Air Vehicle Design

AOE 4065 – 4066

I. Foundational Elements

Course Module F3

Basics of Systems Engineering

Kevin T. Crofton Department of Aerospace and Ocean Engineering
Blacksburg, VA, USA

AOE 4065-4066:
Capstone Air Vehicle Design (AVD) Course Modules (CMs)

Overview of AVD Courses

I. Foundational Elements

F1. Design: *An Engineering Discipline*

F2. Systems and Systems Thinking

F3. Basics of Systems Engineering

F4. Decision Making with Ethics and Integrity

II. Air Vehicle Design Fundamentals

A1. Purpose & Process

Conceptual Design

A2. Understand the Problem

A3. Solve the Problem

A4. Initial Sizing: *Takeoff Weight Estimation*

A5. Initial Sizing: *Wing Loading and Thrust Loading Estimation*

A6. Cost Considerations

A7. Concept to Configuration: *Key Considerations*

A7A. Configuration Layout: *Drawings & Loft*

Conceptual & Preliminary Design

A8. Trade Studies

A9. Use of Software Tools

A10. Preliminary Design: *Baseline Design Refinement & Validation*

III. Project Management Topics

P1. Basics of Project Management and Project Planning

P2. Project Organization

P3. Roles & Responsibilities of Team Members

P4. Project Execution: *Teamwork for Success*

P5. Project Risk Management

P6. Delivering Effective Oral Presentations

P7. Writing Effective Design Reports

Disclaimer

Profs. H. Pat Artis and Pradeep Raj, Aerospace and Ocean Engineering, Virginia Tech, collected and compiled the material contained herein from publicly available sources solely for educational purposes.

Although a good-faith attempt is made to cite all sources of material, we regret any inadvertent omissions.

CRUCIALLY IMPORTANT

CMs only introduce key topics and highlight some important concepts and ideas…but without sufficient detail.

We must use lots of Reference Material* to add the necessary details!

(*see Appendix in the Overview CM)

Outline

F3. Basics of Systems Engineering

F3.1 SE Overview

F3.2 SE Approach

F3.3 SE Process*

F3.3.1 Process Overview
F3.3.2 Requirements Analysis
F3.3.3 Functional Analysis and Allocation
F3.3.4 Design Synthesis
F3.3.5 Outputs
F3.3.6 Implementation

*Based on *Systems Engineering Fundamentals,* Defense Acquisition University Press, Fort Belvoir, VA, 2001

Systems Engineering (SE) Overview

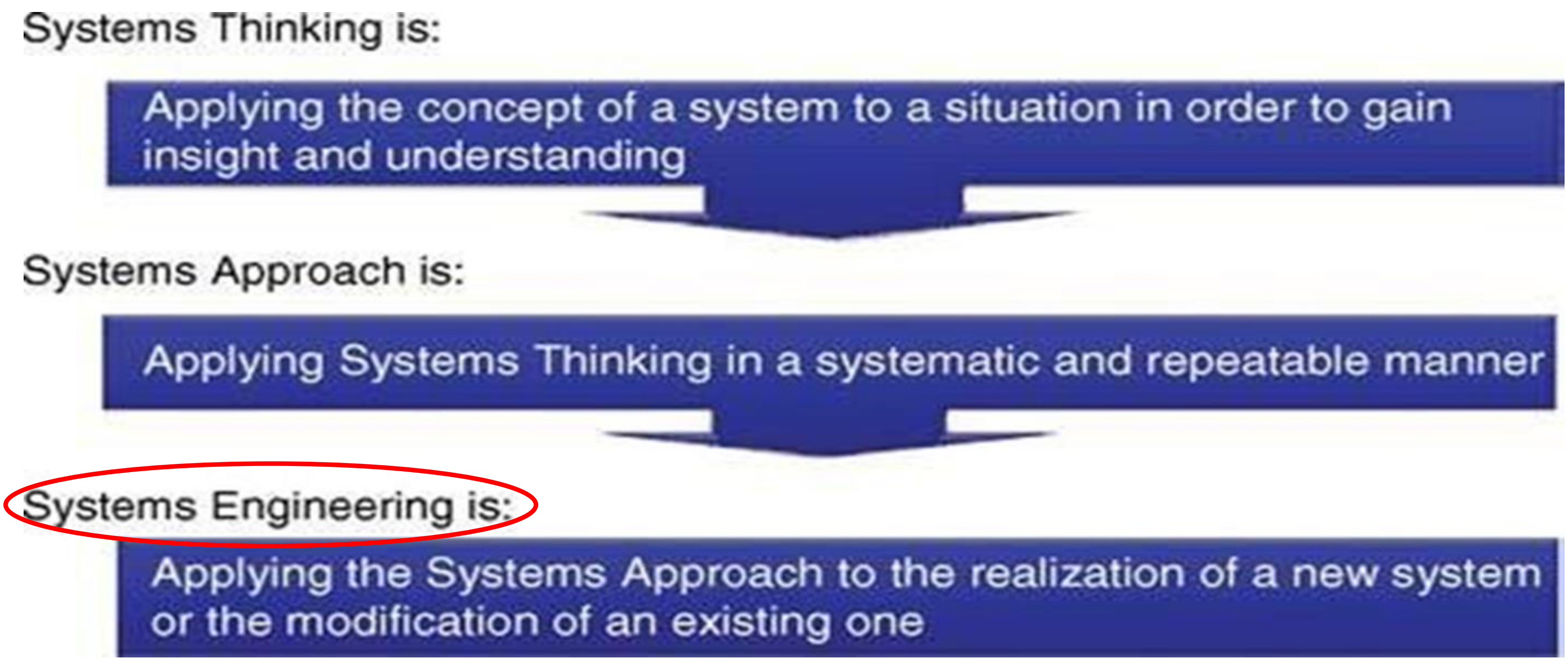
Systems engineering (SE) is a methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system.

Systems engineering is the art and science of developing an operable system capable of meeting requirements within often opposed constraints.

Systems Engineering is a structured methodology with proven tools and processes to guide the engineering of complex systems throughout their life cycle in order to deliver quality, affordable solutions to best meet customer needs.

A branch of engineering which concentrates on the design and application of the whole as distinct from the parts, looking at a problem in its entirety, taking account of all the facets and all the variables and linking the social to the technological.

Role of Systems Thinking in SE



Systems Thinking is:

Applying the concept of a system to a situation in order to gain insight and understanding

Systems Approach is:

Applying Systems Thinking in a systematic and repeatable manner

Systems Engineering is:

Applying the Systems Approach to the realization of a new system or the modification of an existing one

Systems Engineering is Systematic Application of Systems Thinking to Realize a New (or Modified) System

Source: Ref. SE 1

Systems Engineering Definitions

US DoD

(United States Department of Defense)

SE involves design and management of a total system which includes hardware and software, as well as other system life-cycle elements. The systems engineering process is a structured, disciplined and documented technical effort through which systems products and processes are simultaneously defined, developed and integrated. Systems Engineering is most effectively implemented as part of an overall integrated product and process development effort using multi-disciplinary teams.

A logical sequence of activities and decisions that transforms an operational need into a description of system performance parameters and a preferred system configuration. (MIL-STD-499A, *Engineering Management*, 1 May 1974. Now cancelled)

**Systems engineering is
an interdisciplinary engineering management process that evolves and verifies an integrated, life-cycle balanced set of system solutions that satisfy customer needs.**

Systems Engineering Definitions

NASA

(National Aeronautics and Space Administration, 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.

IEEE

(Institute of Electrical and Electronics Engineers, 1994)

An interdisciplinary, collaborative approach that derives, evolves, and verifies a life-cycle balanced system solution which satisfies customer expectations and meets public acceptability. (IEEE P1220, Standard for Application and Management of the Systems Engineering Process, [Final Draft], 26 September 1994.)

Systems Engineering Definitions

INCOSE

(The International Council on Systems Engineering, 2007)

Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem:

- Operations
- Performance
- Test
- Cost and schedule
- Training and Support
- Disposal
- Manufacturing

Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.

Consider the "Whole System" When Making Decisions!

Outline

F3. Basics of Systems Engineering

*Based on *Systems Engineering Fundamentals,* Defense Acquisition University Press, Fort Belvoir, VA, 2001

SE Approach: *Benefits and Drawbacks*

Non-Systems Engineering Approach

Benefits

- Delivers an initial solution concept to the customer quickly and consequently the customer feels good progress is being made

Drawbacks

- The delivered solution is not based upon a complete understanding of the customers' problem and therefore does not always provide a right first-time solution leading to redesigns
- Because the problem is not fully understood issues with the solution are not identified until very late, resulting in a fire-fighting approach to problem resolution
- Piecemeal approach leads to uneven information maturity resulting poor decision making
- Due to the redesign and "fire-fighting", the final system is often delivered late and at a higher cost than planned
- Due to the piecemeal approach and "fire-fighting" subsequent system upgrades are difficult and costly

Source: Ref. SE 1

Systems Engineering Approach

Benefits

- Faster delivery of the correct solution because more work is done up front, in the early stages, to avoid fire-fighting later at the back-end
- Better solution because the solution space is fully populated and systematically explored leading to greater innovation and robust designs
- Lower overall costs because the approach proactively looks for issues resolving them before they are designed-in
- Better communication and information maturity through:
  - a logical and systematic approach, with traceable and visible decision making and an abundance of shared information leading to better corporate learning.
  - building generic system models which are reusable in future designs. This ultimately leads to better control of the system development and its evolution thereby reducing risk.
  - the use of tools that aid true multi-disciplinary team-working leading to
    - a greater consensus in decision making.
    - early identification of errors
- Promotes a life-cycle view making systems less expensive to operate and easy to upgrade

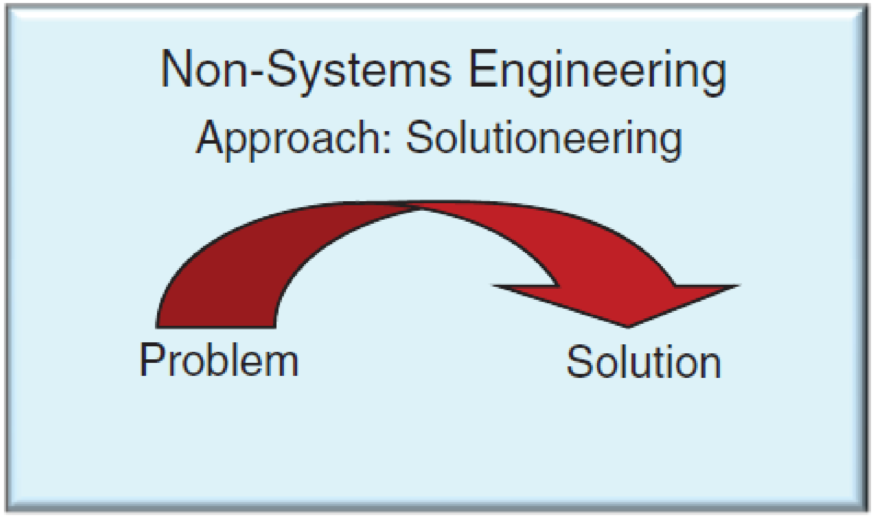
Drawbacks

- Takes time to deliver the initial solution concept to the customer giving the impression progress is not being made

Non-SE vs SE Approaches

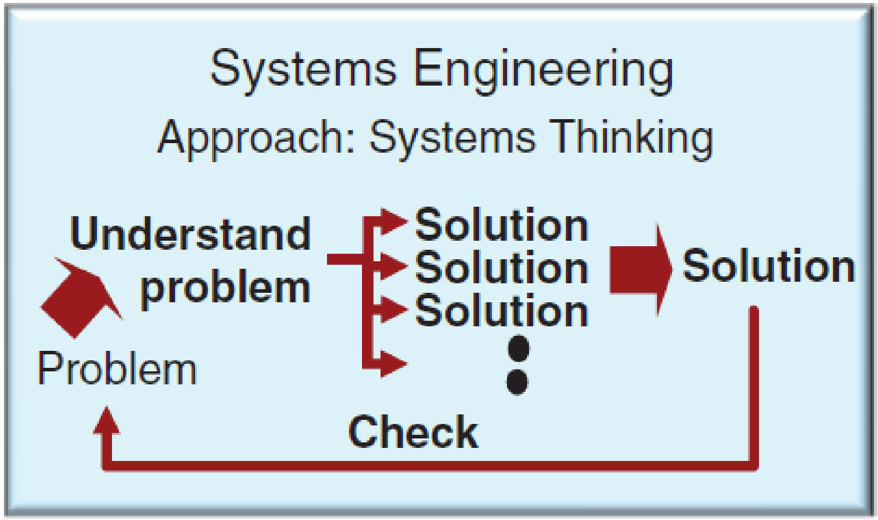
Non-Systems Engineering (Non-SE) Approach: ‘*Solutioneering*’

- Predicated on very quickly offering the customer an answer to their problem.


Non-Systems Engineering
Approach: Solutioneering

Systems Engineering (SE) Approach: ‘*Systems Thinking*’

- Does not provide a quick answer because it puts time and effort into understanding the problem at a profound level *before* identifying all possible solutions and searching for the best.


Systems Engineering
Approach: Systems Thinking

Source: Ref. SE 1

SE Follows a Convoluted Path

- Analysis and exploration of the problem to gain a profound understanding of what is required
- Identification of all possible solutions to the problem
- Evaluation of the possible solutions to determine the ***best*** solution
- Verification and validation of the solution to be sure that it indeed solves the problem

Unlike 'solutioneering,' good SE practice can be counterintuitive and goes against a human trait: giving a quick answer to a problem is a positive quality.

Succumbing to this trait leads to the inevitable retreat to the old tried and tested non-SE ways that, with a liberal dose of fire-fighting, will get there eventually!

Source: Ref. SE 1

SE: *Purpose*

To **guide** the **engineering** of **systems** that are **complex**

guide

- To lead, manage or direct, usually based on superior experience
- To show the way

engineering

- The application of scientific principles to practical ends
- Design, construction, and operation of *efficient* and *economical* structures, equipment, and systems

system

- An assembly of electronic, electrical or mechanical components with *interdependent* functions, usually forming a self-contained unit.
- A set of *interrelated/ interconnected* elements that working together produce results not obtainable by individual elements.

complex

- [constituent] elements of the system are diverse and have intricate relationships with one another

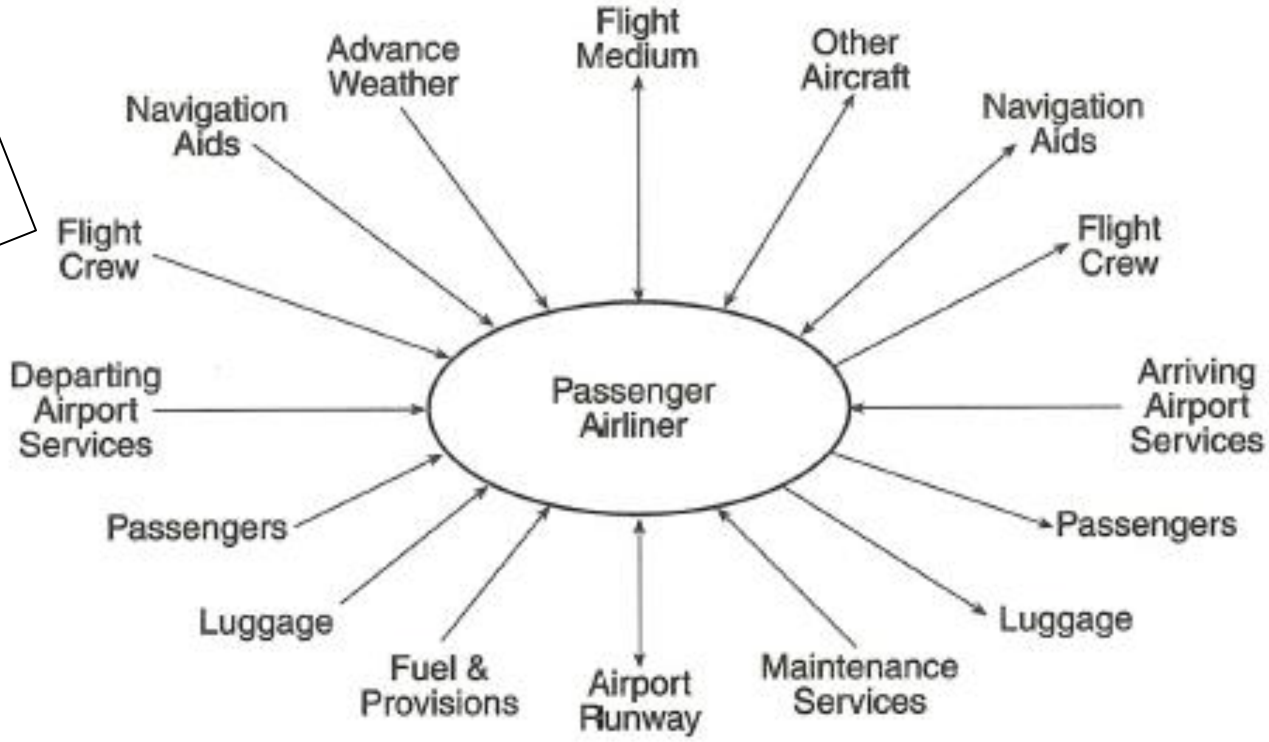
Enable Delivery of the Best Integrated System Solutions On Time and On Budget!

Source: Ref. SE 2 (Kossiakoff and Sweet)

SE: *Context Diagram*
Example--*Passenger Airliner*

- Depicts a high level view of the system--*as a whole*--and its inputs and outputs from/to external elements/factors in its environment
- Defines the boundary between the system and its environment, showing the entities that interact with it

Context Diagram for a passenger airliner



Many diverse effects must be considered in developing a complex system!

Source: Fig. 14-2, Ref. SE 2 (Kossiakoff and Sweet)

SE: Context Diagram Example

The Aviation System

Numerous stakeholders have a different perspective of, and influence on, system design!

Source: Fig. 1.1, Ref. AS 2 (Moir and Seabridge)

SE: ***Principles***

1. **Start with Your Eye on the Finish Line**
    - Agree on what will constitute success at the end, what the measures of success are
2. **Stakeholder Involvement is Key to Success**
    - Involve customer, users, operators, and others in the project development
3. **Define the Problem *Before* Implementing the Solution**
    - Determine the best solution on the basis of a clear understanding of the requirements
4. **Delay Specifying* Technology Choices**
    - Define needs, requirements, and high-level design *before specifying technology*
5. **"Divide and Conquer"**
    - Break down a big system problem into many smaller components that can be individually solved and then recombined
6. **Connecting the Dots – Traceability**
    - Relates a requirement to the subsystem that will implement the requirement
    - Allows you to be certain that the final system at the end is directly connected with the user needs that were identified at the beginning.

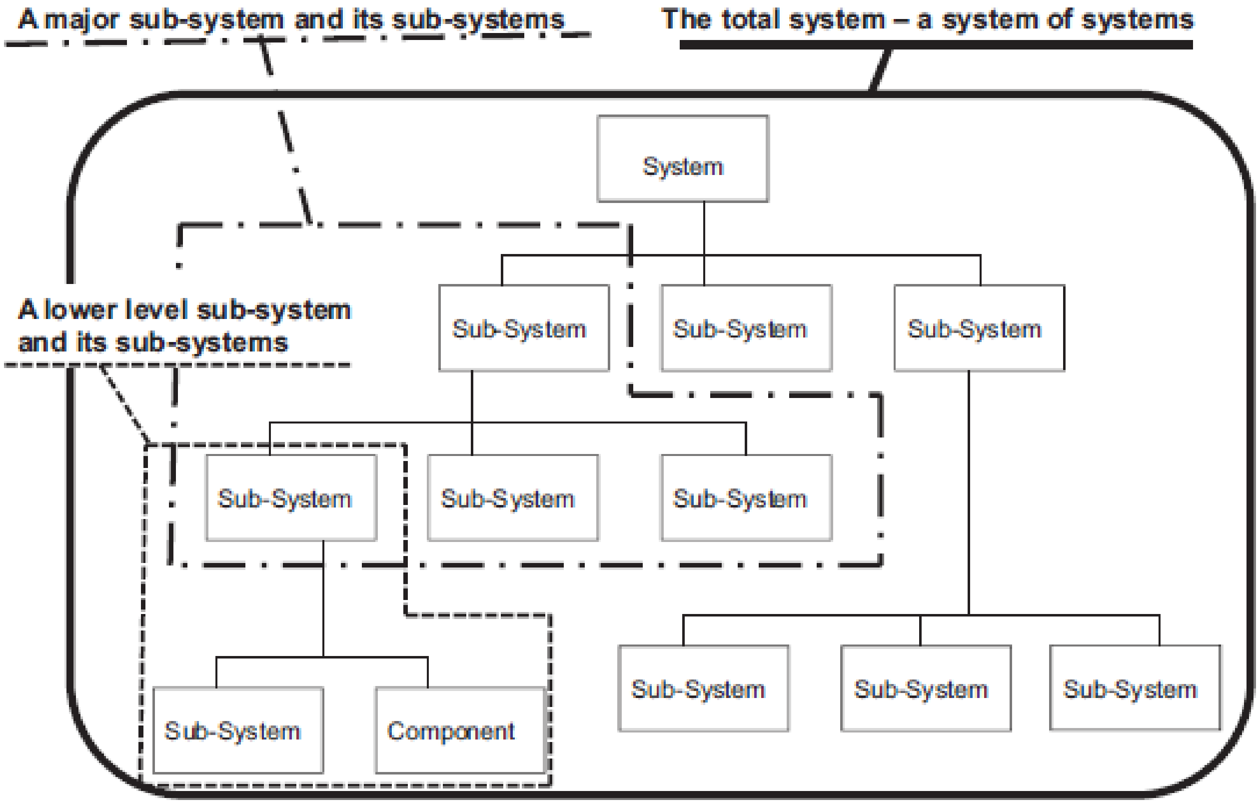
Key to Successful Realization of Complex Systems

Source: Adapted from Systems Engineering for Intelligent Transportation Systems, USDOT
http://ops.fhwa.dot.gov/publications/seitsguide/section3.htm

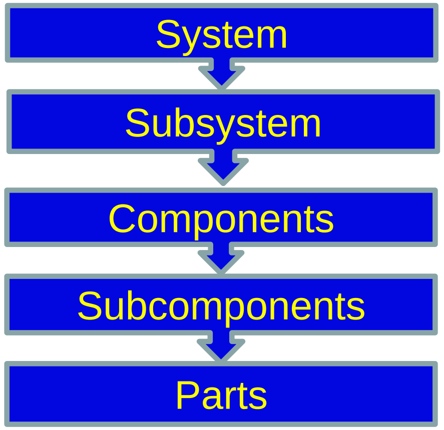
****does not imply identifying, which must be done early***

SE: *Perspective*

Systems viewed as a top-down multi-level hierarchical structure



A Typical System Decomposition


System

Subsystem

Components

Subcomponents

Parts

Number of levels depends on

- Complexity of the system
- Ability to view functions and interfaces

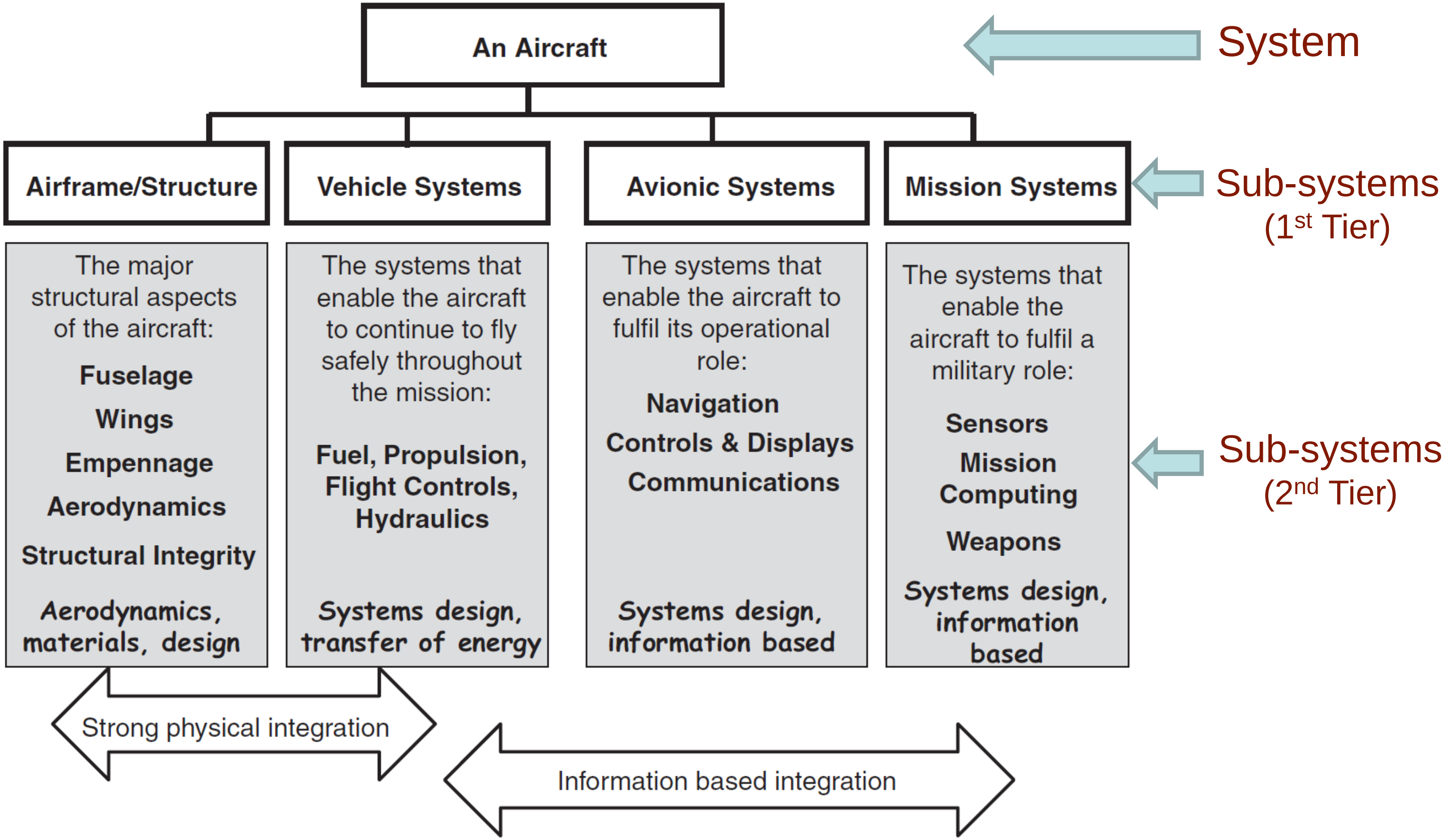
Also known as System Decomposition

- Easier to understand, design, and maintain

"That's NOT what I meant when I said we need to decompose our computer system!"

Source: Fig. 1.2, Ref. SE 2 (Moir and Seabridge)

Example of a Top-down Hierarchical Decomposition of an Aircraft



An Aircraft — System

Sub-systems (1st Tier):

- **Airframe/Structure**
- **Vehicle Systems**
- **Avionic Systems**
- **Mission Systems**

Sub-systems (2nd Tier):

Airframe/Structure	Vehicle Systems	Avionic Systems	Mission Systems
The major structural aspects of the aircraft:	The systems that enable the aircraft to continue to fly safely throughout the mission:	The systems that enable the aircraft to fulfil its operational role:	The systems that enable the aircraft to fulfil a military role:
Fuselage **Wings** **Empennage** **Aerodynamics** **Structural Integrity**	**Fuel, Propulsion, Flight Controls, Hydraulics**	**Navigation** **Controls & Displays** **Communications**	**Sensors** **Mission Computing** **Weapons**
Aerodynamics, materials, design	*Systems design, transfer of energy*	*Systems design, information based*	*Systems design, information based*

Strong physical integration

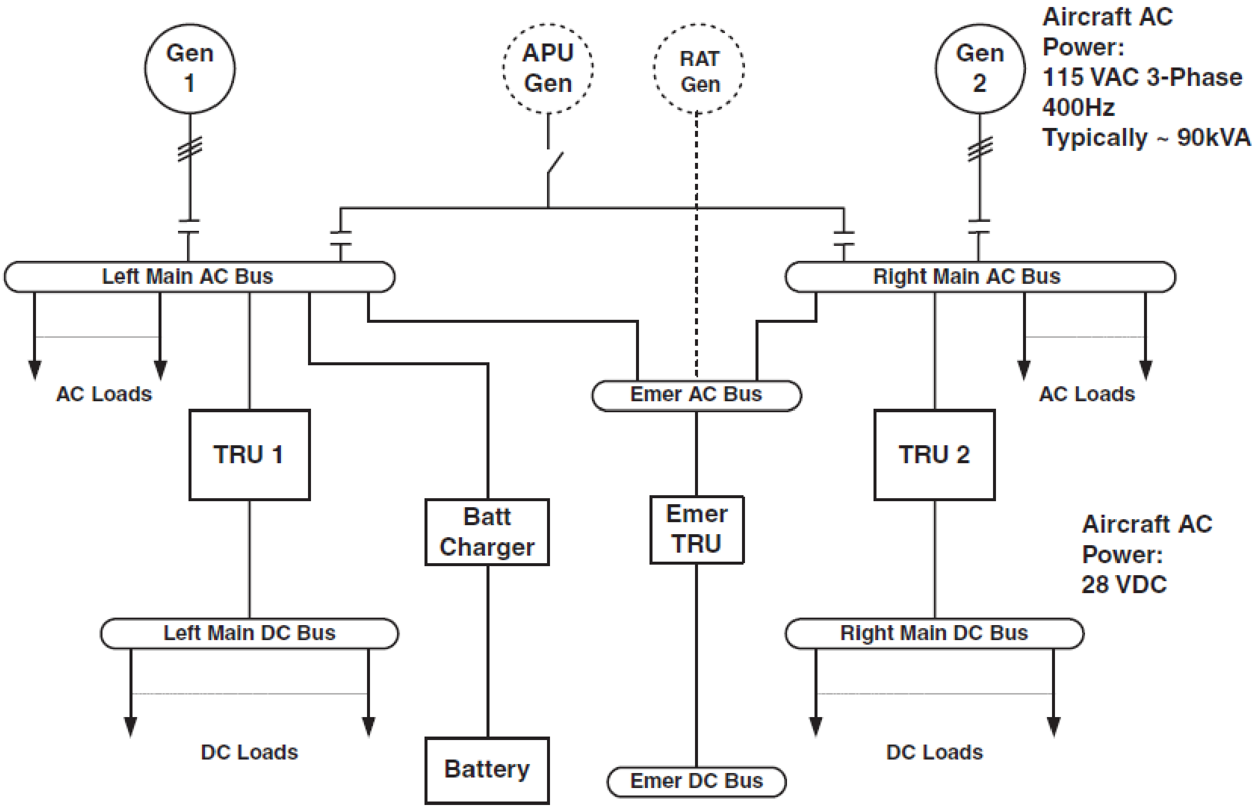
Information based integration

The Key to Success is Integration!

Source: Fig. 2.6, Ref. AS 2 (Moir and Seabridge)

A Typical Aircraft Electrical System

A 2nd Tier Subsystem of 1st Tier Vehicle Systems



Aircraft AC Power:
115 VAC 3-Phase
400Hz
Typically ~ 90kVA

Aircraft AC Power:
28 VDC

Notes:

Most High power loads are 115 VAC

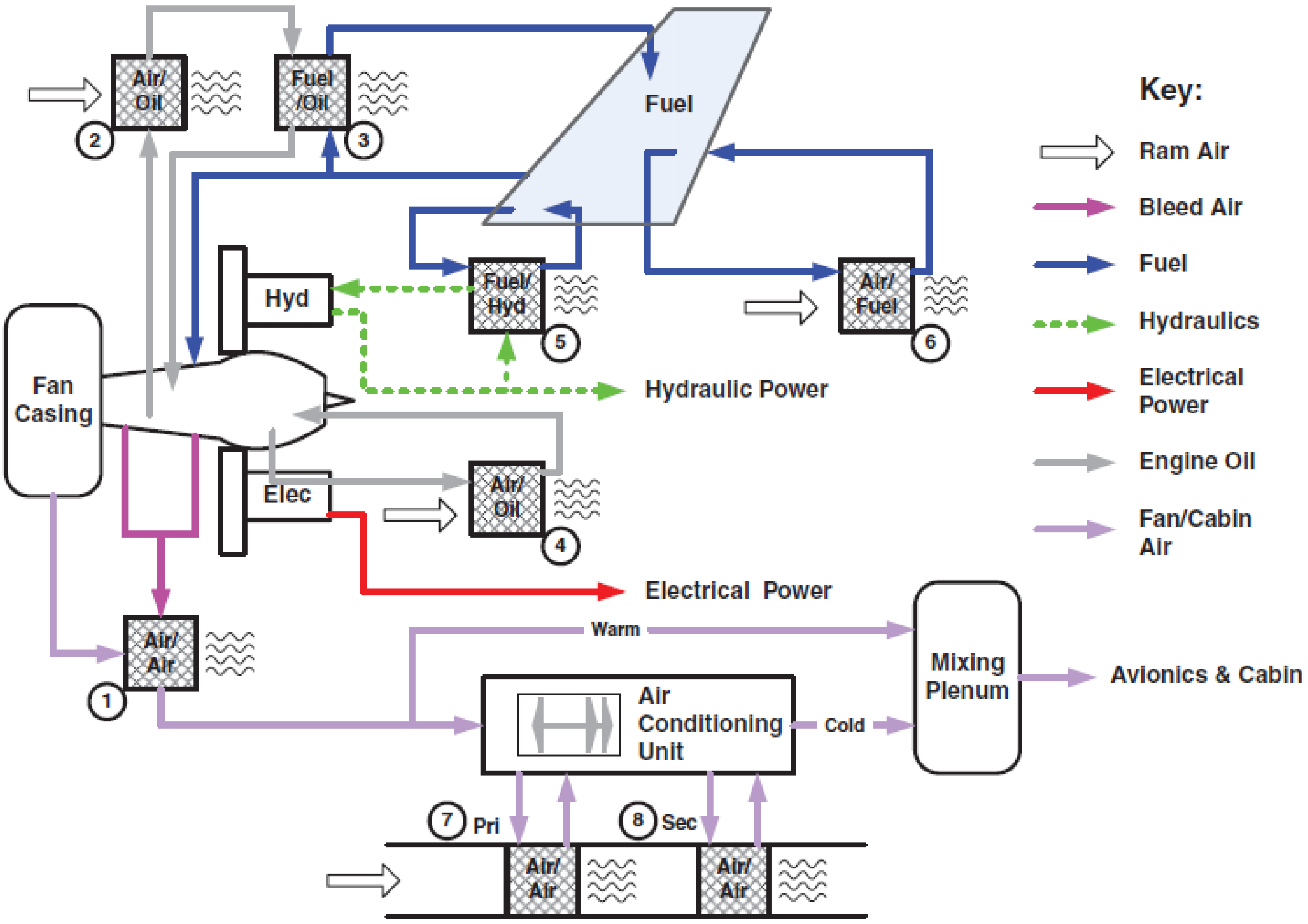
Most Electronic/Avionic Loads are 28 VDC

A relatively simple subsystem of a complex aircraft system

Source: Fig. 11.1, Ref. AS 2 (Moir and Seabridge)

An Aircraft Thermal Management System

A 2nd Tier Subsystem of 1st Tier Vehicle Systems



Eight heat exchangers use ram air and fuel to manage waste heat

A somewhat complex subsystem of the full aircraft system

Source: Fig. 2.7, Ref. AS 2 (Moir and Seabridge)

Outline

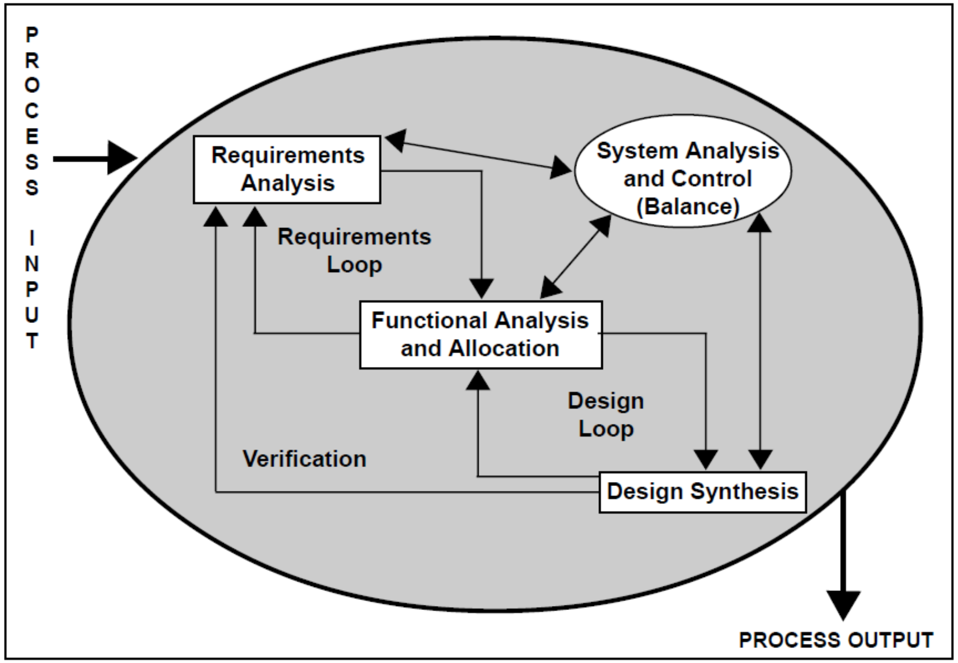
F3. Basics of Systems Engineering

*Based on *Systems Engineering Fundamentals,* Defense Acquisition University Press, Fort Belvoir, VA, 2001

Systems Engineering: *Process*

A top-down comprehensive, iterative, and recursive problem solving process, applied sequentially through all levels (or stages) of system development, that is used to

- Transform needs and requirements into a set of system product and process descriptions
- Generate information for decision makers
- Provide input for the next level of development



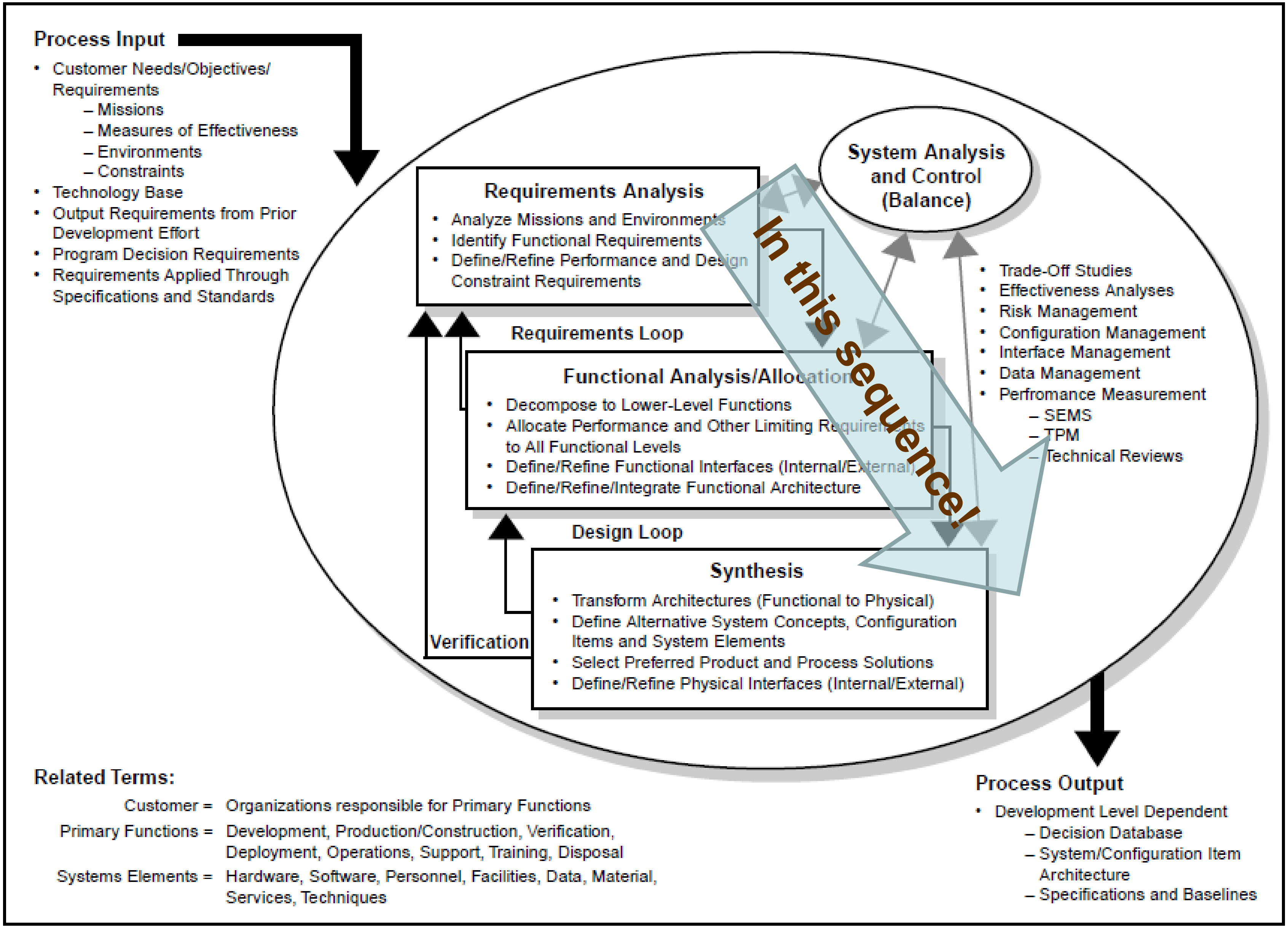
Application of SE Process produces ‘configuration baselines’ including specifications which become more detailed with each level of development

- *Concept Level Development*—description of system concept
- *System Level Development*—description of system in terms of performance requirements
- *Subsystem/Component Level Development*—description of performance of a set of subsystems and component products, then a set of detailed descriptions of products’ characteristics, essential for their production

Throughout the process, configurations must be controlled and risks must be managed.

Source: Ref. SE 5

Systems Engineering: *Process*



Process Input

- Customer Needs/Objectives/ Requirements
  - Missions
  - Measures of Effectiveness
  - Environments
  - Constraints
- Technology Base
- Output Requirements from Prior Development Effort
- Program Decision Requirements
- Requirements Applied Through Specifications and Standards

Requirements Analysis

- Analyze Missions and Environments
- Identify Functional Requirements
- Define/Refine Performance and Design Constraint Requirements

System Analysis and Control (Balance)

- Trade-Off Studies
- Effectiveness Analyses
- Risk Management
- Configuration Management
- Interface Management
- Data Management
- Perfromance Measurement
  - SEMS
  - TPM
  - Technical Reviews

Requirements Loop

Functional Analysis/Allocation

- Decompose to Lower-Level Functions
- Allocate Performance and Other Limiting Requirements to All Functional Levels
- Define/Refine Functional Interfaces (Internal/External)
- Define/Refine/Integrate Functional Architecture

Design Loop

Verification

Synthesis

- Transform Architectures (Functional to Physical)
- Define Alternative System Concepts, Configuration Items and System Elements
- Select Preferred Product and Process Solutions
- Define/Refine Physical Interfaces (Internal/External)

In this sequence!

Related Terms:

Customer = Organizations responsible for Primary Functions
Primary Functions = Development, Production/Construction, Verification, Deployment, Operations, Support, Training, Disposal
Systems Elements = Hardware, Software, Personnel, Facilities, Data, Material, Services, Techniques

Process Output

- Development Level Dependent
  - Decision Database
  - System/Configuration Item Architecture
  - Specifications and Baselines

Source: Ref. SE 5

Outline

F3. Basics of Systems Engineering

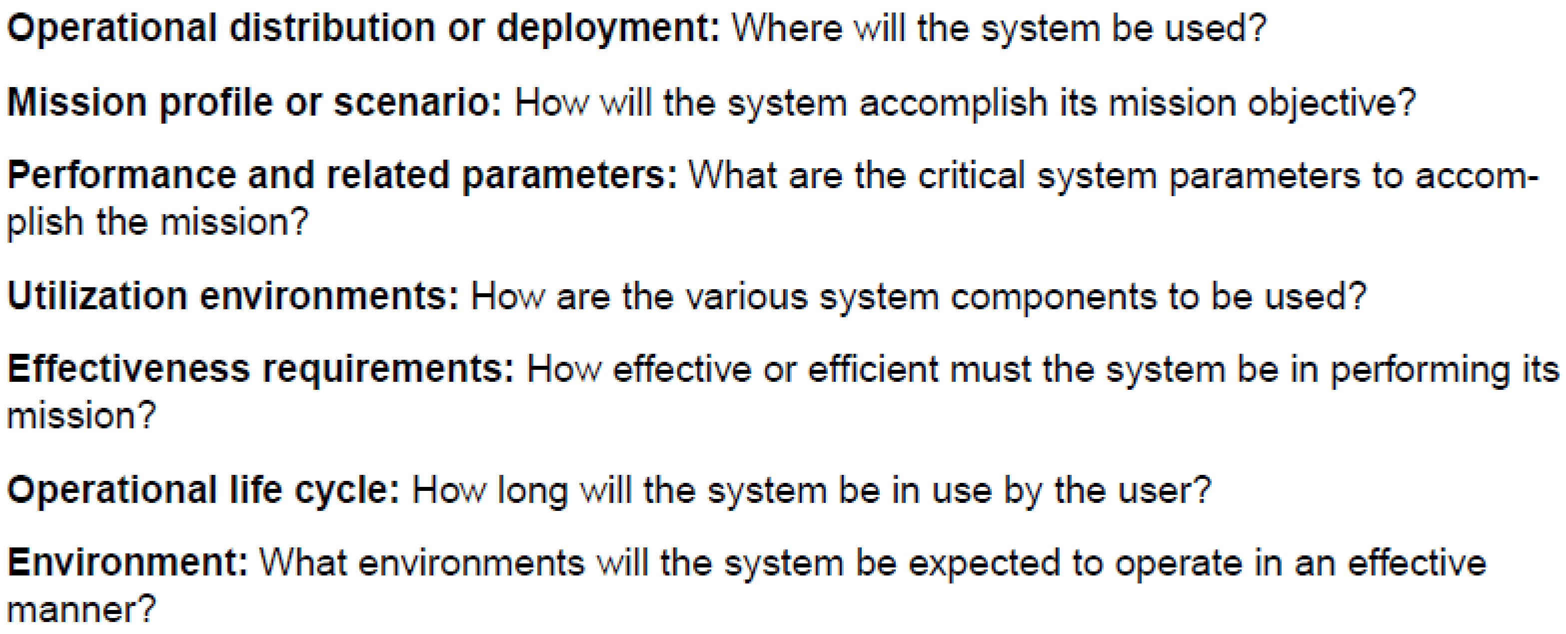
*Based on *Systems Engineering Fundamentals,* Defense Acquisition University Press, Fort Belvoir, VA, 2001

SE Process: *Requirements Analysis*

Solving the design problem must start with analyzing the requirements and determining what the system has to do <u>before</u> physical alternatives are chosen.

<u>Common Categorization of Requirements</u>

- **Customer Requirements** define expectations of the system in terms of mission objectives, environment, constraints, measures of effectiveness and suitability. Operational requirements define the basic need and answer the questions listed below



Operational distribution or deployment: Where will the system be used?

Mission profile or scenario: How will the system accomplish its mission objective?

Performance and related parameters: What are the critical system parameters to accomplish the mission?

Utilization environments: How are the various system components to be used?

Effectiveness requirements: How effective or efficient must the system be in performing its mission?

Operational life cycle: How long will the system be in use by the user?

Environment: What environments will the system be expected to operate in an effective manner?

Source: Ref. SE 5

SE Process: *Requirements Analysis*

Common Categorization of Requirements (contd.)

- **Functional Requirements** define the necessary task, action or activity that *must* be accomplished by the system
- **Performance Requirements** define the extent to which a mission or function must be executed, i.e., how well does it have to be done; generally measured in terms of quantity, quality, coverage, timeliness, or readiness
- **Design Requirements** define the "build to," "code to," and "buy to" requirements for products, and "how to execute" for processes, all expressed in technical data packages and technical manuals
- **Derived Requirements** define the implied requirement, e.g., requirement for long range or high speed may result in a design requirement for low weight
- **Allocated Requirements** established by allocating high-level requirement into multiple lower-level requirements, e.g., a 100-pound system that consists of two subsystems might result in weight requirements of 70 pounds and 30 pounds allocated for the two lower-level subsystems

Source: Ref. SE 5

SE Process: *Requirements Analysis*

Attributes of Good Requirements

- **Achievable**—reflect a need for which a solution is technically achievable at costs considered affordable
- **Verifiable**—not defined by words such as excessive, sufficient, resistant, etc. Expressed in a manner that allows verification, preferably quantitative
- **Unambiguous**—must have but one possible meaning
- **Complete**—must contain all mission profiles, operational and maintenance concepts, utilization environments, and constraints: all information necessary to understand customer's need must be there
- **Need, *not Solution***—expressed in terms of need, not solution, i.e., *address the "why" and "what," not "how"*
- **Consistent**—each requirement must be consistent with other requirements; conflicts must be resolved up front
- **Appropriate for Level of System Hierarchy**—should not be too detailed to constrain solutions for the current level of design, e.g., detailed requirements related to components would not normally be in a system-level specification

Source: Ref. SE 5

SE Process: *Requirements Analysis*

Desired Outcome

A clear understanding of

- **Functions**: what the system has to do—spelled out in terms of *discrete actions* (verbs, not nouns, e.g., fly not flight or stable not stability)—to achieve the objectives
- **Performance**: how well the functions have to be performed
- **Interfaces**: environment in which the system will perform
- **Other requirements and constraints**

Understandings from Requirements Analysis establish the basis for Functional and Physical design to follow.

Thorough Requirements Analysis is Fundamental to Successful Design

Source: Ref. SE 5

SE Process: *Requirements Analysis*

Typical Questions to Initiate the Thought Process

- What are the reasons behind the system development? Why does the customer have this need?
- What are the customer expectations?
- Who are the users and how do they intend to use the product?
- What do the users expect of the product?
- What is their level of expertise?
- With what environmental characteristics must the system comply?
- What are the interfaces?
- What functions will the system perform, expressed in customer language?
- What are the constraints (hardware, software, economic, procedural) that the system must meet?
- What will be the final form of the product, such as model, prototype, or mass production?

Note: It’s only the beginning! Consider developing a *tailored procedure* to produce the necessary outputs *(see Supplement 4-A, Systems Engineering Fundamentals, Defense Acquisition University, Jan 2001)*

Source: Ref. SE 5

SE Process: *Requirements Analysis*

Outputs

Operational View addresses **WHY** the user needs the system and how it will serve its users

- Operational need definition
- System missions
- Operational sequences
- Operational environments
- Operational constraints on the system
- Mission performance requirements
- User and maintainer roles
- Operational interfaces with other systems
- Events to which a system must respond
- Structure of the organizations that will operate, support, and maintain the system

Functional View focuses on **WHAT** the system must do to produce the required operational behavior

- System functions
- Tasks or actions to be performed
- System performance
- Inter-function relationships
- Hardware and software functional relationships
- Performance constraints
- Interface requirements
- Unique hardware or software
- Verification requirements (including inspection, analysis/simulation, demo, and test)

Source: Ref. SE 5

SE Process: *Requirements Analysis*

Outputs (contd.)

Physical View focuses on **HOW** the system is constructed

- System Configuration
  - Interface descriptions
  - Characteristics of information displays and operator controls
  - Relationships of operators to system/physical equipment
  - Operator skills and levels required to perform assigned functions
- Characterization of Users
  - Handicaps (special operating environments)
  - Constraints (movement or visual limitations)
- System Physical Limitations
  - Physical limitations (capacity, power, size, weight)
  - Technology limitations (range, precision, data rates, frequency, language)
  - Government Furnished Equipment (GFE), Commercial-of-the-shelf (COTS), reusability requirements
  - Necessary or directed standards

All three views are necessary and must be coordinated to fully understand the customer's needs and objectives.

Source: Ref. SE 5

Outline

F3. Basics of Systems Engineering

F3.1 SE Overview

F3.2 SE Approach

F3.3 SE Process*

- F3.3.1 Process Overview
- F3.3.2 Requirements Analysis
- **F3.3.3 Functional Analysis and Allocation**
- F3.3.4 Design Synthesis
- F3.3.5 Outputs
- F3.3.6 Implementation

*Based on *Systems Engineering Fundamentals,* Defense Acquisition University Press, Fort Belvoir, VA, 2001

SE Process: *Functional Analysis and Allocation*

Overview

Purpose: Transform the functional, performance, interface, and other requirements [from the Requirements Analysis step] into a coherent description of system functions to guide the Design Synthesis step.

Accomplished by

(a) arranging functions in logical sequences;
(b) decomposing higher-level functions into lower-level functions; and
(c) allocating performance from higher- to lower-level functions.

Output is a functional architecture, i.e., a description of the system in terms of functions and performance parameters, *NOT a physical description.*

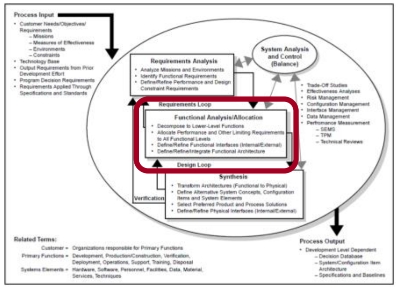
Functions are discrete actions (verbs, not nouns) necessary to achieve the objectives. May be stated explicitly [in RFP] or derived from stated requirements.

Functions will ultimately be performed and accomplished through the use of equipment, personnel, facilities, software, or a combination.

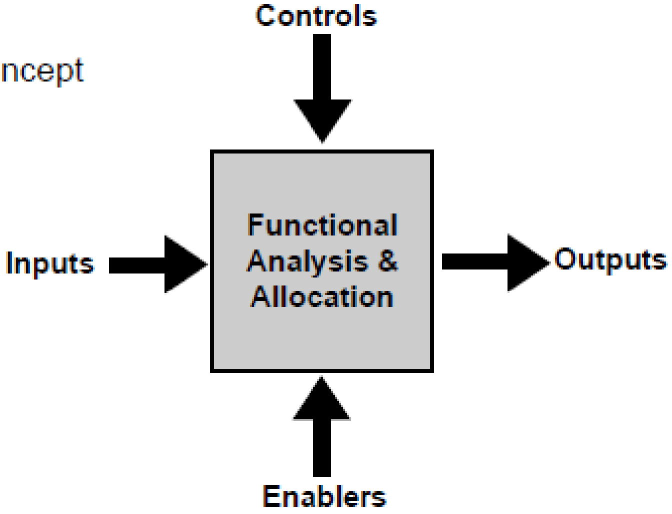
Purpose is NOT to Design a Solution…Yet!

Source: Ref. SE 5

SE Process:
Functional Analysis and Allocation



- **Outputs:**
  - Functional architecture and supporting detail
- **Inputs:**
  - Outputs of the Requirements Analysis
- **Enablers:**
  - Multi-discipline product teams, decision database; Tools & Models, such as QFD, Functional Flow Block Diagrams, IDEF, N2 charts, Requirement Allocation Sheet, Timelines, Data Flow Diagrams, State/Mode Diagrams, Behavior Diagrams
- **Controls:**
  - Constraints; GFE, COTS, & Reusable S/W; System concept & subsystem choices; organizational procedures
- **Activities:**
  - Define system states and modes
  - Define system functions & external interfaces
  - Define functional interfaces
  - Allocate performance requirements to functions
  - Analyze performance
  - Analyze timing and resources
  - Analyze failure mode effects and criticality
  - Define fault detection and recovery behavior
  - Integrate functions



Controls

Inputs

Functional Analysis & Allocation

Outputs

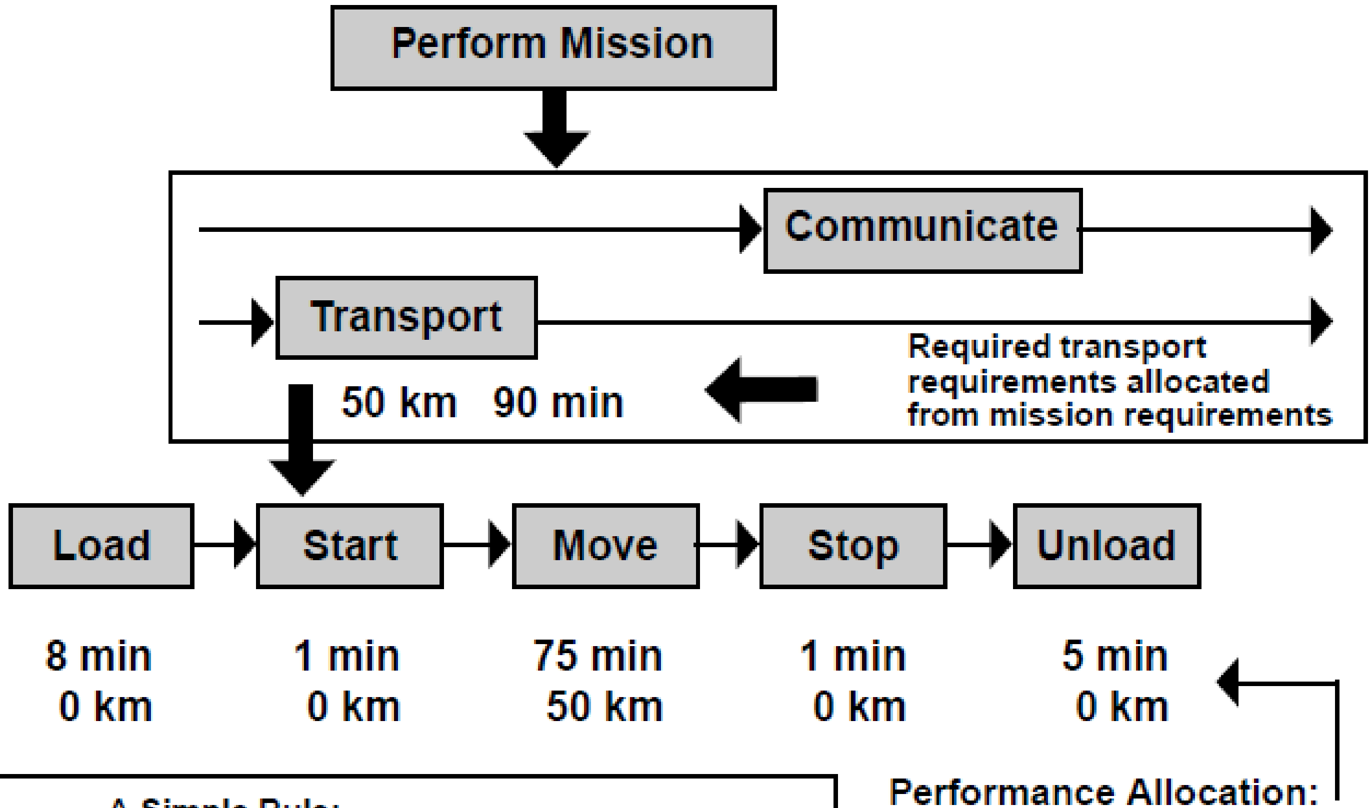
Enablers

Source: Ref. SE 5

SE Process:
Functional Analysis and Allocation

Functional Architecture Example

Marine Corps Requirements: transport troops [squad-level units] 50 km within 90 minutes, and maintain constant communication during transportation.



First Level:
Basic Functional Requirement

Second Level:
Transport and communicate showing as parallel functions

Third Level:
Showing decomposition of the transport function

A Simple Rule:
Look to see if all the functions are verbs. If there is a function identified as a noun, then there is a problem with the understanding of the functions.

Performance Allocation:
Performance requirements allocated to functions

Source: Ref. SE 5

Outline

F3. Basics of Systems Engineering

F3.1 SE Overview

F3.2 SE Approach

F3.3 SE Process*

- F3.3.1 Process Overview
- F3.3.2 Requirements Analysis
- F3.3.3 Functional Analysis and Allocation
- F3.3.4 Design Synthesis
- F3.3.5 Outputs
- F3.3.6 Implementation

*Based on *Systems Engineering Fundamentals,* Defense Acquisition University Press, Fort Belvoir, VA, 2001

SE Process: *Design Synthesis*

Overview

Purpose: **Develop a physical architecture (a set of product, system, and/or software elements) capable of performing the required functions subject to the prescribed performance parameters.**

It's a creative activity that produces

(a) System concepts and basic relationships among the subsystems during the Concept Development stage;

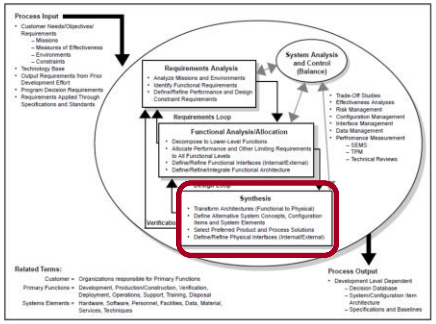
(b) Subsystem and component descriptions with detailed interfaces between all system components during System Development stage

Physical architecture forms the basis for baselines, specifications, and work breakdown structure (WBS). Its key characteristics are:

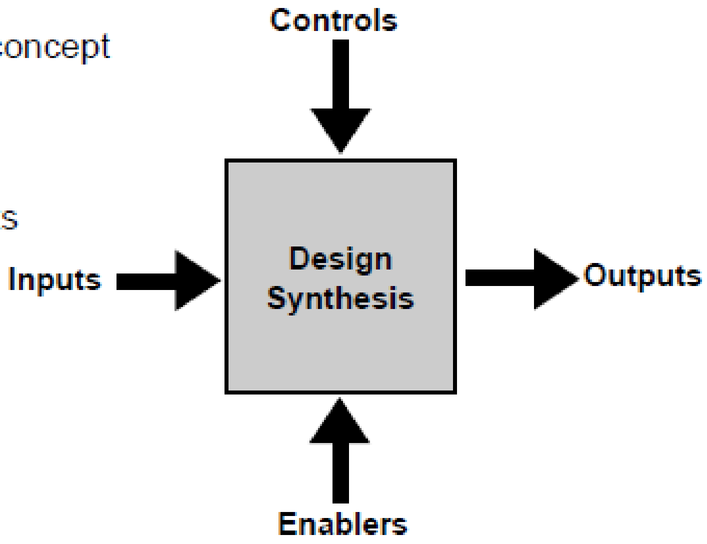
- Each component meets at least one (or part of one) functional requirement, though one component can meet more than one
- Trade studies and effectiveness analyses justify the architecture
- WBS developed from the physical architecture
- Metrics to track progress among key performance parameters (KPPs)
- All supporting information documented in a database

Source: Ref. SE 5

SE Process: *Design Synthesis*



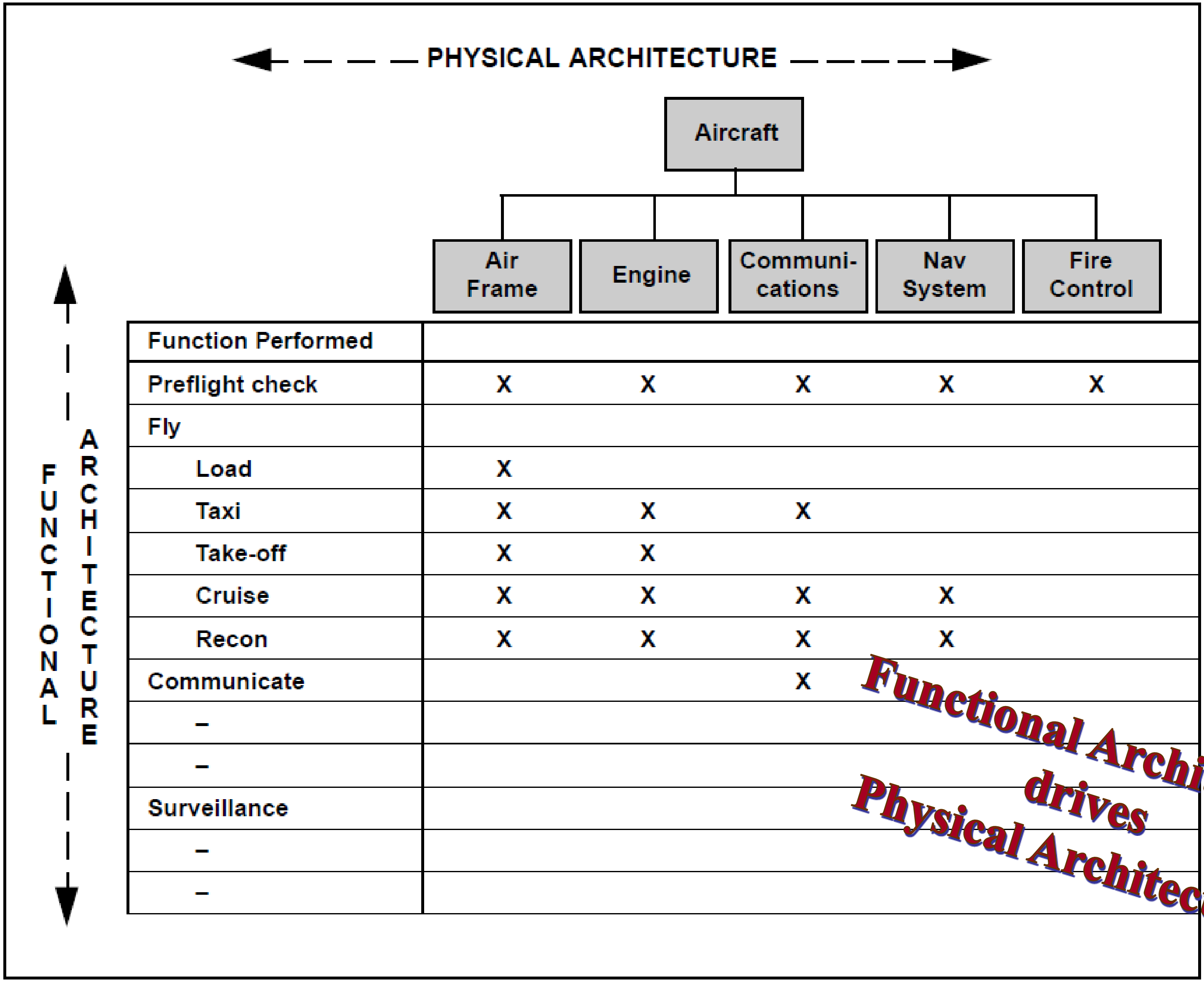
- **Outputs:**
  - – Physical Architecture (Product Elements and Software Code)
  - – Decision Database
- **Inputs:**
  - – Functional Architecture
- **Enablers:**
  - – IPTs, Decision Database, Automated Tools, Models
- **Controls:**
  - – Constraints; GFE, COTS, & Reusable S/W; System concept & subsystem choices; organizational procedures
- **Activities:**
  - – Allocate functions and constraints to system elements
  - – Synthesize system element alternatives
  - – Assess technology alternatives
  - – Define physical interfaces
  - – Define system product WBS
  - – Develop life cycle techniques and procedures
  - – Integrate system elements
  - – Select preferred concept/design



Source: Ref. SE 5

SE Process: *Design Synthesis*

Example of Functional/Physical Mapping Matrix



Function Performed	Air Frame	Engine	Communi-cations	Nav System	Fire Control
Preflight check	X	X	X	X	X
Fly					
Load	X				
Taxi	X	X	X		
Take-off	X	X			
Cruise	X	X	X	X	
Recon	X	X	X	X	
Communicate			X		
–					
–					
Surveillance					
–					
–					

Functional Architecture drives Physical Architecture

Source: Ref. SE 5

Outline

F3. Basics of Systems Engineering

F3.1 SE Overview

F3.2 SE Approach

F3.3 SE Process*

- F3.3.1 Process Overview
- F3.3.2 Requirements Analysis
- F3.3.3 Functional Analysis and Allocation
- F3.3.4 Design Synthesis
- F3.3.5 Outputs
- F3.3.6 Implementation

*Based on *Systems Engineering Fundamentals,* Defense Acquisition University Press, Fort Belvoir, VA, 2001

SE Process: *Outputs*

Outputs are documents that contain system requirements and design solutions.

Key documents include

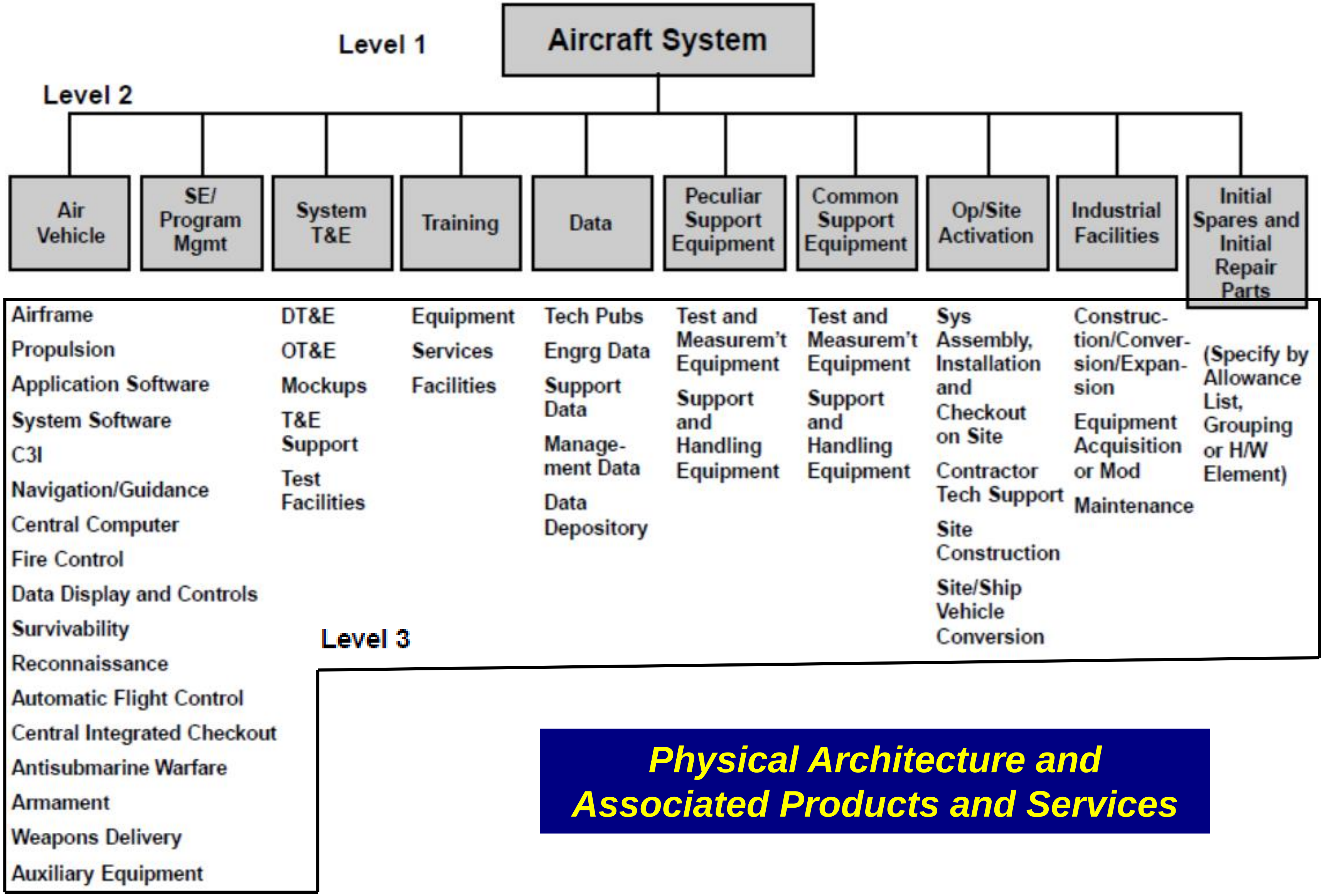
- **System and Configuration Item Architectures Documents**
    - Complete SYSTEM ARCHITECTURE: Physical architecture expanded to include enabling products and services
- **Specifications and Baselines Documents**
    - Describes the essential technical requirements for items, materials, or services including the procedures to determine that the requirements have been met. This helps avoid duplication and inconsistencies, and provides guidance to testers
    - Program-unique specifications form the core of configuration baselines that are defined at different levels within the system hierarchy in different phases of the design process. These baselines are used to manage and control technical development
- **Decision Database Documents**
    - Supports and explains the configuration solution decisions
    - Includes trade studies, cost-effectiveness analyses, models, simulations, etc.

Each document becomes increasingly technically detailed as system definition proceeds from concept to detailed design.

Source: Ref. SE 5

SE Process: *Outputs*

A. System Architecture



Level 1

Aircraft System

Level 2

- Air Vehicle
  - Airframe
  - Propulsion
  - Application Software
  - System Software
  - C3I
  - Navigation/Guidance
  - Central Computer
  - Fire Control
  - Data Display and Controls
  - Survivability
  - Reconnaissance
  - Automatic Flight Control
  - Central Integrated Checkout
  - Antisubmarine Warfare
  - Armament
  - Weapons Delivery
  - Auxiliary Equipment
- SE/ Program Mgmt
- System T&E
  - DT&E
  - OT&E
  - Mockups
  - T&E Support
  - Test Facilities
- Training
  - Equipment
  - Services
  - Facilities
- Data
  - Tech Pubs
  - Engrg Data
  - Support Data
  - Management Data
  - Data Depository
- Peculiar Support Equipment
  - Test and Measurem't Equipment
  - Support and Handling Equipment
- Common Support Equipment
  - Test and Measurem't Equipment
  - Support and Handling Equipment
- Op/Site Activation
  - Sys Assembly, Installation and Checkout on Site
  - Contractor Tech Support
  - Site Construction
  - Site/Ship Vehicle Conversion
- Industrial Facilities
  - Construction/Conversion/Expansion
  - Equipment Acquisition or Mod
  - Maintenance
- Initial Spares and Initial Repair Parts
  - (Specify by Allowance List, Grouping or H/W Element)

Level 3

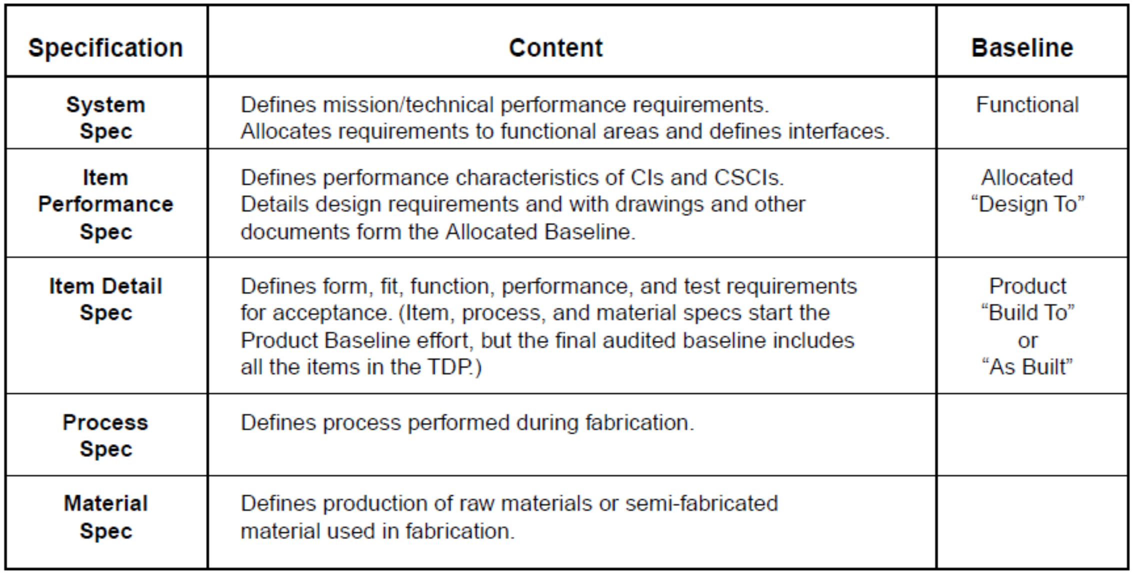
Physical Architecture and Associated Products and Services

Source: Ref. SE 5

SE Process: *Outputs*

B. Specifications

Table of Specification Types



Specification	Content	Baseline
System Spec	Defines mission/technical performance requirements. Allocates requirements to functional areas and defines interfaces.	Functional
Item Performance Spec	Defines performance characteristics of CIs and CSCIs. Details design requirements and with drawings and other documents form the Allocated Baseline.	Allocated "Design To"
Item Detail Spec	Defines form, fit, function, performance, and test requirements for acceptance. (Item, process, and material specs start the Product Baseline effort, but the final audited baseline includes all the items in the TDP.)	Product "Build To" or "As Built"
Process Spec	Defines process performed during fabrication.	
Material Spec	Defines production of raw materials or semi-fabricated material used in fabrication.	

- System Spec
- Item Performance Specs
- Item Detail Specs
- Process Material Specs
- Product Baseline "Build To" Specs

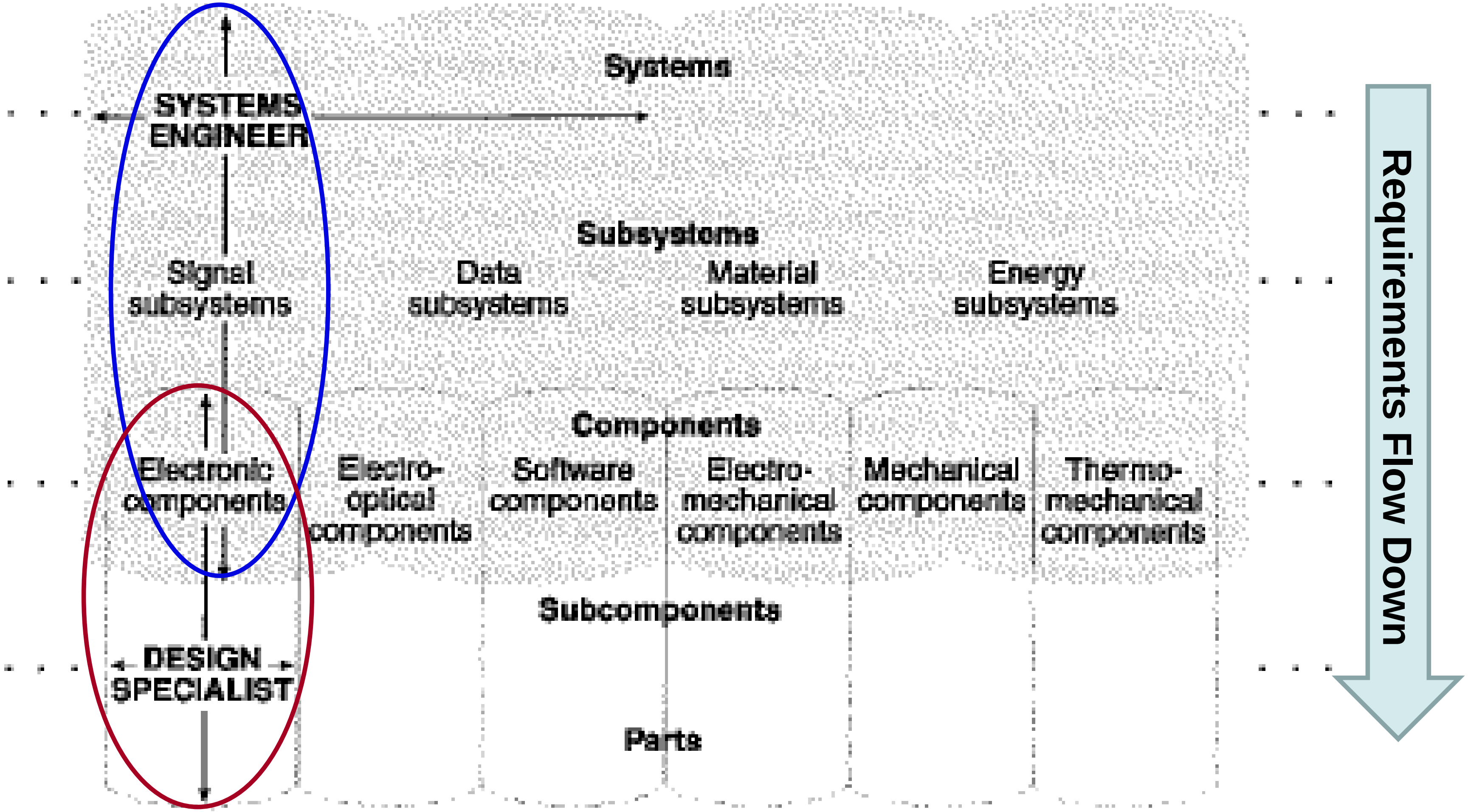
Technical Data Package which includes:

- Engineering Drawings and associated lists
- Technical manuals
- Manufacturing part programs
- Verfication provisions
- Spares provisioning lists
- Specifications, those listed above plus any of the following may be referenced;
  - Defense specs
  - Commercial item descriptions
  - International specs
  - Non-government standards
  - Commercial standards
  - Etc.

Illustrates Requirements Flow Down from top-level System Spec to design documentation

Source: Ref. SE 5

Knowledge Domains of Systems Engineer and Design Specialist



The key to success is constant communication!

Source: Fig. 2-2, Ref. SE 2 (Kossiakoff and Sweet)

SE Process: *Outputs*

Specifications Preparation: Rules of Thumb

- Use a table of contents, and define all abbreviations and acronyms
- Use active voice
- Use "shall" to denote mandatory requirement and "may" or "should" to denote guidance provisions
- Avoid ambiguous provisions, such as "as necessary," "contractor's best practice," "smooth finish," and similar terms
- Use the System Engineering Process to identify requirements. Do not over-specify
- Avoid "tiering." Any mandatory requirement in a document below the first tier, should be stated in the specification
- Only requirement sections of the MIL-STD-491D formats are binding; do not put requirements in non-binding sections, such as Scope, Documents, or Notes
- Data documentation requirements are specified in a Contract Data Requirements List

Source: Ref. SE 5

SE Process: *Outputs*

Decision Database: *Trade Studies*

Trade Studies (trade-off analyses) help engineering teams make better and more informed decisions in selecting best alternatives. Good analyses require participation of engineers from all disciplines who would be directly impacted by a decision.

Both formal and informal trade studies are conducted.

(a) Formal studies: typically well documented and become part of the data bases for use in formal decision forums

(b) Less-formal studies: help make engineering choices at every level; documented in summary detail only, but they are crucial to defining the design as it evolves.

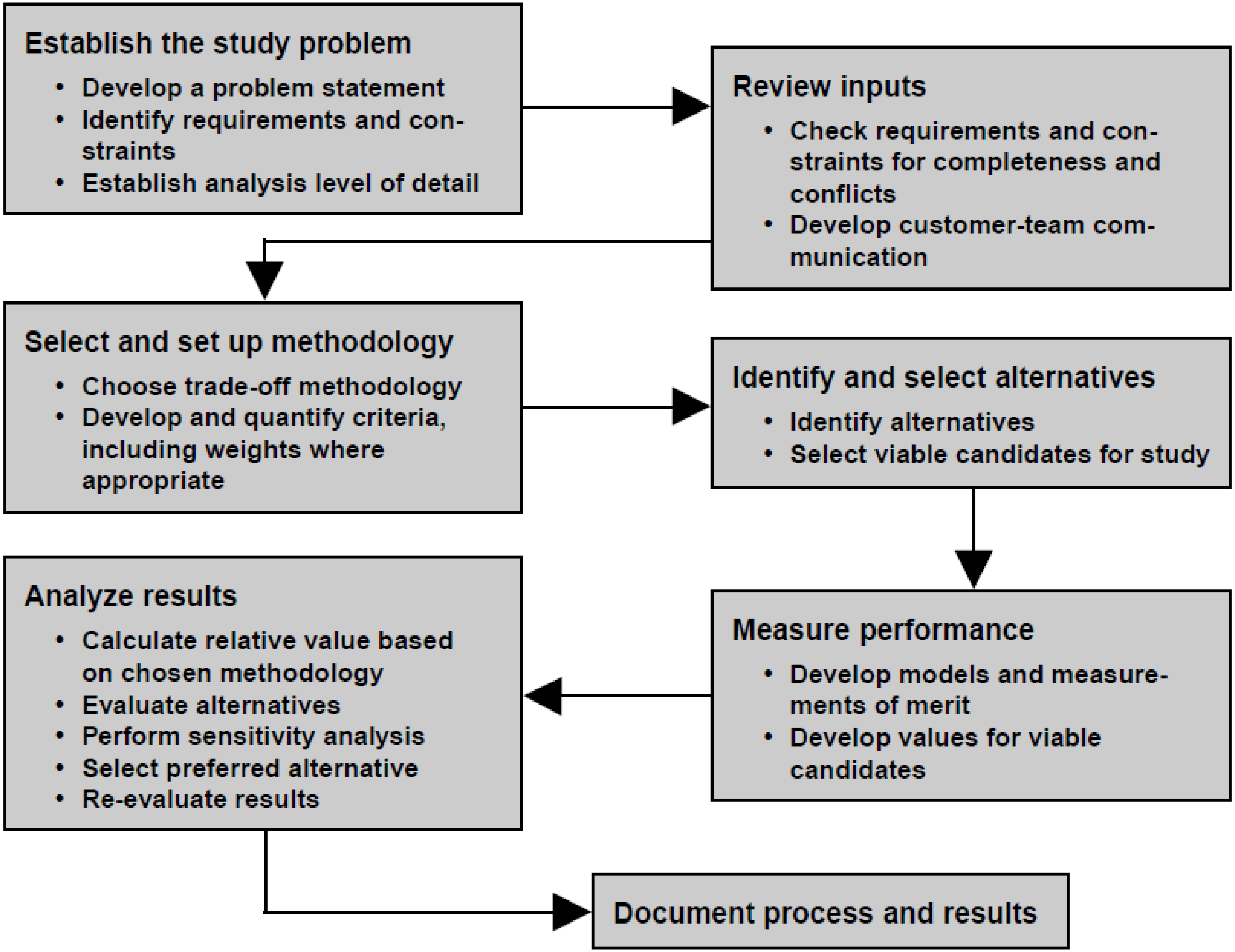
Trade studies examine viable alternatives to determine the preferred one.

- Important to establish criteria acceptable to all participants as a basis for a decision
- Must have agreed-upon approach to measuring (evaluating) alternatives against the criteria
- A good study should produce decisions that are rational, objective, and repeatable.
- Results must be easy to communicate to customers and decision makers

Source: Ref. SE 5

SE Process: *Outputs*

Decision Database: *Trade Studies Process*



Establish the study problem
- Develop a problem statement
- Identify requirements and constraints
- Establish analysis level of detail

Review inputs
- Check requirements and constraints for completeness and conflicts
- Develop customer-team communication

Select and set up methodology
- Choose trade-off methodology
- Develop and quantify criteria, including weights where appropriate

Identify and select alternatives
- Identify alternatives
- Select viable candidates for study

Measure performance
- Develop models and measurements of merit
- Develop values for viable candidates

Analyze results
- Calculate relative value based on chosen methodology
- Evaluate alternatives
- Perform sensitivity analysis
- Select preferred alternative
- Re-evaluate results

Document process and results

Source: Ref. SE 5

SE Process: *Outputs*

Decision Database: *Cost-effectiveness Analyses*

Cost-effectiveness analyses are a special trade study that compares system and component performance to its cost. The analyses help determine affordability and relative values of alternative solutions.

Specifically, they are used to:

(a) Support identification of affordable, cost optimized mission and performance requirements

(b) Support the allocation of performance to an optimum functional structure

(c) Provide criteria for the selection of alternative solutions

(d) Provide analytic confirmation that designs satisfy customer requirements within cost constraints

(e) Support product and process verification and validation

Cost-effectiveness analyses provide assessments of alternative solution performance relative to cost.

Source: Ref. SE 5

Outline

F3. Basics of Systems Engineering

F3.1 SE Overview

F3.2 SE Approach

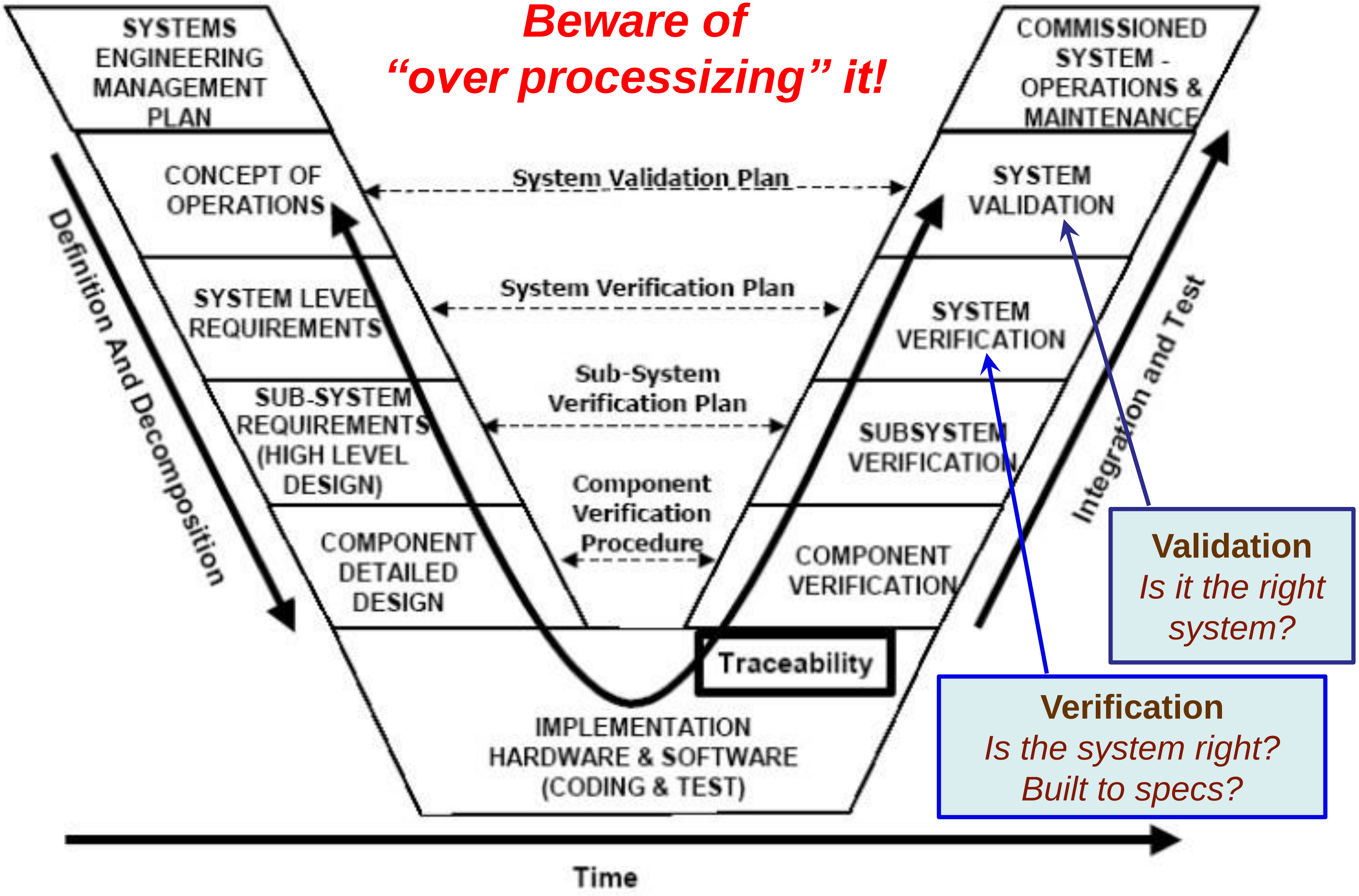
F3.3 SE Process*

- F3.3.1 Process Overview
- F3.3.2 Requirements Analysis
- F3.3.3 Functional Analysis and Allocation
- F3.3.4 Design Synthesis
- F3.3.5 Outputs
- **F3.3.6 Implementation**

*Based on *Systems Engineering Fundamentals,* Defense Acquisition University Press, Fort Belvoir, VA, 2001

Systems Engineering: *Implementation*

The “V” Model



Beware of “over processizing” it!

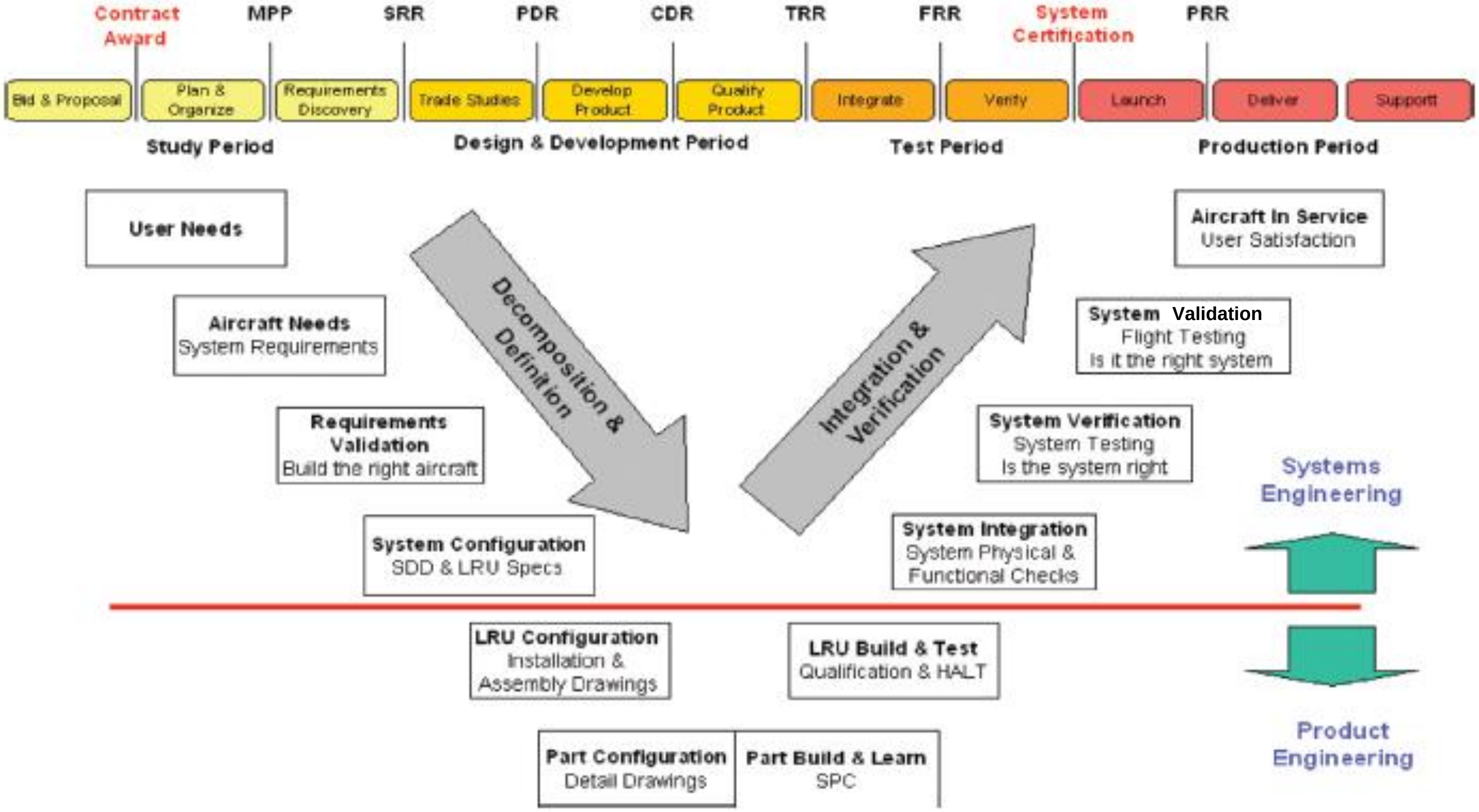
Validation
Is it the right system?

Verification
Is the system right? Built to specs?

Image Source: Internet

SE "V" Model Example

LRU (Line Replaceable Unit) Development



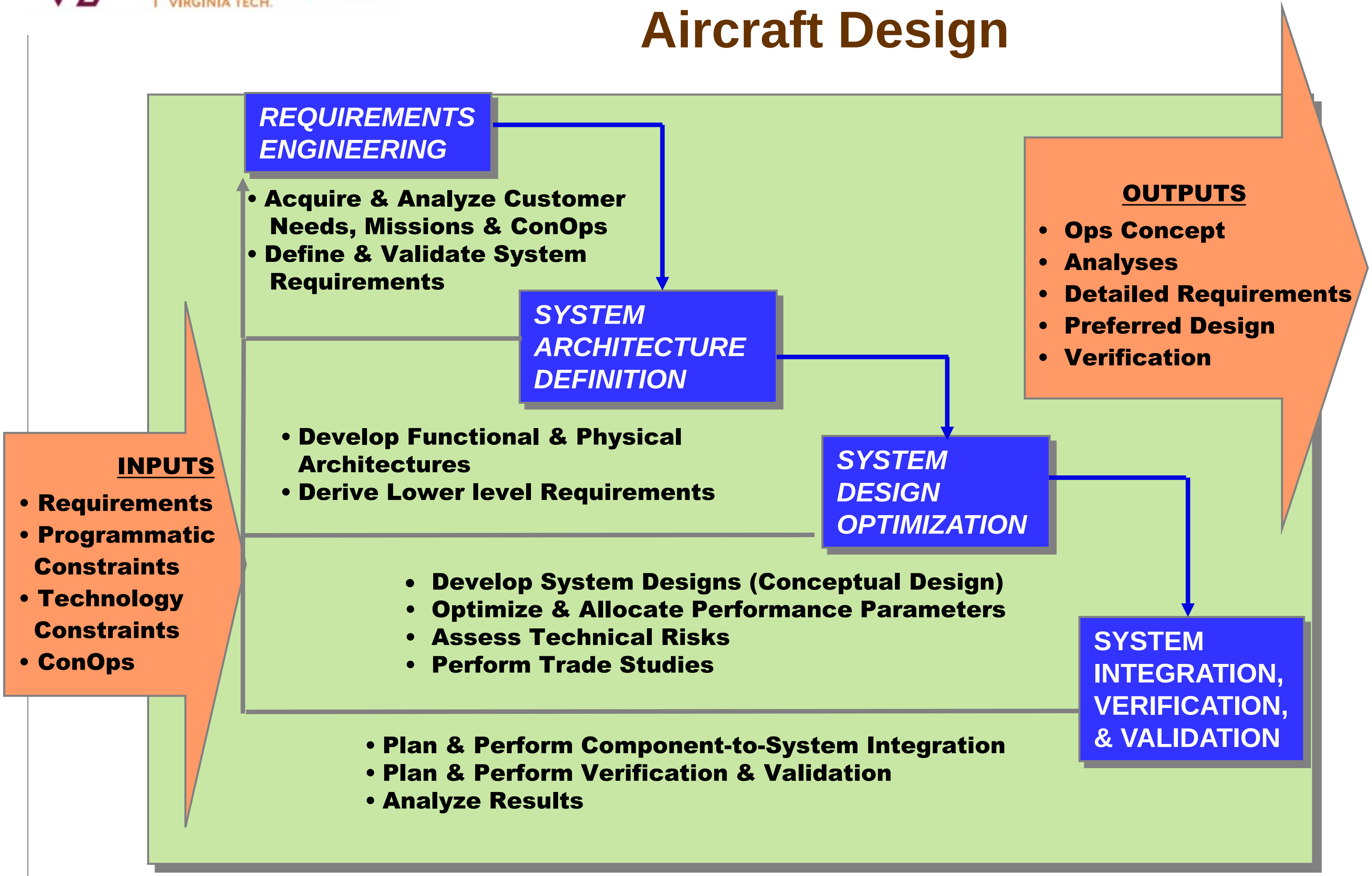
MPP – Master Program Plan
SRR – System Requirements Review
PDR – Preliminary Design Review
CDR – Critical Design Review

SDD – System Description Document
HALT – Highly Accelerated Life Test

TRR – Test Readiness Review
FRR – Final Readiness Review
PRR – Production Readiness Review
SPC – Statistical Process Control

Source: Fig. 6.19, Ref. AS 2 (Moir and Seabridge)

Systems Engineering Process for Aircraft Design



INPUTS
- **Requirements**
- **Programmatic Constraints**
- **Technology Constraints**
- **ConOps**

REQUIREMENTS ENGINEERING

- **Acquire & Analyze Customer Needs, Missions & ConOps**
- **Define & Validate System Requirements**

SYSTEM ARCHITECTURE DEFINITION

- **Develop Functional & Physical Architectures**
- **Derive Lower level Requirements**

SYSTEM DESIGN OPTIMIZATION

- **Develop System Designs (Conceptual Design)**
- **Optimize & Allocate Performance Parameters**
- **Assess Technical Risks**
- **Perform Trade Studies**

SYSTEM INTEGRATION, VERIFICATION, & VALIDATION

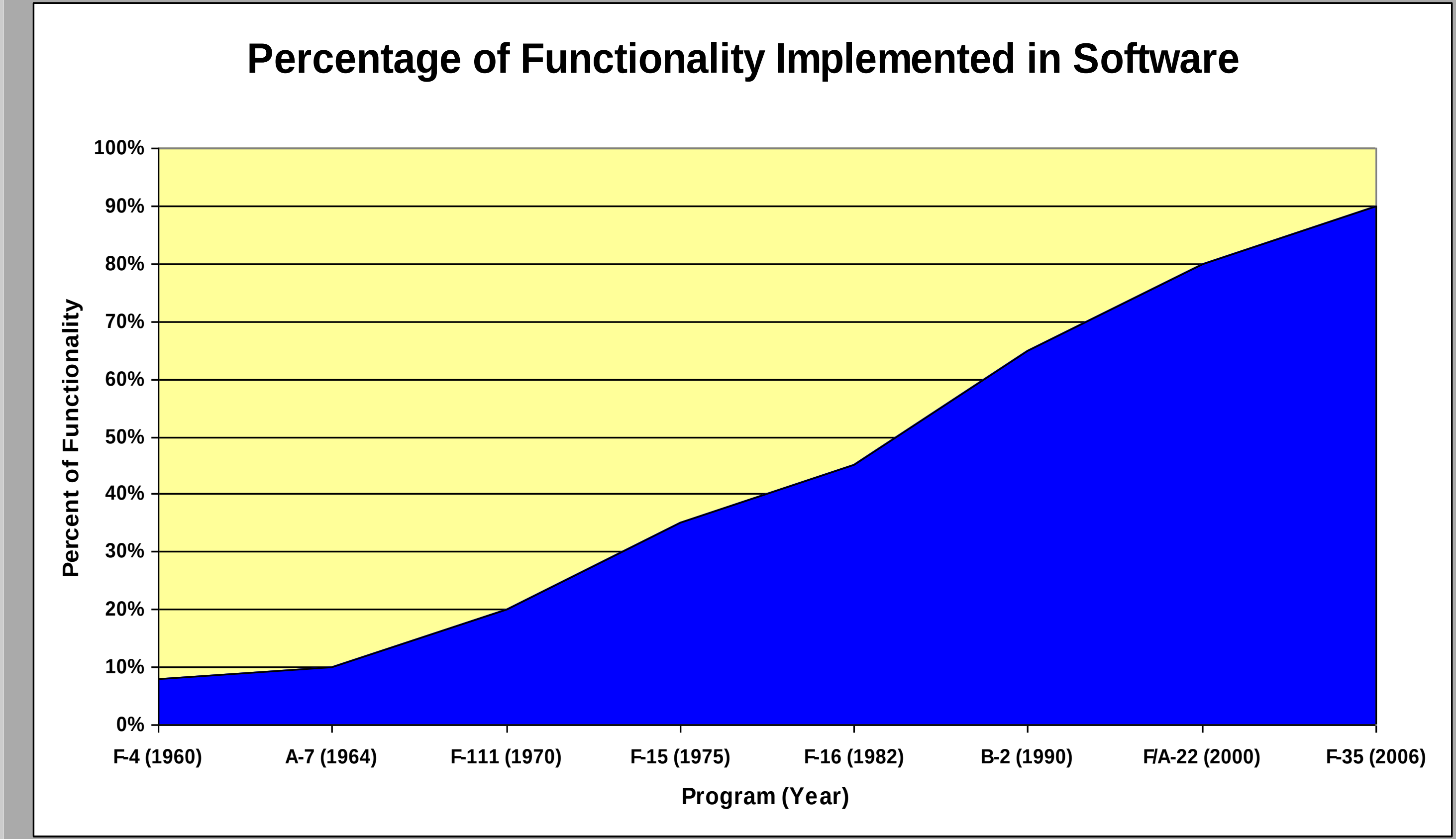
- **Plan & Perform Component-to-System Integration**
- **Plan & Perform Verification & Validation**
- **Analyze Results**

OUTPUTS
- **Ops Concept**
- **Analyses**
- **Detailed Requirements**
- **Preferred Design**
- **Verification**

Courtesy of Dr. Lee Nicolai

Software:

An Indispensable Element of Modern Aircraft

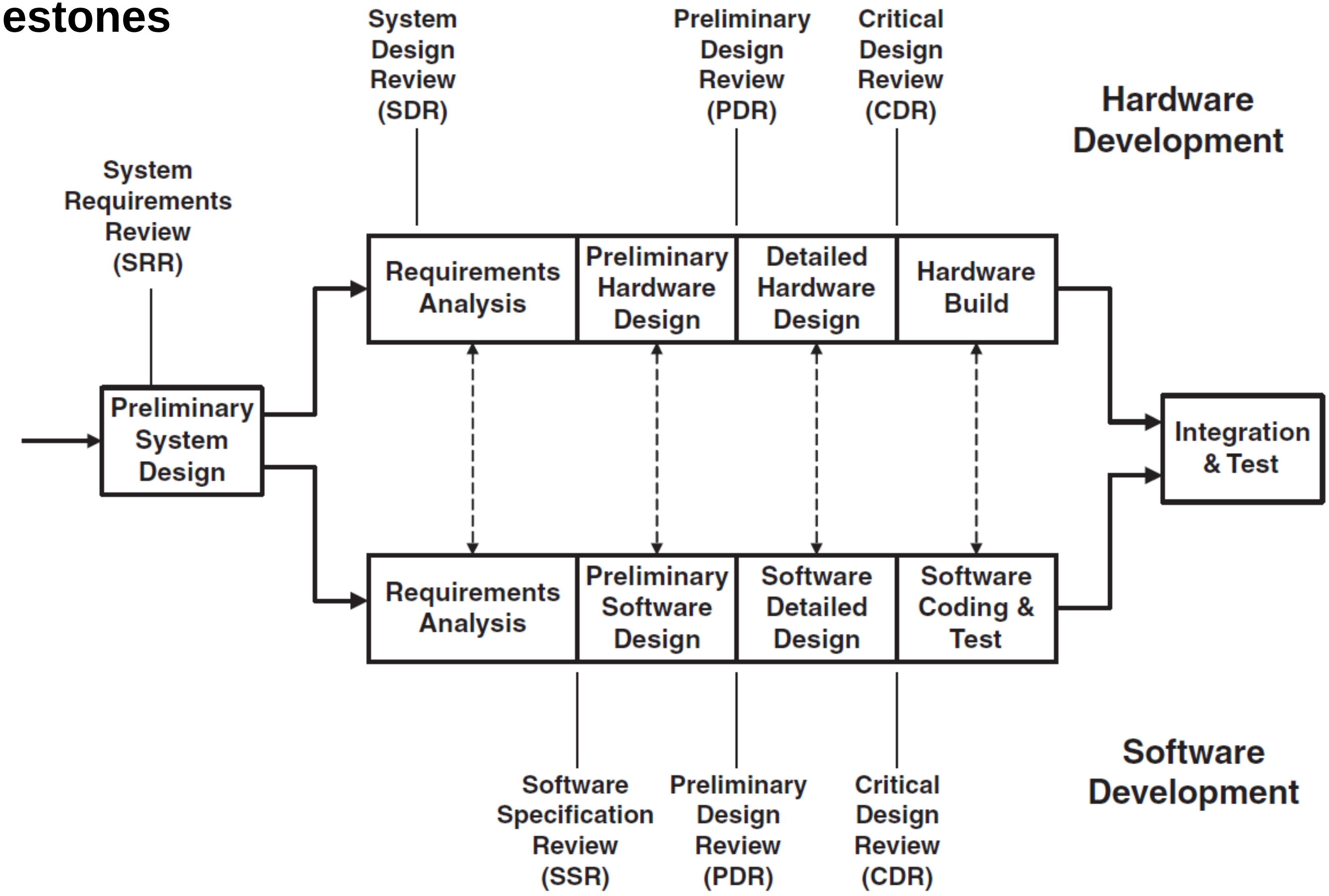


Source: Publicly Released Lockheed Martin Copyrighted Material

80% to 90% of Functionality is Implemented in Software

Systems Engineering Application to Integrated Hardware-Software System

Development Milestones



Source: Fig. 6.20, Ref. AS 2 (Moir and Seabridge)

Systems Engineering

“*Final Thoughts*”

- Systems Thinking isn’t *‘rocket science.’*
- Systems Thinking is *common sense.*
- “Common sense is not so common.”
  — *Voltaire*

**François-Marie Arouet
M. de Voltaire**

French Writer, Philosopher, Historian
21 Nov 1694 – 30 May 1778

Systems Engineering provides structured methodology with proven tools and processes to facilitate effective application of Systems Thinking. The goal is to guide the engineering of systems that are complex in order to achieve quality, affordable solutions to best meet customer needs.

Bibliography

Ref. No.	Author(s)	Title
SYSTEMS THINKING & SYSTEMS ENGINEERING (SE)		
SE 1	Burge, S.E.	***Systems Engineering: Using Systems Thinking to Design Better Aerospace Systems ,*** Wiley Online Library
SE 2	Kossiakoff, A. and Sweet, W.N.	***Systems Engineering Principles and Practice ,*** John Wiley and Sons, Ltd., 2003.
SE 3	Haberfellner, R., de Weck, O., Frickle, E., and Vossner, S.	***Systems Engineering: Fundamentals and Applications ,*** Birkhauser, 2019.
SE 4	NASA	***NASA Systems Engineering Handbook* , NASA SP-2007-6105 Rev 1**, December 2007
SE 5	DoD	***Systems Engineering Fundamentals ,*** Defense Acquisition University Press, Fort Belvoir, VA, 2001