Lean Aerospace Engineering

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MIT Ford Professor of Engineering Emeritus

William Littlewood Memorial Lecture

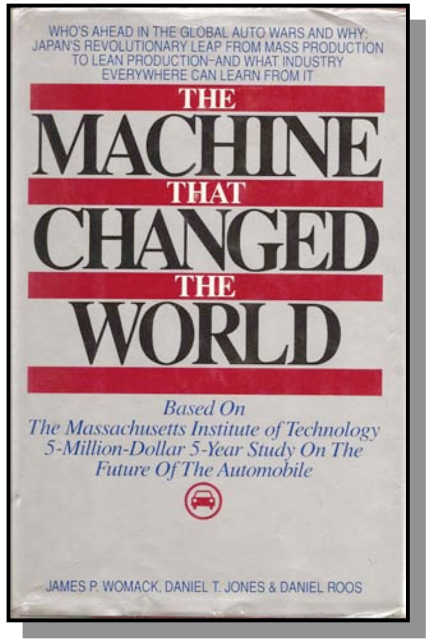
46th AIAA Aerospace Sciences Meeting

January 8, 2008

MIT Studies on Industrial Productivity

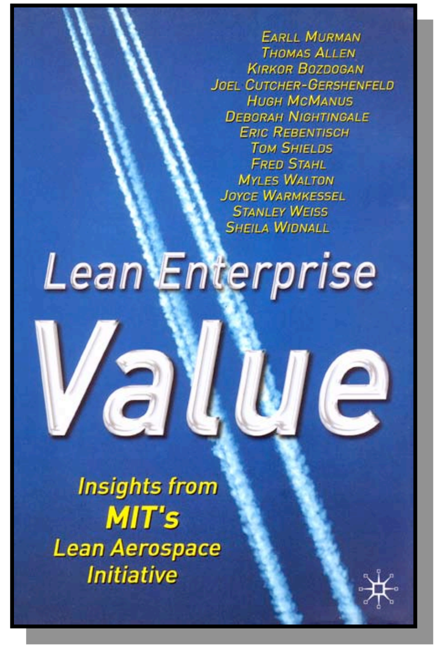
1989

Identified sources of major weaknesses in US productivity, including commercial aircraft & education.



1990

Identified Lean, based upon Toyota Production System, as a successor to mass production.



2002

Translated Lean principles to aerospace context.

F/A-18E/F Super Hornet
"An Evolving Lean Enterprise"

Requirements

- 25% greater *payload*
- 3 times greater ordnance *bringback*
- 40% increase in unrefueled *range*
- 5 times more *survivable*
- Designed for future *growth*
- Replace the A-6, F-14, F/A-18 A/B/C/D
- Reduced support costs
- Strike fighter for multi-mission effectiveness

Program Execution/Outcomes

- Completed on budget - $4.88B
- Completed on schedule - 8.5 years from "go-ahead" to IOC
- Program was never re-baselined
- Aircraft 1029 lbs underweight
- Deemed "operationally effective and suitable" after Operational Evaluation
- Won 1999 Collier Trophy

Air Superiority | Fighter Escort | Reconnaissance | Aerial Refueling | Close Air Support | Air Defense Suppression | Day/Night Precision Strike | All Weather Attack

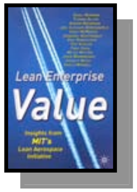
Highly capable across the full mission spectrum

Hypothesis: The application of Lean Thinking principles, practices and tools to *engineering* can lead to superior aerospace product development results - and happier more satisfied engineers.

Littlewood Lecture Outline

- Introduction to Lean Thinking
- Lean Thinking and Aerospace
- Lean Engineering framework
- Tailoring Lean Engineering
- Lean Engineering challenges

Caveat: This talk uses primarily civil aviation examples in keeping with the scope of the Littlewood Lecture. The principles introduced are equally applicable to other aerospace domains, and experience from these domains is included in the body of knowledge used.



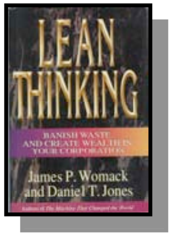
Lean Thinking

Lean **emerged from post-WWII Japanese automobile industry as a fundamentally more efficient system than *mass* production.**

	Craft	*Mass Production*	*Lean Thinking*
Focus	Task	Product	Customer
Operation	Single items	Batch and queue	Synchronized flow and pull
Overall Aim	Mastery of craft	Reduce cost and increase efficiency	Eliminate waste and add value
Quality	Integration (part of the craft)	Inspection (a second stage after production)	Inclusion (built in by design and methods)
Business Strategy	Customization	Economies of scale and automation	Flexibility and adaptability
Improvement	Master-driven continuous improvement	Expert-driven periodic improvement	Worker-driven continuous improvement

Lean thinking **is the dynamic, knowledge-driven, and customer-focused process through which all people in a defined enterprise continuously eliminate waste and create value.**

Source: Murman, E., et al., *Lean Enterprise Value: Insights from MIT's Lean Aerospace Initiative,* Palgrave, 2002.



Five Lean Thinking Fundamentals

- **Specify *value*: Value is defined by customer in terms of specific products and services**

- **Identify the *value stream*: Map out all end-to-end linked actions, processes and functions necessary for transforming inputs to outputs to identify and eliminate waste**

- **Make value *flow* continuously: Having eliminated waste, make remaining value-creating steps "flow"**

- **Let customers *pull* value: Customer's "pull" cascades all the way back to the lowest level supplier, enabling just-in-time production**

- **Pursue *perfection*: Pursue continuous process of improvement striving for perfection**

Source: James Womack and Daniel T. Jones, *Lean Thinking,* Simon & Schuster, 1996.

What Moves In a Value Stream?

In manufacturing… material flows

In design & services…information flows

In human services…people flow

Source: LAI Lean Academy® Thinking Lean Module v6.0

Value Added and Non Value Added

Value Added Activity

Emphasize

- Transforms or shapes material, information or people
- And it's done right the first time
- And the customer wants it

Non-Value Added Activity – Necessary Waste

Minimize

- No value is created, but cannot be eliminated based on current technology, policy, or thinking
- Examples: project coordination, regulatory, company mandate, law

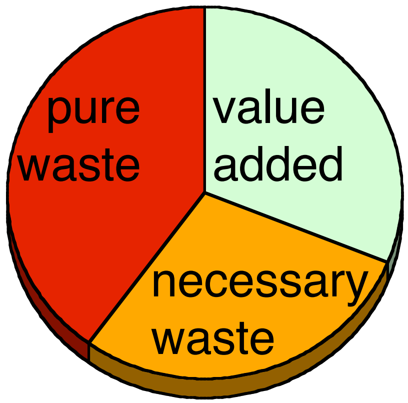
Non-Value Added Activity - Pure Waste

Eliminate

- Consumes resources, but creates no value in the eyes of the customer
- Examples: idle/wait time, inventory, rework, excess checkoffs

Source: LAI Lean Academy® Thinking Lean Module v6.0

Waste Exists in Engineering



- **Effort is wasted**
  - **40% of PD effort "pure waste", 29% "necessary waste"** *(workshop opinion survey)*
  - **30% of PD charged time "setup and waiting"** *(aero and auto industry survey)*
- ***Time* is wasted**
  - **62% of *tasks* idle at any given time** *(detailed member company study)*
  - **50-90% task idle time found in Kaizen-type events**

Source: McManus, H.L. "Product Development Value Stream Mapping Manual", LAI Release Beta, April 2004

Brief History of Lean Thinking in Aerospace

- Aeronautical organizations before about late 1950s exhibited many Lean Thinking behaviors.
- By the 1980s, aerospace was a non-lean craft industry with a mass production mentality
- 1980's - Lean journey begins with Total Quality Management approaches
- 1990 - *The Machine that Changed the World* published
- 1993 - Lean Aircraft Initiative started at MIT
- 1990s - Most aerospace companies implemented some form of lean in manufacturing
- 2000s - Enterprise implementation of Lean, including engineering. Government agencies implement lean

Aerospace lean journey has some déjà vu!

Lean Aerospace Initiative (LAI) Formed in 1993

- Industry
  - Airframe, engine, avionics, missile and space companies
- Government
  - Air Force agencies, system program offices, and headquarters
  - Army, Navy
  - Department of Defense
- Academia
  - MIT - Schools of Engineering and Management
  - Educational Network (2003)
- Lean Advancement Initiative (2007)
  - Members & applications beyond aerospace

A national consortium for research, implementation and diffusion of lean practices

Some Aerospace Enterprise Lean Programs

- **Industry**
  - Boeing - Lean+
  - Lockheed Martin - LM21
  - Textron - Textron Six Sigma
  - Pratt and Whitney - ACE
  - Raytheon - R6σ
- **DoD**
  - US Air Force - AFSO21
  - NAVAIR - AIRSpeed
- **NASA**
  - Faster, Better, Cheaper was not based upon Lean Thinking principles, practices and tools

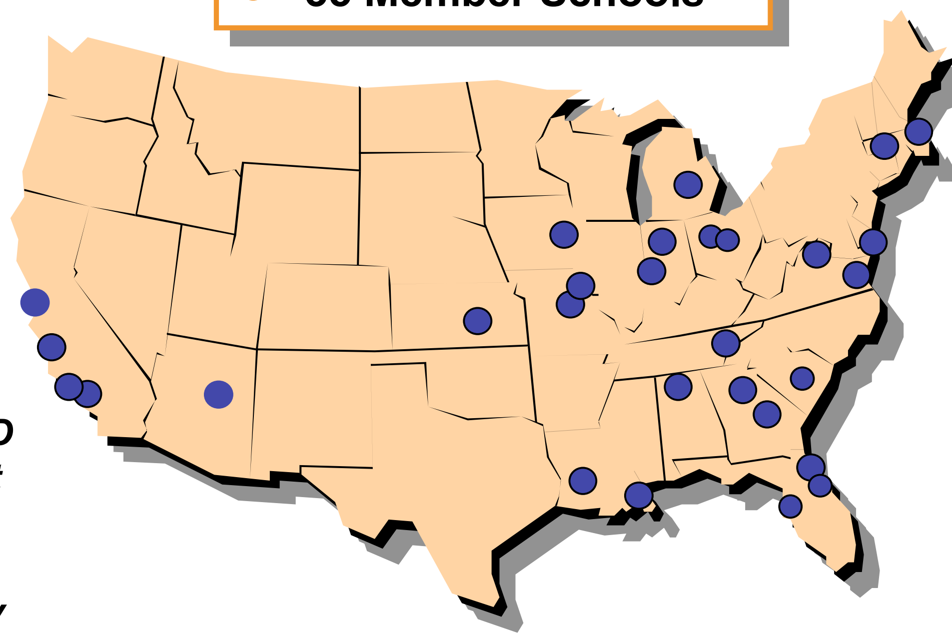
Lean Electronics

Rockwell Collins

The LAI Educational Network

January 2008

● 35 Member Schools



AFIT
AZ State U
Cal Poly SLO
Cranfield (UK)
DAU
Embry-Riddle
Georgia Tech
Indiana State Univ
Jacksonville Univ
Loyola College, MD
Loyola Marymount
Macon State Col
MIT
Old Dominion Univ
North Carolina State
Purdue Univ
St. Louis Univ, MO
San Jose State Univ

3 UK ● ● ●

2 Mexico ● ●

Tecnológico de Monterrey (MX)
Universidad Popular Autónoma del Estado de Puebla (MX)
U of AL, Huntsville
U of Iowa
U of Michigan
U MO Rolla
USC
U of Bath (UK)
U of South Florida
U of Tenn, Knoxville
U of New Orleans
U of Louisiana, Lafayette
University of VA
U of Warwick (UK)
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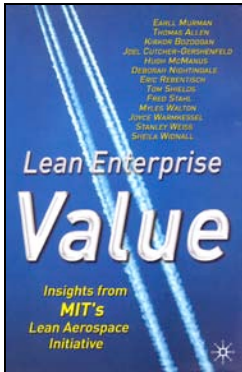
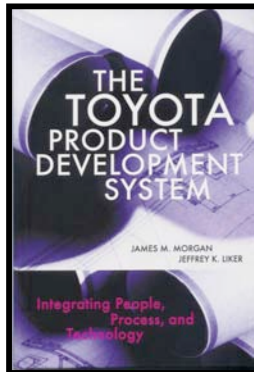
Wright State Univ
WPI

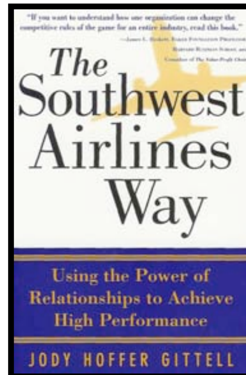
LAI Lean Academy™ **Introductory Course**

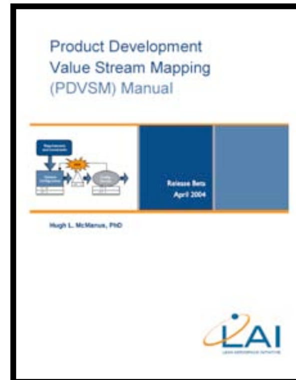
Lean Engineering Framework Based On…

Books

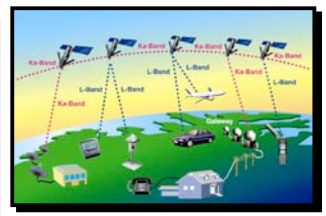








Case Studies



Communities of Practice

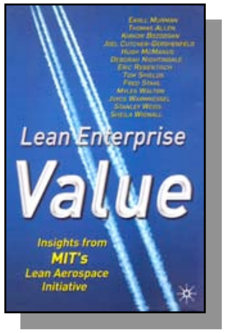
LAI MIT
LEAN ADVANCEMENT INITIATIVE ™

INCOSE
International Council on Systems Engineering
Lean Systems Engineering Working Group

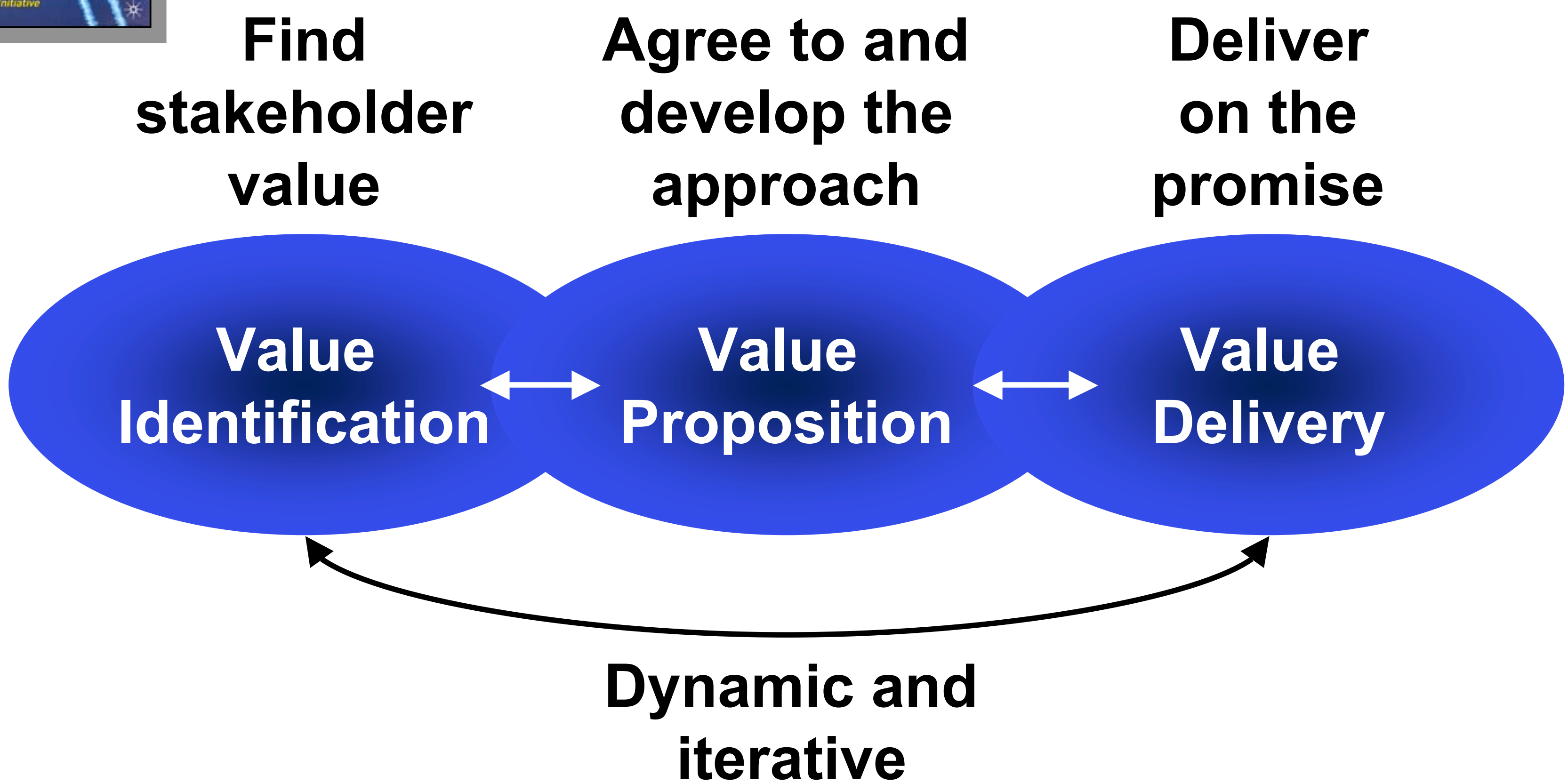
EdNet LAI
EDUCATE MOTIVATE INNOVATE ™

Synthesized from observations of practice

Source citations given in written paper



Value Creation Framework



Do the Right Job & Do the Job Right

Source: Murman, E., et al., *Lean Enterprise Value: Insights from MIT's Lean Aerospace Initiative,* Palgrave, 2002.

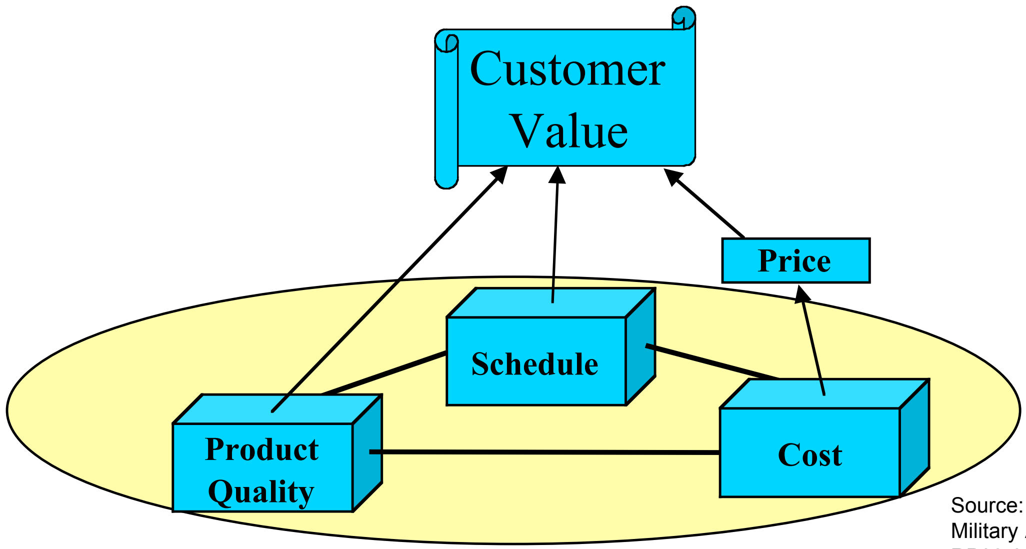
Lean Engineering Framework

Value Identification | Value Proposition | Value Delivery

- Capable *People*
  - Engage Customer Early & Often
  - Organize for Lean Behavior
  - Strive for Perfect Coordination
  - Pursue Excellence and Continuous Improvement
- Effective & Efficient *Processes*
  - Implement Integrated Product and Process Development
  - Design for Lifecycle Value
  - Assure Smooth Information Flow
  - Optimize Process Flow
  - Manage all Risks
- Adaptable *Tools*
  - Utilize Integrated Engineering Tools
  - Employ Lean Process Improvement Methods

Eleven interrelated actionable practices

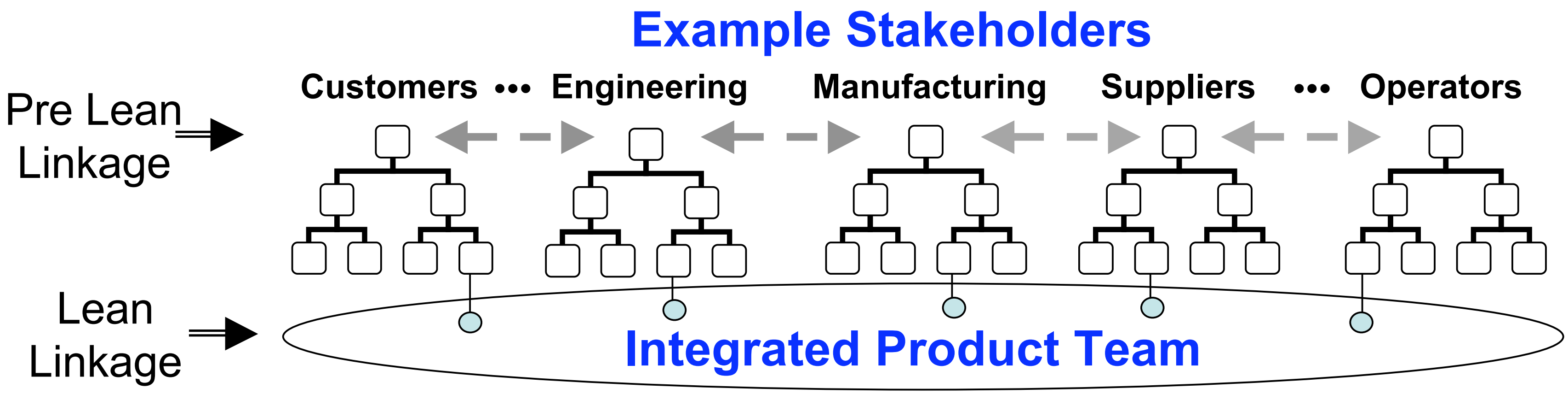
Engage The Customer Early and Often



Source: Slack, R.A., "The Lean Value Principle in Military Aerospace Product Development", LAI RP99-01-16, Jul 1999. web.mit.edu/lean

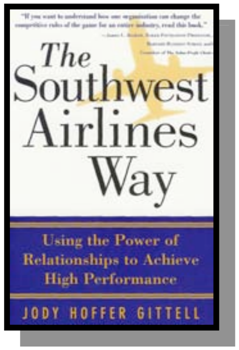
- Identify external & internal customers
- Establish customer value
- *Listen carefully* for customer priorities
- Be willing to challenge customer's assumptions
- Look for unspoken requirements & future needs
- Understand the operational environment
- Involve customer frequently during design & development

Organize for Lean Behavior

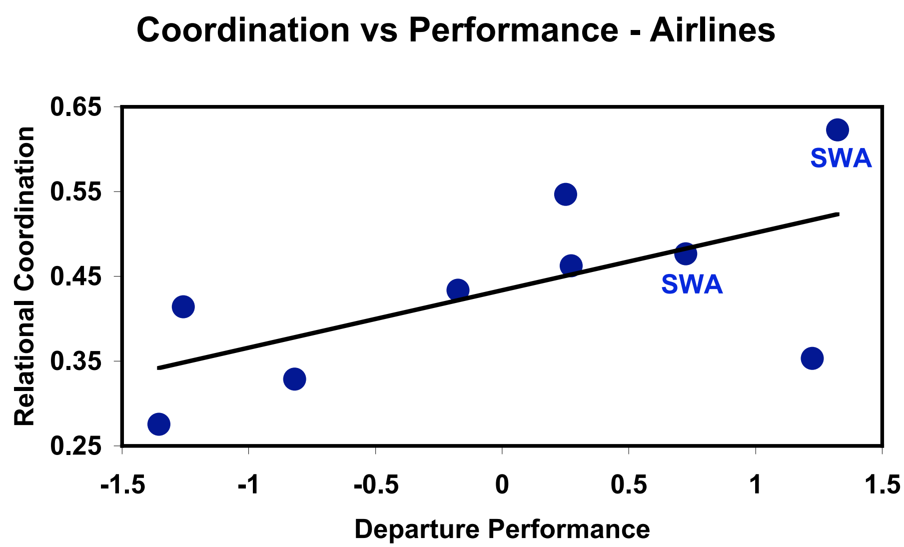


Source: LAI Lean Academy® *People* Module, V6.0

- **Have Chief Engineer integrate development from start to finish**
- **Identify and involve all relevant stakeholders**
- **Use co-located IPTs with capable leaders to balance functional expertise with cross-functional integration**
- **Make decisions at lowest appropriate level with flowdown of Responsibility, Accountability and Authority (RAA)**
- **Integrate suppliers early into design and development**
- **Promote teamwork at all levels**
- **Overcome narrow specialization**



Strive for Perfect Coordination



Source: Hoffer-Gittell, Jody, *The Southwest Airlines Way*, McGraw-Hill 2005

SWA Shared Goals

- Safety
- On-time departure
- Satisfied customer

- **Align organization with shared goals**
- **Develop relationships based on mutual trust and respect**
- **Make processes and activities visible to all stakeholders**
- **Practice open, honest, frequent and timely communication**
- **Use simple, efficient communication techniques**
- **Hire and train employees for communication and coordination**

Pursue Excellence & Continuous Improvement

2007 Welliver Faculty Fellowship Program
Photo provided by The Boeing Company

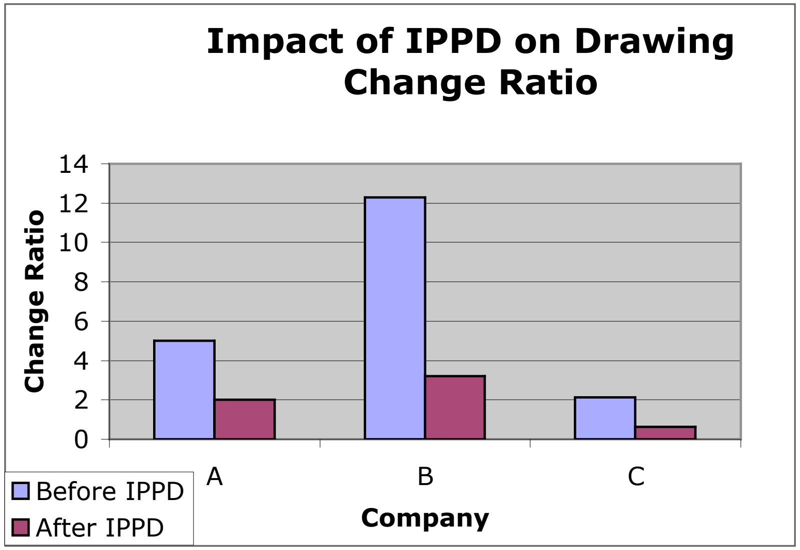
The Boeing Welliver Faculty Fellowship Program

Objective: To provide faculty with a better understanding of the practical industry application of engineering, manufacturing, information technology and business skills.

http://www.boeing.com/educationrelations/facultyfellowship/index.html

- **Develop towering technical competence in all engineers**
- **Get hands-on experience. Go see for yourself - *Genchi genbutsu***
- **Standardize what can be, to free resources for innovation**
- **Share lessons learned across programs**
- **Challenge all assumptions**
- **Treat failure as an opportunity for learning**
- **Continuously improve process and tool capability**

Implement Integrated Product and Process Development



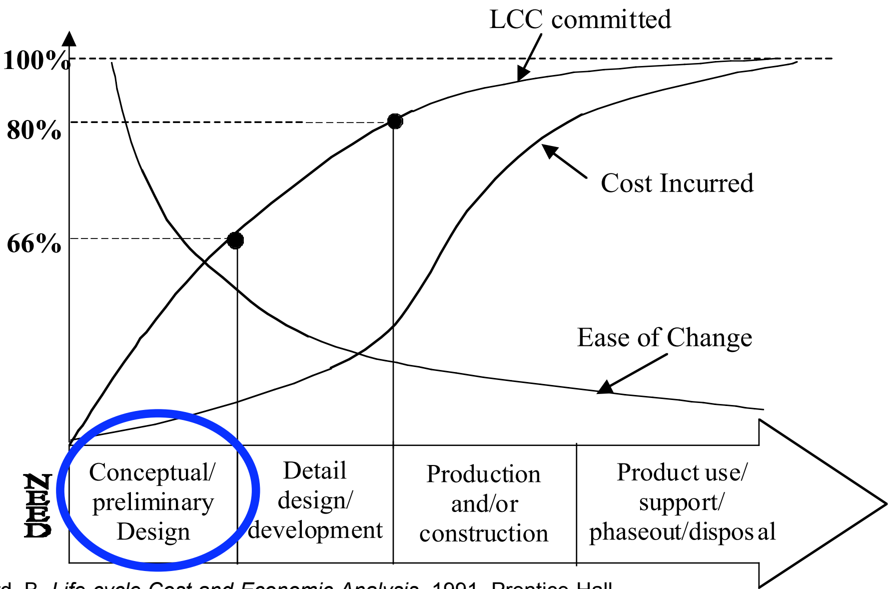
Change Ratio - The average number of changes made to each drawing after it is released by design

Source: Hernandez, C., "Challenges and Benefits to the Implementation of IPTs on Large Military Procurements". MIT Sloan School SM Thesis, June 1995

- **Adopt systems engineering tailored to program**
- **Form Integrated Product Teams (IPTs) involving all relevant stakeholders, including suppliers & regulatory reps**
- **Assure continuity of IPTs during transitions in project phases**
- **Use integrated design tools *adapted* to fit project & people**
- **Exploit rapid and/or virtual prototyping to maximize learning**
- **Track Key Performance Parameter metrics during design, development, production and sustainment**

Design for Lifecycle Value

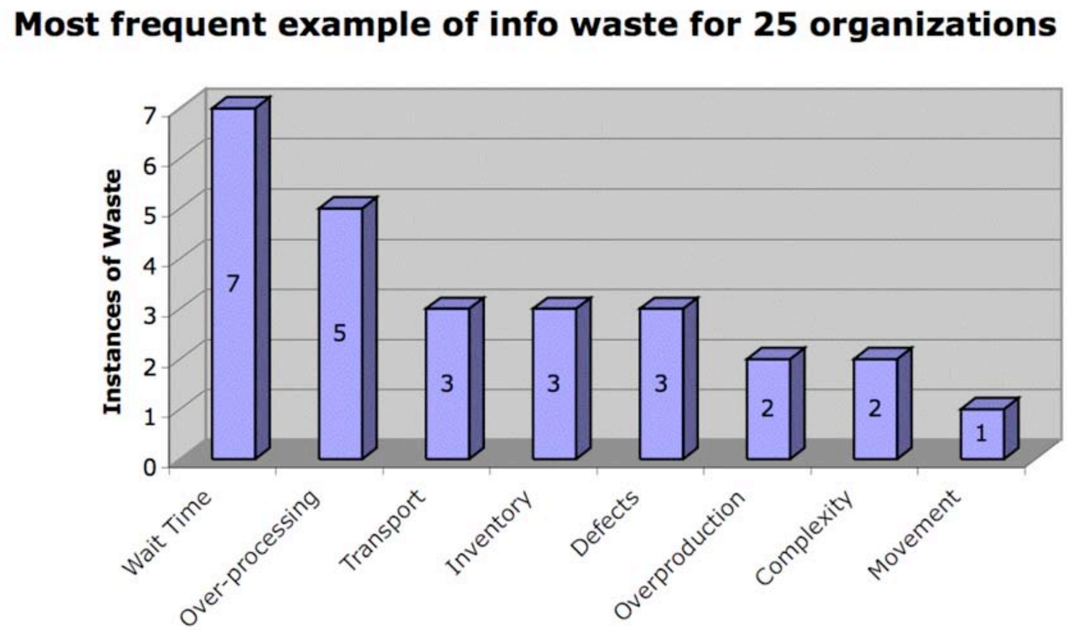
Early decisions are critical!



Source:Fabrycky, W & Blanchard, B. *Life-cycle Cost and Economic Analysis*, 1991, Prentice-Hall

- **Front load the process while maximum flexibility exists**
- **Use system engineering requirements flowdown to Design for X (DFX), where X = safety, quality, environment, production, testing, reliability, maintainability, human factors, operability, support, disposal & lifecycle costs (LCC)**
- **Exploit commonality and design reuse**
- **Design in supply chain strategy**
- **Build in flexibility for upgrade and change during product lifecycle**

Assure Smooth Flow Of Information



Source: Slack, Robert A., "Application of Lean Principles to the Military Aerospace Product Development Process," Masters thesis in Engineering and Management, Massachusetts Institute of Technology, December 1998.

- Align organization with simple visual communication
- Use intranets for ubiquitous access to data and documents
- Employ common or interoperable databases
- Minimize documentation: assuring traceability and visibility
- Co-locate physically or virtually

Optimize Process Flow

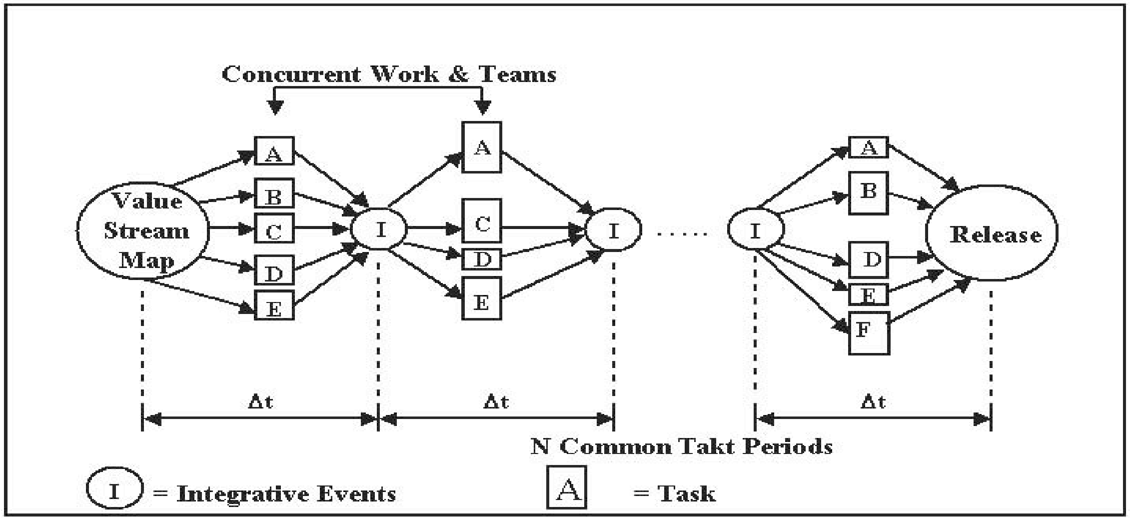
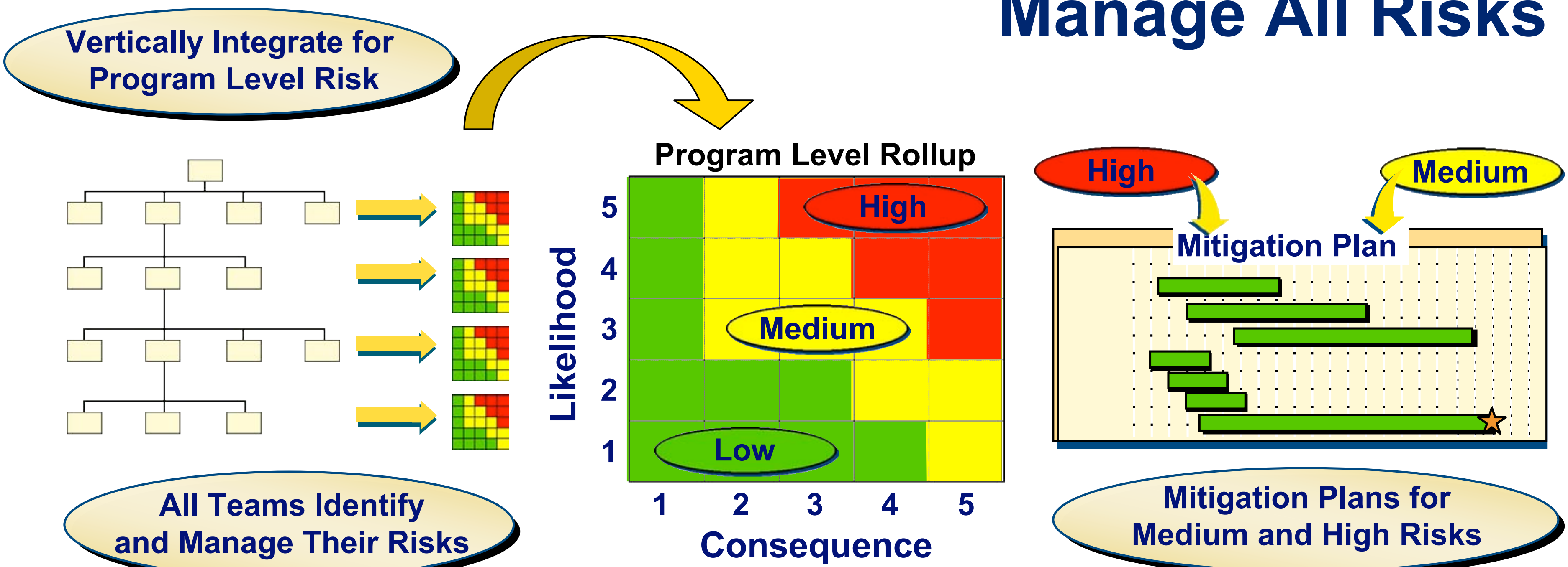


Fig.1 Schematics of Lean Product Development Flow

Source: Oppenhiem, B., "Lean Product Development Flow", INCOSE J of Systems Engineering, Vol 7, No 4, pp 352-376, 2004

- **Use customer-defined value to separate value added from waste**
- **Eliminate unnecessary tasks/streamline remaining tasks**
- **Synchronize flow with integration events (stand up meetings, virtual reality reviews, design reviews, etc.)**
- **Minimize handoffs to shorten cycle time and avoid rework**
- **Maximize horizontal flow, minimize vertical flow**
- **Iterate early - minimize "downstream" iterations**

Manage All Risks

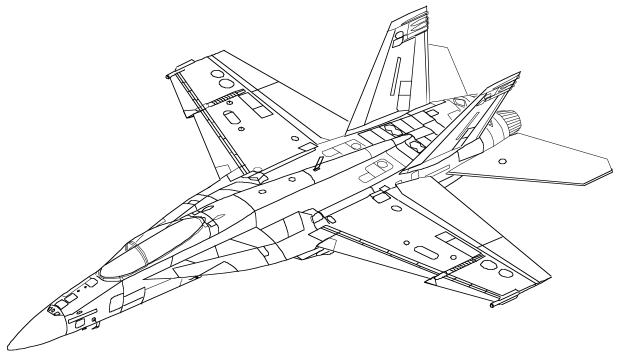


Source: "Risk Management Lecture, MIT, Al Haggerty, Nov 2004

- Take unproven technology off the critical path - separate research from design & development
- Look for simple solutions - avoid unnecessary elegance
- Consistently use a tailored risk management approach for identification, assessment, mitigation and tracking
- Keep management reserves at program level
- Balance stability and adaptability

Utilize Integrated Engineering Tools

F/A-18 E/F is 25% larger but has 42% fewer parts than C/D due to DFMA



Total Parts

C/D	E/F
14,104	8,099

Source: LAI Lean Academy® *Lean Engineering* Module, V5.3

- **Preliminary design methods supporting uncertainty in specifications.**
- **Design for Six Sigma (DFSS) methods, including variability reduction & key characteristics**
- **Integrated software/hardware design tools**
- **Multidisciplinary design and optimization for fluids, structures, controls, dynamics, et al.**
- **Design for manufacturing and assembly (DFMA)**
- **Product lifecycle management (PLM) tools**
- **Production and system simulations**
- **Verification and validation mockups, prototypes, tests**

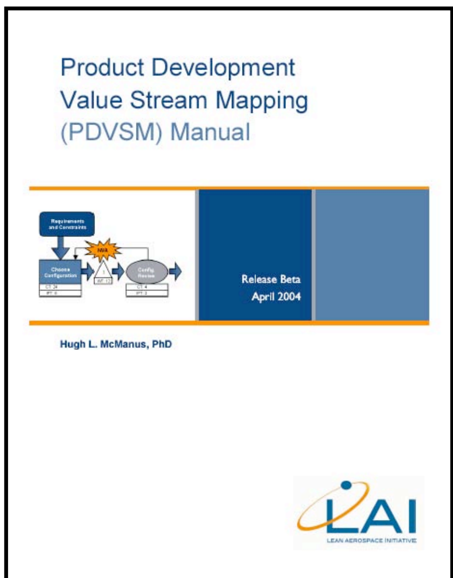
Employ Lean Process Improvement Methods

Lean improvements to spacecraft environmental testing

Category	Before	After	Reduction
Test Cycle Time	14.7 Days	8.6 Days	41%
Labor	$1,687,908	$701,564	58%
Material	$554,304	$132,864	76%
Travel Distance	85,560 Feet	7,200 Feet	92%

Critical Path System Test Cycle Time Reduced By 6 Days

Source: Lockheed Missiles and Space



- **Value Stream Mapping and Analysis**
- **Rapid Process Improvement Events**
- **5S**
- **Root cause analysis/corrective action**
- **Pareto and PICK charts**
- **Visual displays in a "big room" - *Obeya***
- **Fever charts**

Principles of Lean Engineering Are Not New

Lean engineering practices are evident in …

B52 Stratofortress

F-117A Nighthawk

F16 Fighting Falcon

DC- 9

Gulfstream IV

B-777

… but few programs apply them consistently.

Source: Haggerty & Murman , "Evidence of Lean Engineering in Aircraft Programs", ICAS 2006

Tailor Lean Engineering To Fit Program

- Apply Lean Thinking to identify Value Added Lean Engineering
- One size does not fit all

Program Type	Possible Lean Engineering Approach
Advance R&D X-vehicle Prototype	• Small focused co-located team in "protected" environment – aka a Skunk Works® type organization. • Rapid design-build-fly cycles for learning, risk reduction, tool calibration and lifecycle experience.
New product development Major upgrade Derivative	• Direct involvement of customer throughout design. • Strong focus on lifecycle value and IPPD with integrated digital and Product Lifecycle Management tools. • Utilize "lessons learned" from past programs. • Avoid unneeded reinvention, risky technology, unproven tools and unnecessarily elegant solutions.
Engineering testing & support Product support Small upgrades	• More standardized tasks and lower engineering risk allows direct adoption of many lean practices and tools used in manufacturing. • Continuous improvement through Value Stream Mapping and Analysis.

Skunk Works® is a registered trademark of the Lockheed Martin Corporation

Advanced R& D Example: HondaJet

Overview

- 4-6 pax Advanced VLJ
- Large cabin volume
- 1,180 nm range
- 420 KTAS @ 30K ft.
- Jan 1998 program start
- Dec 2003 first flight

Value Delivered

- Technology proven for:
  - Laminar flow wing
  - Laminar flow fuselage
  - Engine installation
- Product launched July 2006 for $3.65M VLJ
- Over 100 orders

People

- Customer engaged one year before program launch.
- Chief Engineer driven
- Small co-located team: 25 engineers, 10 techs
- Flat organization
- Engineers did design, production, testing
- *Genchi genbutsu*
- Vision aligned the team

Processes

- Customer needs drove technical design
- DFX for choices aircraft "will live with"
- IPPD
- New technology only where needed.
- Co-location, no walls
- Rapid communication & decisions, no meetings
- 2 yr risk reduction study

Tools

- Rapid simulation tools for early studies
- Rapid prototyping wind tunnel models
- Simple/partial mockups for engineer learning
- SOA computational simulation & testing
- *Obeya* - big room

Sources:Warwick, G., "Opening doors: Car maker Honda's aircraft research and development facility gears up for the HondaJet", Flight International, Dec 1, 2007. Personal communication with M. Fujino, Dec. 2007

New Product Example: Cessna Citation X

Overview

- 8-12 pax business jet
- 3300 nm range @ M=.82
- Low noise, fuel burn
- Glass cockpit
- Fastest civil at M=0.92
- Dec 90 - Jun 96 (cert)
- Adopted TQM

Value Delivered

- Over 260 units delivered
- Production increased by 65% for 2006-2010
- Excellent safety record
- Collier Trophy winner
- Experienced, satisfied engineers

People

- Proactive Customer Advisory Council
- Prog Mgr as Chief Eng
  - On the floor during build
- Integrated Design Teams
  - Co-located near hardware
  - Flowdown of RAA
- *Genchi genbutsu*
  - Engineers can install their parts on prototype
- New employee mentoring

Processes

- Designed for:
  - Safety
  - Quality
  - Manufacture & Assembly
  - Maintenance hours
- Open, frequent meetings
- Suppliers as partners
- Risk reduction
  - Prototype
  - Design for simplicity
  - Test for verification
  - Limit % of new employees

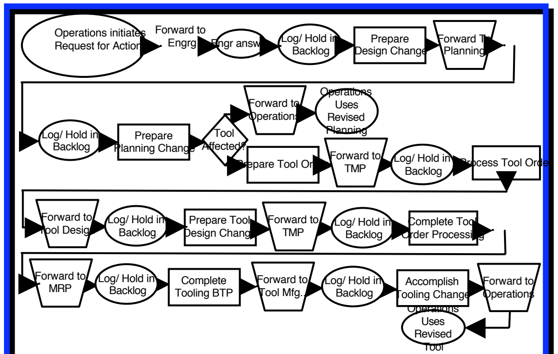
Tools

- CATIA & CFD
- Prototype for learning
- Common databases with good IT support
- Lessons learned widely available
- Simple process based management tools
- Schedule used to synch flow

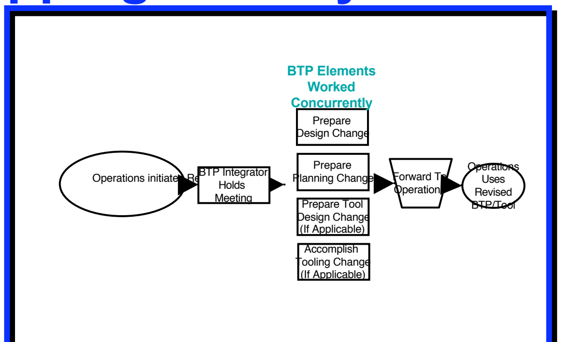
Sources: Denis, A., Freuler, P.N., Robinson, T., Serrano, M., Vatz, M.E., "Citation X: A Case Study", MIT 16.885 Aircraft Systems Engineering, Dec 9, 2003. Personal communication P. Kalberer, R. Curtis, Jan 2008

Engineering Support Example: F-16 Lean Build-To-Package Support Center

Value Stream Mapping & Analysis



Process Before VSM



Process After VSM

Lean Thinking Outcome

Multifunctional team co-located "at the spot" responds "on demand" to customer with process achieving single piece flow using standard work.

Value Delivered

Category	Reduction
Cycle-Time	75%
Process Steps	40%
No. of Handoffs	75%
Travel Distance	90%

849 BTP packages

Source: "F-16 Build-T- Package Support Center Process", Gary Goodman, Lockheed Martin Tactical Aircraft Systems LAI Product Development Team Presentation, Jan 2000

Engineering Support Example - AEDC Engine Ground Test Throughput in ASTF

Issue: Typical Large Commercial Engine Installation Time of 74 days unacceptable to customer needs.

Goal: Reduce engine installation time by 50% with no increase in customer cost

Action: Create a detailed engine installation schedule and implementation plan to help eliminate waste and highlight problem areas

Lean Engineering Practices & Tools

- Voice of the Customer
- Integrated Product Team
- Rapid Process Improvement Events
- Value Stream Mapping and Analysis
- Pareto and PICK charts
- Critical path analysis
- *Obeya* - visual displays
- Standard work

Results: Planned installation time reduced from 74 to 36 days:

- Eliminated 13 shifts of work of which 12 were on the critical path
- 14 shifts of work moved off of critical path
- 23 calendar days saved by judicious use of weekend and 24/7 support

$10K investment saved 1 mo of program time

Finding: Further improvement dependent on stakeholder alignment across multiple government and industry enterprises.

Sources: Smith, V.K. and Kraft, E., “A Lean Enterprise Approach to Test and Evaluation in Turbine Engine Development and Sustainment”, Arnold Engineering and Development Center. Unpublished.

Lean Engineering Challenges

- Implementation is not simple or quick
  - Different culture than found in Cold War aerospace
  - Engineers are skeptical - involves the “soft stuff”
  - May span enterprises - hard to align stakeholders
- Body of Knowledge based on observation
  - Principles compared to laws of science
  - Best Practices compared to formulae and graphs
  - Holistic compared to reductionist thinking
- Inclusion in college level curriculum
  - Faculty lack experience and knowledge
  - Curriculum constrained - need to look for synergy
  - Needs industry-university partnerships

Hypothesis: The application of Lean Thinking principles, practices and tools to *engineering* can lead to superior aerospace product development results - and happier more satisfied engineers.

Lean Aerospace Engineering Is….

- Not some new fangled approach ignoring accepted engineering body of knowledge
- Not "Less Aerospace Engineers Needed"
- The right amount of engineering at the right time for the right objective
- A smart combination of
  - "Traditional" engineering based upon principles and tools of science and mathematics
  - "Process" engineering based upon Lean Thinking principles derived from engineering practice
- Excellent Aerospace Engineering!