Air Vehicle Design

AOE 4065 – 4066

I. Foundational Elements

Course Module F2

Systems and Systems Thinking

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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

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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)

What is Systems Thinking?

Systems Thinking is applying the concept of a system to any situation in order to gain insight and understanding.

The Concept of a System is at the Heart of Systems Thinking

Therefore, in this CM, we first cover the concept of a System followed by an overview of Systems Thinking

Note: Much of the material herein is adapted from Ref. SE 1

Outline

F2. Systems and Systems Thinking

F2.1 Concept of a System

F2.1.1 Definition and Types of System

F2.1.2 Characteristics and Properties of a System

F2.1.3 Engineered Systems

F2.2 Overview of Systems Thinking

What is a System?

- **A system is an assembly of electronic, electrical or mechanical components with interdependent functions, usually forming a self-contained unit. *(Dictionary Definition)***
- **A system is a set of *interrelated/ interconnected elements that work together to* perform functions and *produce results* not obtainable by individual elements.**
  - Elements can include people, hardware, software, facilities, policies, etc., that is, ***all things*** required to produce [system-level] results.
- **A system is an integrated composite of people, products, and processes that provide a capability to satisfy a stated need.**
- ***No universally agreed definition exists!* But, all imply that a system has three key characteristics: *(1) Purpose; (2) Components (or Elements); (3) Interconnections***

The Concept of a System Forms the Basis of the Framework of Systems Thinking and Systems Engineering!

 Source: Refs. SE 1 through SE 4

A Simple Example of a System: *A Ballpoint Pen!*

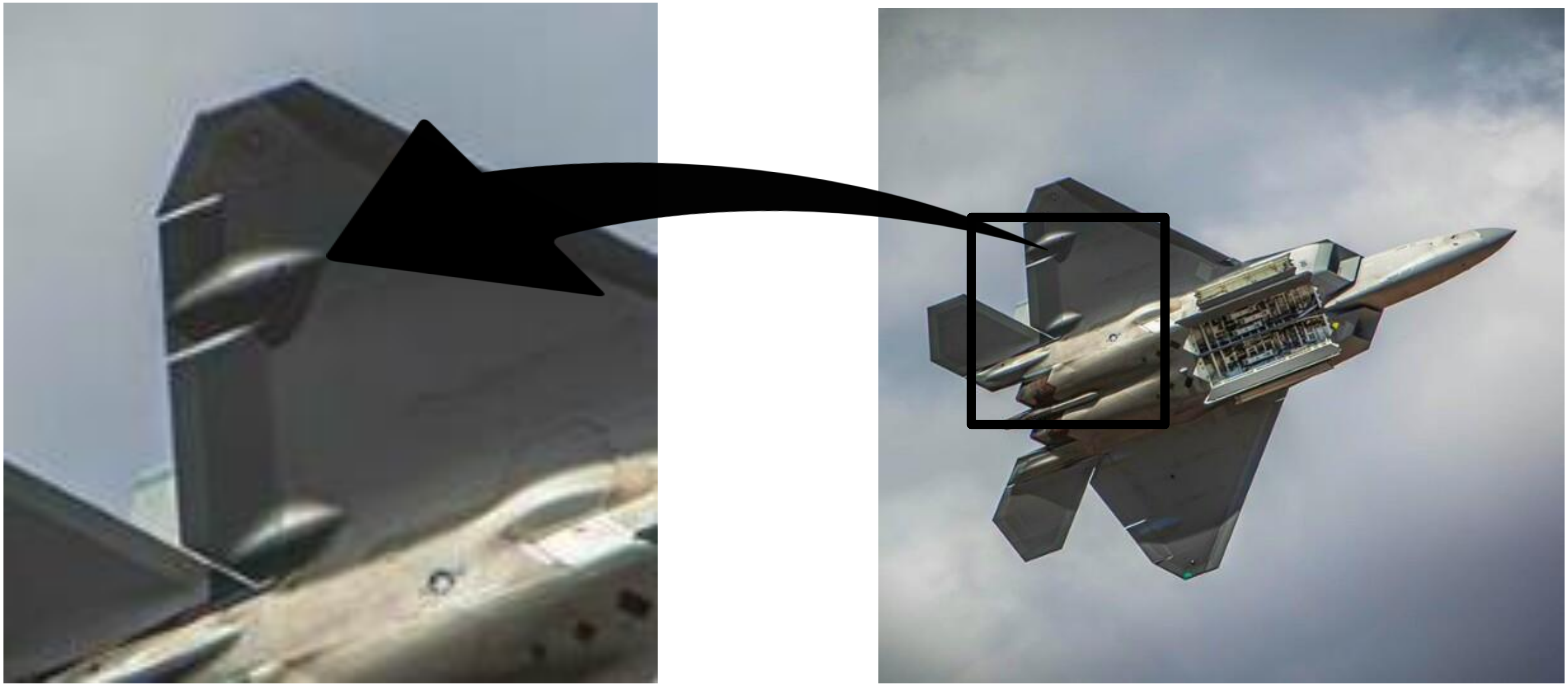
1. **Purpose**
   - To perform the function of turning thoughts into marks on paper
   - The result is written documents!
2. **Components (or Elements)**
   - Plastic body, ink cartridge, spring, etc.
   - Full functionality of the pen is not found in any of the individual components!
3. **Interconnections**
   - Purpose is achieved by connecting the components in the right sequence

Functionality of a System Cannot be Deduced by Studying the Individual Components <u>in Isolation</u>.

Source: Ref. SE 1

A Fundamental Aspect of All Systems

“Change in One Element Affects All Others!”



Changing actuator size affects aerodynamics, stealth, structures, weights, performance, and other subsystems!

Systems Have Interrelated and Interconnected Elements with Interdependent Functions

Five Basic Types of System

- **Natural Systems**
  - An open system whose elements, boundary, and relationships exist independently of human control, e.g., solar system, real number system
- **Designed Physical Systems (or Engineered Systems)**
  - Human-designed systems that rely on a group of tangible elements (that we can touch and feel) to perform a function, e.g., automobiles, aircraft
- **Designed Abstract Systems**
  - Human-designed systems that do not contain any physical artifacts but are designed to serve some explanatory purpose, e.g., formulas or drawings that represent a real system
- **Human Activity Systems**
  - Systems in the world of human activities that are more or less consciously ordered as a result of some underlying purpose, e.g., financial system
- **Transcendental Systems**
  - Systems that go beyond knowledge!

Declaring Something a System Implies That It Takes On Some Systemic Properties and Characteristics

Source: https://www.sebokwiki.org/wiki/Types_of_Systems

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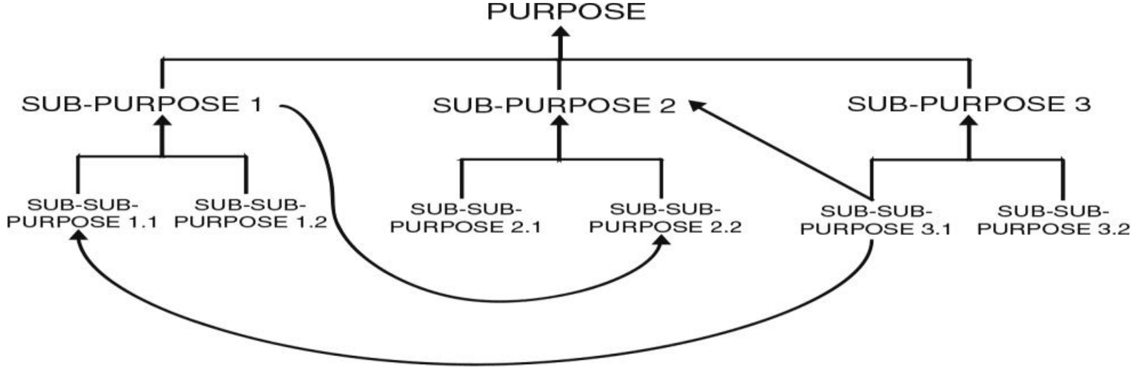
Characteristics and Properties of a System

- **Components, holism and emergence**
  - The behavior of a system is not found in any of the components in isolation; ***it emerges as a consequence of the integration of the components*.** Components are affected by being in the system and the behavior of the system is changed when a component is added to the system or when one leaves it. In order to understand the behavior of a system it is necessary to consider the whole of the system throughout its entire life: ***it is necessary to be holistic*.**

- **Systems have a purpose**
  - All systems seek to achieve a purpose. Whether human made or natural, all ***systems strive to do something***. When creating a new system or modifying an existing one, it is done in order that the resultant ***system does something "useful"***. The reason useful is in quotation marks is that usefulness of a system depends upon the viewpoint of the observer.



The purpose of a pen is to turn thoughts into marks on paper

Source: Ref. SE 1

Characteristics and Properties of a System (contd.)

- **Systems have a life cycle**
  - All systems have a life. That is, they pass through many phases and stages as time elapses. A full understanding of a system will therefore only emerge if consideration is given to the life-cycle of a system. In particular, the potential impact of upstream activities on downstream ones. This recognition of the life cycle contributes to the concept of holism. ***<u>Every system will have a different life cycle</u>***. It is possible, nevertheless, to generalize these for categories of system.

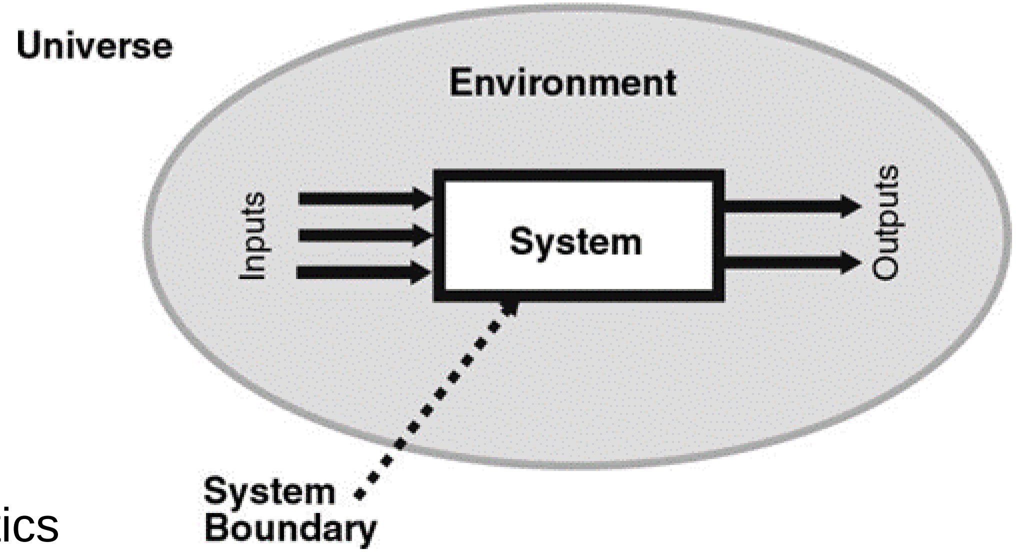
- **Systems have a context**
  - All systems have a context and the ***<u>understanding of a system requires us to understand the context in which a system is placed</u>***. The context depends on (i) Purpose of the system; (ii) Application of the system; and (iii) Environment.

(a) A ball-point pen works fine in the context for which it was designed to be used;
(b) not in a vacuum, or in space; (c) may not be safe in some environments like submarines

Source: Ref. SE 1

Characteristics and Properties of a System (contd.)

- **Systems have a boundary and an environment**

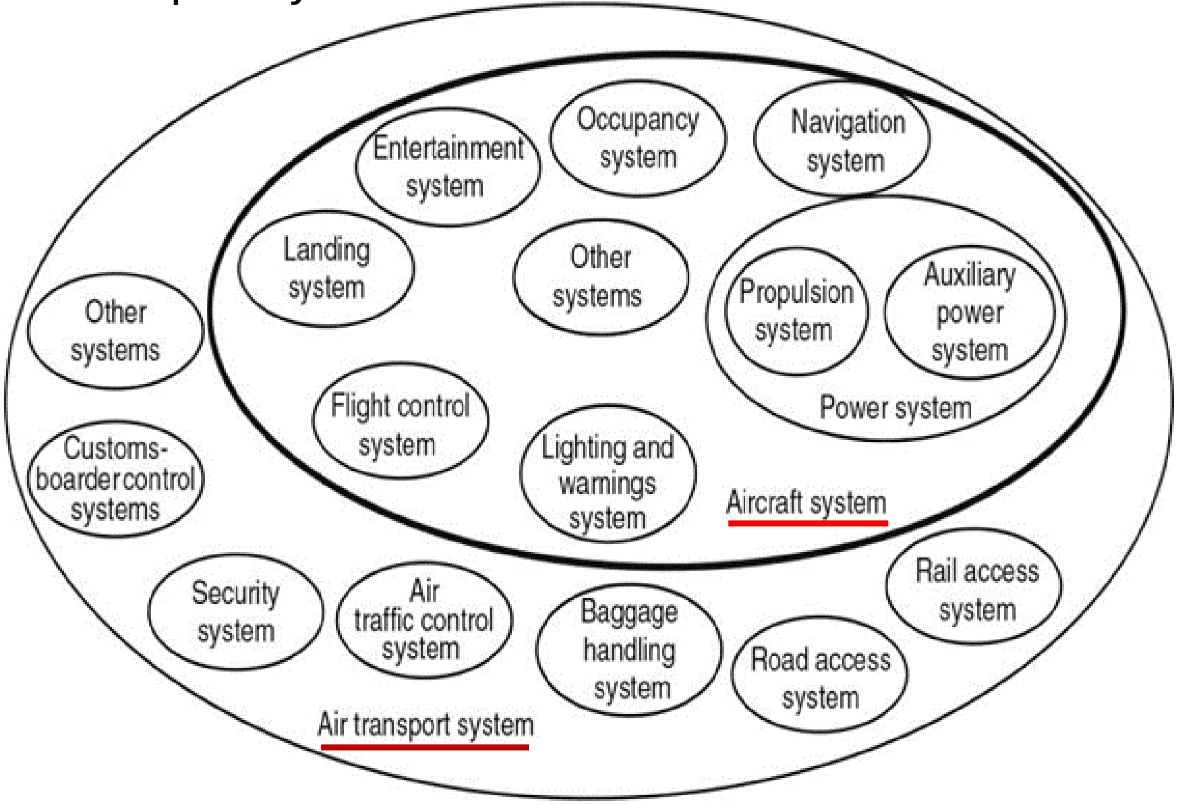


  - What happens outside of a system will affect it.
  - A key aspect of systems thinking is to identify ***what is inside and outside in the environment***.
  - Important system characteristics include
    - The ***boundary separates the system*** of interest ***from its environment.***
    - The environment contains those elements and further systems that interact in some way with the system of interest. Typically the ***environment of a system provides its inputs and consumes its outputs***.
    - Any element or system that does not interact with the system of interest lies outside the environment in the universe.

Source: Ref. SE 1

Characteristics and Properties of a System (contd.)

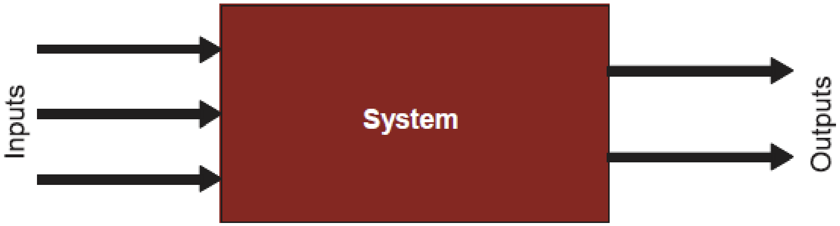
- **Systems within Systems**
  - Anything that is defined as a system is typically made up of smaller systems. Equally ***<u>any identified system will be a sub-system of a bigger system</u>***.
  - Consider the simplified ***Systems Map*** for a commercial aircraft system. The aircraft system comprises many sub-systems, while it is a sub-system of a bigger air transport system.



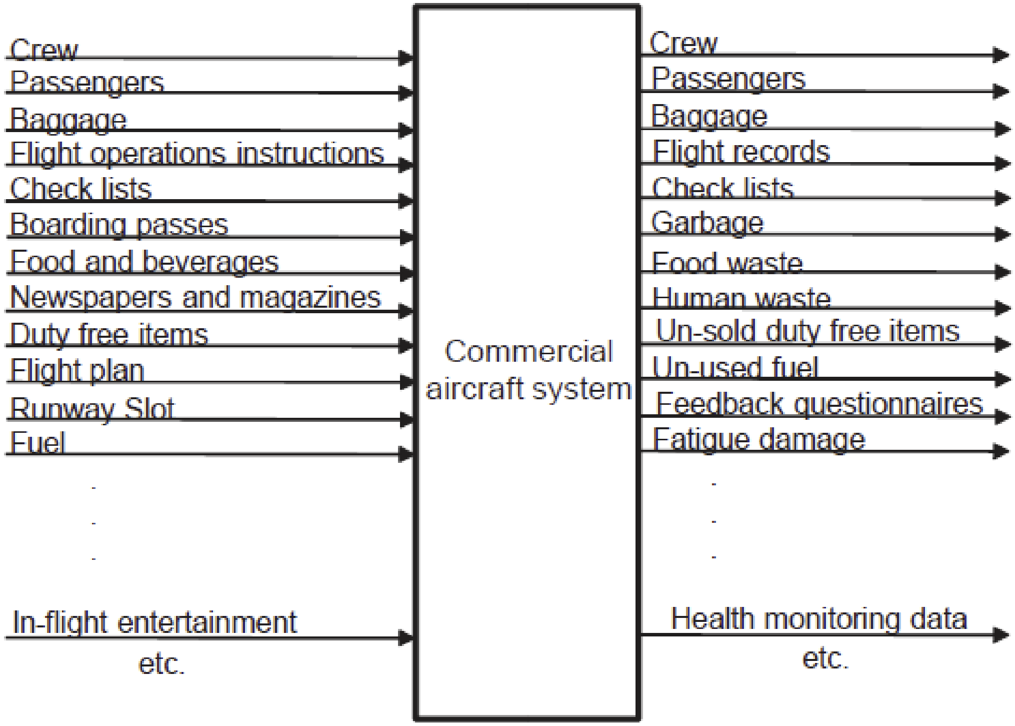
Source: Ref. SE 1

Characteristics and Properties of a System (contd.)

- **System as a transformation**
  - Many systems can be viewed as transformations which ***receive inputs and transform them into outputs***.



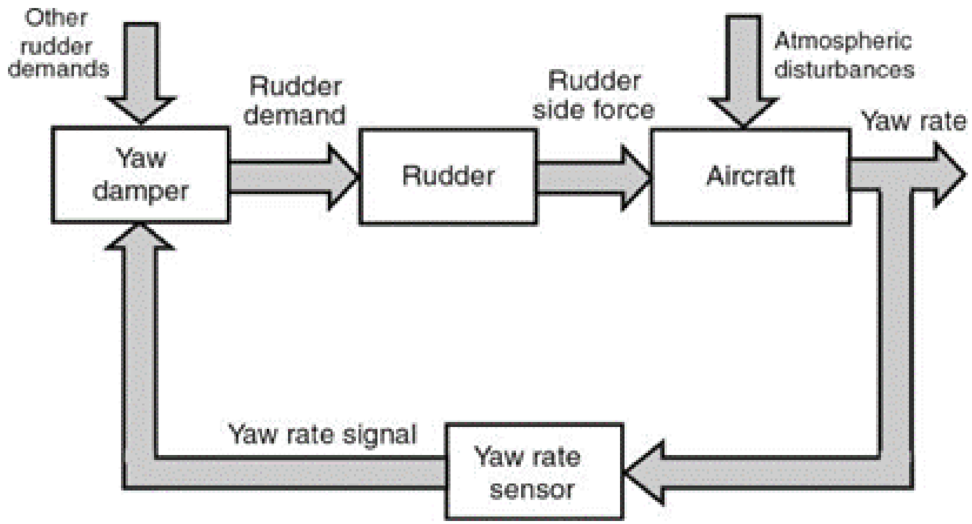
  - All human designed products and processes are transformation type systems, such as a commercial aircraft system:



Source: Ref. SE 1

Characteristics and Properties of a System (contd.)

- **Systems are dynamic**
  - What is clear about transformational systems is that if the inputs change then the outputs will also change. That is, ***<u>systems display dynamic behavior</u>*** (some systems either react so fast or so slowly that they can be treated as static, but in reality ***there is no such thing as a static system***). The behavior of a system manifests itself in several ways as events and patterns.
- **System behavior results from the effects of reinforcing and balancing processes**
  - **Reinforcing (positive) feedback** is where successive changes add to the previous change in the same direction.
  - **Balancing (negative) feedback** is where change in one direction is opposed by producing change in the opposite direction. A simple example of this is a yaw damper included in aircraft control systems.



Source: Ref. SE 1

Characteristics and Properties of a System (contd.)

- **Systems change (adapt and evolve)**
  - All systems adapt and evolve over time either because of changes in their environment or because of internal changes.
  - Natural systems are superlative adapters, but often survive as an evolved system at the expense of some of the components.
  - ***Human-made systems either change because of technology push or because of a changing environment leading a technology pull.***
    - A classic example of this is concerned with providing an internal combustion engine with the correct air-fuel mix. Carburetor was the dominant solution to this problem up to the 1980s.
    - While fuel injection had been available since the 1920s, it became the dominant technology in the 1980s when it was integrated with digital electronics to give startling performance at the right price.
  - Extinctions can also happen in human-made systems but these can occur at the component level and at the organizational level.

Source: Ref. SE 1

Characteristics and Properties of a System: *A Summary*

- A system seeks to achieve a **purpose**
- A system can affect its **environment**, and its environment can affect the system– **context** is important
- The **behavior** or functionality of a system cannot be determined by consideration of its components in isolation; we must consider the integrated set of components
- **Components** are affected by being in the system and the behavior of the system is changed when a component is added to the system or when one leaves it
- The examination of anything that is defined as a system will show it to be made up of smaller **sub-systems**
- Any identified system will be a sub-system of a bigger system
- A system will exhibit **dynamic behavior** (although there are cases when it is possible to treat the system behavior as static)
- The dynamic behavior of a system depends upon the structure and **interconnectedness** through reinforcing and balancing feedback
- An understanding of a system depends upon the **perception of the observer** and their reason for looking at the system
- A **system can change and evolve** during its life cycle

Source: Ref. SE 1

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Engineered Systems

- **A system designed or adapted to interact with an anticipated operational environment to achieve one or more intended purposes while complying with applicable constraints.**
- **An open, concrete system of technical or socio-technical elements whose characteristics include (i) being created by, and for, people; (ii) having a purpose; and (iii) satisfying key stakeholders' value propositions.**
- **Cyber Physical System (CPS)**
  - CPS is an important type of modern engineered system
  - In a cyber-physical system (CPS), physical and software components are deeply intertwined, able to operate on different spatial and temporal scales, exhibit multiple and distinct behavioral modalities, and interact with each other in ways that change with context. Examples are modern air vehicles; autonomous automobiles; smart electrical grids; robotic systems; etc.
  - A big challenge in developing a CPS is the large differences in the design practices of various engineering disciplines involved, such as software and mechanical engineering. Additionally, there is no common "language" for the design practices of all the disciplines involved.

Source: https://www.sebokwiki.org/wiki/ Engineered System_(glossary)

Classes of Engineered Systems

Simple System:

- Consist of few parts
- **Small number of interfaces**
- **Interactions well understood & well controlled**
- Typically used as building blocks for more sophisticated parts & components

Complicated System:

- Consist of many parts, components, subsystems
- **Moderate to large number of interfaces**
- **Interactions/reactions understood for controlled cases**
- Vigilant control required to properly construct
- V & V is the basis to accept/reject bad parts, components, subsystems
- Global system behavior is mostly predictable; Part decomposition & analysis leads to reasonable global property predictions

Complex System:

- Can possess extreme numbers of parts, components, subsystems
- **Extreme numbers of interfaces- sometimes impossible to identify**
- **Interactions understood for limited number of highly controlled cases but mostly unknown due to dynamic adaptations**
- Vigilant control often exercised but system sensitivity is nonlinear & dependent on initial conditions (path dependent)
- Current analysis tools are poor predictors of system behavior
- Complete system V & V not possible
- Global system behavior can be emergent (reductionist approaches fail)

From Moser, Rogan, and Lightfoot presentation at NASA PM Challenge 2012

Source: Adapted from Design of Projects lectures of Bryan Moser, MIT

Example of a Simple System: *A Ballpoint Pen*

1. Purpose

- To perform the function of turning thoughts into marks on paper
- The result is written documents!

2. Components

- Plastic body, ink cartridge, spring, etc.
- Full functionality of the pen is not found in any of the individual components!

3. Interconnections

- Purpose is achieved by connecting the components in the right sequence

Source: Ref. SE 1

Example of a Complicated System

Star Caliber Patek Phillipe Mechanical Watch

- We understand:
  - how it is constructed
  - the required tolerances
  - the order of assembly

- Each component works in unison to accomplish a global function: keep time precisely

- We can take a reductionist path to define the smallest required parts and can further write equations of motion to predict the performance and functionality of the watch

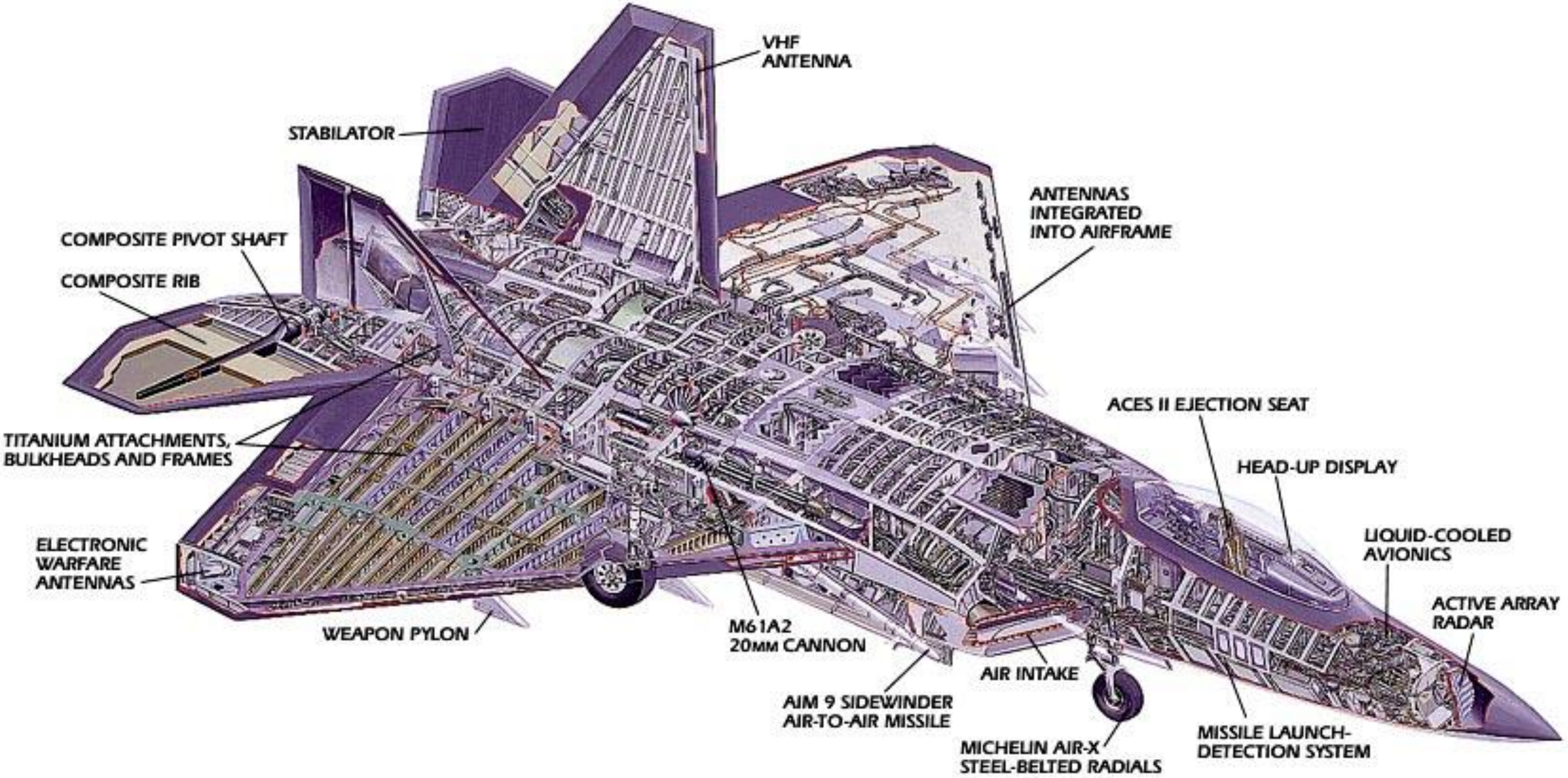
From Moser, Rogan, and Lightfoot presentation at NASA PM Challenge 2012

Source: Courtesy of Bryan Moser, MIT

Example of a Complex System

F-22 *Air Superiority Fighter*

Composed of *diverse elements* having *intricate relationships* with one another.



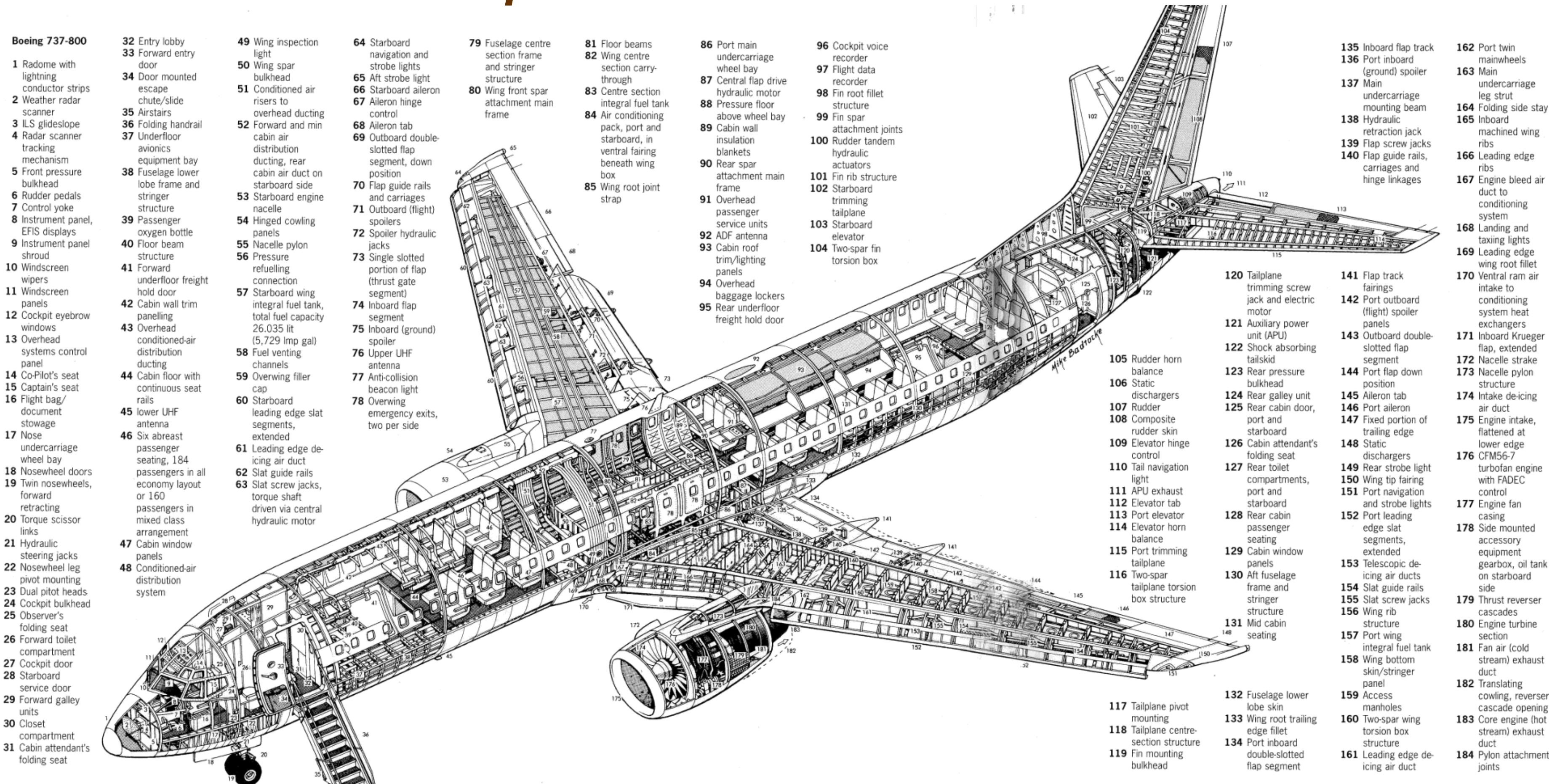
Interactions understood for limited number of highly controlled cases but mostly unknown due to dynamic adaptations.

Source: http://www.f22fighter.com/Specs.htm

Example of a Complex System

B737-800

Popular Fuel-efficient Airliner



Source: https://thelexicans.wordpress.com/2013/07/24/cutaway-thursday-boeing-737-800/

"A million parts flying in formation!"

Creation of Engineered Systems

Engineered systems are "designed" to deliver a desired "capability" to meet customer needs

"Design"

- **Form –** *Geometry and materials*
- **Fit –** *Internal assemblies, tolerances, and interfaces to other parts*
- **Fabrication Process –** *Instructions for fabrication (or manufacturing), assembly and inspections of parts*

"Capability"

- **Function –** *Performance relative to the desires, needs and wants of the customer*

Desired "Capability" is the Major Driver of "Design"

An Enduring Challenge for *Aerospace Engineering*

To design, build, and operate a BEST aircraft—*a complex system indeed*—such that it would perform its intended functions safely in the most cost-effective way possible considering performance, cost, schedule, and risk.

'Systems Thinking' holds the key!

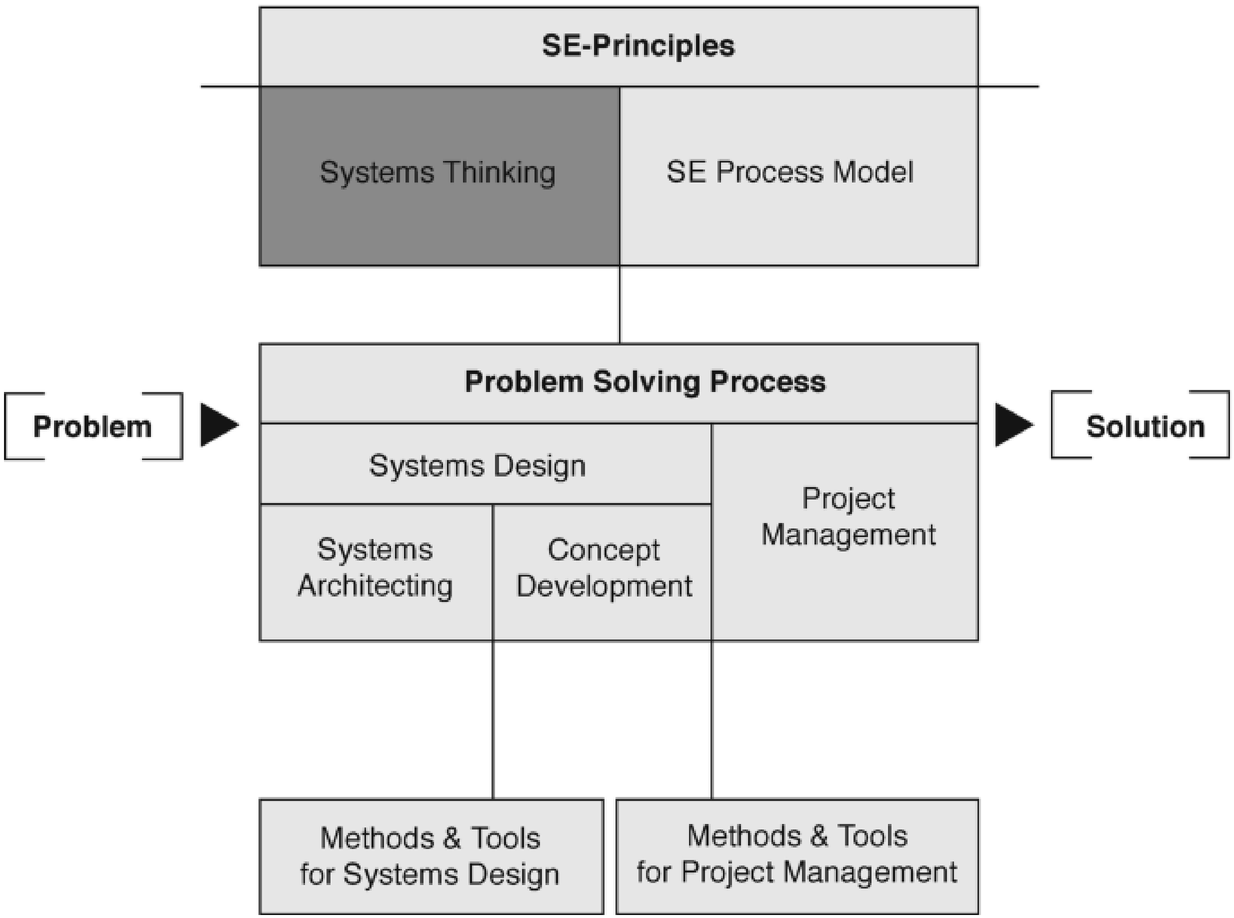
A logical way of thinking.

Taking a holistic view.

Systems Thinking provides a powerful means of applying the concept of a system to any situation in order to gain insight and understanding

Systems Thinking

Systems Thinking is considered one of the two key principles of Systems Engineering (SE) which offers an effective framework for problem solving.



Source: Ref. SE 3

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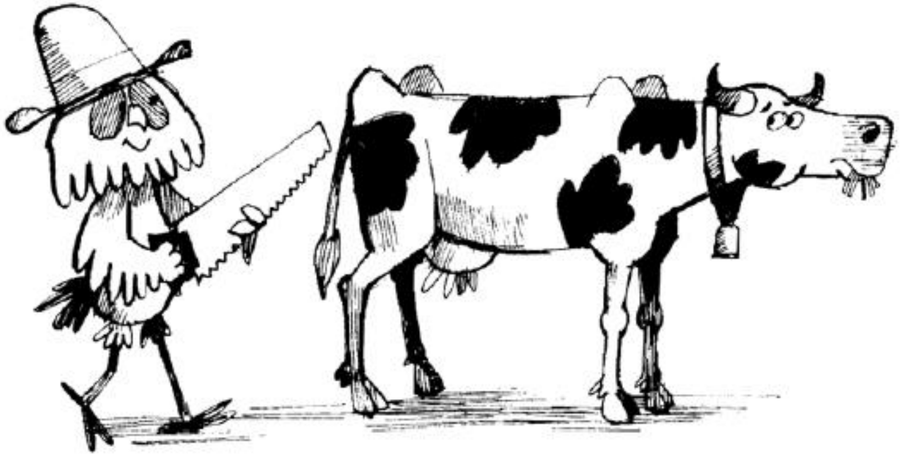
What is Systems Thinking?

Systems Thinking is applying the concept of a system to a situation in order to gain insight and understanding.

Systems Thinking is the process of understanding how things, regarded as systems and components of systems, influence one another within a whole.



"Dividing a cow in half does not give two smaller cows"

Systems Thinking is a holistic approach that focuses on the way that a system's constituent parts interrelate and how systems work over time and within the context of larger systems.

Focus on the Entire System and How the Parts Interrelate.

Source: Delicado, Introduction to Systems Engineering, May 2019

Systems Thinking

Systems Thinking offers a means of understanding the complexity of a system by **focusing on relationships and interactions among the integrated set of components** instead of breaking down a system into separate elements.

Systems Thinking can be used in any endeavor and has been applied to study medical, environmental, political, economic, human resources, and educational systems, among many others.

Attention to feedback is an essential component of **Systems Thinking**. After all, system behavior results from the effects of reinforcing and balancing feedback. A reinforcing feedback leads to the increase of some particular behavior. If reinforcement is unchecked, it eventually may lead to collapse. **A balancing feedback tends to maintain equilibrium in a particular system**.

For example, in project management, prevailing wisdom may prescribe the addition of workers to a project that is lagging. However, in practice, that tactic might have actually slowed development in the past. Attention to that relevant feedback can allow management to look for other solutions rather than wasting resources on an approach that has been demonstrated to be counterproductive.

***More of a Mindset, Not Just a Set of Tools and Processes*.**

Source: Adapted from miscellaneous sources

Systems Thinking

Systems Thinking is a way of viewing systems from a broad perspective that includes seeing overall structures, patterns, and cycles in systems, rather than seeing only specific events in the system. This broad view can help to quickly identify the real causes of problems and know just where to work to address them.

By focusing on the entire system, one can attempt to identify solutions that address as many problems as possible in the system. The positive effect of those solutions leverages improvement throughout the system.

Systems thinking offers the most effective way of understanding complex situations by:

- Simplifying situations to understand key issues
- Allowing diverse perspectives to be considered simultaneously to understand and predict emergent behavior
- Looking for dependencies and influences between elements and predict emergent behavior
- Bringing experience to bear upon a situation for better understanding

Source: Ref. SE 1

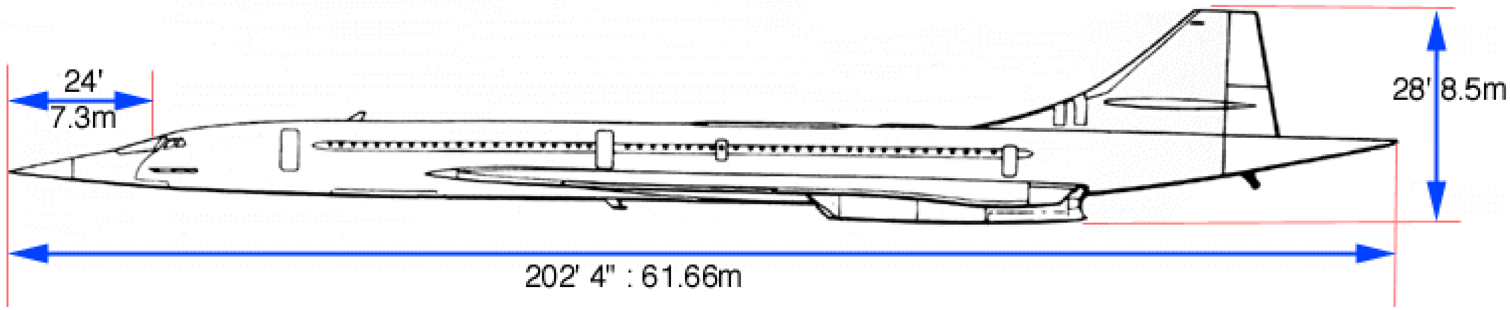
How to do Systems Thinking?

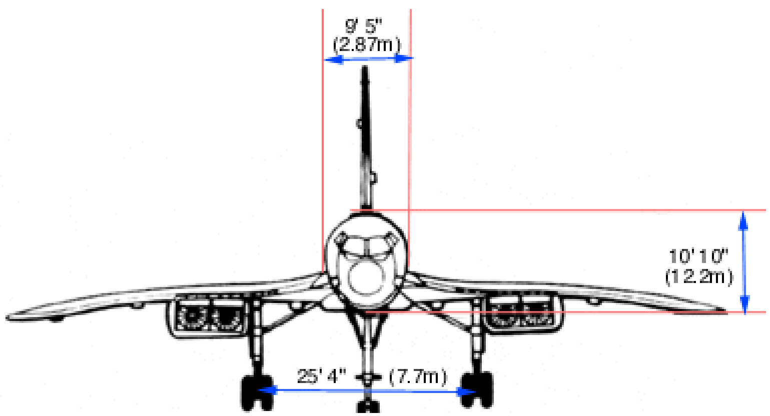
https://www.youtube.com/watch?v=_vS_b7cJn2A

By Building Unified System Models.

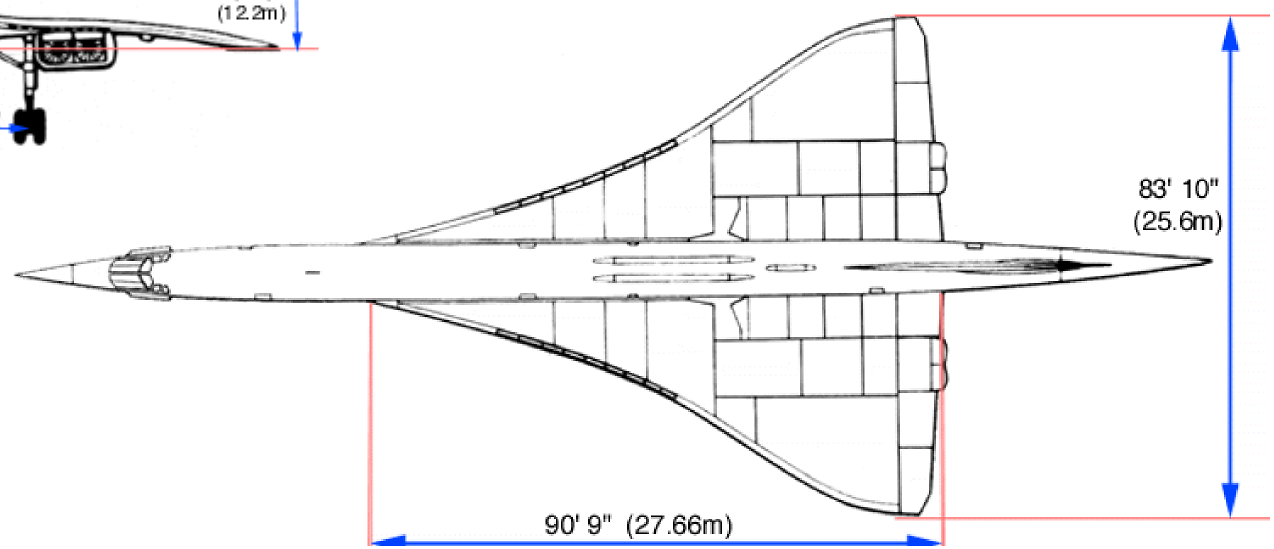
Example of System Models

Concorde Supersonic Airliner





A. Outer Mold Line (OML) Model

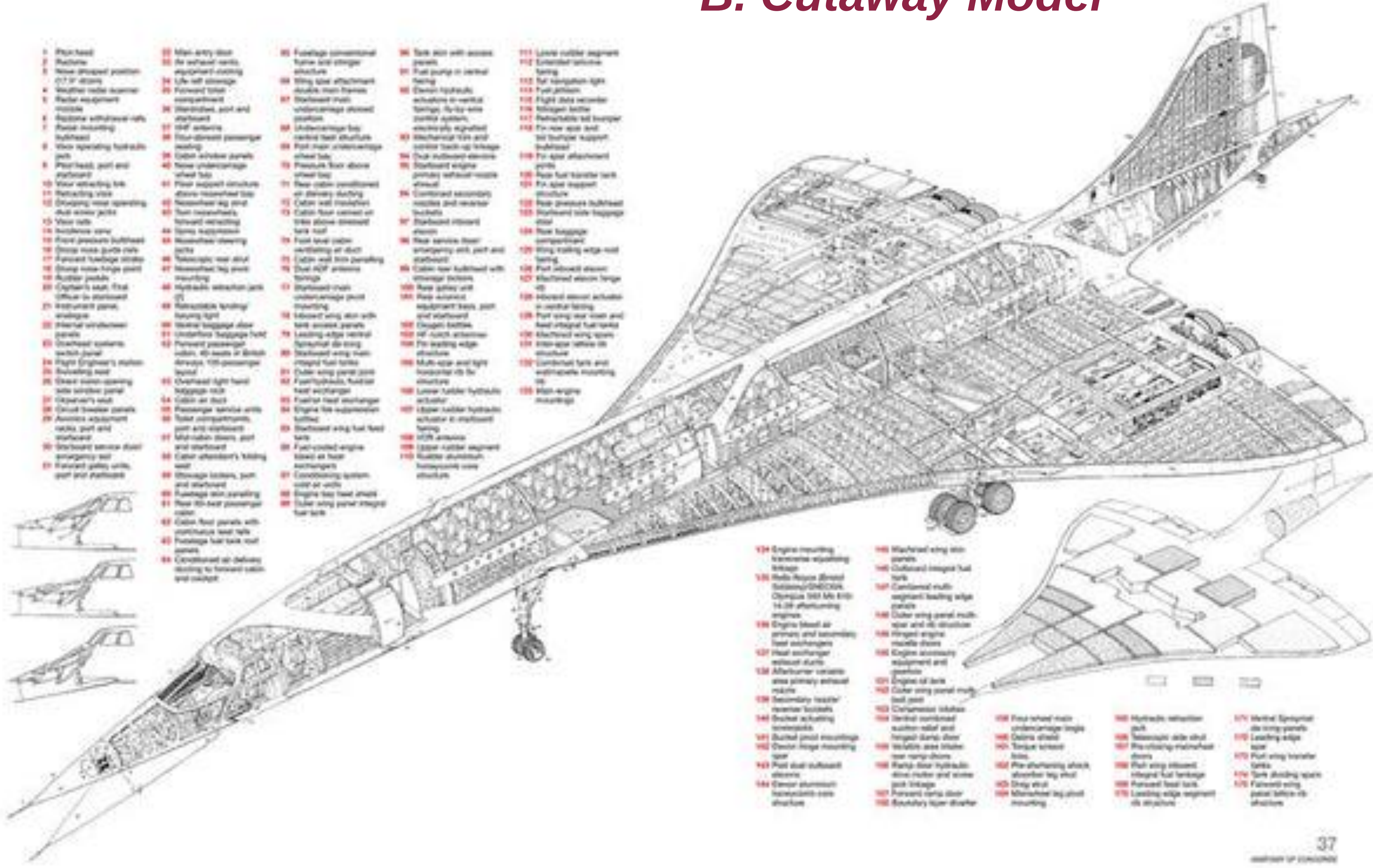


Source: www.concordesst.com

Example of System Models

Concorde Supersonic Airliner

B. Cutaway Model

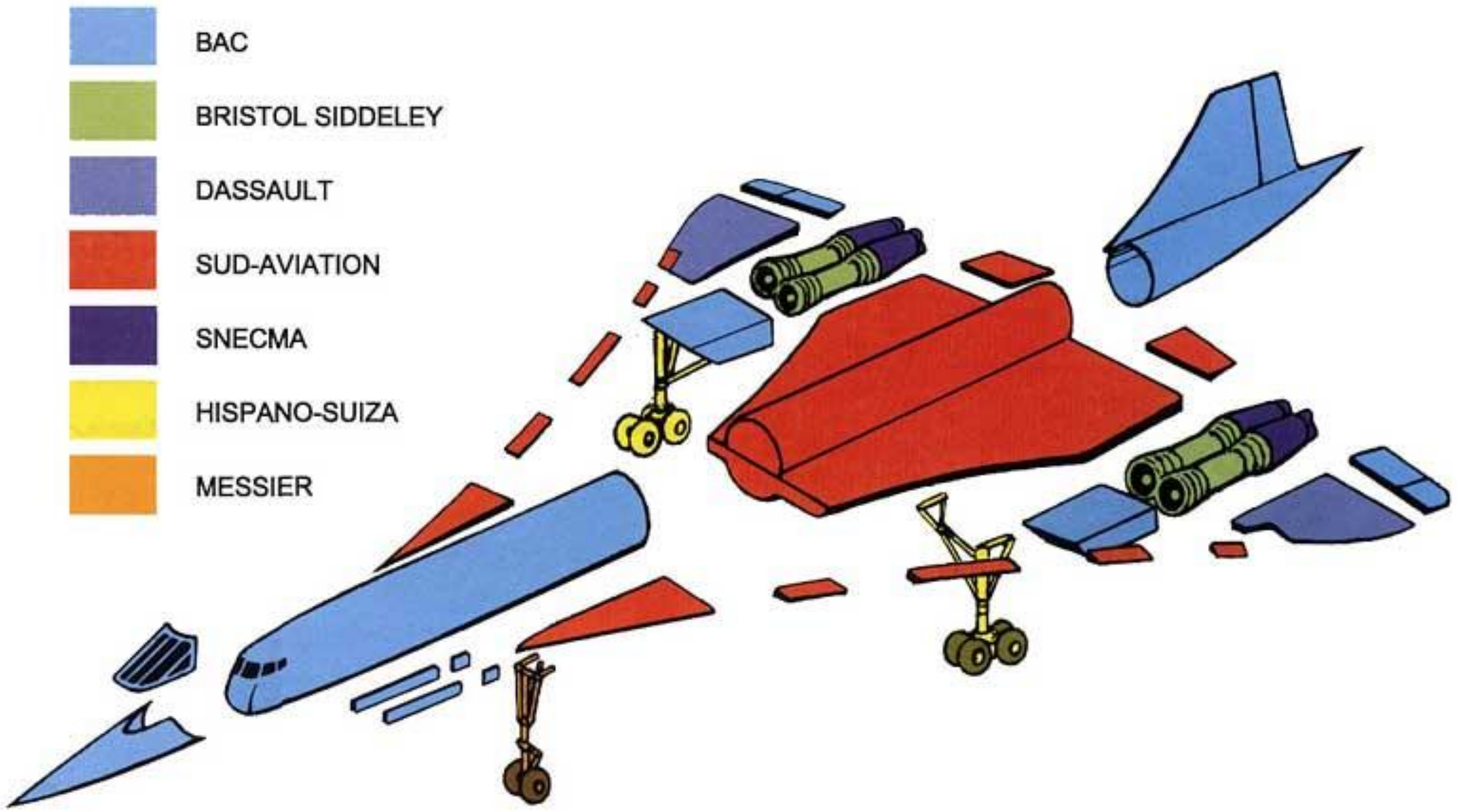


Source: www.concordesst.com

Example of System Models

Concorde Supersonic Airliner

C. Schematic of Partners in Design and Building

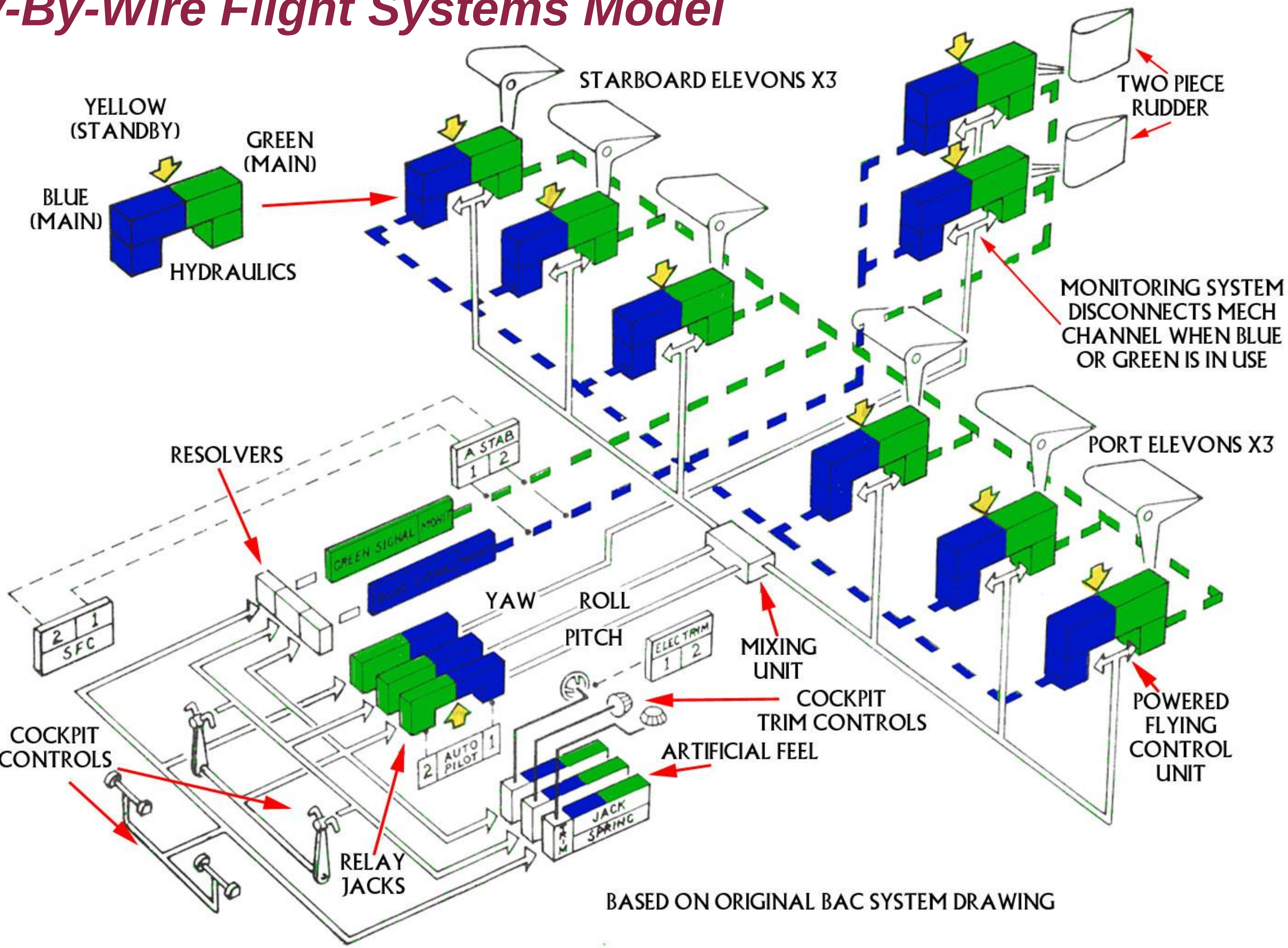


Source: www.concordesst.com

Example of System Models

Concorde Supersonic Airliner

D. Fly-By-Wire Flight Systems Model



Source: www.concordesst.com

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Systems Thinking

A Tremendously Powerful and Universal Framework to

- **Gain understanding of a complex situation**
  - *For example, biologists apply Systems Thinking to help understand a complex bio-system*

- **Gain sufficient understanding to make predictions of future system behavior**
  - *For example, economists (and perhaps politicians should) apply Systems Thinking to understand the dynamics of the world's economies in order to predict behavior when aspects are changed*

- **Solve a problem**
  - *Scientists and Engineers apply Systems Thinking to solve problems*

- **Create a new or modified system**
  - *Engineers, System Designers or Architects apply Systems Thinking to design better systems – in this context it is called Systems Engineering*

Engineers Must Use It…To Engineer Better Systems

Source: Ref. SE 1

Systems Thinking Enables Systems Engineering

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

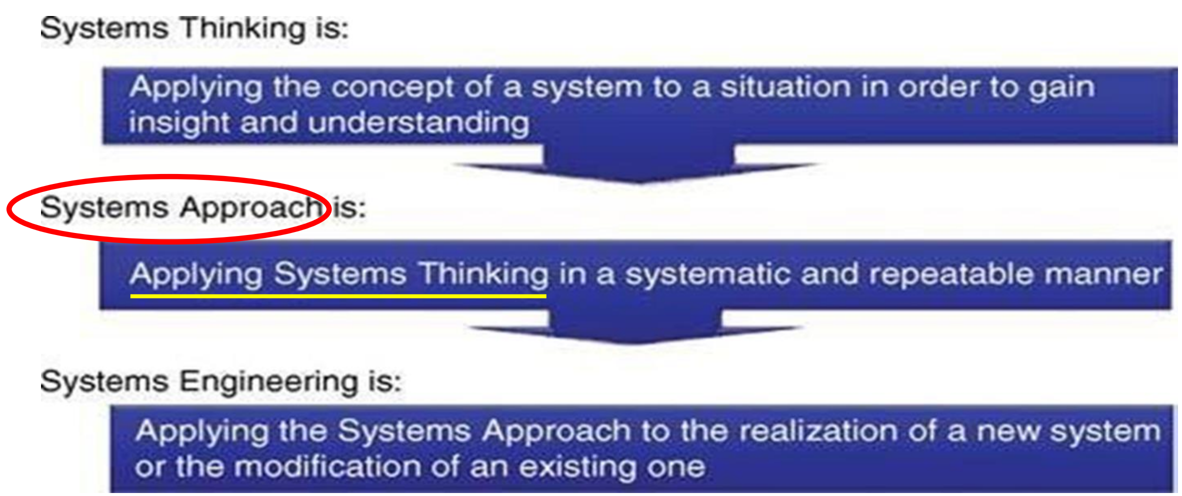
“Thinking Precedes Engineering!”

Source: Ref. SE 1

What is Systems Approach?

Systems Approach is *applying System Thinking in a systematic and repeatable manner.*

- Efforts for systematic and repeatable application of Systems Thinking to complex situations have produced *tangible processes and tool sets*.



- The outcome of such well-meaning efforts has been an overly bureaucratic collection of processes and reviews along with costly and ineffective software tools.
- As a consequence, Systems Approach is often perceived by many in the engineering community as implementation and execution of a set of standardized processes, i.e., *it's just "processing."*
- What's lost in the shuffle is the essence of **Systems Approach** which is:
  an ***intangible state of mind which emphasizes "thinking."***

Source: Ref. SE 1

How to Apply Systems Thinking?

By asking relevant questions in eight areas:

1. **Generating Purpose** *(goal, objective, function)*
   What is the mission of the system (top-level function)? What does the mission need to accomplish? What are the *qualitative* goals, and why? What are the broad objectives and constraints? Is cost a fundamental limitation? Are you returning to the goals to confirm whether or not you are doing what you set out to do?

2. **Raising Questions about Problem & Issue at hand** *(problems, issues)*
   What are your quantitative targets to achieve the broad objectives given your needs, applicable technology, and cost constraints? Do you plan to subject your quantitative targets to trade studies ("what-if" scenarios) as you go along or are you setting them concretely at an early stage?

3. **Gathering Information** *(data, facts, evidence, observations, experiences)*
   If your system interacts with user equipment, did you define the characteristics from known information for well-established services, or by a trade study involving everything? Do you understand fully the choices made, even those which are neither technical nor optimal? Are you documenting the results and reasons? Did you analyze as many reasonable alternatives as possible to understand how the system behaves as a function of its principal design features–system drivers? Did you determine and clarify what features would significantly affect the overall system performance? Did you conduct a feasibility assessment, sizing estimate, or point design for quick, limited trades? Did you conduct a trade study, performance assessment, or utility assessment for more detailed trades?

Source: Adpated from inputs by Stephanie Butron (Class of 2013)

How to Apply Systems Thinking? (contd.)

4. **Interpretation and Inferences** *(conclusions, solutions)*

   Did you conduct a mission utility analysis to quantify mission performance as a function of design, cost, risk, and schedule? How well do alternative systems meet overall objectives? Does that help you decide whether or not to proceed with a more detailed study? Are you providing technical information to the decision-makers to determine whether they should spend their limited resources on your system or another alternative? If you are selected as the end product, are you providing the technical information needed to allow the decision-makers to select how many systems and the level of redundancy to include?

5. **Utilizing Concepts** *(theories, definitions, laws, principles)*

   How will the mission work in practice? What are the elements of the mission? Are the key elements: data delivery; tasking, scheduling, and control; communications architecture; and mission timeline? How will the data be sensed and delivered to the end user? How will the mission be controlled? What is the overall mission timeline? What are alternative/distinct approaches to the problem? Are you using low-cost approach? What is the mission architecture (mission concept *plus* definition of the elements of the mission)? What alternatives of each mission elements would best meet mission objectives?

6. **Making Assumptions** *(presuppositions, axioms, taking for granted)*

   Did you correctly identify the principal mission parameters/system drivers/characteristics which influence performance cost, risk, or schedule *and* which the user or designer can control? Are you looking for drivers of performance, cost, risk, or schedule? Did you develop a formula to express the 1st order estimate of the value of the parameter identified? Did you examine the factors of the expression, which can be adjusted, and which have the strongest effect on results? Are there any implicit variables affecting more than one characteristic?

Source: Adpated from inputs by Stephanie Butron (Class of 2013)

How to Apply Systems Thinking? (contd.)

7. **Generating Implications** *(effects)*

   Does the proposed system meet overall mission objectives? Is the system technically feasible? Is the level of risk acceptable? Are the schedule and budget within established constraints? Does the mission meet political objectives? Are the organizational responsibilities acceptable to all organizations involved in the decision? Is the mission compatible with the infrastructure in place?

8. **Points of View** *(perspectives, frame of reference, orientation)*

   Who are the primary stakeholders (those who have an interest in the final system)? Who ultimately decides how well the system should do and at what cost? Have you identified your own point of view? Have you considered the point of view of other stakeholders? Have you tried to be fair-minded about considering diverse points of view?

"An organization which operates using a Systems Approach delivers better engineering." – John Parnaby, 1995

Source: Ref. SE 1

Source: Adpated from inputs by Stephanie Butron (Class of 2013)

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