SYSTEMS ENGINEERING (SUPER SHORT) REVIEW

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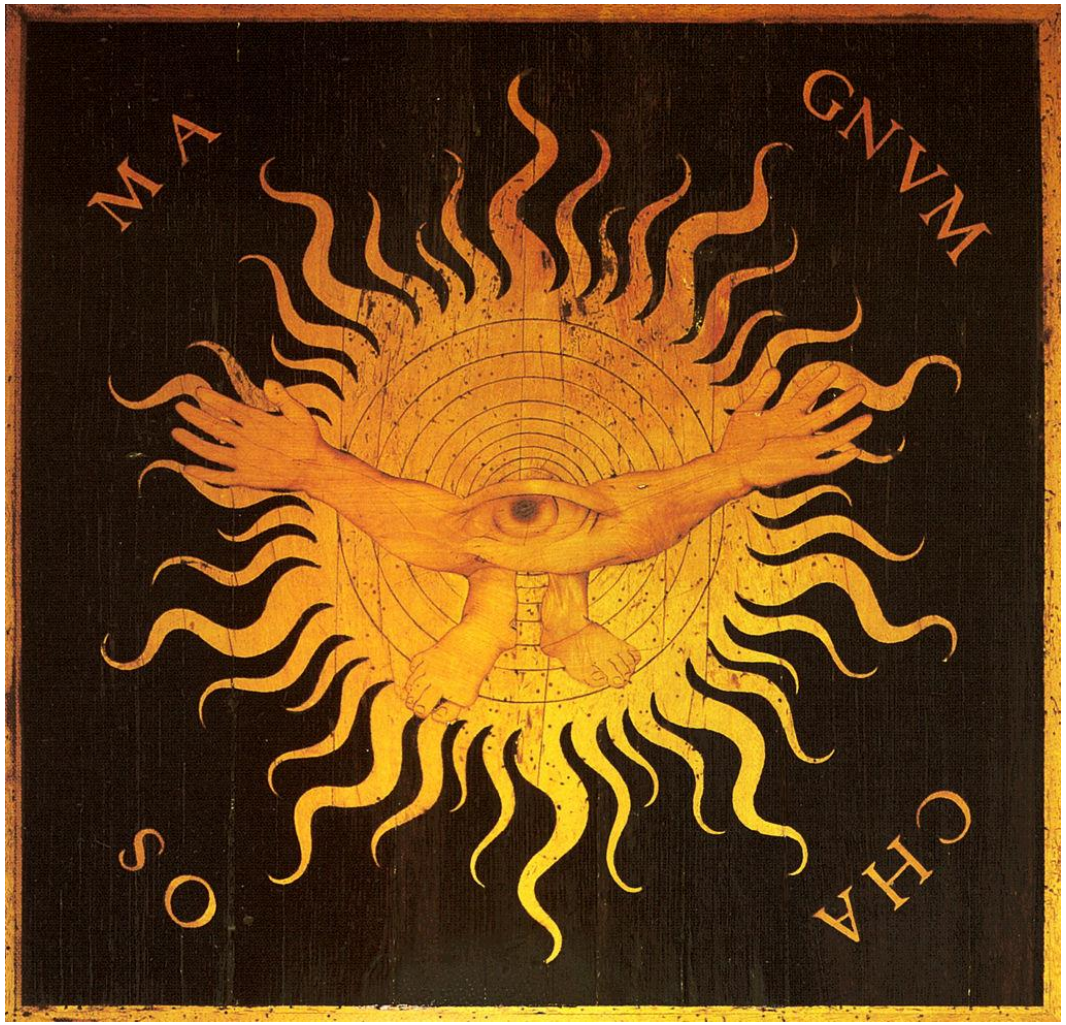
2025

Context

At the beginning there was only chaos



- **At the beginning there was only Chaos, Night, dark Erebus, and deep Tartarus. Earth, the air and heaven had no existence.** [695] Firstly, blackwinged Night laid a germless egg in the bosom of the infinite deeps of Erebus, and from this, after the revolution of long ages, sprang the graceful Eros with his glittering golden wings, swift as the whirlwinds of the tempest. He mated in deep Tartarus with dark Chaos, winged like himself, and thus hatched forth our race, which was the first to see the light. [700] That of the Immortals did not exist until Eros had brought together all the ingredients of the world, and from their marriage Heaven, Ocean, Earth and the imperishable race of blessed gods sprang into being. Thus our origin is very much older than that of the dwellers in Olympus. We are the offspring of Eros; there are a thousand proofs to show it. We have wings and we lend assistance to lovers. [705] How many handsome youths, who had sworn to remain insensible, have opened their thighs because of our power and have yielded themselves to their lovers when almost at the end of their youth, being led away by the gift of a quail, a waterfowl, a goose, or a cock.

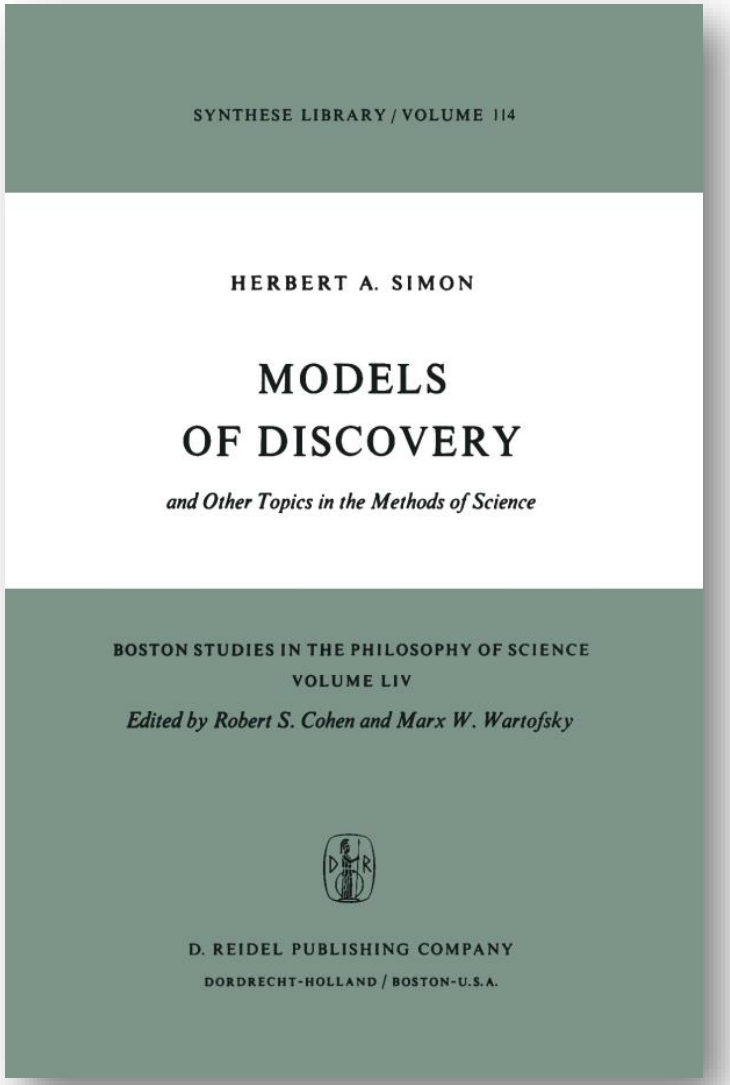
Chaos (cosmogony) - Wikipedia

Aristophanes, Birds, line 685 (tufts.edu)

We started to understand the chaos

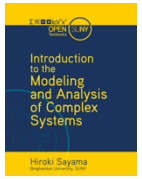
Figure 1 – The Flammarion woodcut (19th Century), illustrating the Flat-Earth cosmology. Seen from the observer's village, the Earth seems flat, as encountered in everyday experience. However, just to the left, a "curious" fellow decides to breach the sphere of the fixed stars to sneak a peek at the mechanisms that move the Sun, Moon and planets.

https://doi.org/10.1590/S0103-40142006000300022

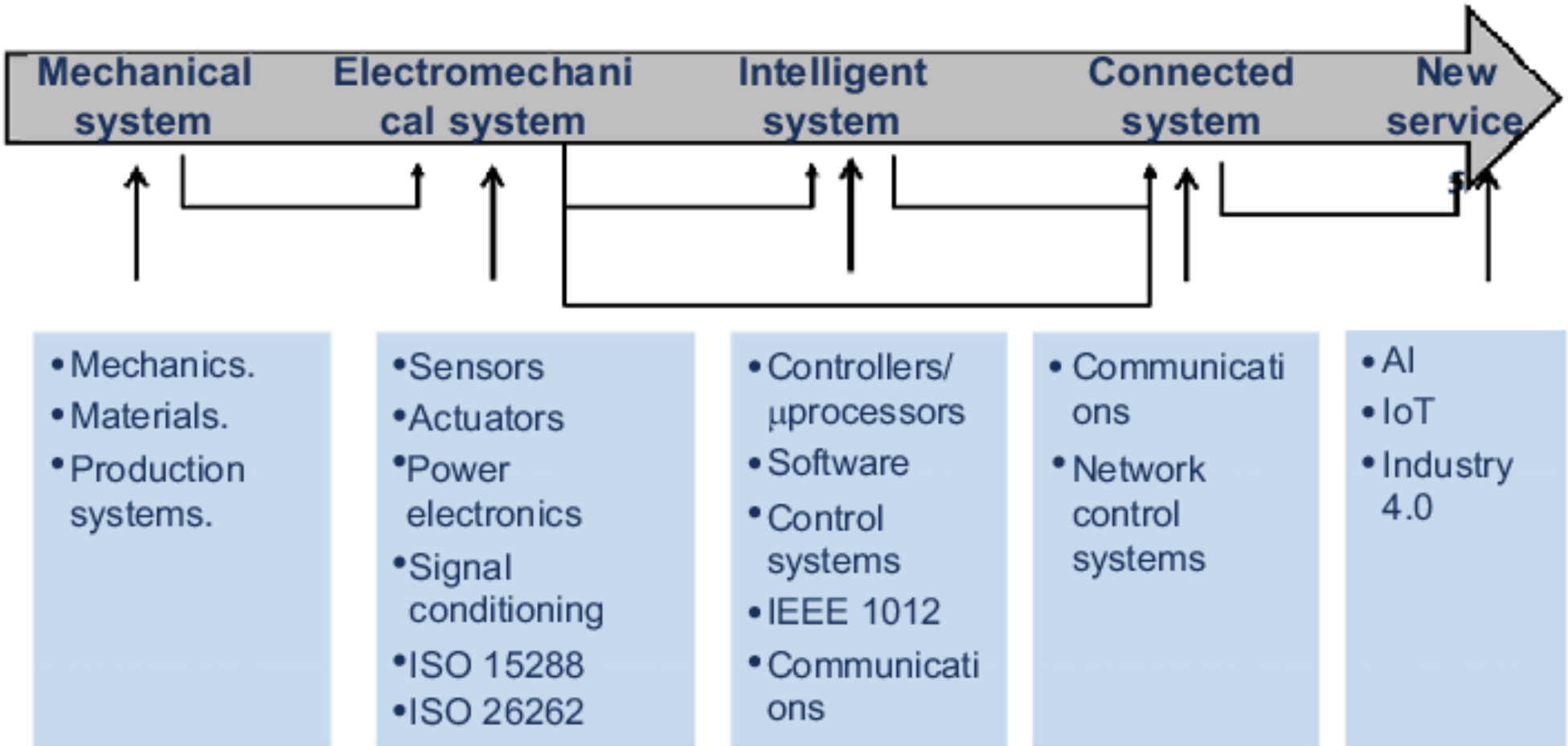


Complex systems

- **Complex systems** are **networks** made of a number of **components that interact with each other**, typically in a **nonlinear** fashion. Complex systems may arise and evolve through **self-organization**, such that they are neither completely regular nor completely random, permitting the development of **emergent behavior** at macroscopic scales.



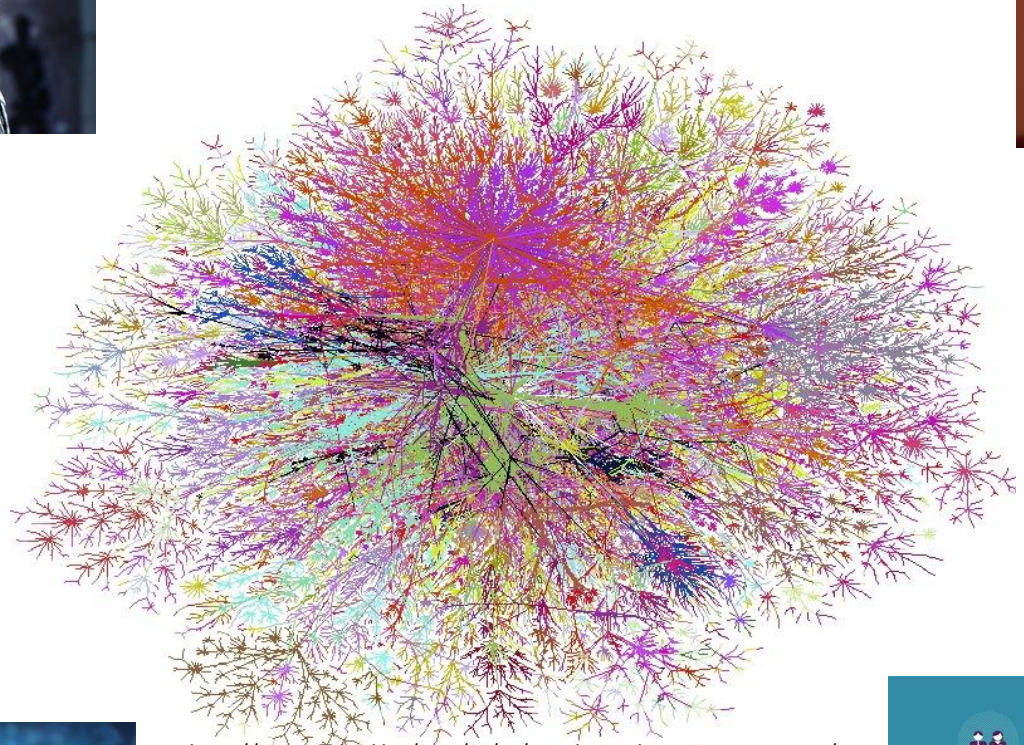
The growth of complexity in systems



https://doi.org/10.4271/12-03-02-0011

Ending scene from 1971 movie THX 1138

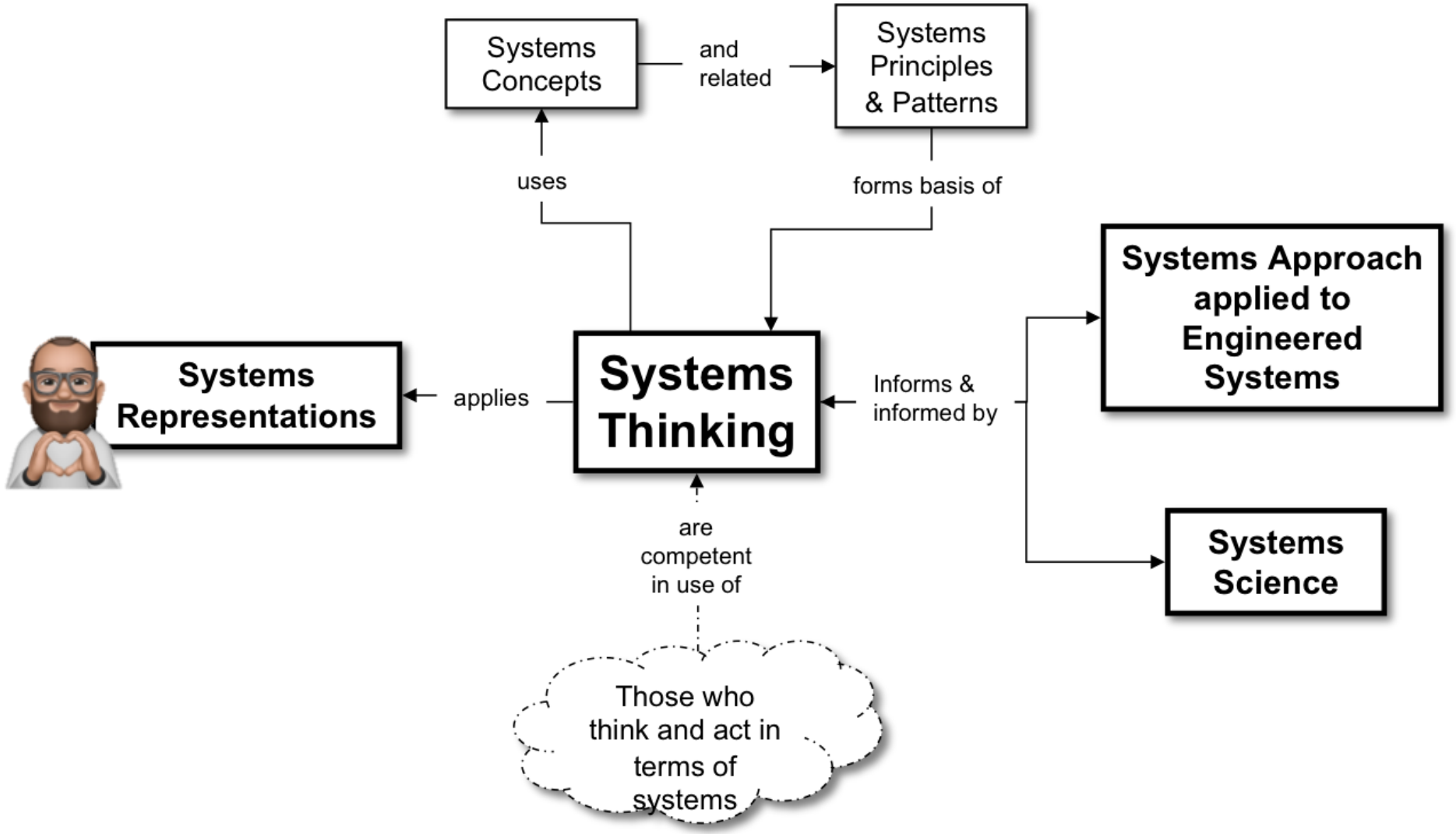
https://www.youtube.com/watch?v=atMdf0rhbpI



https://ioannouolga.blog/2017/09/14/complexity-theory-ii-m-woermann/

Some definitions

Systems thinking



Concepts of Systems Thinking - SEBoK (sebokwiki.org)

Principles of Systems Thinking - SEBoK (sebokwiki.org)

Systems Thinking and Systems Science RA - Systems Thinking - SEBoK (sebokwiki.org)

What is Systems Engineering?

Systems Engineering is **a transdisciplinary approach and means**, based on systems principles and concepts, to enable the successful realization, use and retiral of engineered systems.

It focuses on

- establishing stakeholders' **purpose and success criteria**, and defining actual or anticipated customer needs and required functionality early in the development cycle,
- establishing an **appropriate lifecycle model** and process approach considering the levels of complexity, uncertainty and change
- documenting and **modelling requirements** and **solution architecture** for each phase of the endeavour
- proceeding with **design synthesis and system validation**
- while considering the **complete problem** and **all necessary enabling systems and services**.

Systems Engineering provides facilitation, guidance and leadership to integrate all the disciplines and specialty groups into a team effort forming an appropriately structured development process that proceeds from concept to production to operation, evolution and eventual disposal.

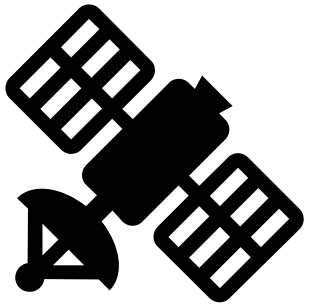
Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality solution that meets the needs of users and other stakeholders and is fit for the intended purpose in real-world operation, and avoids or minimizes adverse unintended consequences.

The practice of Systems Engineering

- The **practice** of systems engineering is concerned with both a **systemic** approach to understanding the problem, devising a solution, and understanding the interdependencies in the work to develop, deliver and evolve the solution;
- and a systematic approach to establishing objectives and success criteria, analyzing and documenting the solution, predicting its effectiveness, and establishing and implementing an effective and efficient process for development, delivery and subsequent evolution.

Engineered System x System Engineering

An engineered system is an system made of technical or sociotechnical elements that exhibits emergent properties not exhibited by its individual elements. It is created by and for people; has a purpose, with multiple views; satisfies key stakeholders' value propositions; has a life cycle and evolution dynamics; has a boundary and an external environment; and is part of a system-of-interest hierarchy.

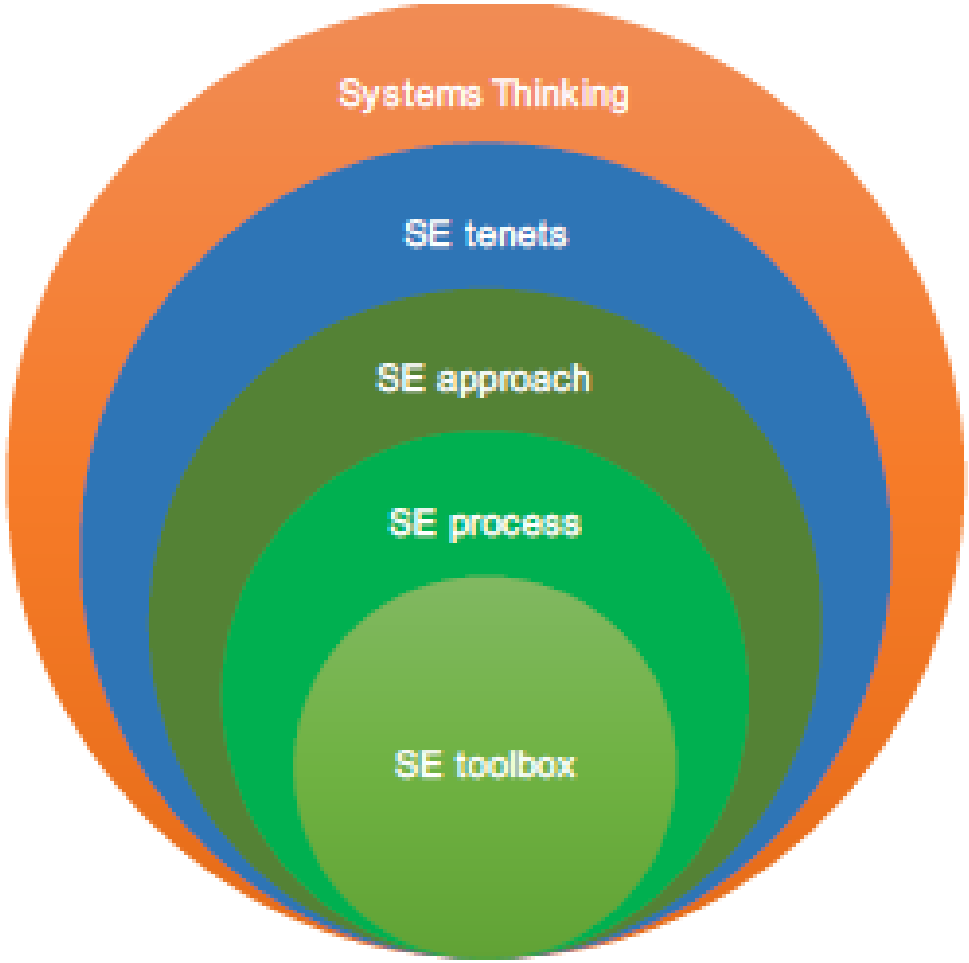


Systems engineering is "an transdisciplinary approach and means to enable the realization of successful (engineered) systems". It focuses on holistically and concurrently understanding stakeholder needs; exploring opportunities; documenting requirements; and synthesizing, verifying, validating, and evolving solutions while considering the complete problem, from system concept exploration through system disposal.

http://sebokwiki.org/wiki/Use_Case_0:_Systems_Engineering_Novices

Four aspects of Systems Engineering

- 1. some very basic and widely applicable **SE tenets** (principles and beliefs);
- 2. a general **SE approach** to complex and complicated problems;
- 3. the "**SE process**", which we see evolving from the current SE process described in the INCOSE SE Handbook into a family of SE process models, targeted towards different system types; and
- 4. an **SE toolbox** of techniques and methods that are widely applicable across the spectrum.



Tenants

- Systems Engineers often talk about using a "**systems approach**" to work their way into a problem that seems wider or fuzzier than "**normal engineering**" (whatever that is ).
- **Such a "systems approach" uses selected systems principles or beliefs that are of proven value in an engineering context and are also useful elsewhere.**
- We will use the term "**systems engineering tenets**" to refer to a key set of principles and beliefs drawn from various branches of systems thinking and the systems sciences, that seem to underpin most or all of what we currently recognize as systems engineering.

12 Systems Engineering Tenets

Envisioning Systems Engineering as a Transdisciplinary Venture (researchgate.net)

1. Understand what **success means**
2. Consider the **whole problem**, the **whole solution** and the **full lifecycle**
3. Understand and manage **interdependencies**
4. Adapt the parts to **serve the purpose** of the whole
5. Recognize that Systems Engineering occurs at **multiple levels**
6. Base decisions on **evidence and reasoned** judgement
7. **Recognize uncertainty** while managing change, risk opportunities and expectations
8. Handle **structure and behavior** as two complementary aspects of any system
9. Understand and use appropriate **feedback (loop)**
10. Understand and manage **value**
11. Be both **systemic and systematic**
12. **Respect** the people

Principle of Emergence:

As the entities of a system are brought together, their interaction will cause function, behavior, performance, and other intrinsic properties to emerge.

- Emergence is the **power and the magic of systems**. Emergence refers to **what appears, materializes, or surfaces when a system operates**. Obtaining the desired emergence is why we build systems. **Understanding emergence is the goal**—and the art—of system thinking.
- What emerges when a system comes together? **Most obviously and crucially, function emerges.** Function is what a system does: its actions, outcomes, or outputs. In a designed system, we design so that the anticipated desirable primary function emerges (cars transport people).

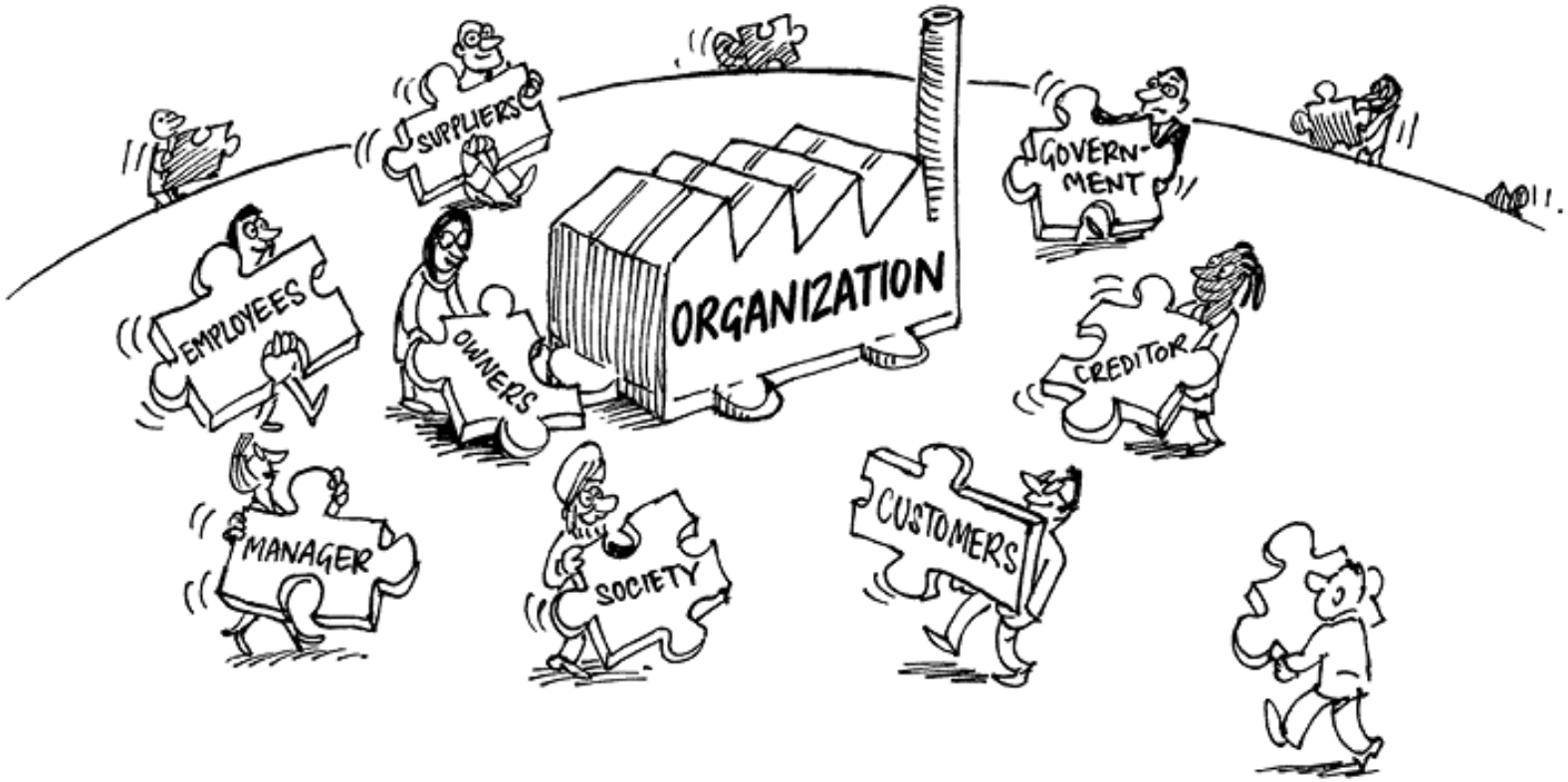
TABLE 2.1 | Types of emergent functions

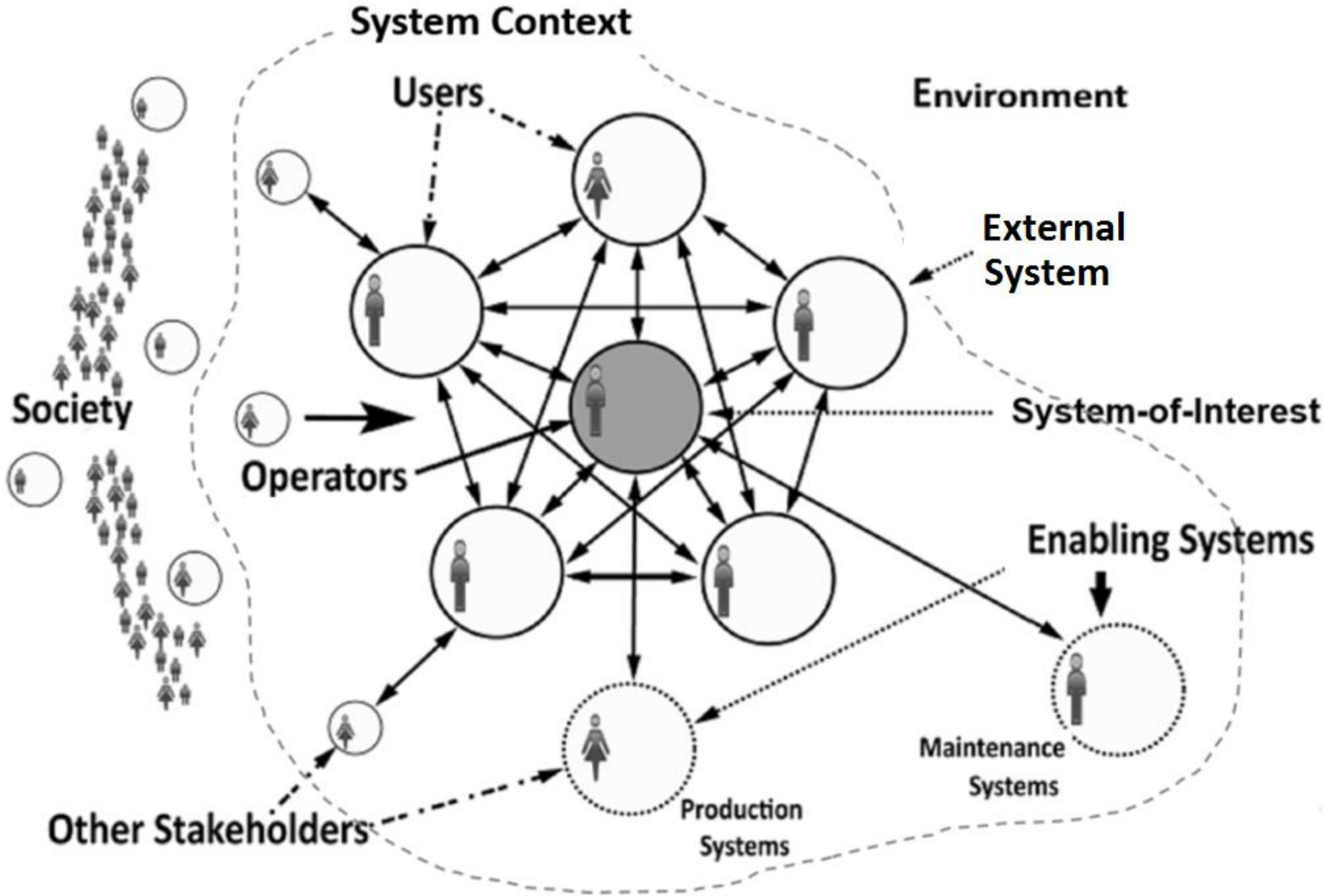
	Anticipated Emergence	Unanticipated Emergence
Desirable	Cars transport people Cars keep people warm/cool Cars entertain people	Cars create a sense of personal freedom in people
Undesirable	Cars burn hydrocarbons	Cars can kill people

Stakeholders

Stakeholders

- A stakeholder is any individual, group or organization that can affect, be affected by a project.




System Context
Users
Environment
External System
Society
Operators
System-of-Interest
Enabling Systems
Maintenance Systems
Production Systems
Other Stakeholders

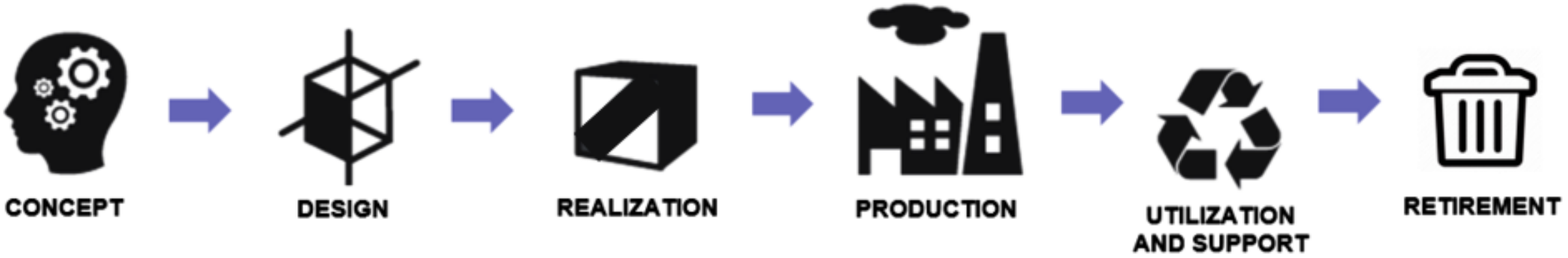
Life cycle

Life cycle

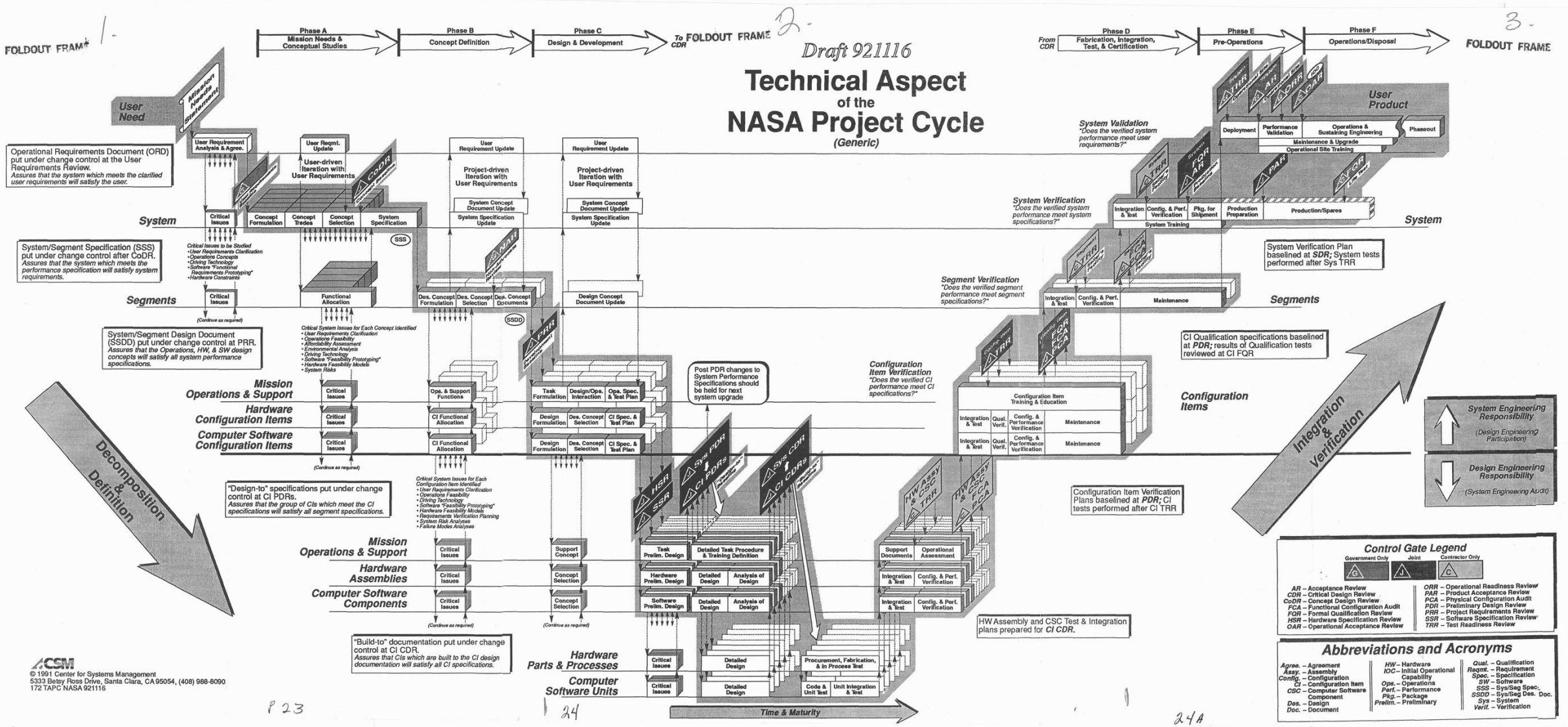
*"Life cycle is the **series of phases** through which **something** passes."*

Life cycle

- Engineered Systems have a **life cycle.**
  - Life cycle is a series of stages through which a system passes during its lifetime
  - Life cycle considers the evolution of a system from conception through retirement

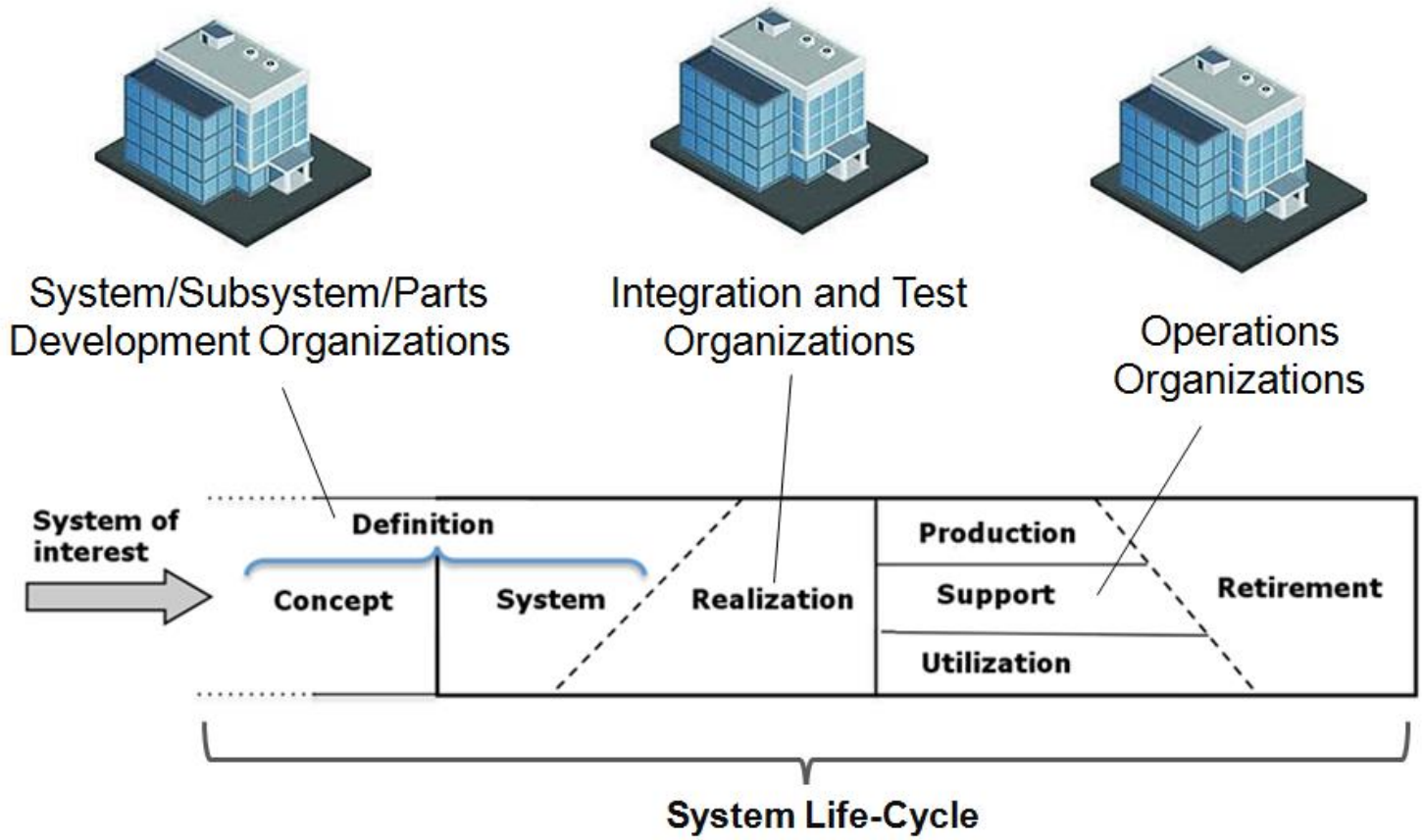


(Classical) VEE Model



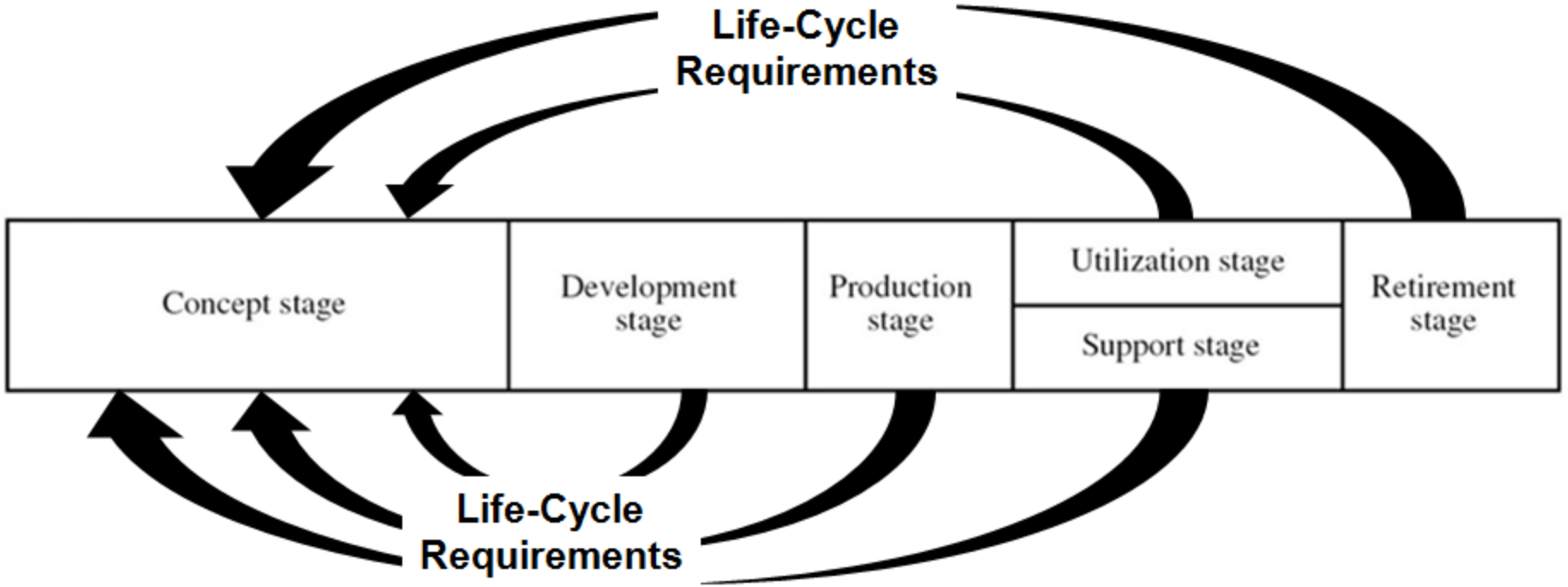
Life cycle concepts

- The life cycle concept is a **description** of the expected system life cycle.
- Life cycle concepts focus on **defining solutions** for the system life cycle.



Life cycle requirements

- Life cycle requirements promote the **anticipated understanding** about future system attributes



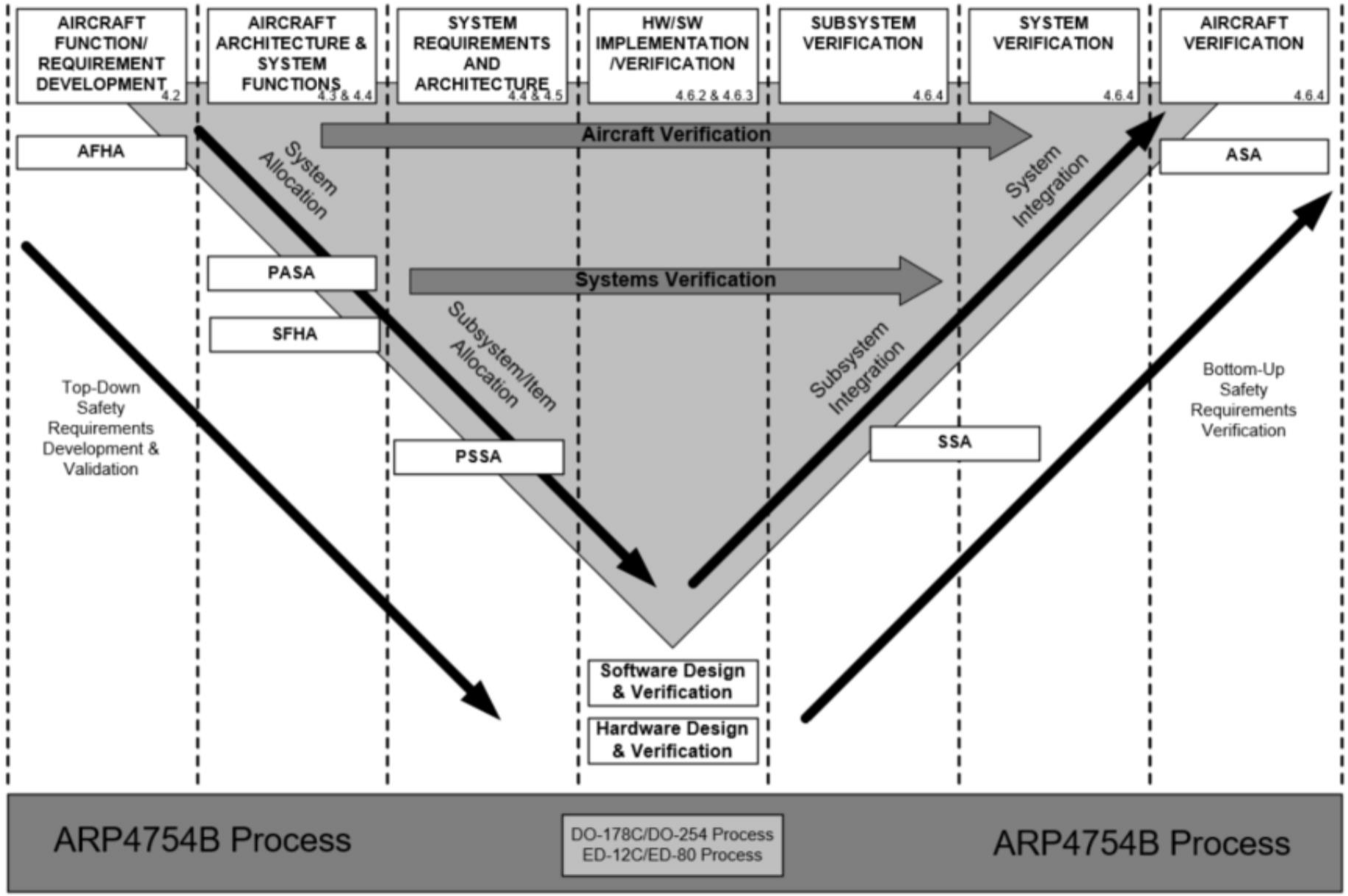
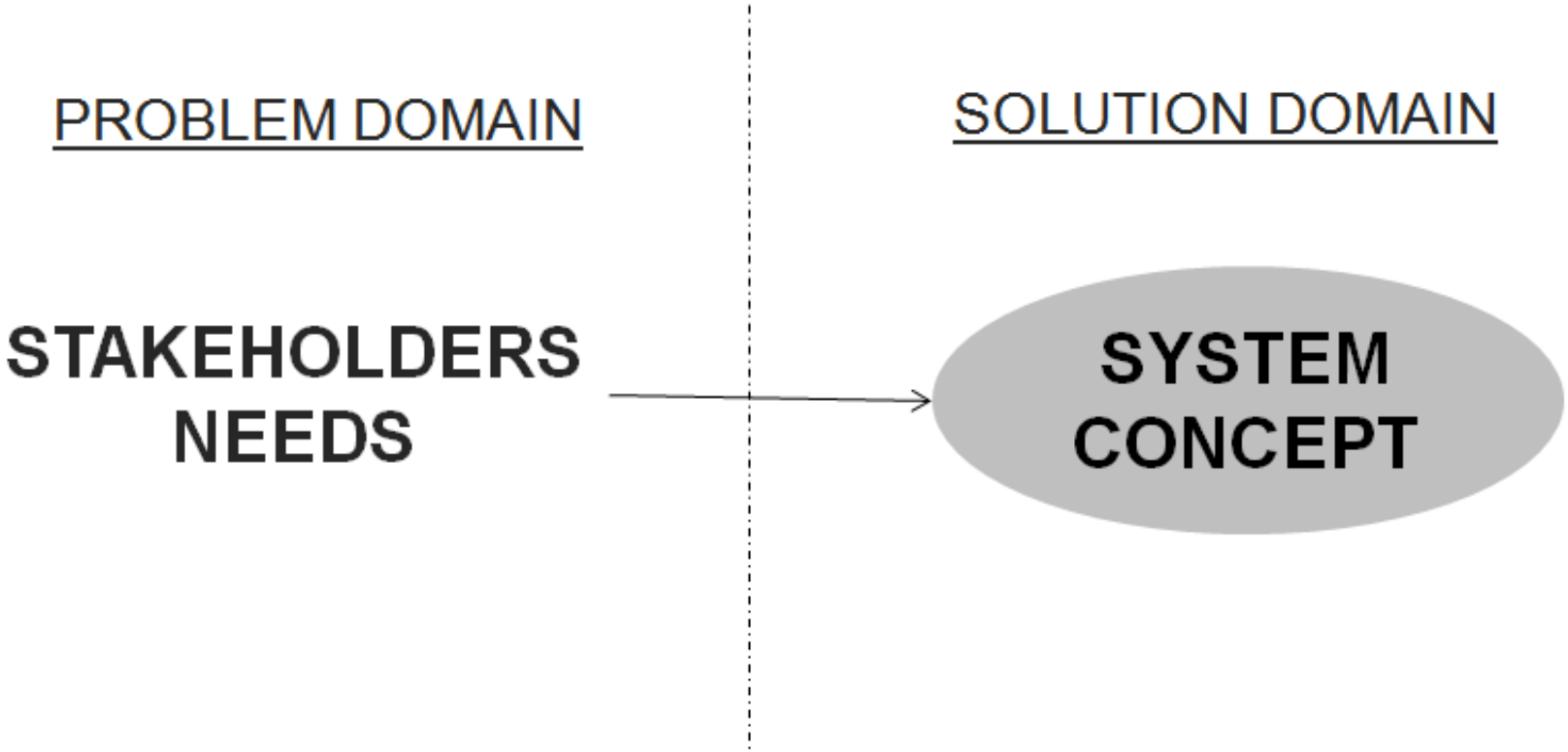


Figure 4 - Interaction between Safety Assessment and development processes

CONOPs

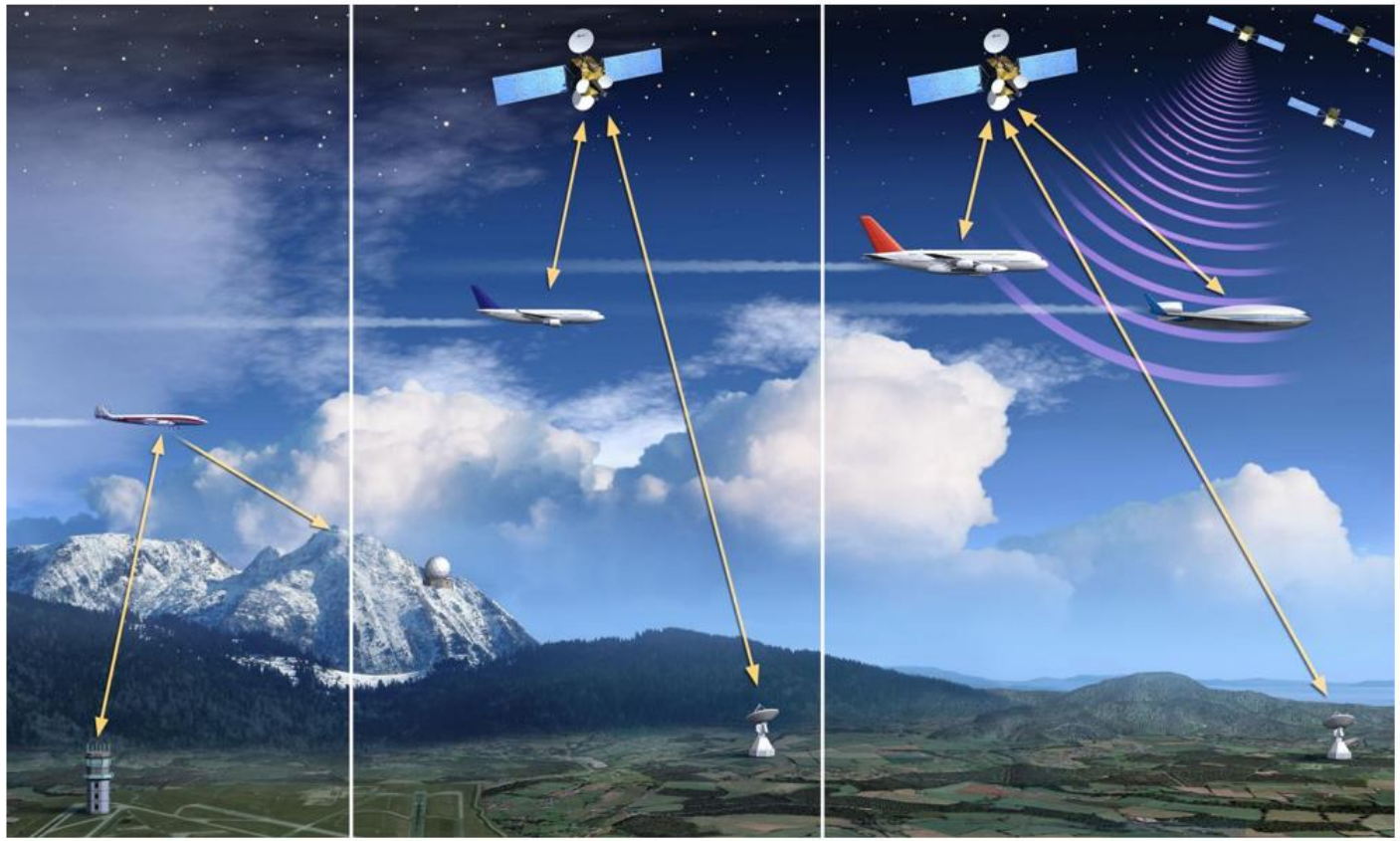
Concept definition phase

- The conceptual design provides a **description of the proposed system** that **fulfills the stakeholders needs**.



Concept of Operations

- Describes the **characteristics** of a proposed system from the viewpoint its operators



What is a CONOPS?

- Description of **how** the System will be operated to meet stakeholder expectations
- Explains your system's characteristics from an operational perspective and helps facilitate an understanding of the **system's purpose**
- Illustrates a day in the life of your system's **intended use**

Why is a CONOPS important?

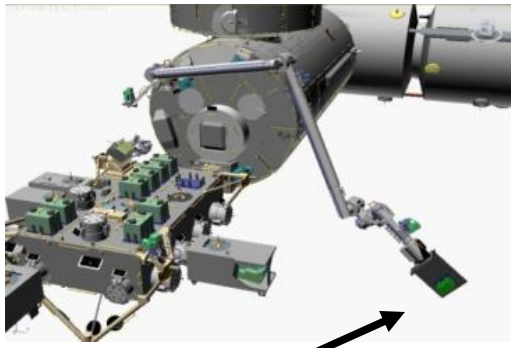
- Drives **development of requirements**
  - Maintains the **context** of a requirement in everyday, informal language
  - Thinking through the ConOps and use cases **reveal requirements and design functions** that might otherwise be overlooked
- Gets everyone on the same page about **what the project is and what it will do**
- Identifies **user interface** issues early
- Identifies **key stakeholder needs** for defining, designing, and implementing the end product
- Provides **guidance** for the development of system definition documentation

The CONOPS contains, as a minimum, the following:

- **Operational goals** from the viewpoint of all stakeholders.
- **Overview of the System** of interest, including supporting systems.
- **Intended use** of the system during all life-cycle phases of the program/project, including but not limited to:
  - 1. Manufacturing and assembly / 2. Integration and test. / 3. Transportation and storage. / 4. Ground operations/launch integration. / 5. Launch Operations - launch, deployment, on-orbit checkout. / 6. Maintenance and disposal.
- Operational **timelines**.
- Command and data **architecture**.
- **End-to-end communication** strategy.
- **Integrated logistic** support (resupply, maintenance, assembly).
- Operational **facilities**.
- **Contingency and off-nominal** operations.

A ConOps does NOT include design solutions.

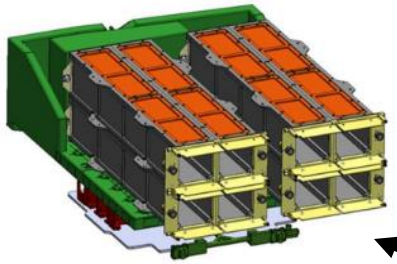
CONOPS Example: SPORT



Soft Package

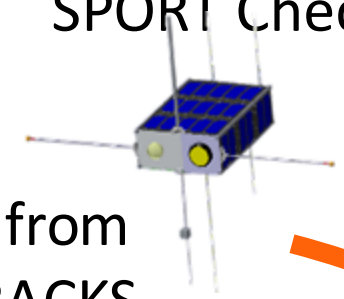
Launch

Installation



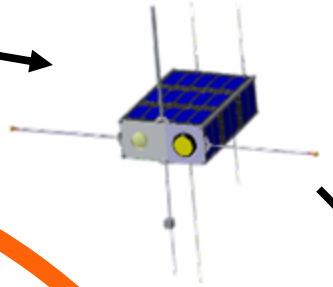
Deploy from NANORACKS 400 km alt

SPORT Checkout



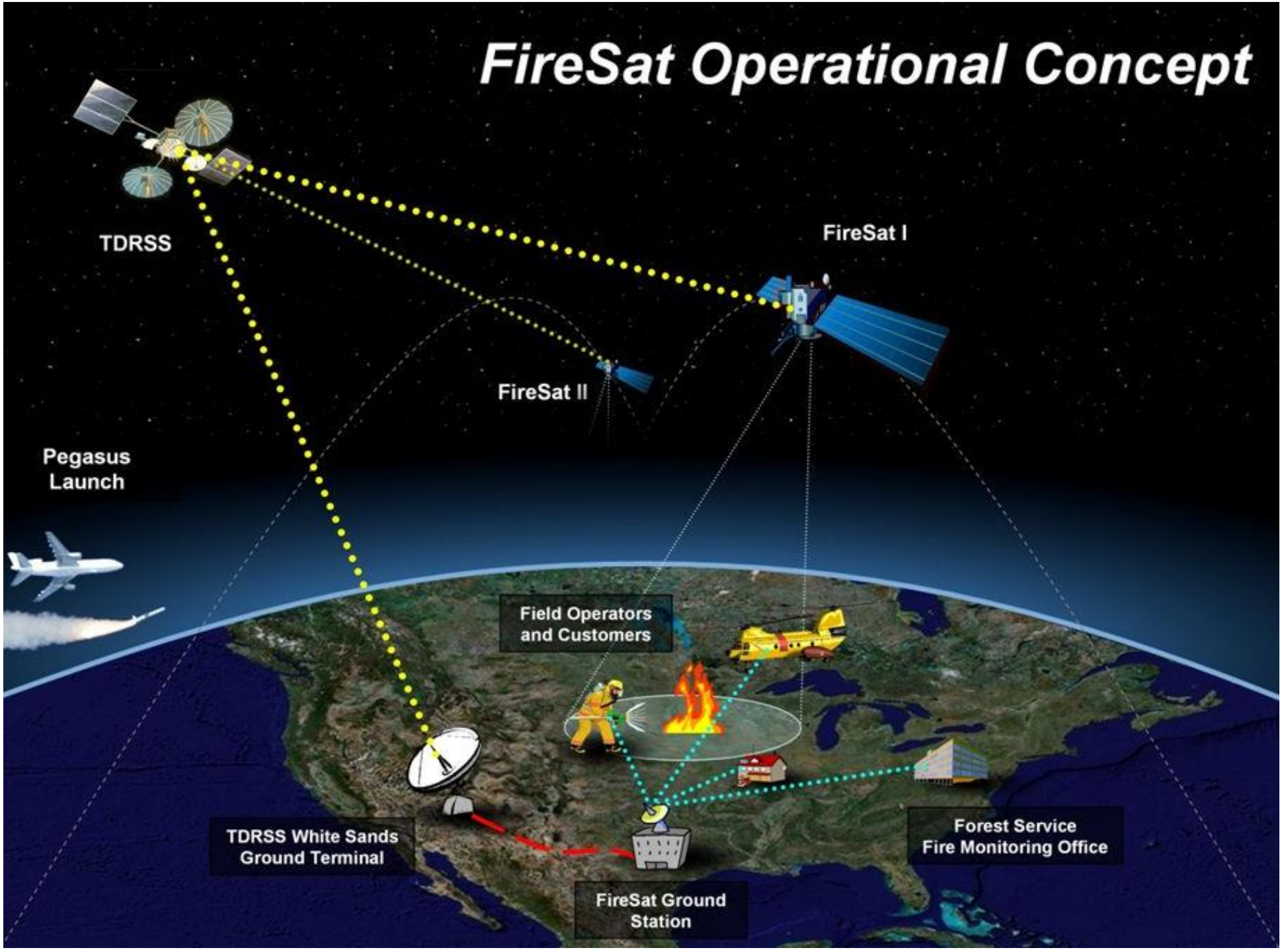
SPORT Operations

On-orbit Operations (> 12 months)



Disposal 300 km alt

Images: Charlie Gray


FireSat Operational Concept
TDRSS
FireSat I
FireSat II
Pegasus
Launch
Field Operators
and Customers
TDRSS White Sands
Ground Terminal
FireSat Ground
Station
Forest Service
Fire Monitoring Office

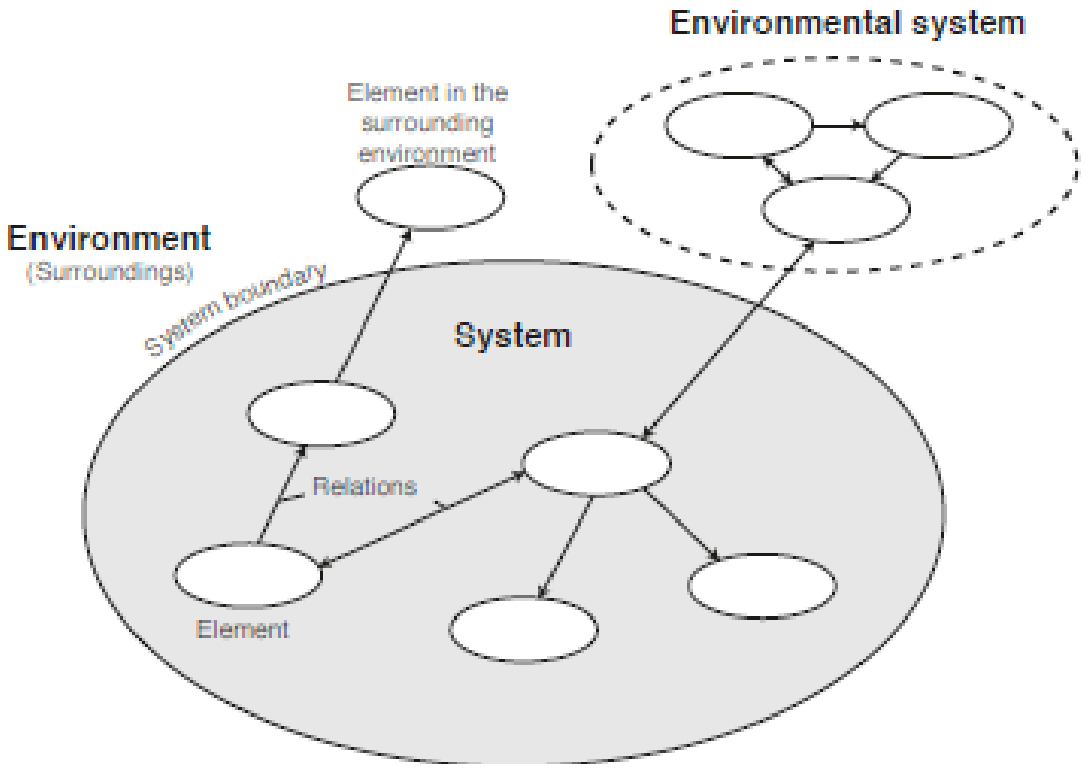
Functions

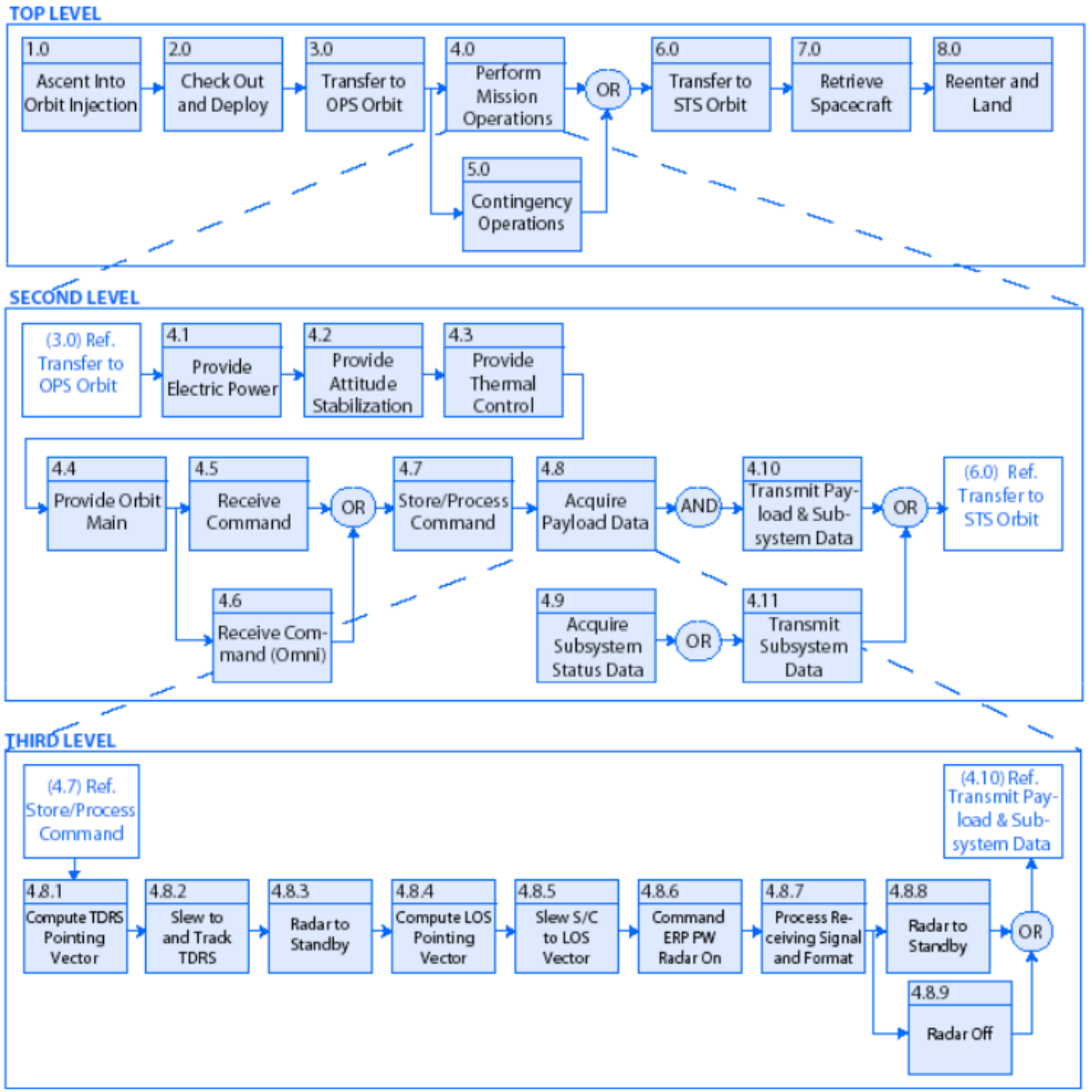
Function (action/activity)

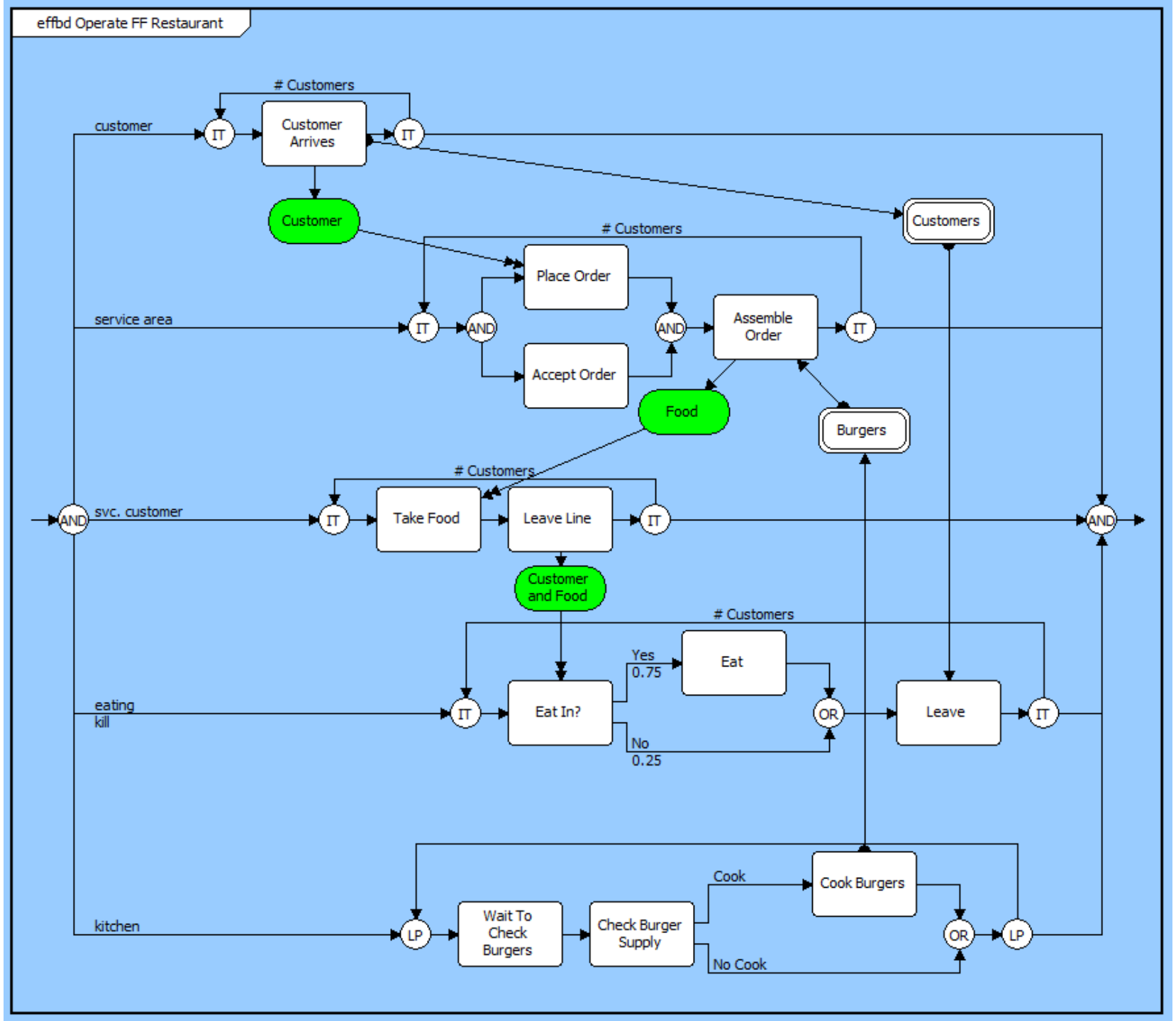
- A function is an **action, an operation or a service**, performed by the system or one of its components, or also by an actor interacting with the system.
- Performing a **function generally produces exchange items** expected by other functions, and to do this, it requires other items provided by other functions.
- Several **functions can be grouped** into a mother function (they are then called subfunctions, or daughter functions, of this function). Symmetrically, a function can be refined into several functions.
- By convention, a function is named with a **verb**.

Boundaries

- Boundary is understood to be a more or less arbitrary **border between the system and its surroundings** or the environment in which it is embedded.




TOP LEVEL
1.0
Ascent Into Orbit Injection
2.0
Check Out and Deploy
3.0
Transfer to OPS Orbit
4.0
Perform Mission Operations
OR
6.0
Transfer to STS Orbit
7.0
Retrieve Spacecraft
8.0
Reenter and Land
5.0
Contingency Operations
SECOND LEVEL
(3.0) Ref. Transfer to OPS Orbit
4.1
Provide Electric Power
4.2
Provide Attitude Stabilization
4.3
Provide Thermal Control
4.4
Provide Orbit Main
4.5
Receive Command
OR
4.7
Store/Process Command
4.8
Acquire Payload Data
AND
4.10
Transmit Pay-load & Sub-system Data
OR
(6.0) Ref. Transfer to STS Orbit
4.6
Receive Com-mand (Omni)
4.9
Acquire Subsystem Status Data
OR
4.11
Transmit Subsystem Data
THIRD LEVEL
(4.7) Ref. Store/Process Command
(4.10) Ref. Transmit Pay-load & Sub-system Data
4.8.1
Compute TDRS Pointing Vector
4.8.2
Slew to and Track TDRS
4.8.3
Radar to Standby
4.8.4
Compute LOS Pointing Vector
4.8.5
Slew S/C to LOS Vector
4.8.6
Command ERP PW Radar On
4.8.7
Process Re-ceiving Signal and Format
4.8.8
Radar to Standby
OR
4.8.9
Radar Off



[Enhanced Function Flow Block Diagram (EFFBD) (vitechcorp.com)]

Requirements

requirement [ri-**kwahy*uh*** **r**-m*uh* nt] SHOW IPA

SEE SYNONYMS FOR *requirement* ON THESAURUS.COM

noun

1. that which is required; a thing demanded or obligatory:
   One of the requirements of the job is accuracy.
2. an act or instance of requiring.
3. a need or necessity:
   to meet the requirements of daily life.

DEFINITIONS

TO DO OR NOT TO DO

- **Functional Requirements** describe what the system should do and **Non-functional Requirements** place constraints on how these functional requirements are implemented.

IMPORTANCE OF HAVING GOOD REQUIREMENTS

- Requirements tell you **what the system needs to do** (functional requirements).
- **How well** the system needs to do it (performance requirements)
- **What environment** the system has to work in (environmental requirements).
- What the system **must do to fit into the bigger system** (interface requirements).
- What **lower level subsystems/assemblies/components must do to fit** into the system and make it all work (allocation of requirements/resources).
- What you need to **do before you fly** (verification activities).
- And basically, **when you are done** (requirements are met).

CLASS EXAMPLE: FUNCTIONS TO REQUIREMENTS

- **NEED STATEMENT: PORTABLE AUTOMOTIVE VEHICLE FOR OFF-ROAD**
  - Use Case: Camping Trip
    - Ops: Load Camping Gear On To Vehicle
      - Function: Provide Space To Store Camping Gear
        - Requirement: The vehicle shall be designed with a minimum cargo storage area of 11 cubic feet.
        - Rationale: Estimated calculation of space needed to accommodate customer's camping equipment
    - Ops: Load Personnel On To Vehicle
      - Function: Provide Capability To Carry Up To 4 People
    - Ops: Drive To Camp Site
      - Function: Provide Capability To Drive 20 Miles Roundtrip
        - Requirement: The vehicle driving range shall be a minimum of 40 miles.
        - Rationale: Customer stated the maximum range (out and back) of use as being 20 miles after getting the vehicle to where it would be used.
      - Function: Provide Capability To Utilize GPS
    - Ops: Get Stuck
      - Function: Provide Vehicle Capability To Get Un-Stuck
    - Ops: Unload Camping Gear/Camp
      - Function: Provide Electrical Interface For DC Powered Camp Eq.
        - Requirement: The vehicle shall provide, 12 VDC +/- 1.5 VDC, 12 Amps maximum, auxiliary utility ports.
        - Rationale: Based on power draw assessment of the connecting equipment
        - Requirement: The vehicle shall provide two utility ports for connecting DC powered camping equipment.
        - Rationale: Customer desired two specific ports to connect equipment simultaneously

Verification

- The verification of a product shows **proof of compliance with requirements** – the product can meet each "must" claim as proven through the performance of a test, analysis, inspection or demonstration (or combination of these).
- **Verification is a process of confirming that a requirement or system is compliant**.
  - In other words, the system checker asks the question: **Does the system meet your requirements?**
  - The requirements checker asks the question: **Does the system really meet this specific requirement?**

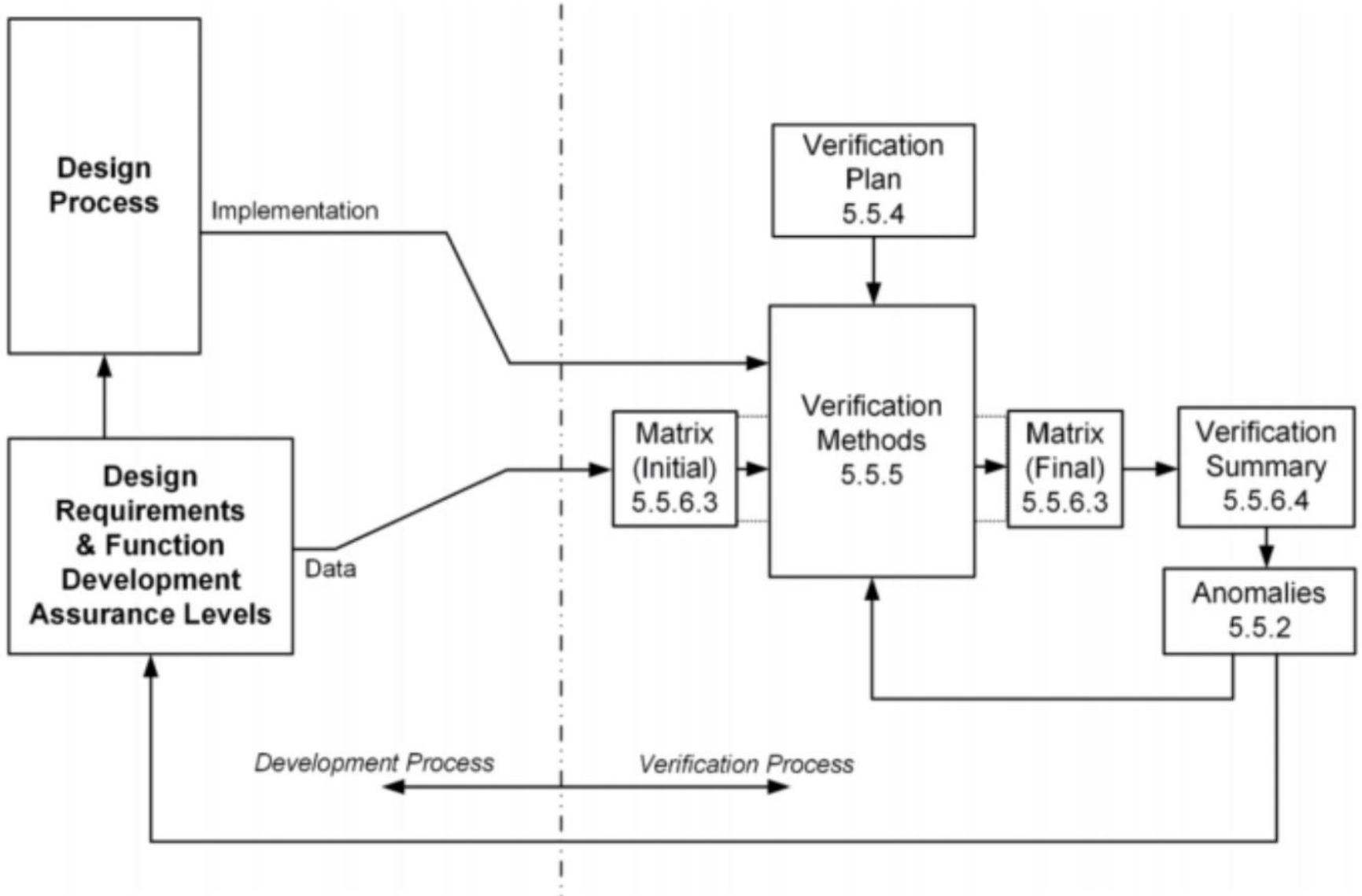


Figure 9 - Verification process

Validation

- VALIDATION of a product shows that the **product fulfills its intended purpose in the intended environment** – that it meets the expectations of the customer and other stakeholders, as demonstrated by the performance of a test, analysis, inspection, or demonstration.
- Validation is a process of confirming that a set of requirements, design, or system **meets the intent** of the developer or customer.

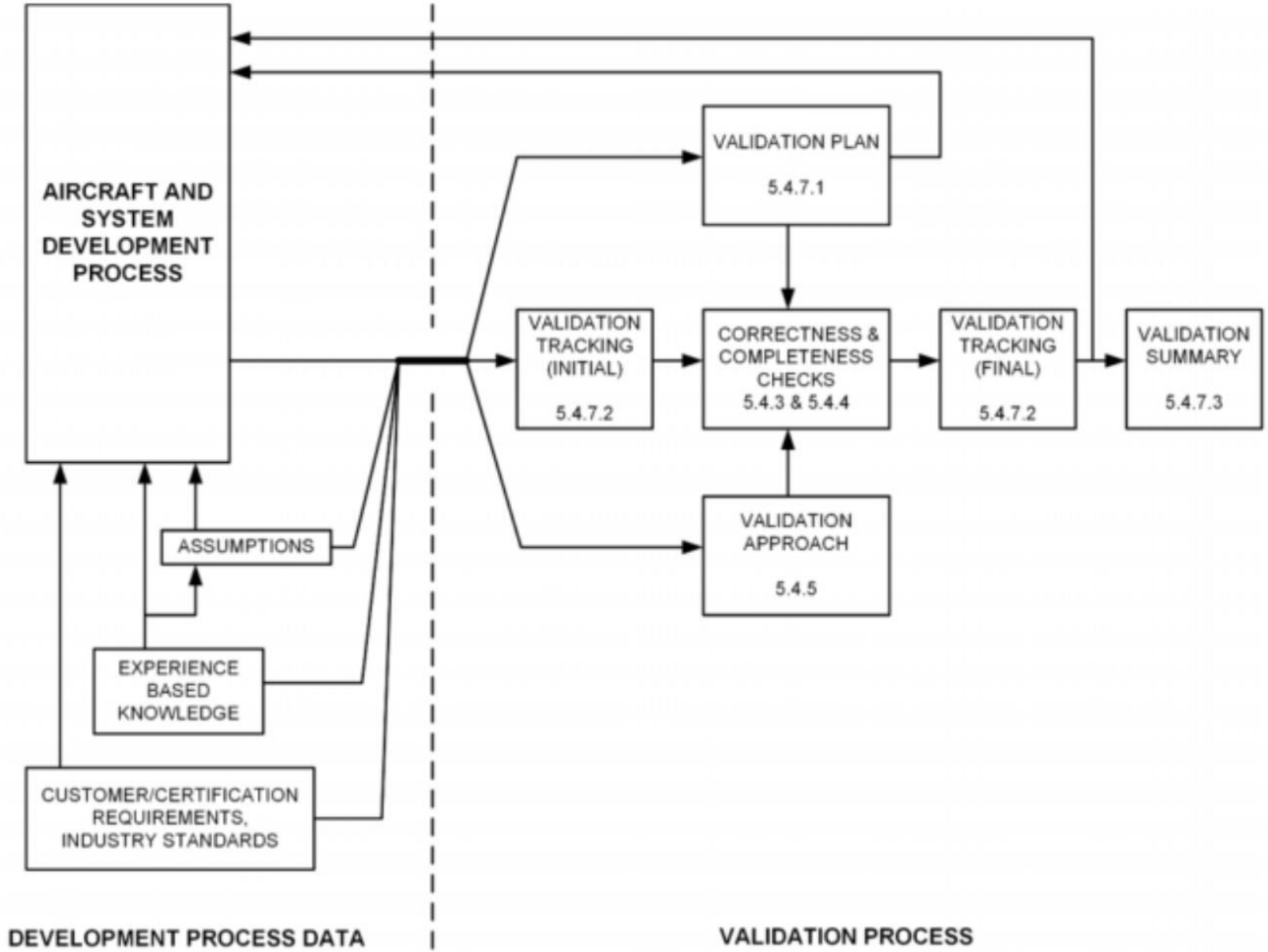


Figure 8 - Validation process

Tasks	Steps
Define verification/validation requirements.	a. Define the method by which the requirement is to be verified. (1) Test. (2) Analysis. (3) Inspection. (4) Demonstration. (5) Validation of Records. (6) Similarity. b. Define the level at which the verification/validation will occur. (1) System. (2) Subsystem. (3) Component. c. Define the phase or purpose of the verification/validation activity to be performed. (1) Development. (2) Qualification. (3) Acceptance. (4) Pre-launch. (5) Flight/Mission. (6) Post-flight. (7) Disposal.
Manage and maintain the verification/validation requirements.	a. Manage and maintain verification/validation requirements. b. Update as necessary in accordance with established data management requirement.

Reference: MSFC-HDKB-2221, Volume I and Volume II

MoCs

Means of Compliance

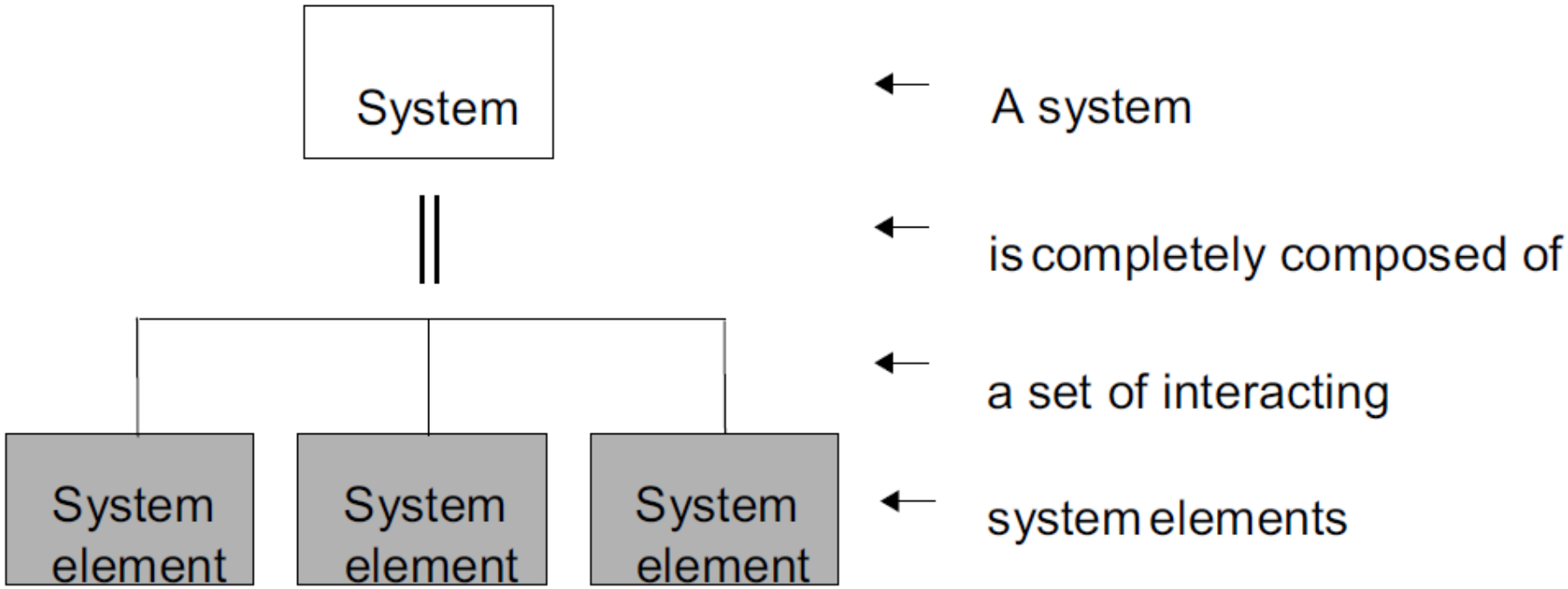
Type of Compliance	Means of Compliance	Associated Compliance Documents
Engineering evaluation	MC0: -Compliance statement -Reference to Type Design documents -Election of methods, factors... -Definition	-Type Design documents -Recorded statements
	MC1: Design review	-Description -Drawings
	MC2: Calculation/Analysis	-Substantiation reports
	MC3: Safety assessment	-Safety analysis
Tests	MC4: Laboratory tests	-Test programmes -Test reports -Test interpretations
	MC5: Ground tests on related product	
	MC6: Flight tests	
	MC8: Simulation	
Inspection	MC7: Design inspection/audit	-Inspection or audit reports
Equipment qualification	MC9: Equipment qualification	-Note: Equipment qualification is a process which may include all previous means of compliance

Architecture

- System architecture is the **embodiment of *concept***, the **allocation of physical/informational *function* to the elements of *form***, and the **definition of *relationships* among the elements** and with the **surrounding *context***.

System Hierarchy

- System and system element relationship



The system is decomposed into a hierarchy of smaller and smaller elements.

One of the most important criteria for judging the goodness of a design:

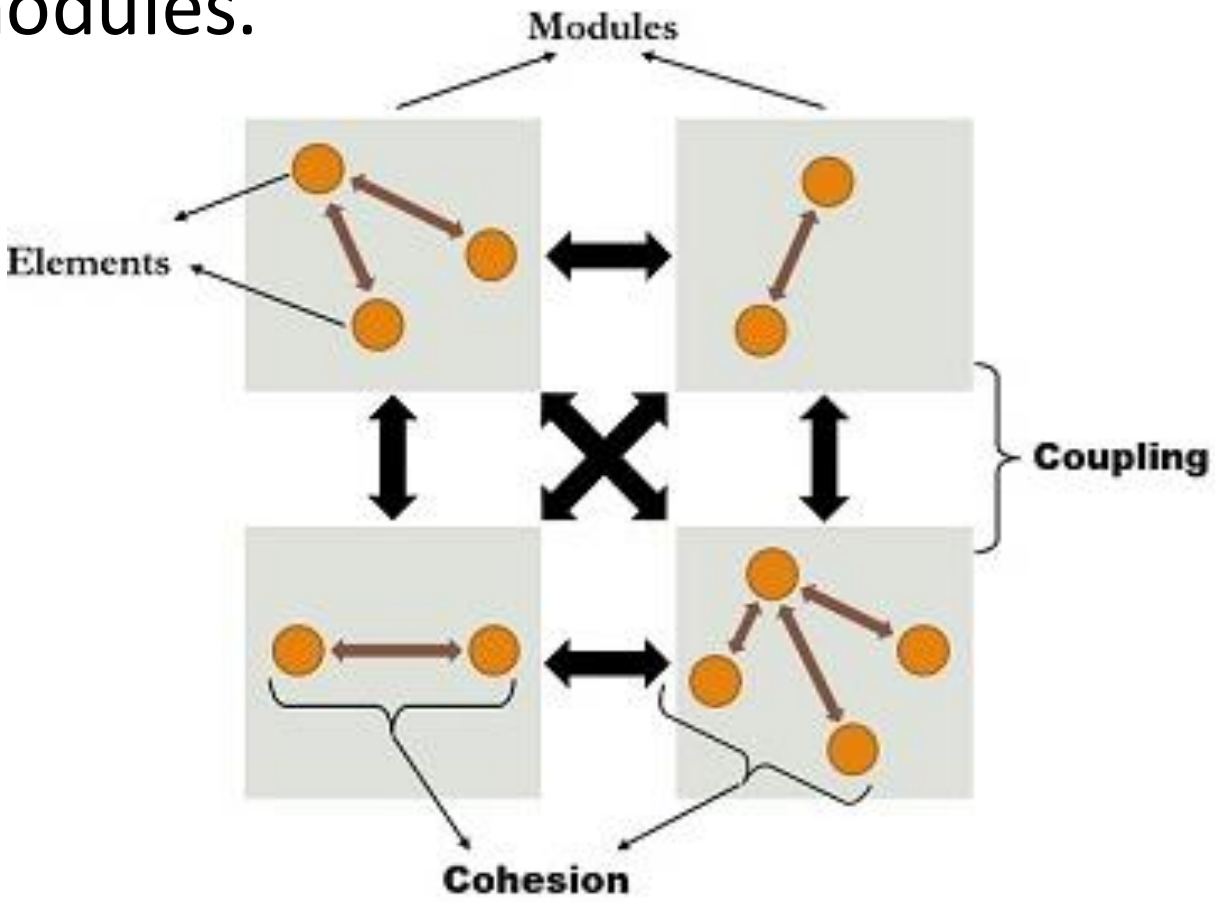
coupling and **cohesion**

together, these two concepts form the central theory of design.

Laplante, P. A. and Ovaska, S. J. Real-Time Systems Design and Analysis. 4th Ed. 2012.

Cohesion is about how well elements within a module belong together and serve a common purpose.

Coupling is about how much one module depends or interacts with other modules.

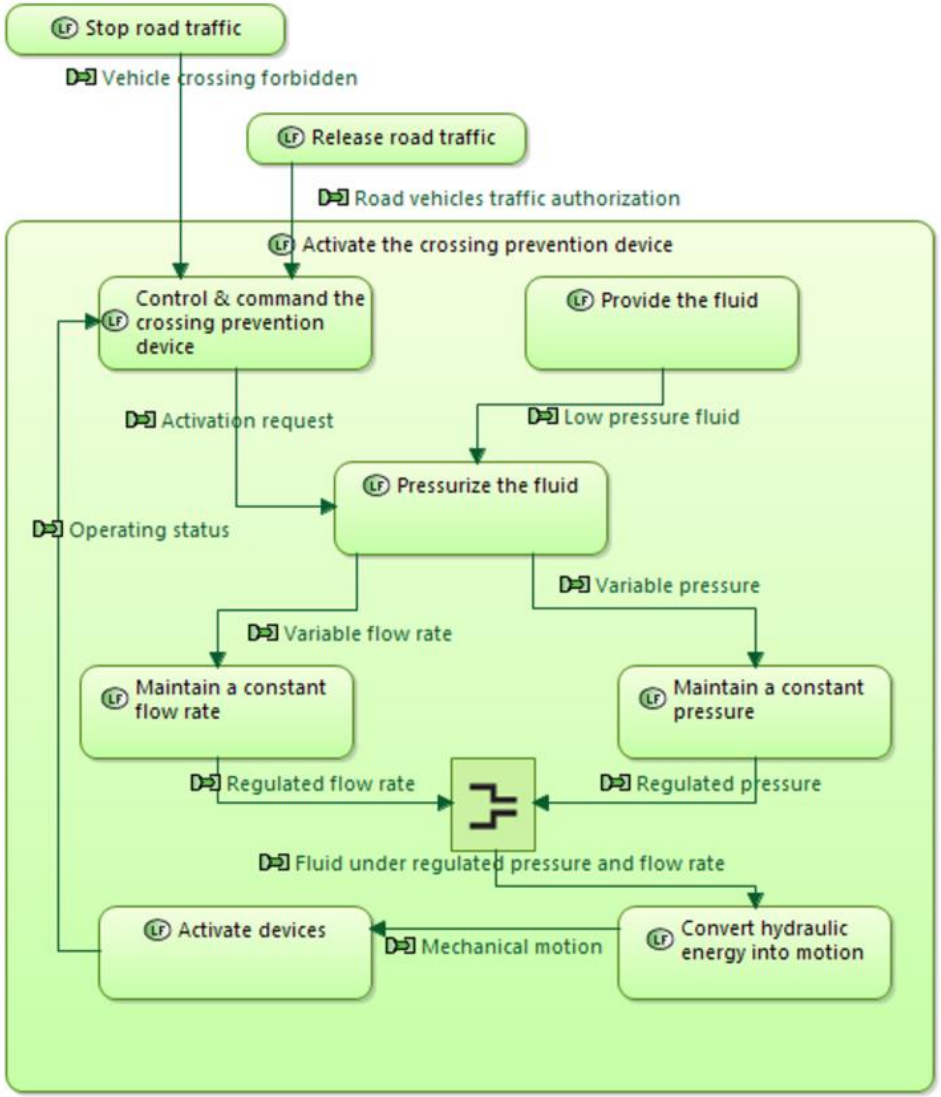


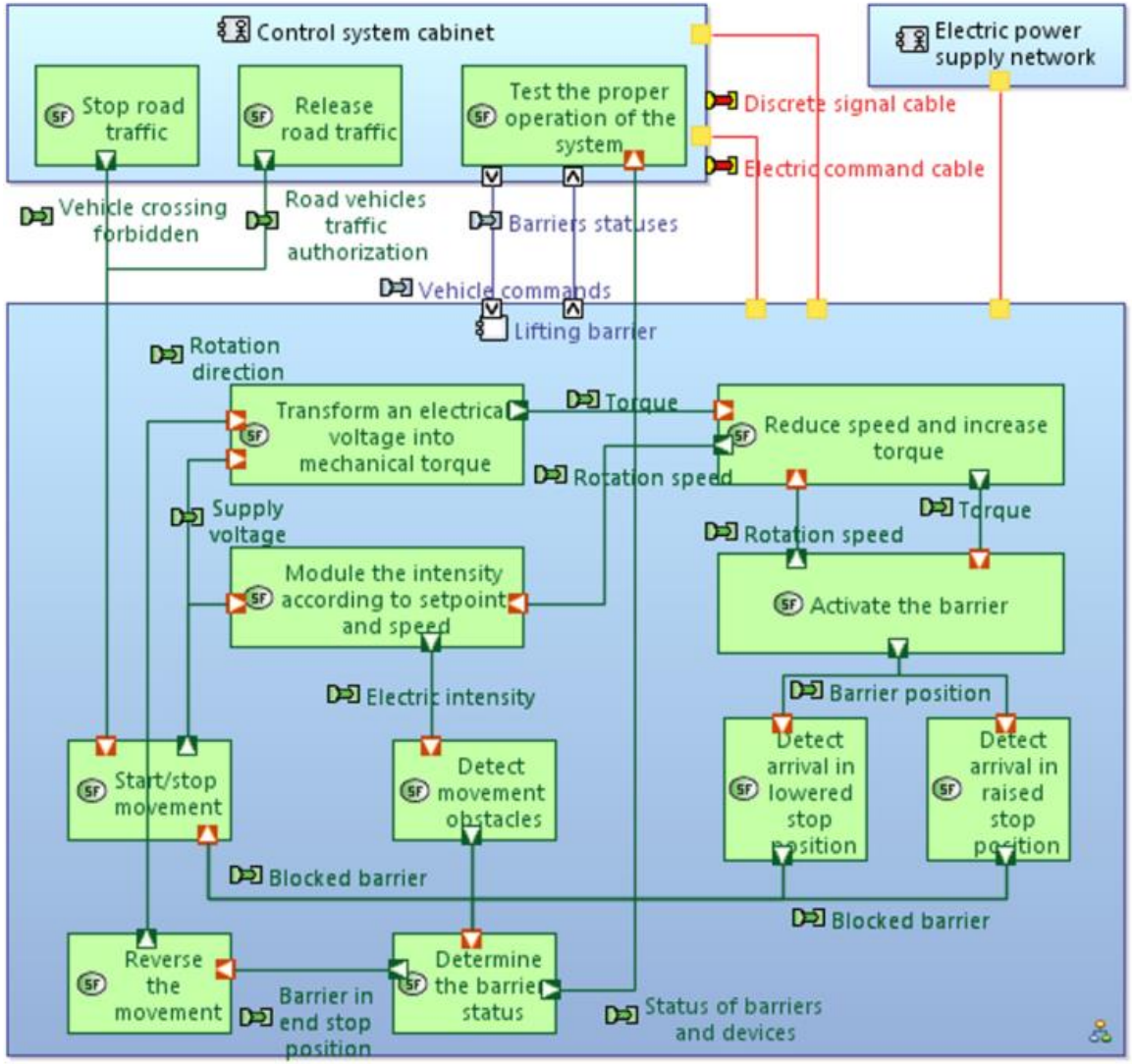
- When a **large system** is **decomposed** into **smaller entities**, it's inevitable that these entities will **interact with one another**.

- If the **boundaries** of these **entities** have been **poorly identified**, then the entities will **heavily depend** and **frequently interact** with **one another**.

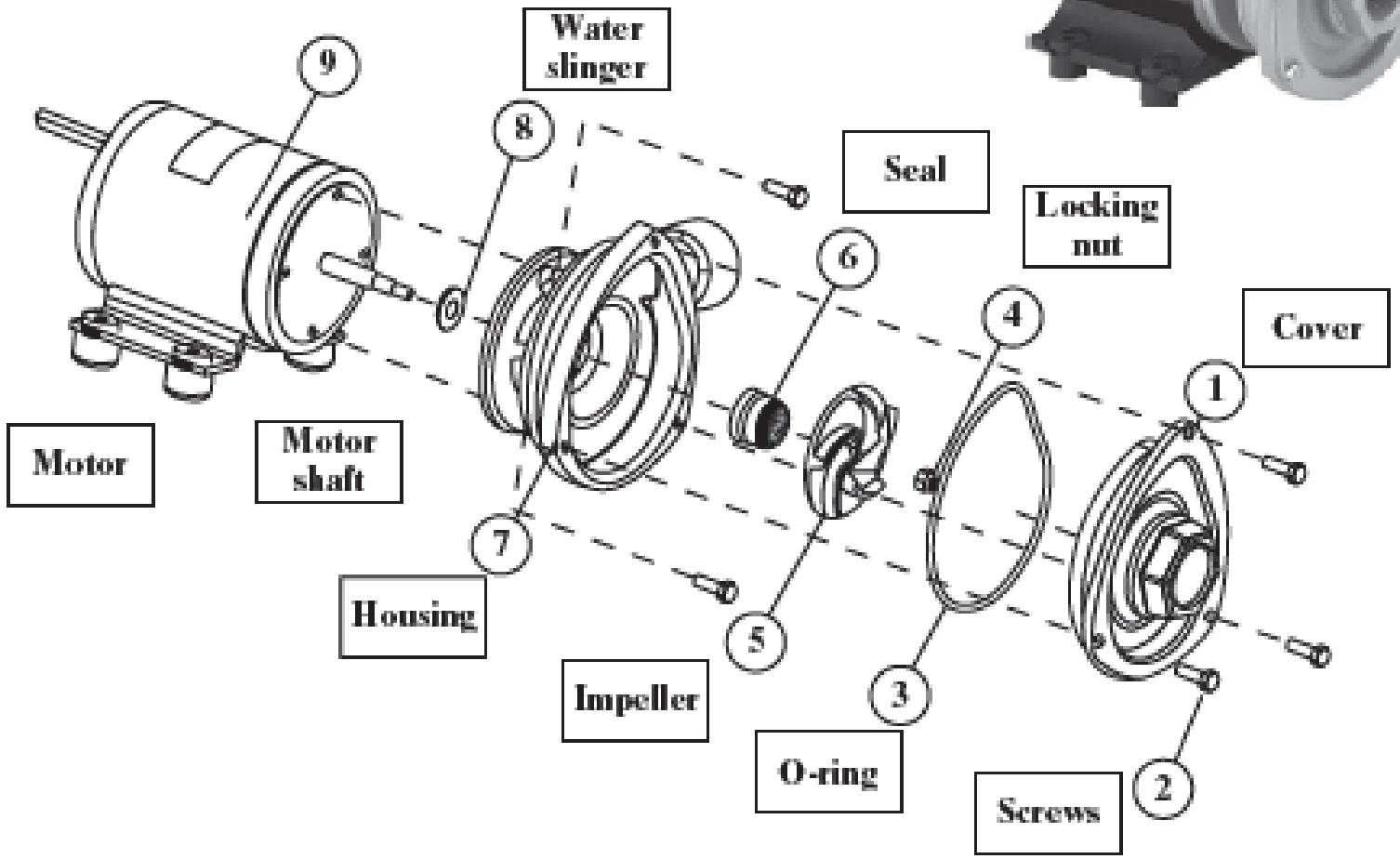
- In a **poor design**, it might also happen that **properties and functions within an entity** perform **diverse tasks** and therefore **don't seem to belong together**.

Examples

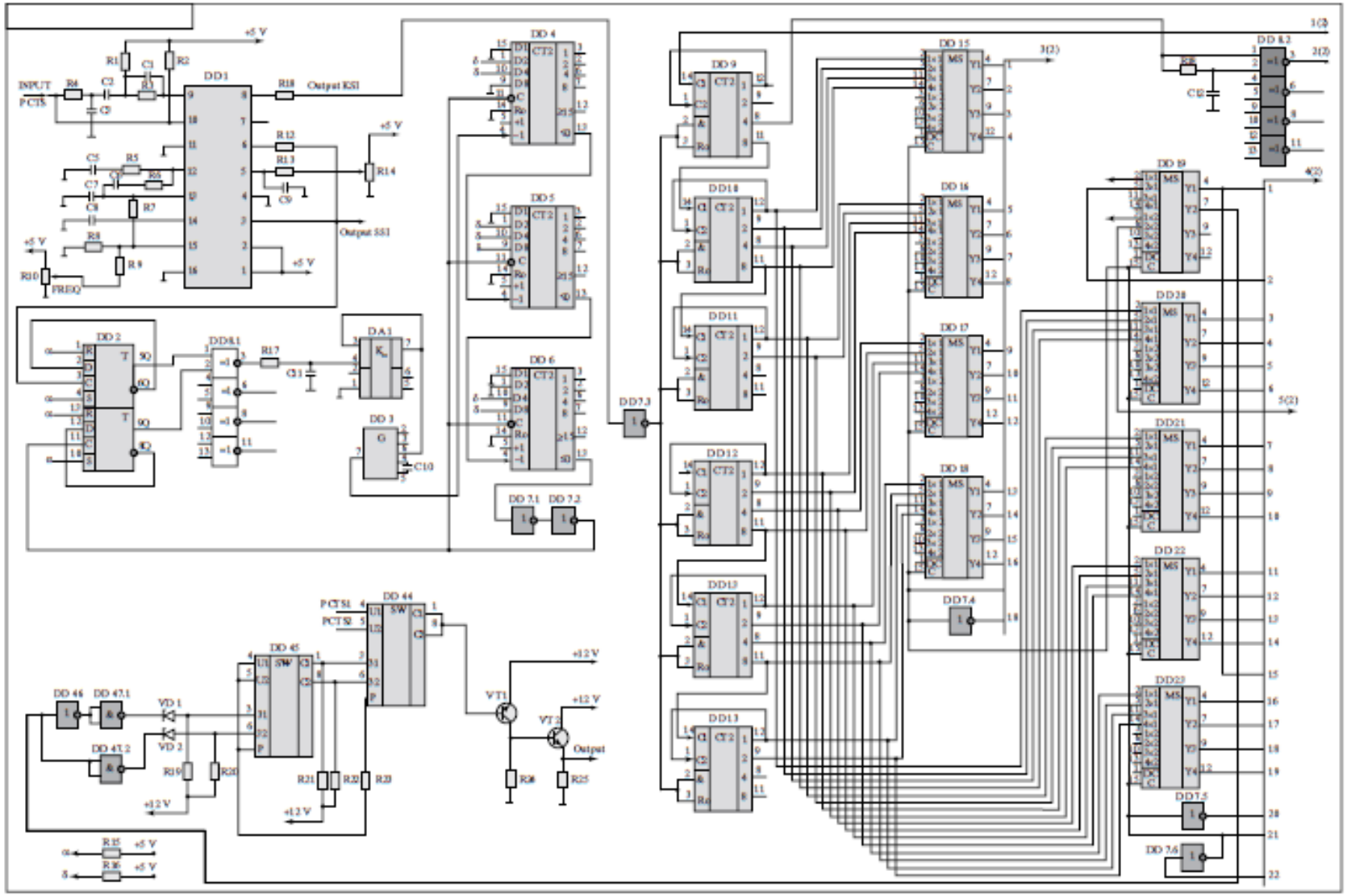

Stop road traffic
Vehicle crossing forbidden
Release road traffic
Road vehicles traffic authorization
Activate the crossing prevention device
Control & command the crossing prevention device
Provide the fluid
Activation request
Low pressure fluid
Pressurize the fluid
Operating status
Variable pressure
Variable flow rate
Maintain a constant flow rate
Maintain a constant pressure
Regulated flow rate
Regulated pressure
Fluid under regulated pressure and flow rate
Activate devices
Mechanical motion
Convert hydraulic energy into motion


Control system cabinet
Electric power supply network
Stop road traffic
Release road traffic
Test the proper operation of the system
Discrete signal cable
Electric command cable
Vehicle crossing forbidden
Road vehicles traffic authorization
Barriers statuses
Vehicle commands
Lifting barrier
Rotation direction
Transform an electrical voltage into mechanical torque
Torque
Reduce speed and increase torque
Rotation speed
Supply voltage
Torque
Rotation speed
Module the intensity according to setpoint and speed
Activate the barrier
Electric intensity
Barrier position
Start/stop movement
Detect movement obstacles
Detect arrival in lowered stop position
Detect arrival in raised stop position
Blocked barrier
Blocked barrier
Reverse the movement
Barrier in end stop position
Determine the barrier status
Status of barriers and devices

EXAMPLE OF FORM: centrifugal pump



Example of form: circuit components

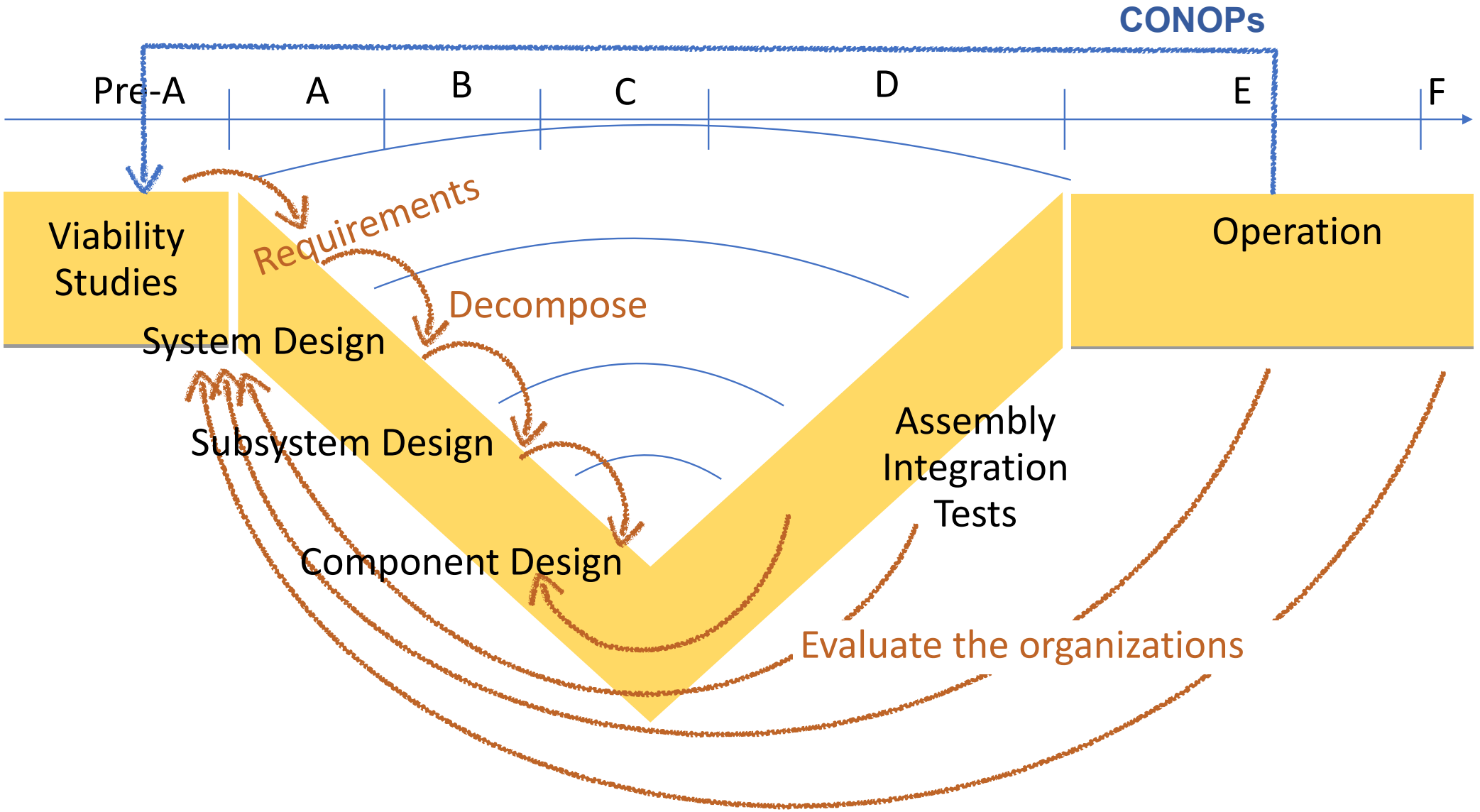


SYSTEM FORM

Example of form: software code

```
1   Procedure bubblesort (List array, number length_of_array)
2         for i=1 to length_of_array - 1;
3               for j=1 to length_of_array – I;
4                     if array [j] > array [j+1] then
5                           temporary = array [j+1]
6                           array[ j+1] = array [j]
7                           array[ j] = temporary
8                     end if
9               end of j loop
10        end of i loop
11  return array
12  End of procedure
```

Final Considerations


CONOPs
Pre-A
A
B
C
D
E
F
Viability Studies
Requirements
Decompose
System Design
Subsystem Design
Component Design
Assembly Integration Tests
Operation
Evaluate the organizations

We know the basic SE Framework