if they are not planned or performed properly and/or not completed prior to moving on to the next step. The strategy suggested by lean thinking to avoid these problems is for the program managers to map out the entire value stream and enable the flow of value throughout. Although it is important for each individual activity to be efficient, it is critical for the interactions between them to be closely managed for value to flow smoothly along the value stream!

4.2. Multiple Test Aircraft

All major flight test programs use multiple aircraft to test the different characteristics of a design concurrently, as seen in Figure 4-2. While this allows the testing program to be completed sooner, having several test articles on one program can decrease efficiency for the individual aircraft. Problems can also occur when multiple programs share the same test facilities, as seen in Figure 4-3. Indirect effects of multiple test aircraft generally arise in the form of competition for support functions such as range facilities and instrumentation. Direct effects tend to stem from risk mitigation strategies and design changes that result from the analysis of data.

Figure 4-2 One Program with Multiple Test Aircraft

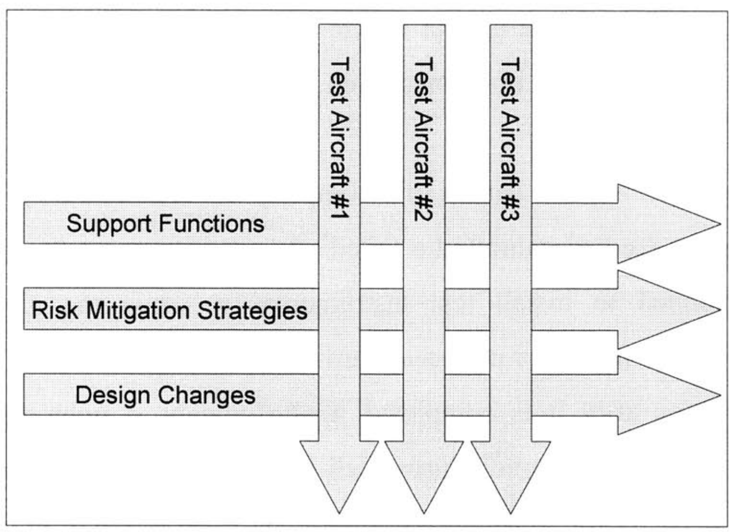
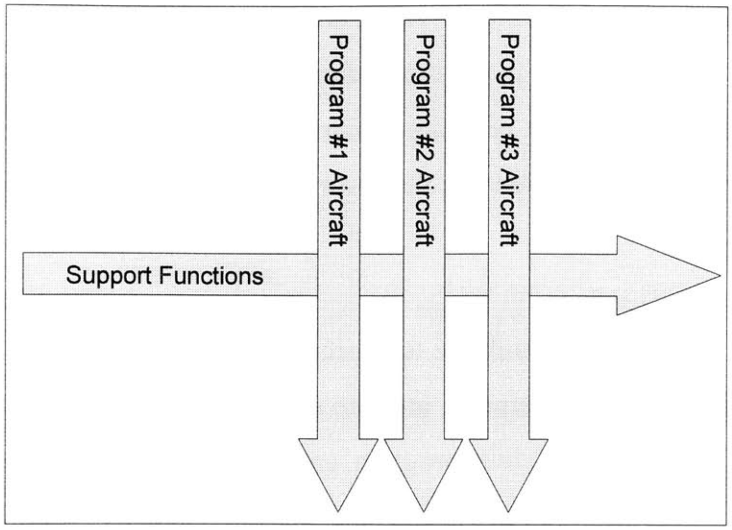


Figure 4-3 Multiple Programs Sharing One Facility



One of the cases studied operated at a test facility capable of supporting only one flight at a time. Since resources had to be shared with another test group, the program was only permitted to fly in the mornings, limiting the rate at which testing could progress. Ironically, flight testing of the aircraft was scheduled to commence a year earlier, when they would have had sole access to the test facilities. Unfortunately, late delivery of the test article pushed back the start of testing. This problem is addressed in greater detail in the next section.

Another test program cited additional adverse impacts of multiple test aircraft. At one point, testing had to be put on hold while one test group waited for another to finish with a necessary piece of test equipment. The scheduling conflicts between these two groups caused much frustration and the sacrifice of precious test time.

Direct effects of multiple test aircraft played a significant role in one of the cases studied. The program's risk management policy directed the entire fleet of test aircraft to be grounded when a technical problem was discovered on one of the aircraft, until a solution was found. While this low risk philosophy was beneficial from a safety standpoint, some of the testers felt that some of the problems did not affect the other airplanes and the disruptions were unnecessary and the delays detrimental to their schedule.

Another program incurred problems from concurrently testing two similar designs. Problems discovered on one of the aircraft often led to additional testing on the other. It was originally thought that the program would be able to save a great deal of testing using this parallel approach, however, the testing that was added may have negated any benefits incurred.

Lean thinking would consider multiple test aircraft/ test programs to be individual value streams in a multi-program enterprise, and the examples discussed above as the adverse effects of their intersections. Multi-program enterprises contain "many program value streams, each directed towards providing one or more distinct customers with value" (Murman 2002). Additionally, the programs share common enterprise value streams such as resources and infrastructure, for which there is often competition.

One strategy for tackling problems such as competition for resources is to implement the value-creation framework from an enterprise point of view (Murman 2002). The value identification phase should consider other programs to be additional stakeholders. Thus, the value proposition phase would establish a common unifying vision not only for the customer, oversight agency, test team, and management of one program, but also with all of the other programs at the facility. The same approach works for multiple aircraft in one program. For this strategy to be effective there must be strong enterprise leaders who are focused on eliminating waste and creating value among all of the programs/test aircraft.

4.3. Conclusions

Upstream activities in the systems engineering value stream and multiple test aircraft are two of the main influences on the efficiency of the value delivery phase. To minimize problems associated with them, lean thinking suggests that program managers focus on enabling flow throughout the value stream and enterprise leaders implement the value-creation framework from an enterprise point of view.

Chapter 5. Value Delivery: Flight Test Operations

This chapter explores the third main influence on value delivery: flight test operations. For readers unfamiliar with flight test, the chapter begins with an overview of the daily activities. Next, examples of observed practices which correlate with lean practices are presented. This is followed by suggested lean solutions to some operational problems. In closing, the importance of the flight test organization to flight test operations is discussed along with overarching practices to guide lean thinking within organizations.

5.1. Flight Test Operation's Daily Activities

As seen in Figure 5-1, the day begins with a pre-flight inspection of the aircraft by the maintainers and instrumentation engineers. The purpose of this inspection is to ensure that the aircraft is functional and properly configured. A configuration check entails verifying that the ballast has been correctly loaded, the right avionics boxes and proper software are installed, and the instrumentation is properly programmed and calibrated. Upon completion of the inspection, the release documents are signed, signifying that the aircraft is ready to go.

The next step is the pre-flight brief. All of the personnel involved with the test convene to review the flight plan and discuss any issues pertinent to the flight. Upon completion, the flight crew reports to the aircraft and the ground-based test team members report to the control room. In smaller aircraft programs where the aircraft does not have the capability to transmit data during flight, the non-flying test team members may work on other tasks. Once all personnel are in place, the pilot runs through pre-flight aircraft and instrumentation checks and takes off.

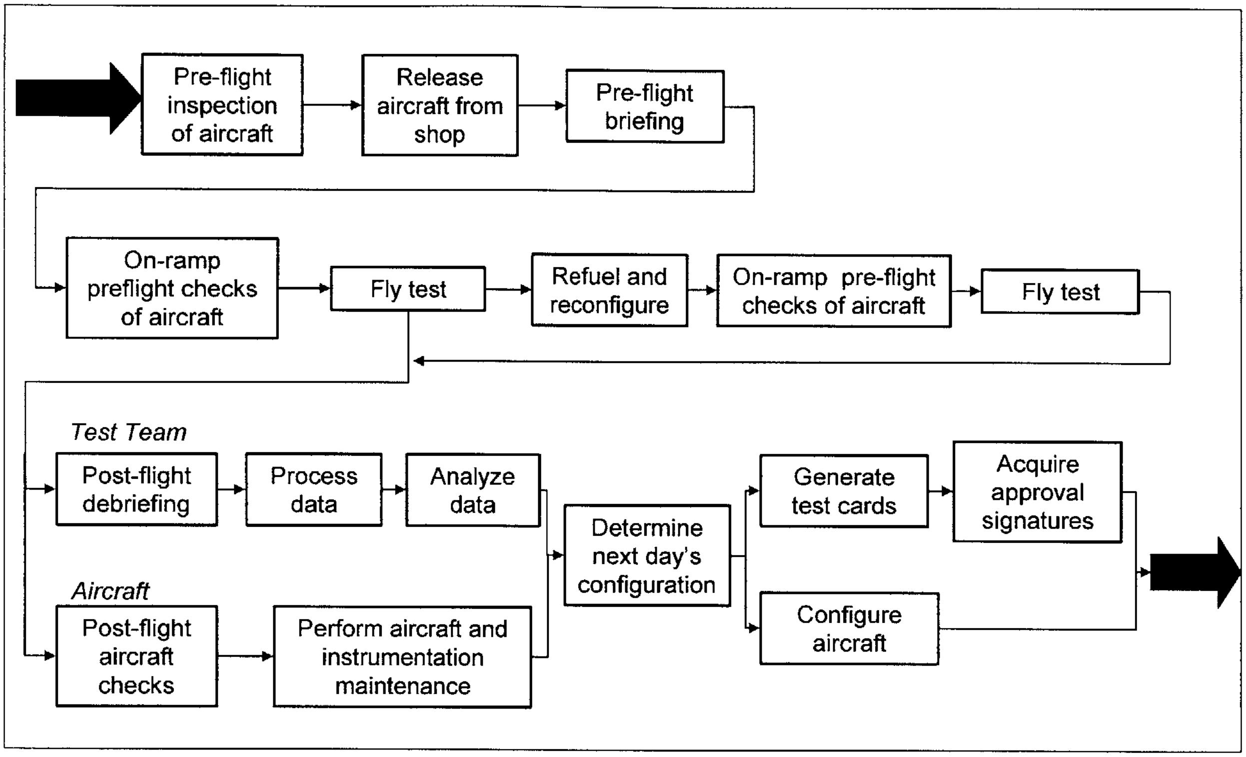
The duration of the flight is generally dictated by the fuel capacity of the aircraft. Test programs with aggressive test rates often return to base to refuel. If a different configuration is desired for the next flight, the ballast loading may be adjusted during this layover. Military aircraft with mid-air refueling capability may be restricted by crew fatigue, aircraft configuration, maintenance, and range issues.

Upon completion of the day's flight(s), the test team reconvenes for a post-flight debrief to review problems with the aircraft and any other significant events of the test. The aircraft is returned to the shop for post-flight checks to ensure integrity and functionality and any required maintenance is immediately begun. Likewise, any piece of instrumentation or equipment necessary for the next flight is inspected and maintained. Quite often all test equipment discrepancies and maintenance is worked by the 2nd and 3rd shifts to be ready for the next day's flight. As part of the inspection, the data tape is removed from the aircraft for processing. Once in a proper format, the data is passed on to the engineers for analysis.

Meanwhile, the engineering staff turns their attention to finalizing the details for the next day. The analysis and operations engineers work together to establish the desired configuration for the next flight. Sometimes the results of the day's test are necessary to plan, while other times the plan can be generated independently. Once the configuration is in place, the operations engineers can begin writing the next day's test cards, the detailed flight plans, and pass them on to the appropriate level of management for approval.

The operations engineers next provide the shop and the instrumentation group with the configuration specifications. The shop proceeds to load the ballast and the instrumentation engineers configure the instruments. They download a series of programs specific to the next flight from the mainframe and upload them onto the aircraft instrumentation. Finally, they perform the mandatory pre-flight inspection. Upon completion, the aircraft is ready for the next day of tests.

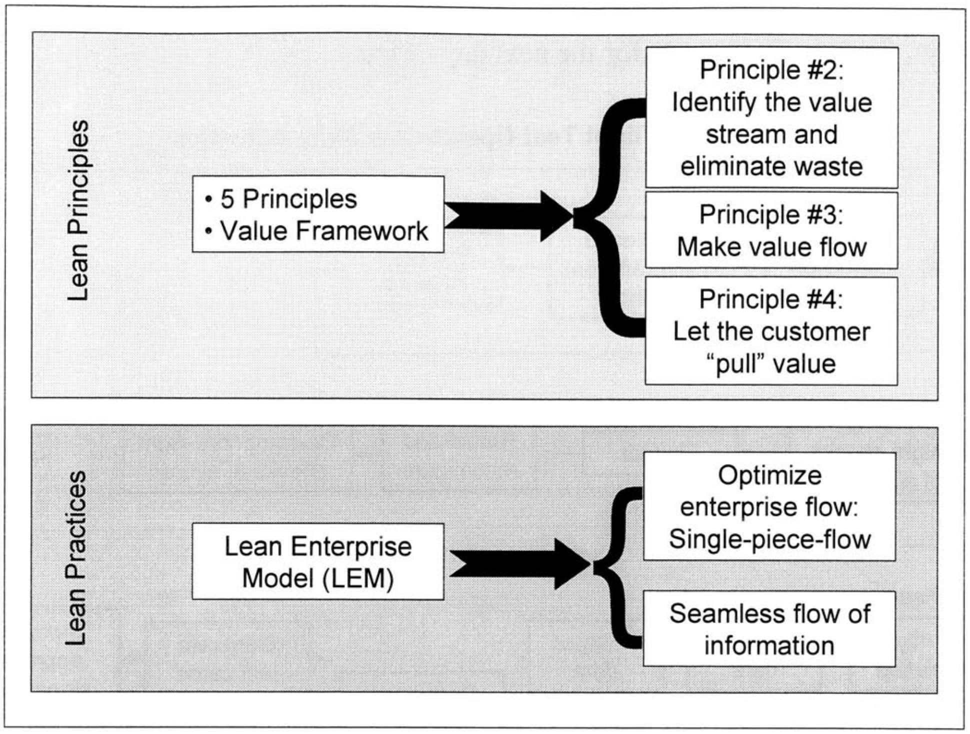
Figure 5-1 Flight Test Operation's Daily Activities



5.2. Lean Principles and Practices Identified in Use

Many of the programs studied employed practices in their daily flight operations which were consistent with lean thinking. The principles and practices identified in use during the case studies are summarized in Figure 5-2. Examples of how they were used follow.

Figure 5-2 Lean Principles and Practices Identified in Flight Operations



Eliminate Waste: Generate Test Cards

Drafting test cards is an important part of the flight testing process because sequencing of test points affects the amount of flight time spent adjusting altitudes and airspeeds. One of the programs studied used a flight card database loaded with all of the test requirements and high-level plans to expedite the writing of test cards and flight reports. This system minimized the amount of non-value-added time spent typing text and allowed the flight test engineers to focus on other valuable activities.

Make Value Flow: Pre-flight Inspection

The instrumentation engineers, in one of the cases studied, would spend several hours during the pre-flight inspection checking the output of each and every instrument to be used during the test. Although this was a tedious and lengthy process, instrumentation was very rarely a problem during flight. The instrumentation group was, in essence, doing their part to enable the flow of value through the highest valued part of the value stream: the time when the aircraft is in flight.

Let the Customer "Pull" Value: Reduce and Analyze Data

Historically, data reduction has been a very time consuming process. One of the programs studied used the concept of "pull" to cut down on wasteful "over-processing". The processing of information off of the data tape would commence with delivery of the list of required data from the analysis engineers, ensuring that only data that was to be used was reduced.

Optimize Enterprise Flow: Reduce and Analyze Data

Under the lean concept of single-piece-flow "a piece travels uninterrupted through all processes needed to complete the part" (Murman 2002). This is an effective way to minimize work-in-progress, improve the quality of the parts, and respond more rapidly to the pull of the customer. Single-piece-flow emerged as an alternative to the mass production philosophy of batch-and-queue, whereby one process is performed on all of the pieces in a batch before they moves on to the next step.

In flight testing, the "parts" are the test points written on the test cards and the processes necessary to complete them include both flying the test and analyzing the data generated. One method for doing this is to fly a series of test cards for several days before pausing to analyze the data collected. This method would be considered batch-and-queue. The flutter group of one of the programs studied derived much benefit from using the alternative strategy of single-piece-flow during flight regimes on the edge of the flight envelope. They would fly a set of test points one day, analyze the data from the flight the next day, and fly again the third. A test was not performed until analysis of the data from the previous test was completed and the flutter boundaries were well understood. This allowed enough time to thoroughly analyze the data and construct the next test sequence, enhancing the safety of the flights. As a side benefit, the extra day afforded ample time for maintenance, keeping the aircraft at a high readiness rate.

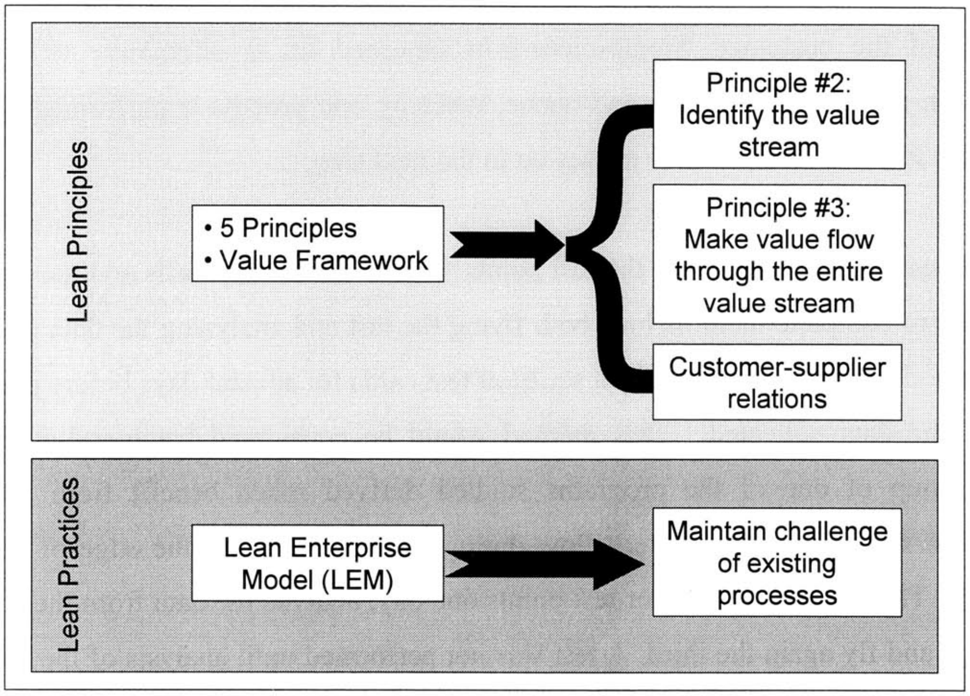
Seamless Flow of Information: Reduce and Analyze Data

The integration of data from ground vibration tests and flutter flight tests allows engineers to update their theoretical model and better predict the flutter margin of the aircraft. One of the programs studied acquired software capable of integrating data from the ground and flight tests, a previously cumbersome and challenging task. Not only did the tool save the engineers time combining the data, the seamless flow of information between the two tests added value by expanded the analysis capability of the engineers.

5.3. Opportunities for Lean Thinking

Although lean thinking was employed to some extent in the programs studied, they also exhibited further opportunities for lean implementation. This section presents examples observed on the case studies of how the lean principles and practices summarized in Figure 5-3 may be applied to future flight operations to improve efficiency.

Figure 5-3 Lean Principles and Practices that could be Applied to Flight Operations



Maintain Challenge of Existing Processes

Before implementing any process improvements, an organization should first assess the sources of its biggest problems. It makes little sense to spend a considerable amount of time improving an activity that has only a minor impact. The research uncovered very little evidence that such data is being gathered and analyzed. This presents an opportunity for improvement. Two of the cases studied, however, did have some useful data available. Analysis of this data produced an interesting insight shown in Figure 5-4 and

Figure 5-5: A minority of the delays incurred in flight testing actually occur during the flight.

Figure 5-4 Sources of Lost Time

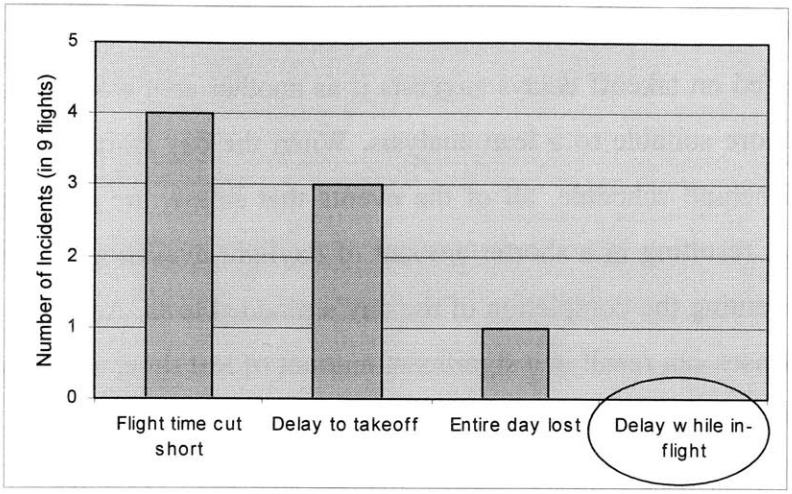
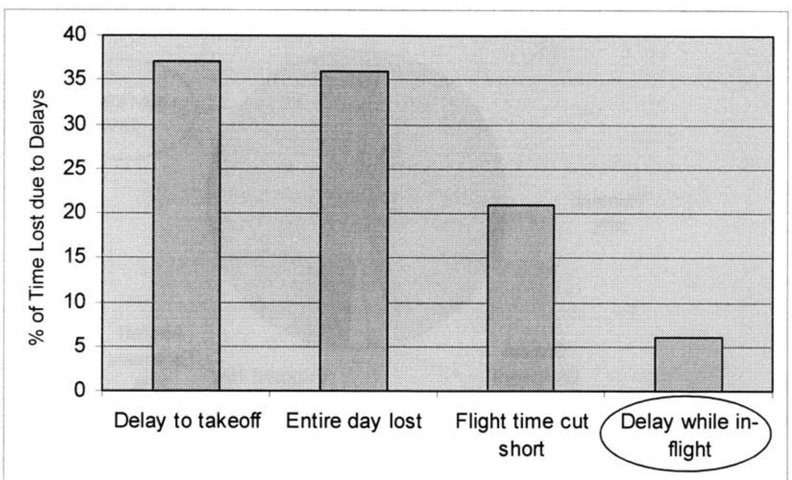


Figure 5-5 Sources of Lost Time



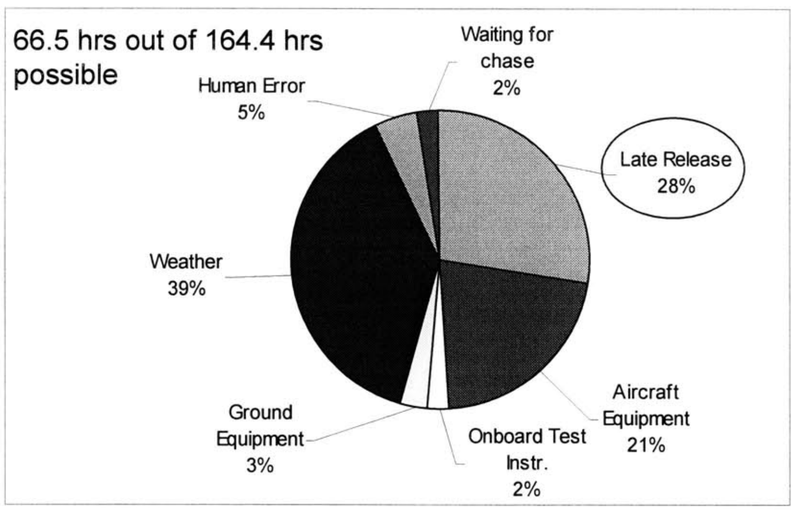
This data suggests that the individuals involved in the flight test groups are good at their jobs: performing flight tests on aircraft. The time when the aircraft is flying is well-planned and efficient, making good use of the costly flight time. Improvements should thus focus on the other aspects of flight testing!

The problem of flights being cut short or cancelled is one area that exhibits potential benefit from improvements. The reasons for these problems include the aircraft malfunctioning or breaking, instrumentation breaking, and bad weather. Since these problems likely do not stem from ineffective processes, the most insight that lean thinking can offer is to keep detailed metrics on the sources and impacts of the problems to know where to best focus improvement efforts.

Identify the Value Stream and Make Value Flow

The data collected on takeoff delays suggests it as another area warranting examination, one which is more suitable to a lean analysis. When the day starts off with an aircraft being released behind schedule, all of the events that follow are affected. The takeoff time is delayed, resulting in a shorter amount of daylight available in which to test and potentially preventing the completion of the day's planned tests. As shown in Figure 5-6 late aircraft releases can result in a significant amount of lost time, approximately 11% of the total test time in the period studied!

Figure 5-6 Sources of Lost Time



A delay to takeoff is analogous to a machine on the factory floor waiting for an input part. The machine and its worker(s) sit idle because a previous step was delayed. Similarly, the test team cannot perform their task because something or someone was not ready.

A lean factory addresses this problem by examining the entire value stream to identify and eliminate the root causes of delays. Testers, however, are typically trained to focus on improving efficiency on only a small part of the value stream, the steps from takeoff to landing. To significantly impact the program's overall efficiency, it is imperative that they too examine the entire value stream. To assist with the analysis, formal value stream mapping techniques have been developed for factory operations (Rother 1999). The following example shows how such techniques could be adapted for flight test operations.

One possible cause of late releases is operations engineers changing the desired flight configuration after it has already been posted. When arranging the details for the next day, they occasionally find problems with critical elements of the plan. For instance, an instrumentation rack intended for use during the flight may not pass the ground inspection because it is not properly calibrated or an avionics software package has not been validated and verified in time for installation on the aircraft. So as not to waste the following day, test plans are rewritten to perform a different test that uses functioning equipment. If the shop and instrumentation engineers have left for the night, the configuration must be adjusted the next morning, likely resulting in a late release.

If testers were to examine a value stream map of their daily activities as shown in Figure 5-7, it would become evident that the configuration for the next day was being planned before the status of the equipment required for the test was verified. Reordering of the activities in the value stream as in Figure 5-8 would likely alleviate the problem, but may create other problems. For example, if the equipment inspection is too time-consuming or broken equipment is common, instrumentation engineers and maintainers may have to wait for the configuration requirements for extensive periods of time.

Figure 5-7 Value Stream Map: Current State

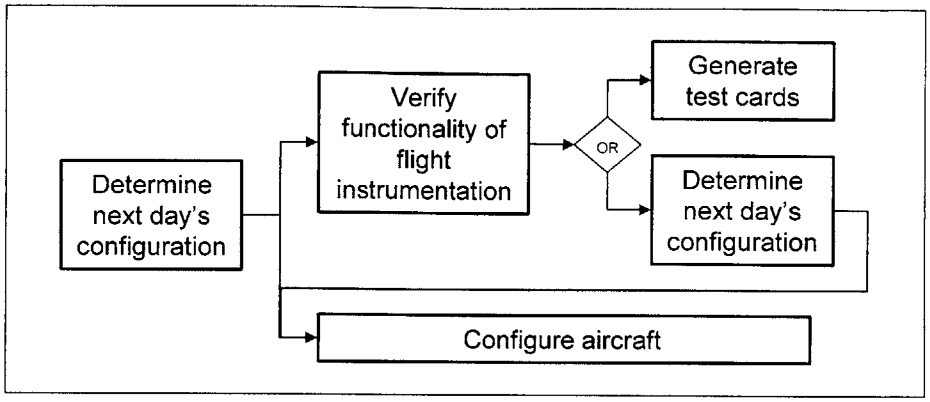
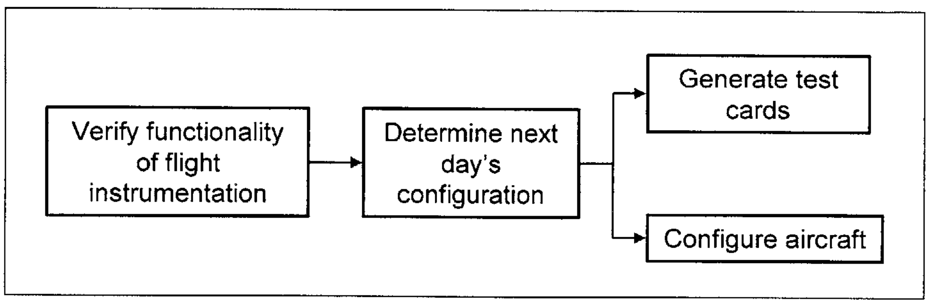


Figure 5-8 Value Stream Map: Future State

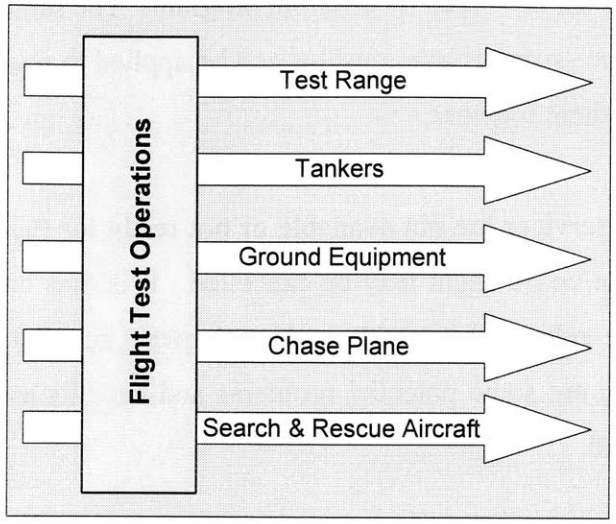


To truly eliminate the problem, value must be made to *flow* through the value stream. If equipment checks require too much time, they should be performed earlier in the day or week. If that is not the problem and instead broken equipment is continually stalling the process, the organization should invest in more reliable components or reduce the time between regularly scheduled inspections to ensure that the assets are maintained at high readiness rates.

Factory operations have been greatly improved by using value stream analysis based upon measured data for the "as is" situation. It is not uncommon for a 50% or more improvement to be realized with little expenditure of resources (Murman 2002). The use of such techniques as discussed above may yield similar improvements in flight test operations and should thus be explored.

Flight Test Support Services

Figure 5-9 Flight Test Support Services



Once the processes within the walls of the factory have been streamlined, other sources of inefficiencies often become evident. Historically, one of the greatest influences on the manufacturing line has been suppliers. Having an efficient process by which to assemble products is not enough to guarantee seamless operations. All of the materials used in the assembly process must be available when they are needed, the well-known concept of Just-In-Time. If a supplier delivers a critical component late, the entire operations of the factory may be stalled.

Just like a factory, a flight test organization does not operate in isolation. It too has critical suppliers, also known as support functions; the main difference is that they provide services as opposed to goods. Examples of support functions include test ranges, ground equipment, fuel tankers, chase planes, and search and rescue capabilities. Some of these resources are external to the company developing the aircraft and can be considered suppliers in the traditional sense; funds are exchanged between the testers and the providers. Test ranges often fall into this category. Whenever flight testing is performed at a facility outside of a company's grounds, an operating fee is usually incurred. Suppliers internal to the company are better categorized as shared services, capabilities which belong to a company but must be shared between different organizations or programs. No funds are exchanged between a flight test group and a shared service. Ground equipment usually falls into this category. Most companies sustain only one set of equipment which must be shared by different programs. The same basic lean principles that pertain to customer-supplier relationships can be applied to shared services, thus this section will consider them together.

If any of the critical services are not available or not ready for the test, the takeoff time will be delayed or the entire flight may be cancelled. It is thus crucial to establish and maintain cooperative relationships with each and every supplier necessary for flight operations. Following are some potential problems and benefits associated with each of the suppliers identified.

Test Range

The policies and procedures at a test range can often have a tremendous impact on the efficiency of a test program. The good relationship that one of the case studies enjoyed with their host base made it possible for them to fly sorties on weekends. This additional flight time allowed them to recover from any schedule slippages incurred during the week.

Test ranges can also adversely affect a program. One of the cases studied experienced significant delays due to limited manpower and bureaucracy at the test site. For example, one day when the aircraft was on the runway ready to go, a radio broke. The only person capable of fixing it was unavailable for the day so the flight was cancelled. A well-planned program can avoid problems due to single-point failures through redundancy of critical resources. It is often more cost-effective to support duplicates of critical equipment and skills then to lose test time when they are inoperable or unavailable.

Ground Equipment

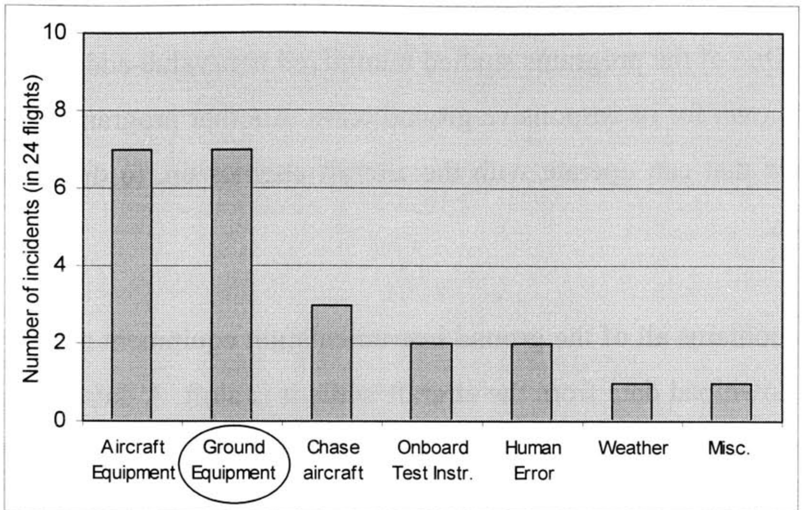
Some of the ground equipment necessary to support flight testing is out of the control of the flight test organization. Examples include ground refueling equipment and telemetry rooms (TM), also referred to as control rooms, both of which are managed by the host base.

The time required for refueling an aircraft between flights depends solely on the logistics at the airfield. One of the programs studied minimized non-value-added time by refueling at an airfield known for its responsive ground crew. Another program used a "hot-pit", a refueling device that can operate with the aircraft engines on, to dramatically decrease turnaround time.

The TM room contains all of the ground instrumentation equipment necessary to monitor the flight and download data from the aircraft while it is aloft. A data stream is sent from the aircraft to an antenna on top of the TM room. For larger ranges, the data may be relayed off of a local ground station through a satellite to the TM room. Some programs telemeter data throughout the entire test program, others only during hazardous testing such as flutter, and other not at all. Problems with TM rooms include incompatibility with the aircraft and loss of signal. Compatibility problems arise when the aircraft and TM room are loaded with different versions of the necessary software. This situation is avoidable and can be eliminated with proper control of the software distribution process. The loss of signal is a technical issue and requires a technical, rather than a process solution.

The TM room was a frequent source of takeoff delays in the data gathered from one of the cases as shown in Figure 5-10. Most of the problems with the room could be solved within 15 minutes. Approximately once a month a quick solution was not evident and a different room had to be used. The changeover would generally take between 20 and 40 minutes. As the length of the delay increased, so did the probability of missing the designated flight window and having the flight cancelled.

Figure 5-10 Sources of Lost Time

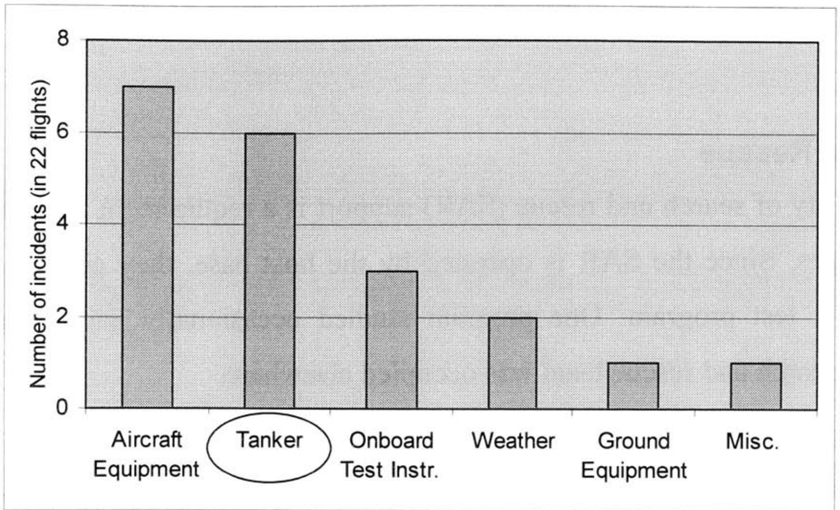


Tankers

Mid-air refueling capabilities allow military aircraft to save a considerable amount of non-value-added time. One program estimated that the time to return to base, refuel, and resume testing was between 45 and 60 minutes. With standard tanker support, both the test aircraft and chase plane could refuel and be ready to continue testing in less than 20 minutes. Tankers with the capability to fly to higher altitudes were able to further reduce this time by minimizing the vertical distance that the test aircraft would have to travel from its test altitude.

Tanker aircraft are provided by the host base and other nearby military installations. Occasionally tankers are not available to support flight test because they are down for maintenance or supporting another mission. The loss of tanker support was a frequent source of lost time in the data analyzed from one of the programs as shown in Figure 5-11.

Figure 5-11 Sources of Lost Time



Chase Plane

A chase plane provides real-time visual insight into the current state of the test aircraft. The purpose of the chase is to keep an eye on the test aircraft during flight to ensure that everything looks normal. Sometimes it is also used to verify the airspeed of the test aircraft. Most chase planes are small and accommodate two people, the pilot and either a photographer or a flight test engineer. Some test programs use a chase on every flight; others only during hazardous testing, such as flutter, where pieces of the aircraft can potentially fall off.

Testers on one of the studied programs cited the chase plane as a continual source of delays. Since the chase plane was smaller than the test aircraft, it would have to land several times during a test to refuel. Sometimes the test aircraft could continue on with more benign test points while the chase plane was on the ground; other times the chase plane was crucial and testing was suspended until it returned. Occasionally, refueling would take so long that the test plane would land with the chase plane and wait for it on the ground.

Another test program revealed additional adverse impacts of the chase plane. Occasionally the test aircraft was sitting on the ground with its engines running, ready to fly, when a problem was discovered with the chase plane. Sometimes a repair could be performed on the ramp; other times another chase plane had to be used. As mentioned previously, a longer delay increases the chance of missing the designated takeoff window.

Search and Rescue

The availability of search and rescue (SAR) support is a requirement to fly test missions at some ranges. Since the SAR is operated by the host base, they are not permanently assigned to a test program. One program studied occasionally had to cancel flights because the search and rescue team was occupied elsewhere.

The lean approach to establish a smooth flow of products and services between customers and suppliers is to develop strategic contractual relationships which help suppliers grow their capabilities. Instead of carrying on the traditional arms-length relationship, suppliers are looked upon as valued members of the product team. Customers share privileged information such as business strategies and work together with suppliers to develop potential pricing arrangements which often include shared cost savings. Strategies such as these could be used with the flight test organization's external suppliers to enable the availability of critical resources.

A similar approach can also be used to improve relationships with internal suppliers, or shared services. In place of contractual agreements, flight test organizations and shared services should work together to develop a common lean vision. Since flight test organizations do not have the option to use another provider, there is less incentive for shared services to improve, making this a more difficult challenge. It is thus important to establish open and honest communication as well as mutual trust and commitment to a common goal.

5.4. Lean Practices for the Flight Test Organization

Although good relationships with suppliers are crucial for lean flight test operations, there are many other required elements. The most important is that the flight test organization be lean. Returning to the factory example: the manufacturing line can have the most efficient assembly process, but how lean can the line be if factory regulations require it to stop every hour for inspection or to change their process each day?

The Lean Enterprise Model (LEM) defines overarching practices for a lean organization. Broadly, the practices have been divided into two groups: human-oriented practices and process-oriented practices (Murman 2002). The following section discusses observations from case studies that correlate with the LEM, as well as potential applications of LEM practices.

Human-Oriented Practices

Relationships Based on Mutual Trust and Commitment

> *"Establish stable and on-going cooperative relationships within the extended enterprise, encompassing both customers and suppliers"* (Murman 2002)

One of the programs studied benefited from a good relationship with one of their vendors. When a piece of instrumentation was found to be defective, the vendor was eager to resolve the problem quickly. Their prompt response helped minimize the impact of the broken equipment on the test program.

Evidence of this practice was also witnessed on another case study. Good relationships with the people at the oversight agency were an important aspect of the program. Their commitment to reviewing data in a timely manner allowed the program to run smoothly.

Make Decisions at Lowest Appropriate Level

> *"Design the organizational structure and management systems to accelerate and enhance decision making at the point of knowledge, application, and need"* (Murman 2002)

Making decisions at the lowest possible level proved valuable to one of the programs studied. Upper management did not interfere with day-to-day activities, but instead allowed test planning to be performed at the test conductors' level. In another program, the number of signatures required on test plans was based on the risk level of the testing, minimizing the number of unnecessary reviews. Conversely many programs require too many levels of management and customers to sign off, a timely and burdensome process.

It is difficult for commercial programs to implement this practice during certification testing, because every test procedure has to be approved by the FAA. There exists a handbook, known as the Advisory Circular, which outlines all of the permitted test procedures. Test organizations are not required to use these prescribed techniques; however, if they wish to use a different method, it has to be approved by the FAA. The Designated Engineering Representatives (DERs) with in the company do not have the authority to approve different techniques. Since this is a relatively involved process, most groups simply choose to follow the Advisory Circular despite the fact that the test team may have knowledge of better, faster, and cheaper ways to perform many tests.

Optimize Capability and Utilization of People

"Assure properly trained people are available when needed" (Murman 2002)

Having enough quality, experienced people is important to every test program. Testers on case studies with successful programs cited this attribute as a key element of their organization. Not surprisingly, testers on programs that struggled mentioned the lack of experienced personnel as a key weakness. One program cited budget cutbacks as the reason for this deficiency: "It's easy to fire people to balance the budget, but it hurts the company in the long run." Another program admitted that their organization had simply lost its capability. It had been quite a while since they had performed such a major developmental program and the personnel did not have the proper experience, adequate planning abilities, and training to accomplish the program without difficulty.

Proper training and support of personnel in the oversight agency is just as important. One of the case studies attributed the frequent changes in test requirements to the limited experience of the people in the oversight group. Additionally, the fact that the office was understaffed and overloaded caused many delays to the test program.

Military oversight agencies are especially vulnerable. One of the testers interviewed discussed the impact:

> *"One of the biggest concerns that we have in getting good results (not just in the flight test arena) on the projects that we work on, is getting and keeping good*

people. Civilians provide a long-term "corporate" memory for the organization but they only represent roughly half of the organization. The other half of the personnel in the office are Military Officers. Our Military team-mates usually come in and stay in the organization just long enough to feel comfortable (2-3 years) but never long enough to have any meaningful impact to the long-term output of the organization."

This problem is a byproduct of the structure of career paths in the military. For the officers assigned to these oversight agencies, their term there is a stop along the way to becoming a program manager. There is no option for them to pursue technical career paths which would allow them to remain in the test organization for an extended period of time.

Process-Oriented Practices

Assure Seamless Information Flow

"Provide processes for seamless and timely transfer of and access to pertinent information" (Murman 2002)

One of the programs studied was able to enhance information flow by collocation of a small team from the oversight agency at the contractor's site. This proximity allowed them to work on issues as they arose and to serve as a vital link between the customer, the oversight agency, and the contractor.

Another program had an excellent idea for implementing this practice. The flight test hangar was going to be built with enough space to permanently station all of the integrated product team (IPT) leads and rotate in various IPT groups as their system was being tested. The collocation of the design team and test teams would have greatly enhanced communication between them, potentially cutting down on rework and cycle time. Unfortunately, management did not approve enough funding for this project and the hangar was built with only enough room for the personnel directly involved in day-to-day flight operations.

The impact of intangible variables such as face-to-face communication was realized in another area by Lockheed Martin Aeronautics Company in the development of their F16

Build-To-Package Support Center (Murman 2002). When a problem is found on the production line, changes must be made to the official product definition known as the Build-To-Package (BTP). Any change must pass through the hands of numerous design and manufacturing engineers and can take a considerable amount of time. Delays in the process can either hold up production or allow defective parts to flow down the line, incurring expensive rework later on. To expedite changes to the BTP, the company created a facility *on the factory floor* where all of the individuals involved in the process could gather and work together. The cycle time involved with the change process dropped by 75% and all of the delays formerly associated with changing the BTP were eliminated.

The company in the aforementioned flight test hangar example passed up the opportunity for improving efficiency by not properly realizing the value of collocation. Perhaps if they had been made aware of the impact that collocation has had on other companies such as Lockheed Martin, they may have decided otherwise.

Maintain Challenges to Existing Processes

> *"Ensure a culture and systems that use quantitative measurement and analysis to continuously improve processes"* (Murman 2002)

Metric-based initiatives were used on two of the case studies to help focus process improvements. A lead operations engineer on one of the programs studied developed a process called "Measuring Operations". At the end of each day, he would get together with the key personnel to assess the amount of time lost due to delays and the source of the problems. At the end of the program, he had a credible database that indicated where the organization should focus improvement initiatives. The success of these initial efforts led to the development of a software tool to aid in the collection of further data.

Another program developed a similar tool to help facilitate real-time implementation of improvement efforts. The "Delay Diary" listed the reasons for major delays and aborts each day. When something arose as a consistent driver of delays, the problem was addressed. For instance, when poor reception between the aircraft and the telemetry room during on-ramp pre-flight checks was identified as the cause of numerous delays, a study was launched to assess the best location for the aircraft to minimize dropouts. An additional benefit of the delay diary was the information that it provided on the performance of the test program. It was used to help plan the future sortie rate and adjust the number of tests to stay on schedule.

Maintain Stability in a Changing Environment

> *"Establish strategies to maintain program stability in a changing customer driven environment"* (Murman 2002)

One program implemented this practice with their philosophy of: "have a plan set early, but be flexible in changing it". Every four to five months the key personnel of the test team and oversight group would gather for an official review to compare progress to the original plan. As data came in and matched theoretical predictions, the oversight agency relaxed the initially stringent test requirements. This process worked well because the environment at the meetings was such that individuals felt they would get what they needed. They did not have to "defend their turf", as one tester put it, because everyone was working towards a common goal.

A lack of stability can be detrimental to a test program. In one of the case studies, pressure from upper management fostered a crisis management mentality. This led to micromanagement of the test program, which generated instability. Since the success of the program was measured by the number of test-hours flown by the aircraft, it was not uncommon for management to walk in on the morning of a test and insist that a longer test be performed. One of the flight testers on the program revealed the impact of this uncertainty in the test schedule: "In flight test, a constant pace is good. If the pace is too slow, the company won't make any money. If it's too fast, things will take twice as long because of the chaos created and the time required to rewrite test cards, locate different instrumentation, and get everyone up to speed."

5.5. Conclusions

Although the focus of flight testing is to determine the characteristics of an airplane and its subsystems in flight, the time when the aircraft is in the air is only a small part of the testing process. As the daily value stream shows, there are many activities that the test group must perform on a day-to-day basis to support the flight, and still more to extract useful information from it. Like a factory floor, the efficiency of the testing operations are greatly influenced by how well these activities work together and how they interact with their suppliers.

Chapter 6. Conclusions, Recommendations, and Future Work

Based on this exploratory study of seven current and recent flight test programs, there is enough evidence to show that the principles of lean thinking can be applied to aircraft flight testing. Research identified several current practices that are consistent with the principles of lean as well as many opportunities for further implementation of lean thinking. The opportunities identified did not involve the elimination of tests or the increase of development risk; instead, the focus was on increasing flight test efficiency through process improvement.

Data has shown that lean thinking has the potential to minimize cost and cycle time in day-to-day flight test operations. However, it is the opinion of the author that improvements upstream in the systems engineering value stream would make a far greater impact on the efficiency of a flight test program. It is not enough to improve the efficiency of individual upstream activities; the interactions between them need to be managed properly. A lean flight testing program is the result of a lean systems engineering process!

The research yielded specific recommendations for organizations seeking to improve their flight testing process:

- Establish a better balance between process improvements and test techniques as part of an overall test and evaluation improvement plan.
- Assess current practices, using the Lean Enterprise Model as a starting point.
- Collect process data on an ongoing basis. In order to improve a process, one must first understand its strengths and weaknesses.
- Share process data, methodologies, and tools among organizations and companies, using LAI or the Society of Flight Test Engineers (SFTE) as a neutral forum.
- Map out the program systems engineering value stream to understand the relationships between activities and eliminate waste.
- Actively manage intersecting value streams such as multiple test aircraft and support services to maximize stakeholder value.
- Adopt the value-creation framework for structured implementation of lean practices.

The research also yielded proposals for future LAI research:

- An in-depth study of fewer aircraft, and perhaps different types of testing, aimed at collecting a larger sample of data. Establish a statistically significant representation of the root causes of delays and quantify potential savings.
- A descriptive study using structured interviews to codify enabling lean practices for flight test organizations.
- An in-depth study of the value identification and value proposition phases aimed at developing structured processes and tools for implementation.
- Incorporate testing and evaluation into the development of lean product development tools.

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APPENDIX A: FLIGHT TEST DELAY TRACKING SHEET

Flight Test Delay Tracking Sheet

Date: ____________
Aircraft #: ____________
Test #: ____________

Engine Start Time: ________
Takeoff Time: ________
Land Time: ________
Engine Shutdown Time: ________

Intended Shop Release Time: ________
Actual Shop Release Time: ________

# of Test Points Planned: ________
# of Test Points Completed: ________

Check all that apply and note time lost

_____ **Test executed as planned**

_____ **Entire flight canceled**
Reason ____

_____ **Start of testing delayed**

Reason		Time Lost
	Late Release	
	A/C Equipment (other than test instrumentation)	
	Onboard Test Instrumentation	
	Ground Test Equipment	
	Weather	
	Human Error (specify):	
	Other (specify):	

_____ **Delay during flight**

Reason		Time Lost
	Late Release	
	A/C Equipment (other than test instrumentation)	
	Onboard Test Instrumentation	
	Ground Test Equipment	
	Weather	
	Human Error (specify):	
	Other (specify):	

_____ **Early termination of flight**

Reason		Time Lost
	Late Release	
	A/C Equipment (other than test instrumentation)	
	Onboard Test Instrumentation	
	Ground Test Equipment	
	Weather	
	Human Error (specify):	
	Other (specify):	

APPENDIX B: KEY FACTS ON AIRCRAFT STUDIED

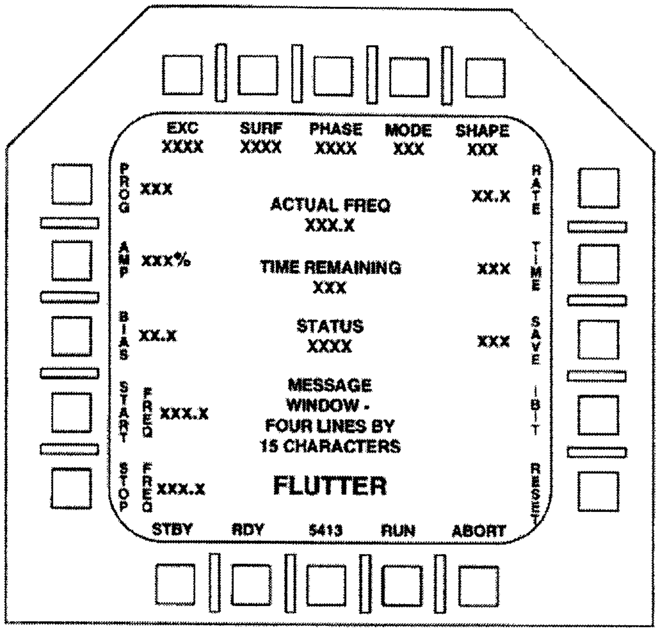
Table 6-1 Key Facts of Aircraft Studied

Aircraft	737-NG	767-400	Hawker Horizon	F-22	F/A-18 E/F	C130-J/ -J-30	T-6A
Nickname	None	None	Horizon	Raptor	Super Hornet	Hercules	Texan II
Company	Boeing	Boeing	Raytheon	Lockheed Martin	Boeing	Lockheed Martin	Raytheon
Type	Twin-Jet Airliner	Wide-bodied Airliner	Business Jet	Air superiority fighter	Multi-role fighter	Tactical transport	Turbo-prop Trainer
Approx. range	1340-3260 nm	5600 nm	3515 nm	N/A	2520 nm	2835 nm	850 nm
Number of passengers	110-162	245-304	8-12	---	---	---	---
Crew	2	2	2	1	1-E 2-F	2	2
1st Flight	2/9/97	10/9/99	8/11/01	9/7/97	11/29/95	4/5/96	12/92
FAA Cert.	11/7/97 – 8/18/98	6/30/00	Anticipated 9/03	---	---	9/9/98	8/99
End of EMD[5]	---	---	---	Anticipated 4/03	4/99	---	---
# a/c in flight test program	10	4	4	9	7	11	5
# flight test hours in program	N/A	~1,150	N/A	N/A	~4,673	~4,300	~1,400
Chase plane	T-38	T-38	Beechjet, Premier, & Hawker 800XP	F-15 & F-16	F/A-18 C/D	C-130J & Citation II	T-6A & Hawker 800 XP
Certification basis	FAA	FAA	FAA	Air Force	Navy	FAA/ Air Force	FAA/ Air Force/ Navy
Test facilities	Boeing Field	Boeing Field	Beech Field	Edwards AFB	Patuxent River NAS	Dobbins AFRB	Beech Field

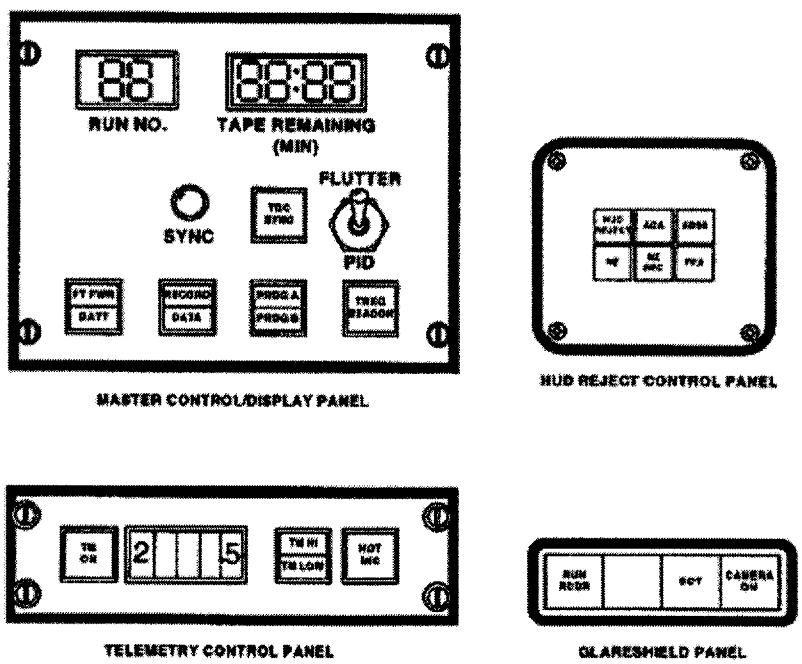
[5] EMD is the Engineering, Manufacturing, and Development phase of military programs. Upon completion of this phase, the aircraft gains the military equivalent of the FAA certification and is authorized to begin Dedicated Operational Testing and Evaluation (DOT&E).

APPENDIX C: FLUTTER EXCITATION SYSTEMS OF AIRCRAFT STUDIED

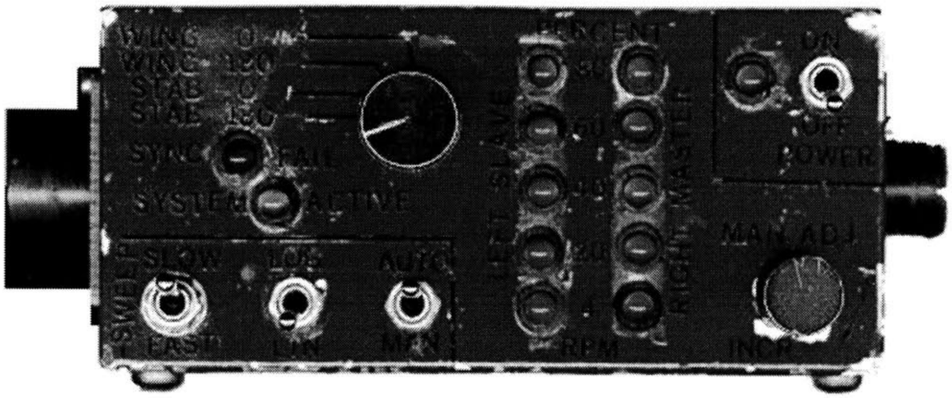
Flutter Excitation Control Unit Display Format (Flutter Mode)



Flight Test Control Panels



Flutter Excitation System Control Head
(Allows the pilot to activate and deactivate flutter exciters



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