16.885J/ESD.35J
Aircraft Systems Engineering

Lean Systems Engineering I

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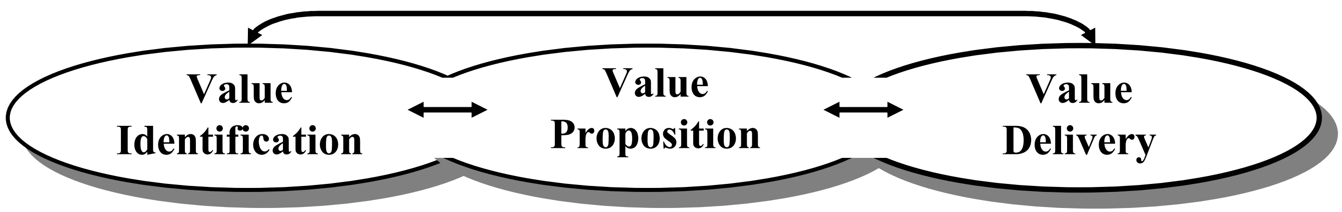
Prof. Earll Murman

Lean Systems Engineering

Value Phases



Value Identification	Value Proposition	Value Delivery
Identify the stakeholders and their value expectations	Develop a robust value proposition to meet the expectations	Deliver on the promise with good technical and program performance

- Systems Engineering (SE) and Lean Thinking (Lean) are two processes for delivering value to the customer and end user.
- They developed independently and in parallel.
- Lean Systems Engineering (Lean SE) is an emergent process that applies lean thinking to systems engineering with the objective of delivering best lifecycle value for complex systems and products.

Today's Topics

- Lean Systems Engineering Intro
  - SE Origins/uses, definitions, application
  - Lean origins, definitions,application to aerospace
  - Lean SE strategy
- Simplified SE Process
  - Process elements and variants
  - Flowdown to subsystems, allocations, interfaces
- Lean basics
- Lean SE illustration
  - Integrated Product and Process Development (IPPD)

Origins of SE and Domains of Use

- Started with ballistic missile programs
  - Technically complex systems that needed to work flawlessly on first use drove a new engineering and project management approach to meet **performance**, cost, and schedule expectations with **manageable risk**
- SE is the accepted engineering approach for space systems
- Widely used in electronics industry and some software
- Aircraft engineering methods predated development of formal systems engineering
  - "Legacy" approach in commercial aircraft field
    - Systems engineering often refers to the subsystems.
  - Increasingly important with information systems and integration
  - Military customer has been strong driver for systems engineering
- Is being adopted in other fields such as auto, transportation, ….

What is a System?

- INCOSE* definition:
  - An interacting combination of elements to accomplish a defined objective. These include hardware, software, firmware, people, information, techniques, facilities, services and other support elements
- Contextual in nature: system must be identified
- Hierarchal →

Air Transportation System

Aircraft System

Subsystems

* International Council of Systems Engineering, www.incose.org

What is Systems Engineering?

- Simon Ramo of TRW (1993)
  - Systems engineering is a branch of engineering that concentrates on the design and application of the whole as distinct from the parts…..looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspects.
- Electronics Industry Association (EIA/IS 6321994)
  - An interdisciplinary approach encompassing the entire technical effort to evolve and verify an integrated life-cycle balanced set of system people, product, and process solutions that satisfy customer needs.

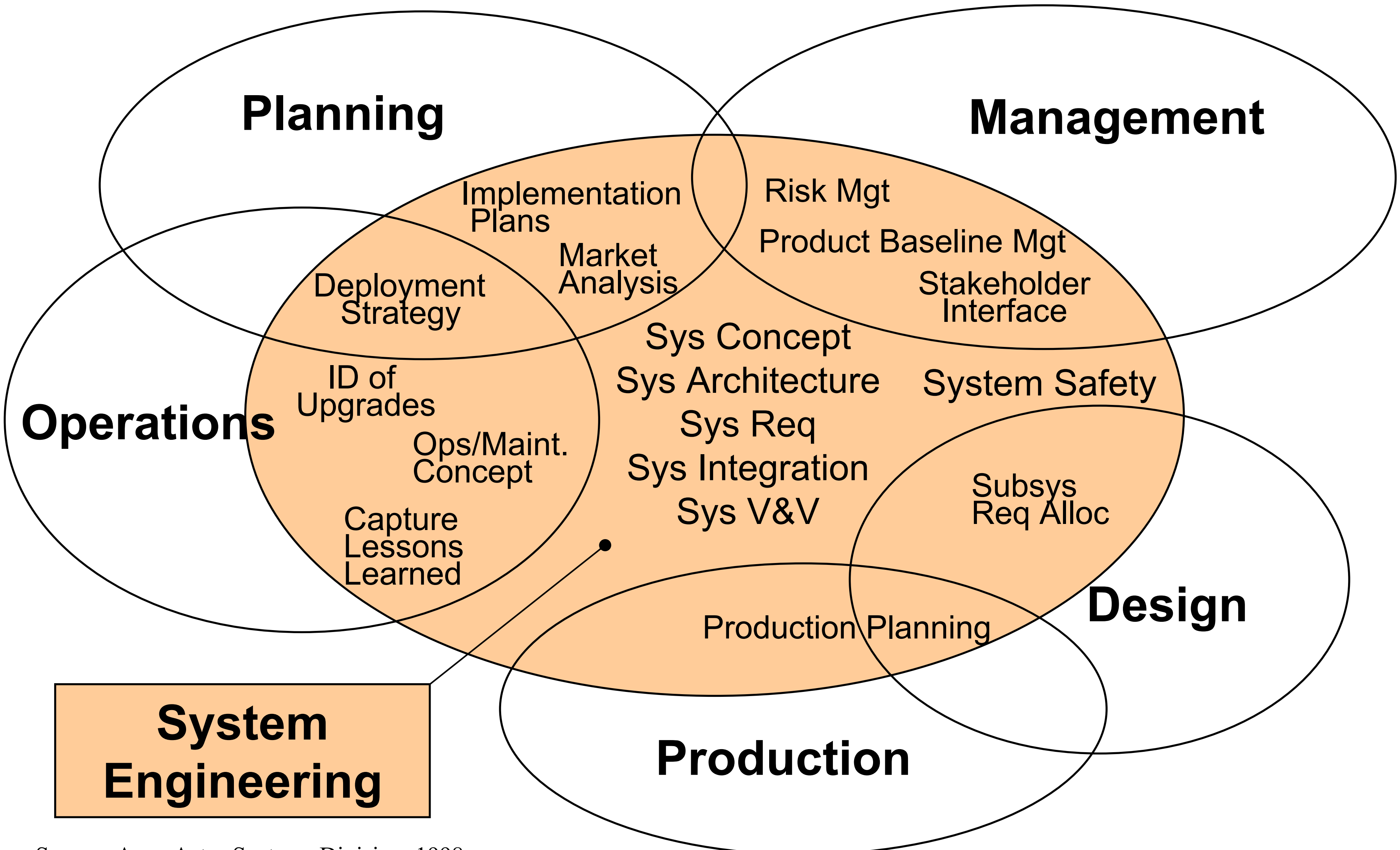
Source: Jackson

What is Systems Engineering?…More

- NASA Systems Engineering Handbook (1995)
  - Systems Engineering is a robust approach to the design, creation, and operation of systems. In simple terms, the approach consists of identification and quantification of system goals, creation of alternative system design concepts, performance of design trades, selection and implementation of the best design, verification that the design is properly built and integrated, and post-implementation assessment of how well the system meets (or met) the goals.
- INCOSE Systems Engineering Handbook (2000)
  - An interdisciplinary approach and means to enable the realization of successful systems. Systems engineering is an overarching discipline, providing the tradeoffs and integration between system elements to achieve the best overall product and/or service. Although there are some important aspects of project management in the Systems Engineering process, it is still much more an engineering discipline than a management discipline.

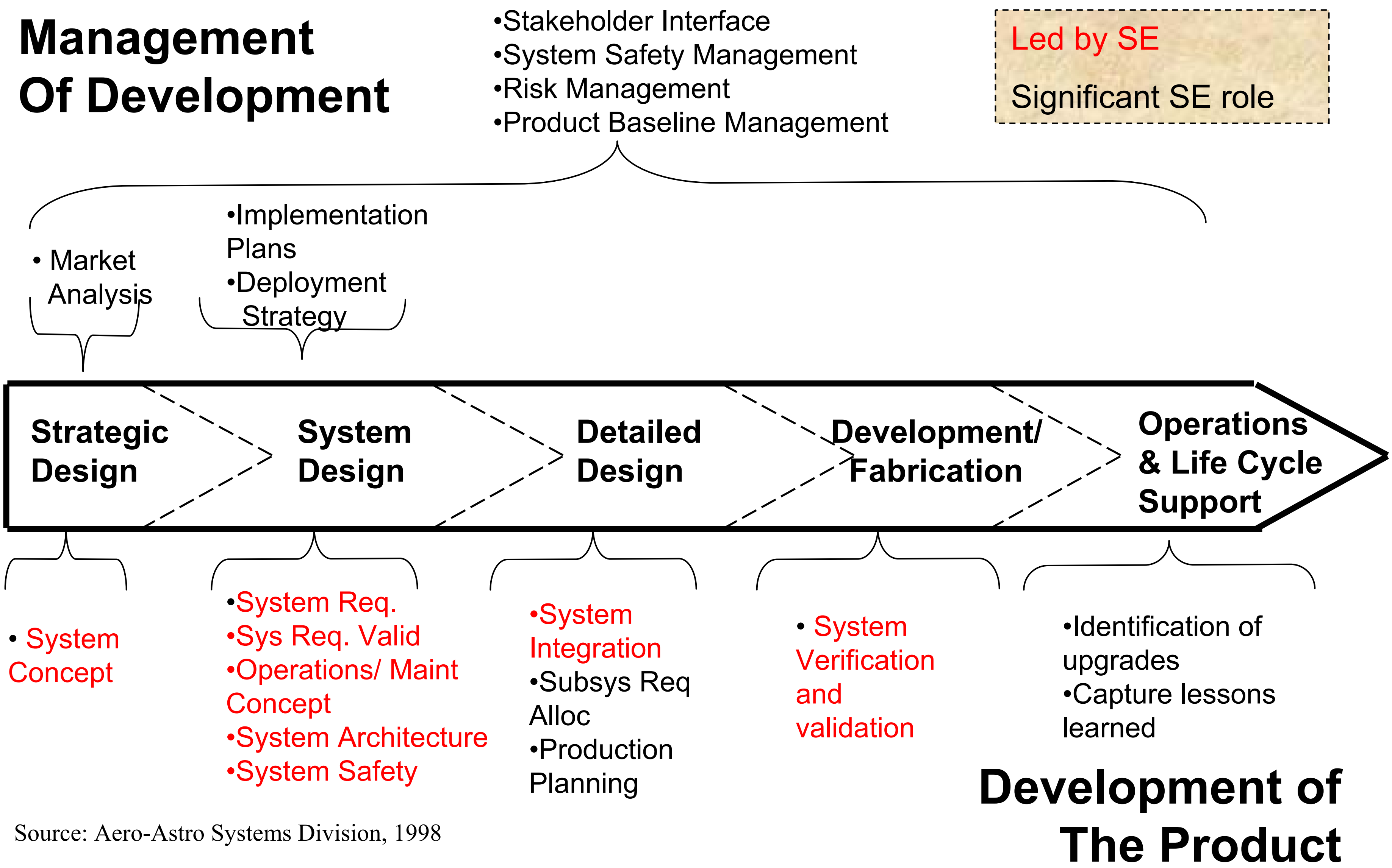
Gist is clear, but there are variations in scope.
Let's avoid getting bogged down in definitions.

Systems Engineering Activities



Source: Aero-Astro Systems Division, 1998

Systems Engineering & Product Lifecycle



Source: Aero-Astro Systems Division, 1998

Application of System Engineering

- Concepts are generally applicable to any system
- Very dependent upon number of "inters"*
  - For simple systems, formal procedures can easily be overkill and counter productive
  - For complex systems formal system engineering procedures are a must
- Whatever level is adopted, it is essential that everybody on a project is following the same procedures.
  - This leads to standards
- Bottom line: concepts are important and application needs thoughtful consideration

* Interconnections (Interfaces), Interactions, Interdependencies

Lean Thinking

Lean **emerged from Post WWII Japanese automobile industry as a fundamentally more efficient system than the *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)	Prevention (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, et. al, *Lean Enterprise Value*

Lean Enterprise Processes

Life Cycle Processes

- **Business Acquisition and Program Management**
- **Requirements Definition**
- **Develop Product and Process**
- **Supply Chain Management**
- **Produce Product**
- **Distribute and Service Product**

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Enabling Infrastructure Processes

- **Finance**
- **Information Technology**
- **Human Resources**
- **Quality Assurance**
- **Facilities and Services**
- **Environment, Health and Safety**

Lean applies to “Produce Product” and other Life Cycles Processes which deliver program value to the customer and revenue to the enterprise

Lean also applies to other enterprise Enabling Infrastructure Processes required to deliver the program value.

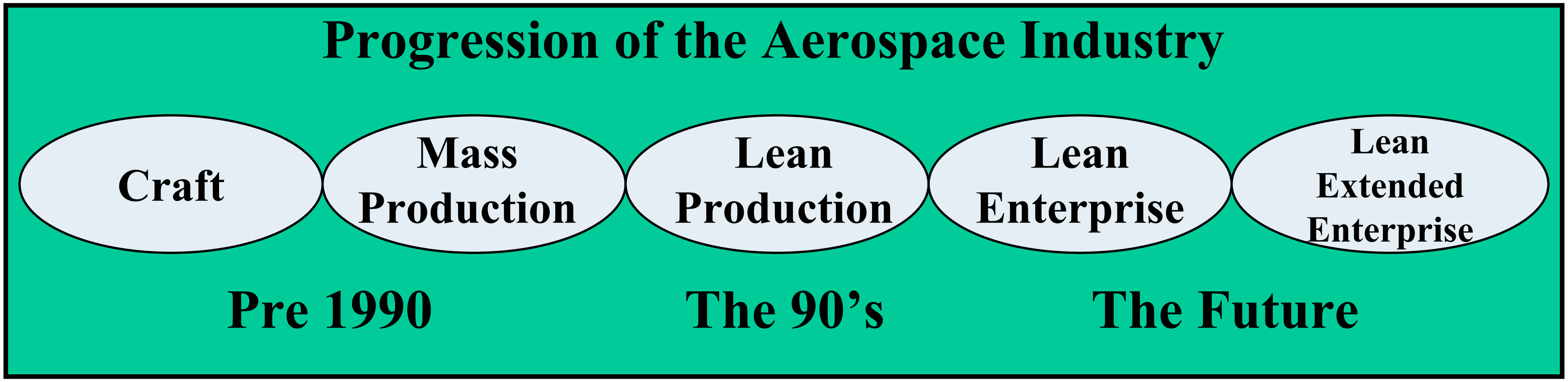
Source: Murman, et. al, *Lean Enterprise Value*

By Implementing Lean in Aerospace…

- C-130J production
  - Throughput of extrusion shop from 12 days to 3 minutes
- P & W general machining center
  - 67% reduction in lead time
- GE Lynn aircraft engine facility
  - 100% on time deliveries
- 777 floor beam
  - 47% assembly time reduction
- Delta IV launch vehicle
  - 63% reduction in floor space
- Joint Direct Attack Munition (JDAM)
  - 63% reduction in unit cost
- C-17 Globemaster III
  - Unit cost reduction >$80M
- F/A-18E/F Super Hornet
  - On time, on budget, performance goals met
- F-16 Falcon
  - Sales price stable and order-to-delivery time down 42% with 75% reduction in volume
- Atlas launch vehicles*
  - Lead time reduced from 48.5 months to 18 months

Source: Murman, et al. *Lean Enterprise Value: Insights from MIT's Lean Aerospace Initiative*, Palgrave, 2002.
* M. Gass, LAI Plenary Conference Presentation, March 2002.

Aerospace Lean Journey

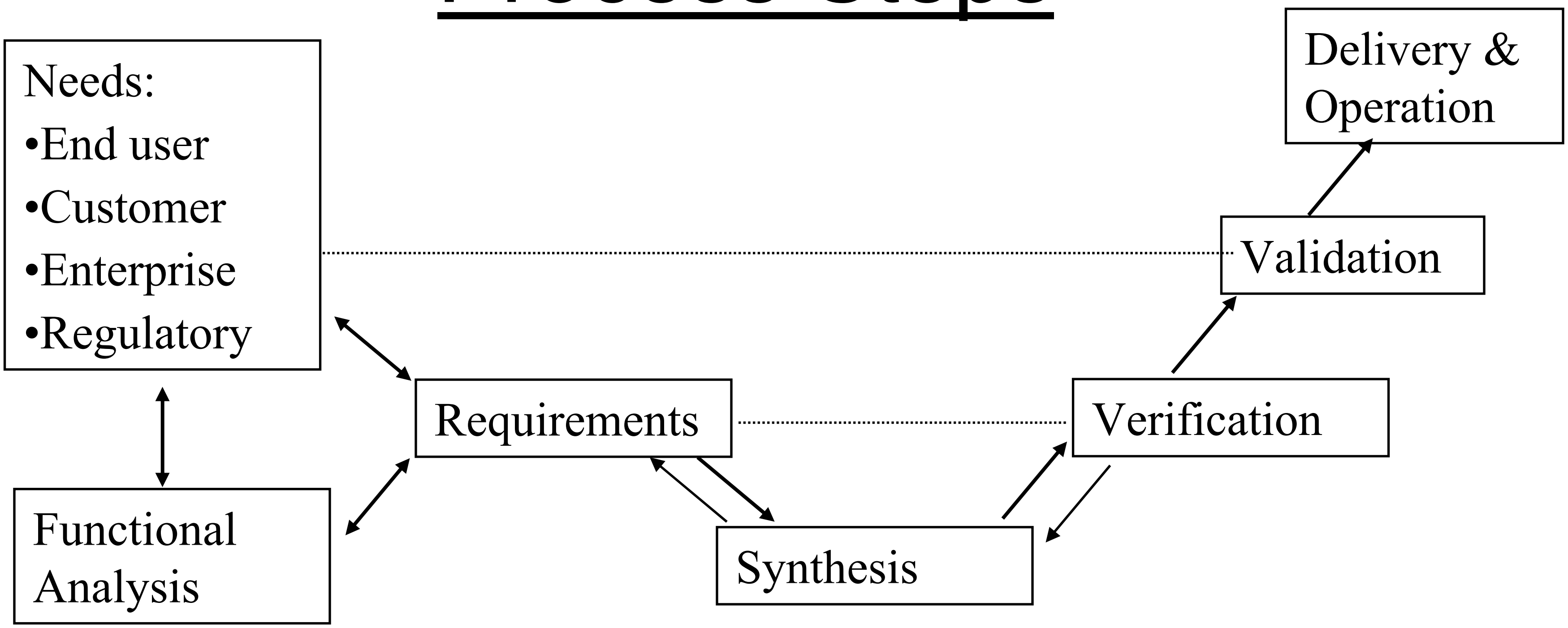


- Lean is a "journey", not a "state".
- The lean journey in aerospace started in the early 90s and is now in full swing
- Lean is focused on delivering value and responding to opportunities with minimum use of resources.
- Lean principles and practices apply not only to manufacturing, but across the enterprise to product development, acquisition, sustainment, business processes.
- The application of lean thinking to systems engineering is currently emerging.

Lean Systems Engineering

- ***Systems Engineering*** grew out of the space industry in response to the need to deliver technically complex systems that worked flawlessly upon first use
  - SE has emphasized technical performance and risk management of complex systems.
- ***Lean Thinking*** grew out of the Japanese automobile industry in response to the need to deliver quality products with minimum use of resources.
  - Lean has emphasized waste minimization and flexibility in the production of high quality affordable products with short development and production lead times.
- Both are processes that evolved over time with the common goal of delivering product or system lifecycle value to the customer.
- ***Lean Systems Engineering*** is an emerging area representing the application of Lean Thinking to Systems Engineering with the goal of delivering best lifecycle value for technically complex systems.

Simplified System Engineering Process Steps



Verification is assuring the system meets the requirements

Validation is assuring the system meets the needs

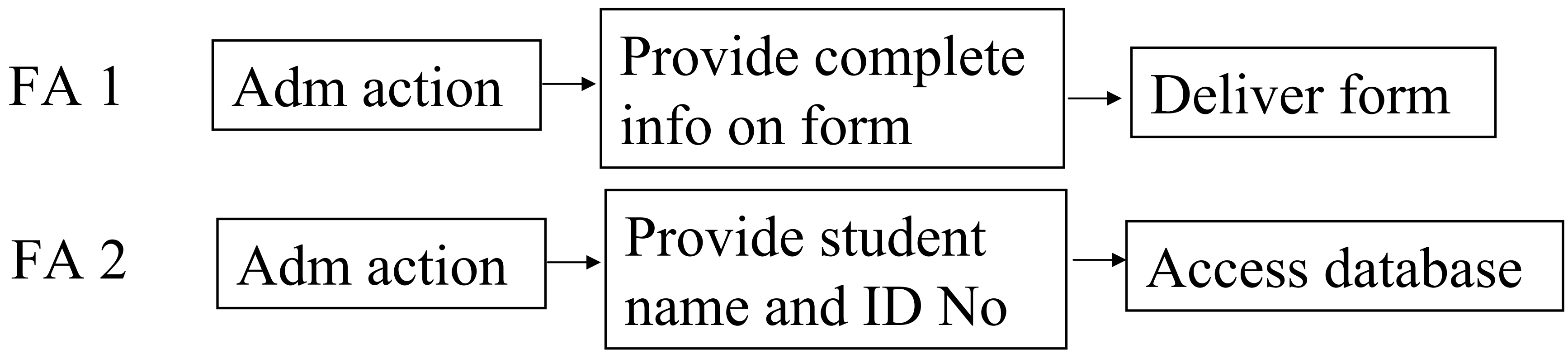
Source: Adapted f rom Jackson, S. *Systems Engineering for Commercial Aircraft*

Functions and Requirements

- "A function is a task, action, or activity performed to achieve a desired outcome" Jackson
- "A requirement is a statement of required performance or design constraint to which a product must perform" Jackson
- From architecture: *Form follows Function*
  - Requirements follow functional analysis
- System Architecture: "The arrangement of elements and subsystems and the allocation of functions to them to meet system requirements" INCOSE Handbook for Systems Engineering

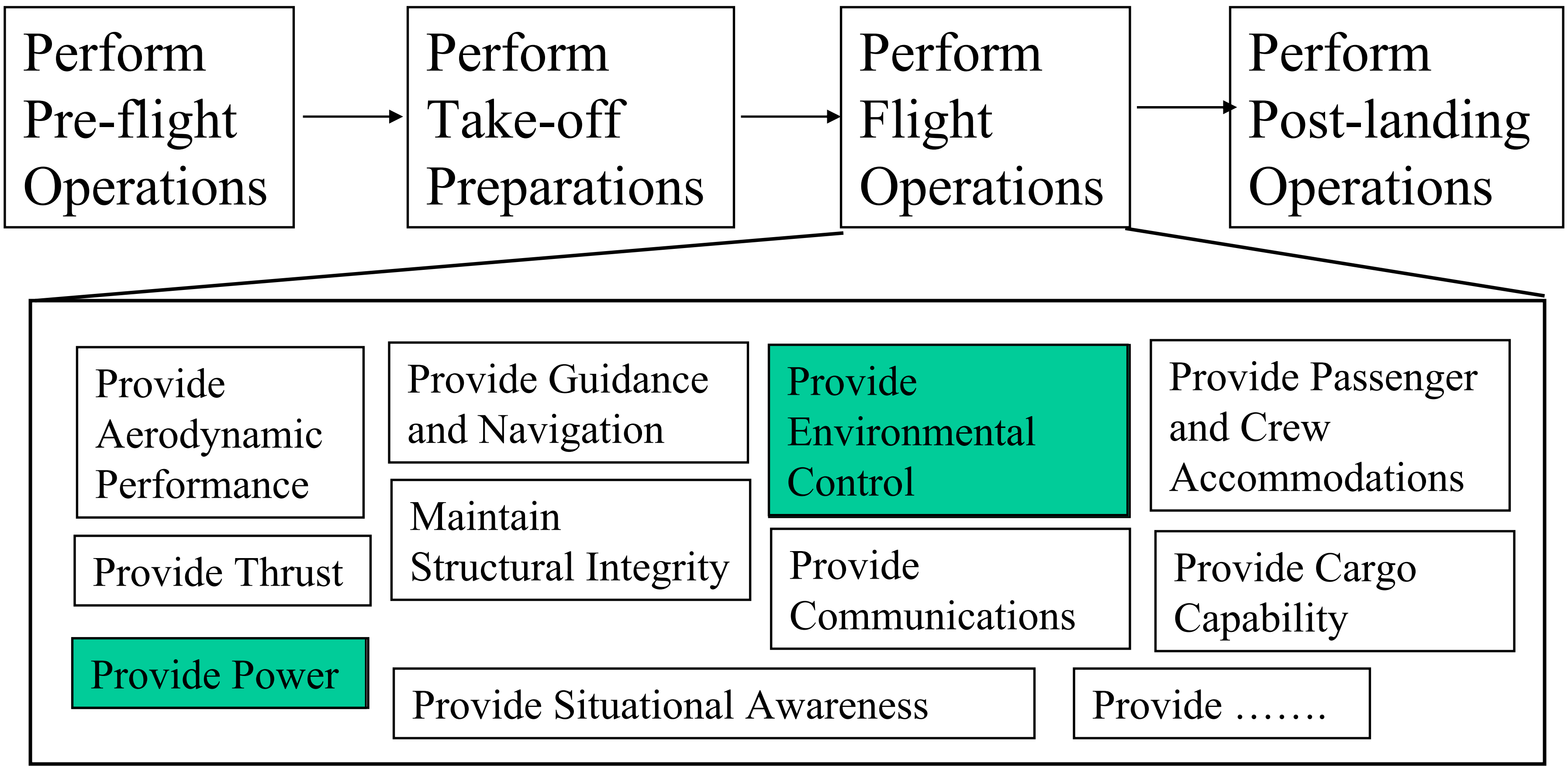
A Simple Example

- Need: All student administrative actions must have access to complete information profile of the student
- Function: Provide information profile for student



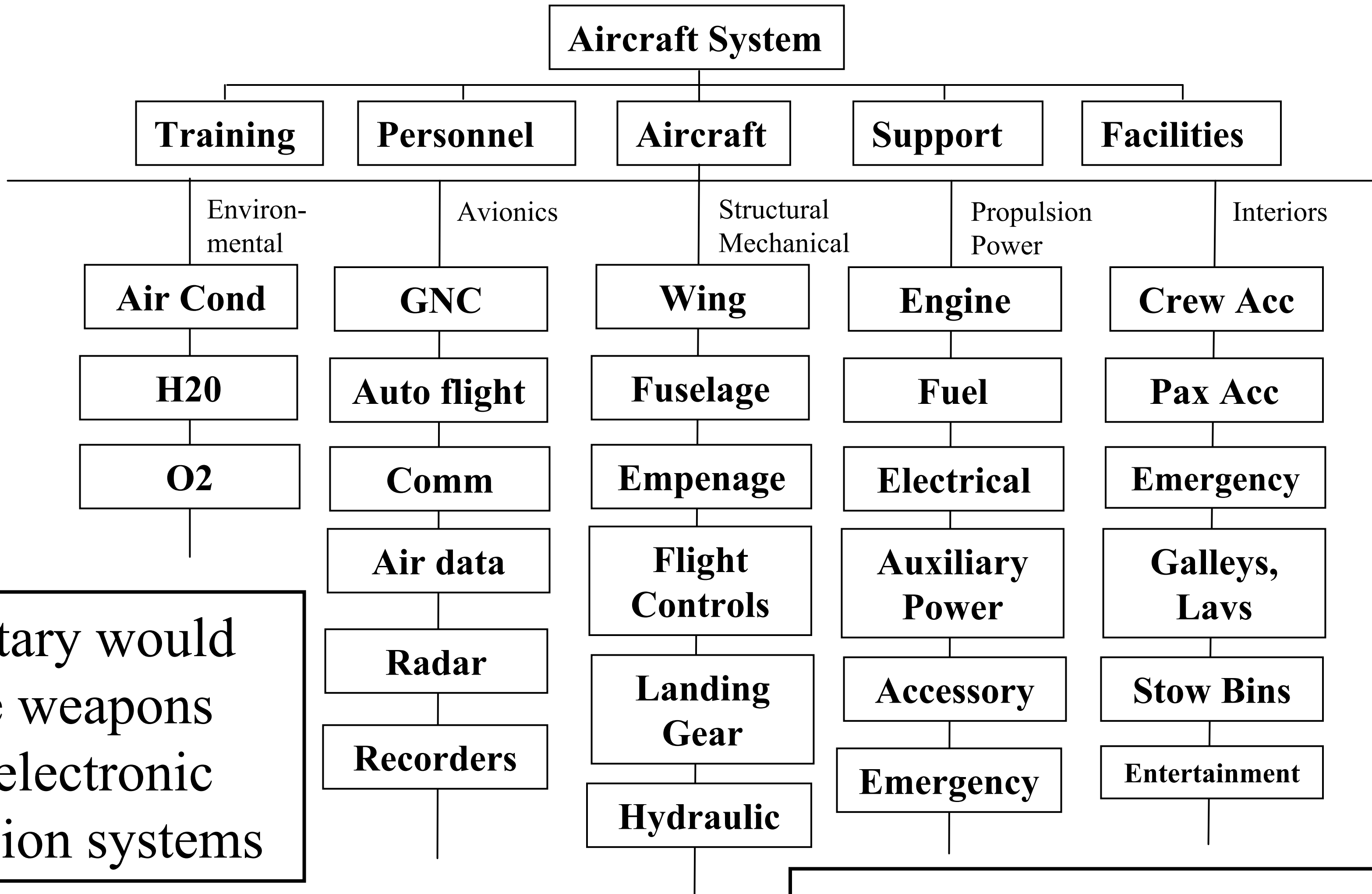
Different functional architectures result from trade studies. They lead to different requirements for design.

Perform Air Transport Mission Function Functional Flow



Source: Adapted f rom Jackson, S. *Systems Engineering for Commercial Aircraft*

Perform Air Transport Mission Function
Aircraft Functional Architecture



Military would have weapons and electronic mission systems

Source: Adapted f rom Jackson, S. *Systems Engineering for Commercial Aircraft*

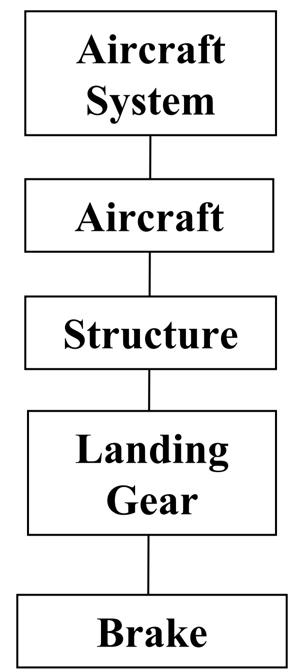
A representative example

Allocation of Functional to Physical

"Except for good and sufficient reasons, functional and physical structuring should match" *Rechtin*

"The Independence Axiom - Maintain the independence of functional requirements" *Suh*

- Functional architecture generally determines physical architecture:
  - "Form follows function"
  - e.g.. *Provide Guidance and Navigation* function would be allocated to the *GNC subsystem*
- Leads to physical work breakdown structure which mirrors functional architecture.
- This leads to organizational structure which mirrors WBS



Requirements

- "One principle agreed upon by most systems engineers is that the basic quality of a requirement is that it must be verifiable." Jackson
  - Requirements have metric information, e.g.
    - Need: Serve intercontinental markets
    - Function: Travel over oceans
    - Requirement: 180 min ETOPS*
  - Verification method should be established simultaneously with requirement
- Requirements stem from many sources: customer, regulatory, safety, enterprise,...

* Extended Twin Engine Operations: A requirement for twin engine aircraft to be able to fly for a certain time with one engine out.

Requirement types

- **Performance** requirements come from functions which are ultimately traceable to system level functions.
  - E.G. 7000 nm range
- **Constraint and Specialty Requirements** come from sources like design standards, physical limits, human factors, regulatory (FAA/JAA, EPA, OSHA,) facilities, manufacturing,….
- **Derived Requirements** depend upon some feature of the solution to determine their value

Synthesis

- Synthesis is the “design part” of systems engineering
- High level synthesis leads to system architecture, including subsystems
- System level leads to major sizing
- Lower level synthesis leads to detailed designs
- All levels involve “trade studies” to develop best solutions.
- Design tools are used for synthesis.

Verification and Validation

- Verification is assuring a requirement is met
  - Verification method should be established simultaneously with requirement
  - Verification methods: analysis, tests or demonstration, simulation, operational data, examination
- Validation is assuring the need is met
  - Takes place at multiple level
  - Early validation should involve key stakeholders in concept reviews, requirements reviews,….
  - Later validation: system representations (prototypes, mock ups, low rate initial production LRIP)
  - Final validation: product success

SE Process Management

- SE process owners are realm of SE professionals
  - Project and Functional SE groups
- Design reviews are important “gates”, e.g.
  - SRR: System Requirements Review
  - SDR: System Design Review
  - PDR: Preliminary Design Review
  - CDR: Critical Design Review
  - FRR: Flight Readiness Review
- Change boards utilized to address requirement and design changes involving multiple stakeholders
- System schedule, cost, and configuration control
- Documentation, tools, etc.

A process that isn’t managed is not in control.

SE Process Variants

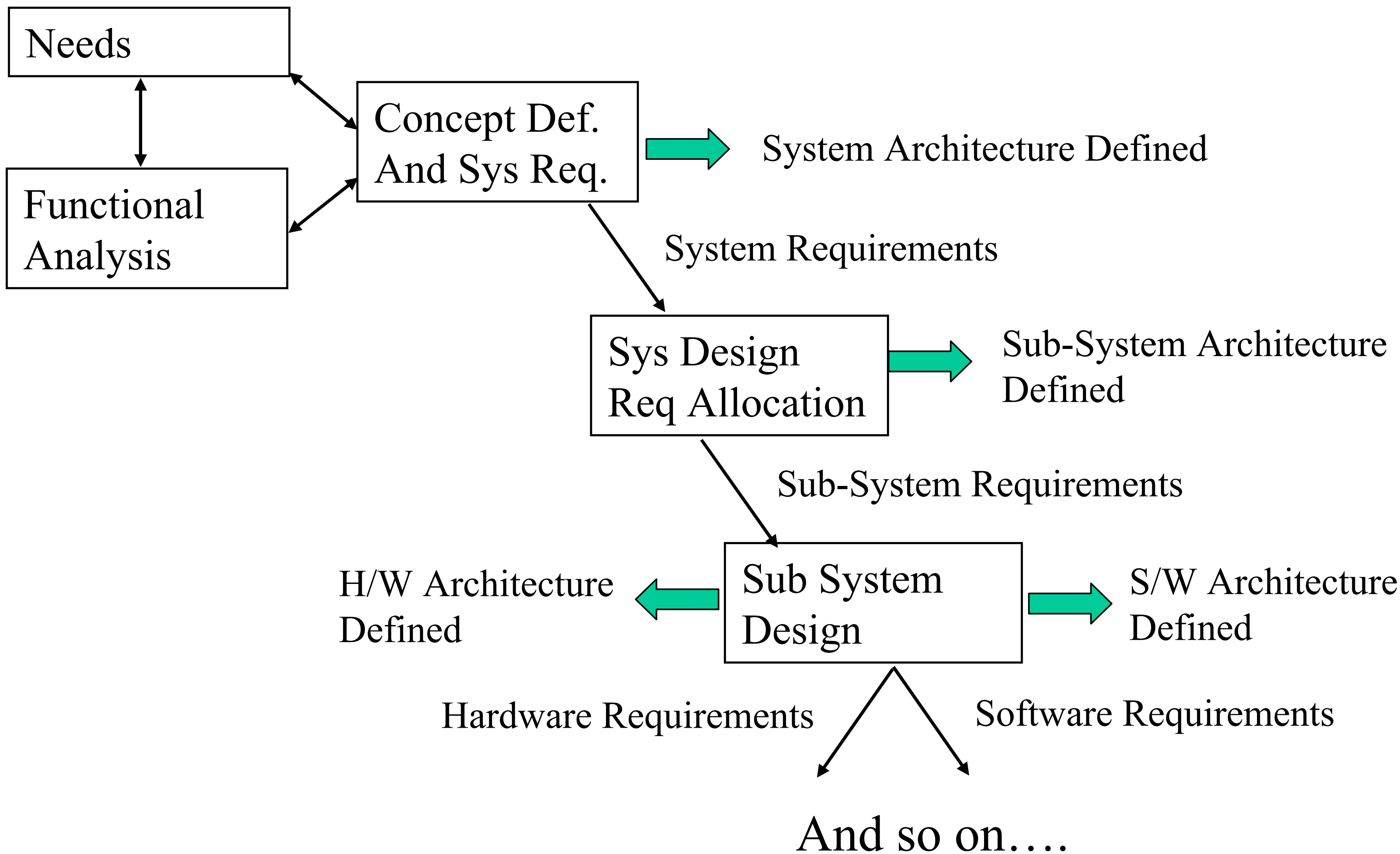
- One will find many variations on the simplified SE process presented.
  - V diagram, Waterfall, INCOSE (pg 16)
  - Basic process elements are the same
  - Some contain other features
  - Some are graphical changes which may more effectively communicate process
  - Showing iterations and feedback is challenging
- Organizations often develop tailor their own version to “internalize” SE process

Spiral Process is Different

- Early product versions, but not fully functional
- Drives learning by exposing project personnel to complete cycle
- Widely used in software
- Now adopted by USAF

16.885 case studies will use a spiral process.

Requirements Flowdown



Requirements Flowdown

- Requirements are “flowed down”, e.g. estimate
  - O(10) aircraft system level
  - O(100) aircraft level
  - O(1K) subsystem level
  - O(10K) component level
- Traceability from sublevels to high levels is needed to assure requirements address a need
  - S/W tools needed
- Assuring requirements are “complete” is a significant issue. Don’t want to miss a key one.
- Requirements documents are developed and maintained. Version control is important.

System Level Attributes

- Physical parameters
  - Mass properties
  - Power
  - Noise
  - EMI (Electromagnetic Interference)
  - …..
- Cost
- "Ilities"
  - Producibility
  - Maintainability
  - Reliability
  - ……

Must be allocated to subsystems

- Initially based upon historical knowledge
- Iterated in early stages of design
- Determined by Preliminary Design Review

With margins kept for uncertainty

Mass Properties

- Weight
  - Max Take-off Weight, Landing Weight, Manufacturer's Empty Weight, ….
- Center of gravity
  - Central to the static stability of the aircraft
- Moments of inertia
  - Central to the dynamic response of the aircraft
- Mass properties central to the physical layout of the aircraft.

Other Physical Parameters

- Power
  - Total electrical power available is limited
  - Growing demand for onboard systems
- Noise
  - Affects crew/passenger comfort
    - Engines, boundary layer, ECS, hydraulic sources
  - Vibrations can affect mechanical component
    - Allowable levels set as an "environmental" requirement
- EMI
  - Affects electronic components
    - On-board equipment and passenger equipment sources

"Reliability"

- Multiplicative not additive
  - $R_{sys} = R_1 \times R_2 \times R_3 \ldots . R_i$!
  - Allocated to subsystems (i) to achieve system level goal.
  - Redundancy used to get high R_i
    - If probability of failure of component i is p_i, reliability R_i=1- p_i; e.g p_i = .01, R_i=.99
    - With "n" redundancy, probability of failure is p_i^n, reliability R_i = 1 - p_i^n; e.g. n=3 & p_i = .01, R = .999999
- Reliability allocation is a major driver of subsystem architecture

Interfaces

- "The greatest leverage in system architecting is at the interfaces" *Rechtin*
- "In partitioning, chose the elements so that they are as independent as possible, that is, elements with low external complexity and high internal complexity" *Alexander*
- Interfaces are often the source of problems with systems.
- Some argue that "complexity" is related to the number of interfaces.

Interface Characterization

- Functional and Physical
  - Provide electrical power
  - 28 vdc, 100 watts nominal, 200 watts peak, form factor of .90 lagging to .96 leading per phase
- External or Internal
  - Ground support power system or APU
  - External interface for one level is internal interface for next higher level
- Input and Output
  - Every interface should have a provider a user
    - N^2 diagrams

F-16 Case Study N^2 Diagram Example

) FROM	STRUCTURE	ENGINE	ELECTR. SYS	HYDR. SYS	FLCS	EPU	ECS	FUEL SYS	AVIONICS
	Space for equipment allocation of <u>all systems</u>	Propulsion and energy for systems operation	Electrical power	Hydraulic power	Control of flight surfaces	Emergency electrical & hydraulic power	Environmental control	Fuel to engine	1 Navigation 2 Fire control 3 Communication 4 Air data
TRUCTURE				Actuation of flight surfaces	Control signals to flight surfaces		Environmental control to crew station		
ENGINE								Fuel to the engine	Air data to engine
LECTRICAL SYSTEM		Power to the generators				Emergency electrical power to Emer. Bus	Cools electrical equipment		
YDRAULIC SYSTEM		Power to hydr. pumps				Emergency power to Hydr. “A”			
FLCS			Power to FLCS electronics			Full electrical & hydr. power for safe operation			• Air data to FLCS • Navigation data to Autopilot
EPU		Compressed bleed air (*if available*) to EPU turbine	Signal for automatic operation	Signal for automatic operation					
ECS		Bleed air for pressurization & air condit.	Power to ECS controllers						
FUEL SYSTEM	Integral fuel tanks in fuselage & wings structure		Power to fuel pumps				Pressurization of fuel tanks		
AVIONICS			Power to sll avionics LRUs			Power to specific “safe-of-flight” avionics (Radio)	Cools equipment		

Table 6.6: F-16 Major Subsystems Interface Diagram

Managing Internal Interfaces

- Mock-ups and digital prototypes
  - Recall 777 video
- ICD - Interface Control Document or Drawing
  - Formal system engineering document
  - Developed and maintained by subsystem "provider" and "user" forming an Interface Control Working Group
  - Change Board approval may be needed for modifications to ICD.

Example Apache TADS/PNVS

- Target-Acquisition-Designation System/ Pilot Night Vision System
  - Provider: Martin-Marietta (now LM)
  - User; McDonnell Douglas (now Boeing)
- Army (customer) also a member of the ICWG
- 66 page ICD defines relevant documents, standards and physical interfaces for:
  - Mechanical
  - Wiring/electrical
  - Signals (serial & analog)
  - Computer
  - Thermal
  - Environmental (pressure, vibration…)
  - Mode control
  - Video signal

The Lean Connection to SE

- What is the strategy of applying Lean Thinking to a process, such as Systems Engineering or some part of Systems Engineering?
- What is the strategy of applying Lean Thinking to an enterprise that creates a system?
- Example: Application of Integrated Product and Process Development (IPPD) to aircraft design.

Fundamentals For Developing a Lean Process

- Specify value: Value is defined by customer in terms of specific products & 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* (New York: Simon & Schuster, 1996).

Basic Steps to VSM

1. Define the boundaries
2. Define the value
3. "Walk" the process
   - Identify tasks and flows of material and information between them
4. Gather data
   - Identify resources for each task and flow
5. Create the "Current State" map
6. Analyze current conditions
   - Identify value added and waste
   - Reconfigure process to eliminate waste and maximize value
7. Visualize "Ideal State"
8. Create the "Future State" map
9. Develop action plans and tracking

Define Value

Value Added

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

Non-Value Added - Necessary

- No value is created but which cannot be eliminated based on current technology or thinking
- Required (regulatory, customer mandate, legal)

Non-Value Added - Waste

- Consumes resources but creates no value in the eyes of the customer
- If you can't get rid of the activity, it's non-value added but necessary

Seven Types of Waste

1. Over-production	Creating too much material or information
2. Inventory	Having more material or information than you need
3. Transportation	Moving material or information
4. Unnecessary Movement	Moving people to access or process material or information
5. Waiting	Waiting for material or information, or material or information waiting to be processed
6. Defective Outputs	Errors or mistakes causing the effort to be redone to correct the problem
7. Over-processing	Processing more than necessary to produce the desired output

Lean Enterprise Model Overarching Practices

People Practices

- Promote lean leadership at all levels
- Relationships based on mutual trust and commitment
- Make decisions at lowest appropriate level
- Optimize capability and utilization of people
- Continuous focus on the customer
- Nurture a learning environment

Process Practices

- Assure seamless information flow
- Implement integrated product and process development (IPPD)
- Ensure process capability and maturation
- Maintain challenges of existing processes
- Identify and optimize enterprise flow
- Maintain stability in changing environment

Practices interact and can't be implemented in piecemeal fashion

Source: Murman, et. al, *Lean Enterprise Value*

Integrated Product & Process Development (IPPD)

- IPPD is development of the manufacturing process concurrently with the development of the product design

> "Detailed design is manufacturing simulation"
>
> **Dr. Wolfgang Schmidt, Daimler Chrysler Aerospace**

- Enablers:
  1. Integrated product teams (IPTs)*
  2. 3D modeling and common data bases (e.g. CATIA)
  3. Training programs
- One study assessed the impact of IPPD by number of changes to released drawings

* IPTs were called Design Build Teams (DBTs) on 777 program.

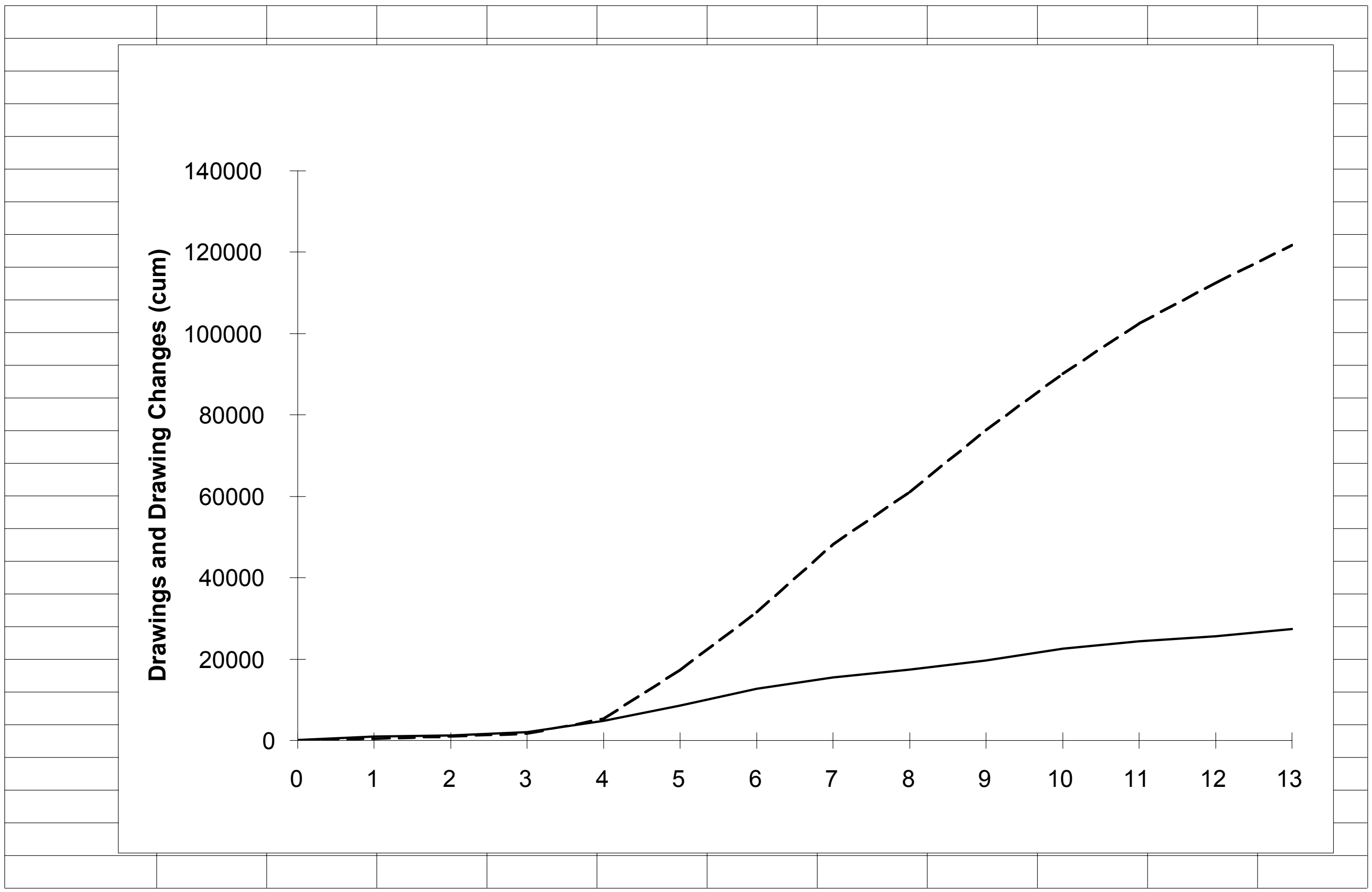
IPT Definition

- Team has finite mission which is the development of a product or process
- Usually multiple levels of teams in hierarchy (up to 5 levels) to match product architectures typical in aerospace: E.G.
  - Engine (level 1); compressor, combustor, turbine (level 2); spools,..
- Membership is cross-functional and includes all the functions that impact the product during its life cycle
  - Engineering and manufacturing
  - Customers and supplier representatives are often team members
  - Membership may vary over the entire life cycle
  - Members may be full or part time
  - For continuity, there should be core group for the life of the team
  - Members can belong to more than one IPT, including one at a higher level
- Team performance outcomes are defined & measurable

Source: J. Klien and G. Sussman, LAI Working Paper 95-03

Definition of Drawing Changes

Program 1, Company A

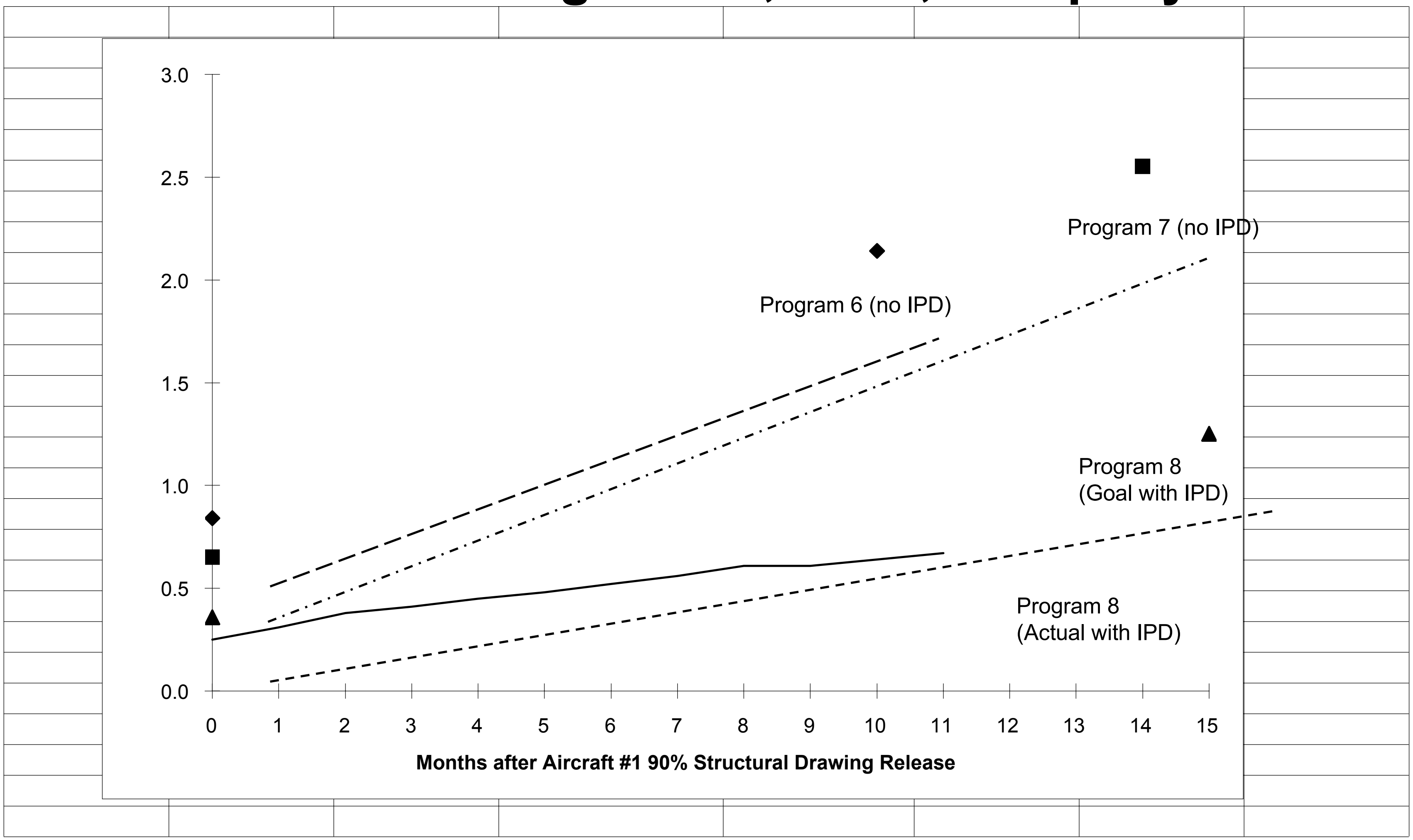


"Change traffic represents opportunities to eliminate waste.

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

IPPD Effectiveness (Cont.)

Results - Programs 6, 7 & 8, Company C



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

Case Study Linkages

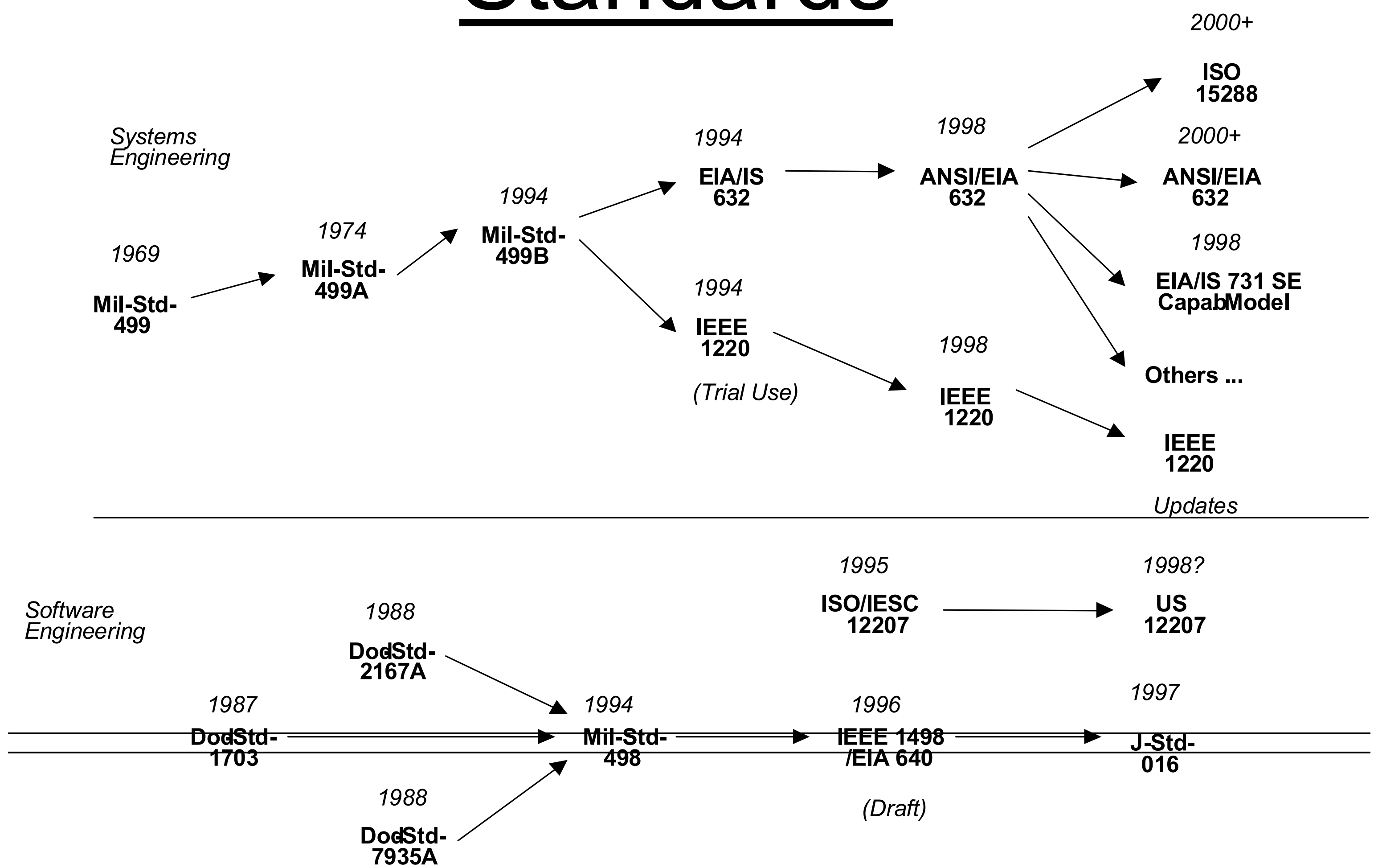
- What was the SE process followed for your case study aircraft?
  - Was it formal or informal?
  - Was it effective?
  - What were some notable practices used?
  - Were there any elements of Lean used, even if they were not called Lean?
- What were the high level requirements?
- Which key requirements drove the system architecture?
  - How did the flowdown of these drive subsystems?
- Develop N^2 diagram for your subsystems.

References

- Scott Jackson, *Systems Engineering for Commercial Aircraft*, Ashgate, 1997
- *Systems Engineering Handbook*, INCOSE*, July 2000
- NASA Systems Engineering Handbook, NASA SP-6105, June 1995
- Petersen, T.J. and Sutcliff, P.L., "Systems Engineering as Applied to the Boeing 777", AIAA Paper 92-1010, Feb, 1992

* International Council of Systems Engineering, www.incose.org

Standards



Application of standards is the realm of Systems Engineers

Source: INCOSE Systems Engineering Handbook