EE584 – S/C Design and Systems Engineering

Lecture 3
Requirements

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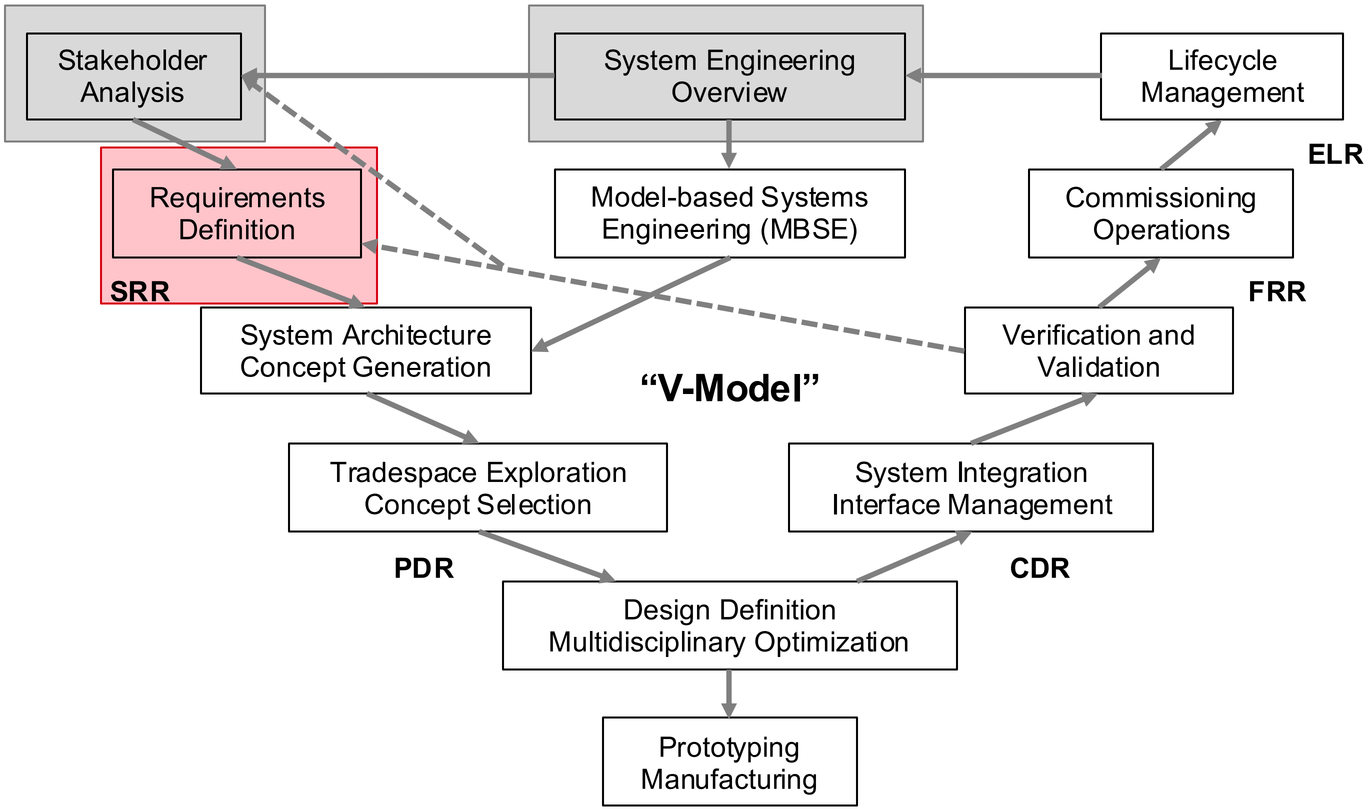
Based on the lecture "Fundamentals of Systems Engineering"
By Prof. Olivier L. de Weck MIT/EPFL

The “V-Model” of Systems Engineering



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Overview

- **Requirements**
  - What are requirements?
    - Definition, Examples, Evolution, Standards
  - Challenges of Requirements Definition
    - Flowdown and Allocation
    - Writing good requirements
    - Validation and Verification
  - What happens at the SRR?
- **System Architecture and Concept Generation**
- **Concept Selection and Tradespace Exploration**

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Requirements Definition

- Requirements describe the **necessary functions and features of the system** we are to conceive, design, implement and operate.
  - Performance
  - Schedule
  - Cost
  - Other Characteristics (e.g. lifecycle properties)
- Requirements are often organized hierarchically
  - At a high level requirements focus on **what** should be achieved, not how to achieve it.
  - Requirements are specified at every level, from the overall system to each hardware and software component.
- **Critically important to establish properly**
  - **Many of the cost overruns are caused by over-ambitious or missing requirements**

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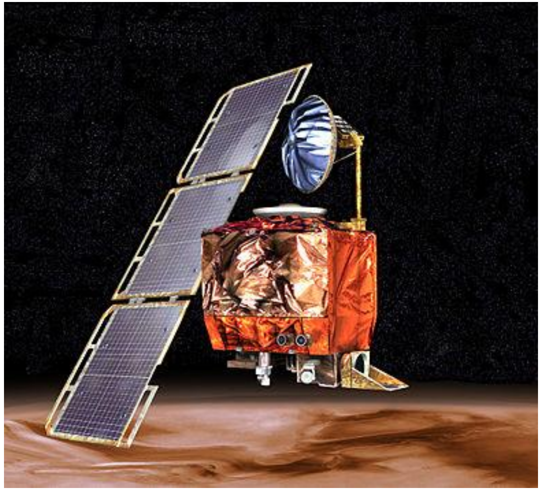
Poor requirements example: MCO

- Mars Climate Orbiter (MCO) was launched by NASA on December 11, 1998
- Intended to study Martian climate, weather and surface changes and act as communications relay back to Earth
- **However, disintegrated during orbit insertion on Sept 23, 1999 → approach too close → requirements not followed**
- Units confusion problem: Ground Software produced output in non-SI units (lbf-sec) instead of SI units: Ns
  - Calculation of total momentum produced by engine burns needed by Guidance, Navigation, and Control (GNC)
- Contract between NASA and Lockheed Martin **did** specify SI-units
  - This requirement was flowed down to the Software Interface Specification (SIS), but not verified later and not implemented in the file used for the propulsion maneuvers.



From the accident report:

“Items that the mission assurance manager could have addressed for MCO included ensuring that the AMD file met the requirements of the SIS ..”

https://llis.nasa.gov/llis_lib/pdf/1009464main1_0641-mr.pdf

Poor requirements example: MCO

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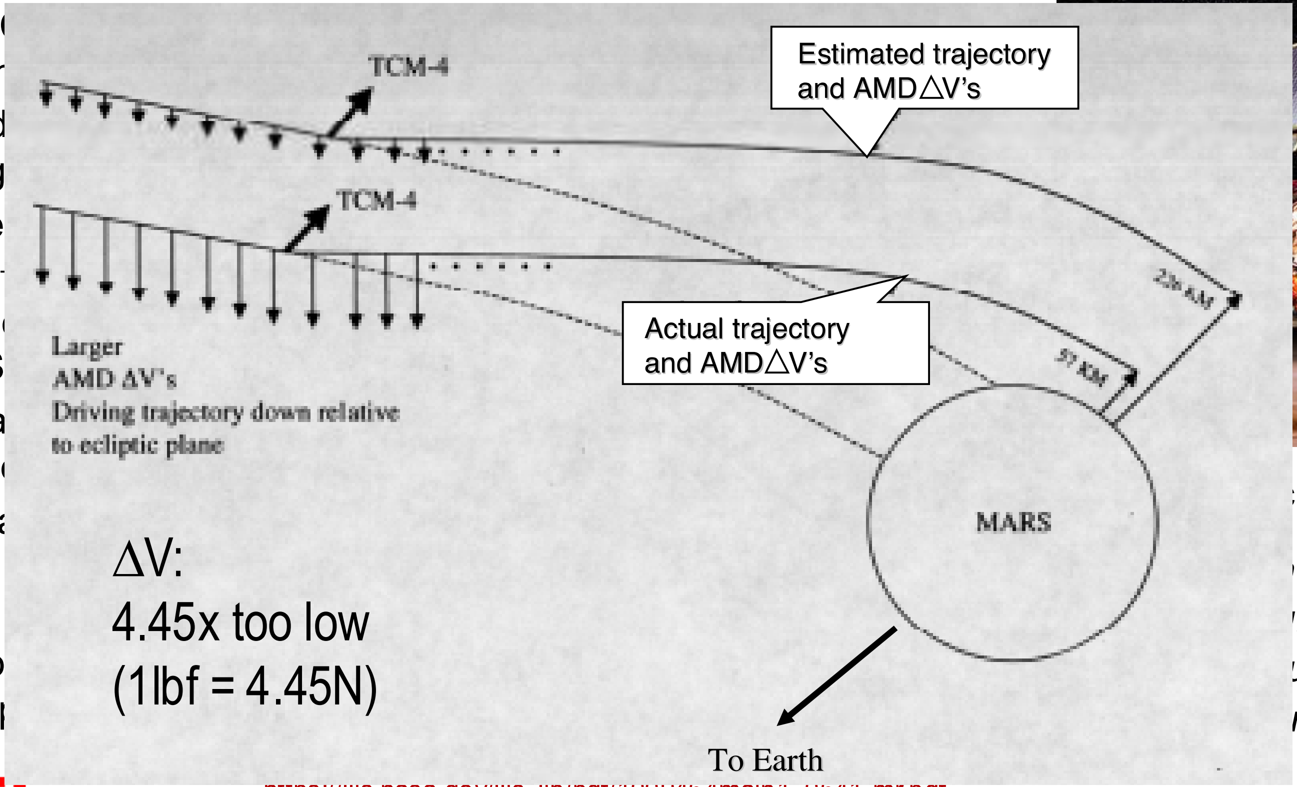

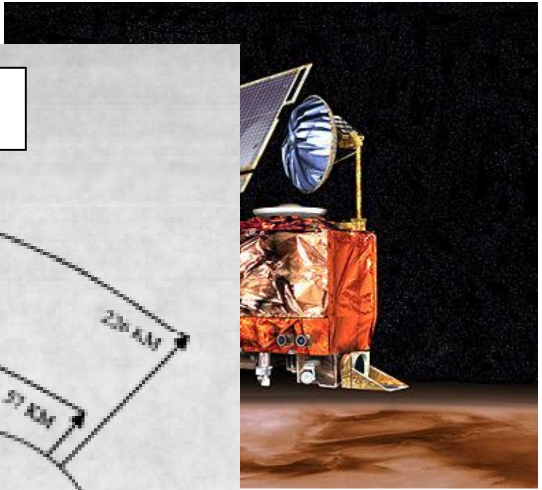

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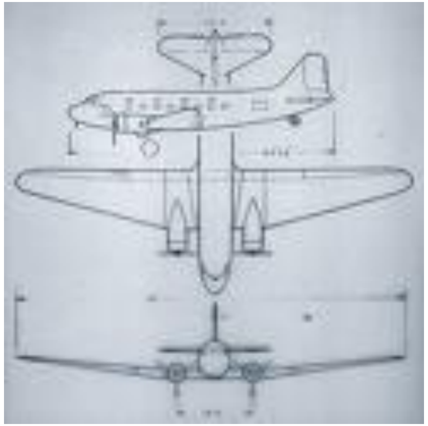
Good requirements example: DC-3

- **Requirements based on desired improvements to DC-2**
- **Very simple**
  - 3 page RfP (McDonnell Museum)
  - “Marathon” phone call between Smith and Douglas
- **Key Requirements**
  - Range: 1000 miles
  - Cruise Speed: 150 mph
  - Passengers: 20-30
    - Depending on configuration
  - Twin Engines
  - “Rugged and Economical”



1st flight: 17 Dec 1935
Over 10,000 built

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Requirements Explosion since 1970s

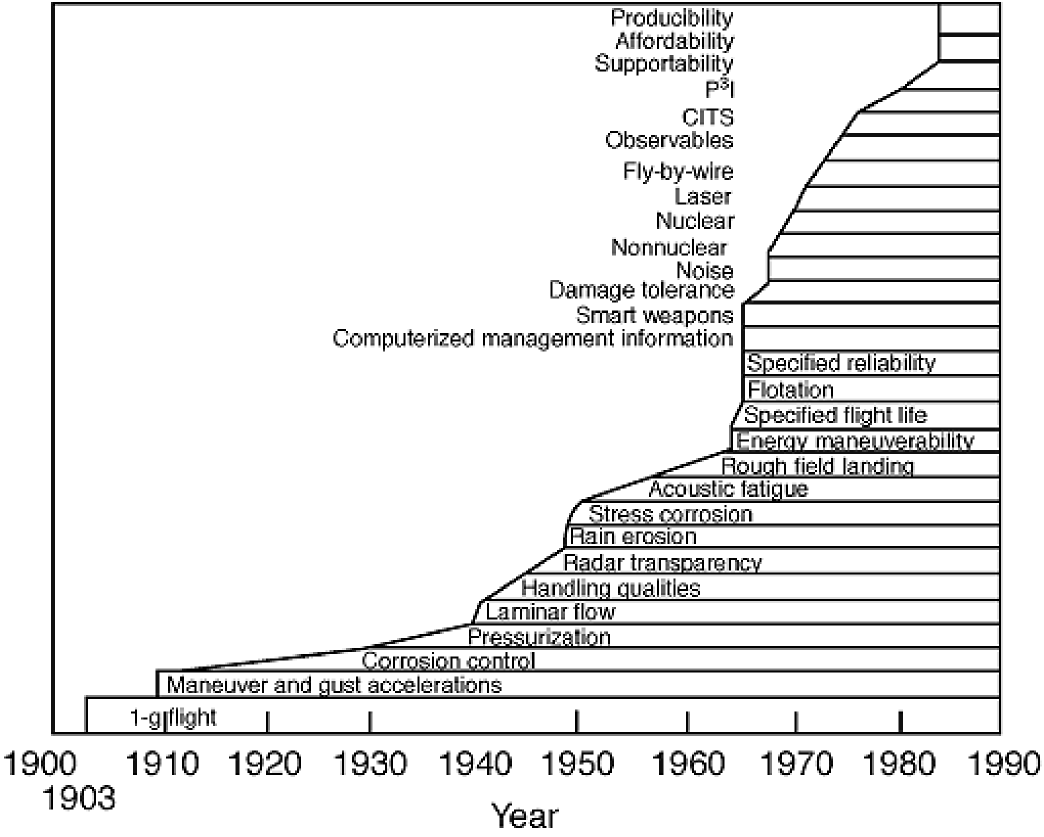

Fig.1 Design requirements growth for aerospace vehicles.

More and more requirements were added as systems grew in performance and complexity

Source:
AIAA MDO TC
White Paper, 1991

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Requirements Standards and Handbooks

- **NASA Systems Engineering Handbook**
  - NASA/SP-2016-6105
    - Section 4.2 (pp. 63-72) – Technical Requirements Definition
    - Section 6.2 (pp. 150-155) – Requirements Management
    - Appendix C (pp. 236-239) – How to write a good Requirement
    - Appendix D (pp. 240-242) – Requirements Verification Matrix
- **International Council of Systems Engineering (INCOSE)**
  - Systems Engineering Handbook, Version 5
  - Requirements Working Group
    - https://www.incose.org/incose-member-resources/working-groups/analytic
- **ISO/IEC 15288 (IEEE STD 15288-2023)**
  - Systems and software engineering —
  - System life cycle processes
    - 6.4.2 Stakeholder needs and requirements definition process
- **ECSS Space Engineering - Technical requirements specification**
  - ECSS-E-ST-10-06C
    - Processes and definitions (ESA may sometimes differ from NASA)

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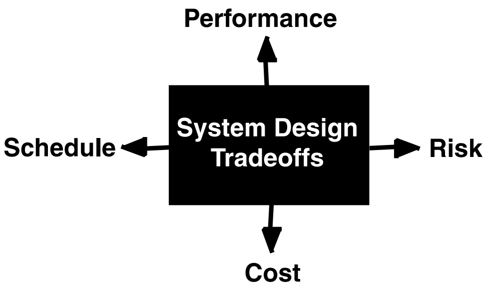
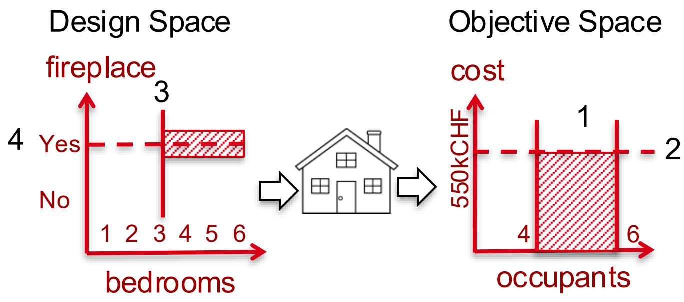
Requirements set *constraints* and *goals* in the design and objective space

- When designing systems we always have tradeoffs between performance, cost, schedule and risk
- "**Shall**" … Requirements help set **constraints** and define the boundaries of the design space and objective space
- "**Should**" … requirements set **goals** once "shall" requirements are satisfied
- Two main spaces:
  - Design Space – the things we decide as engineers
  - Objective Space – the things our systems/products achieve and what our customers care about





1. "The house shall sleep between 4 and 6 people"
2. "The total build cost should be less than 550kCHF"
3. "The house shall have at least 3 bedrooms"
4. "The house should have a fireplace"

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Purpose of Technical Requirements Definition

- **The Technical Requirements Definition Process**
  - Is used to transform the baselined stakeholder expectations (input) into unique, quantitative, and measurable technical requirements (output)
- **Requirements**
  - Come in many flavors
  - Should be expressed as well-written “shall” statements that can be used for defining a design solution

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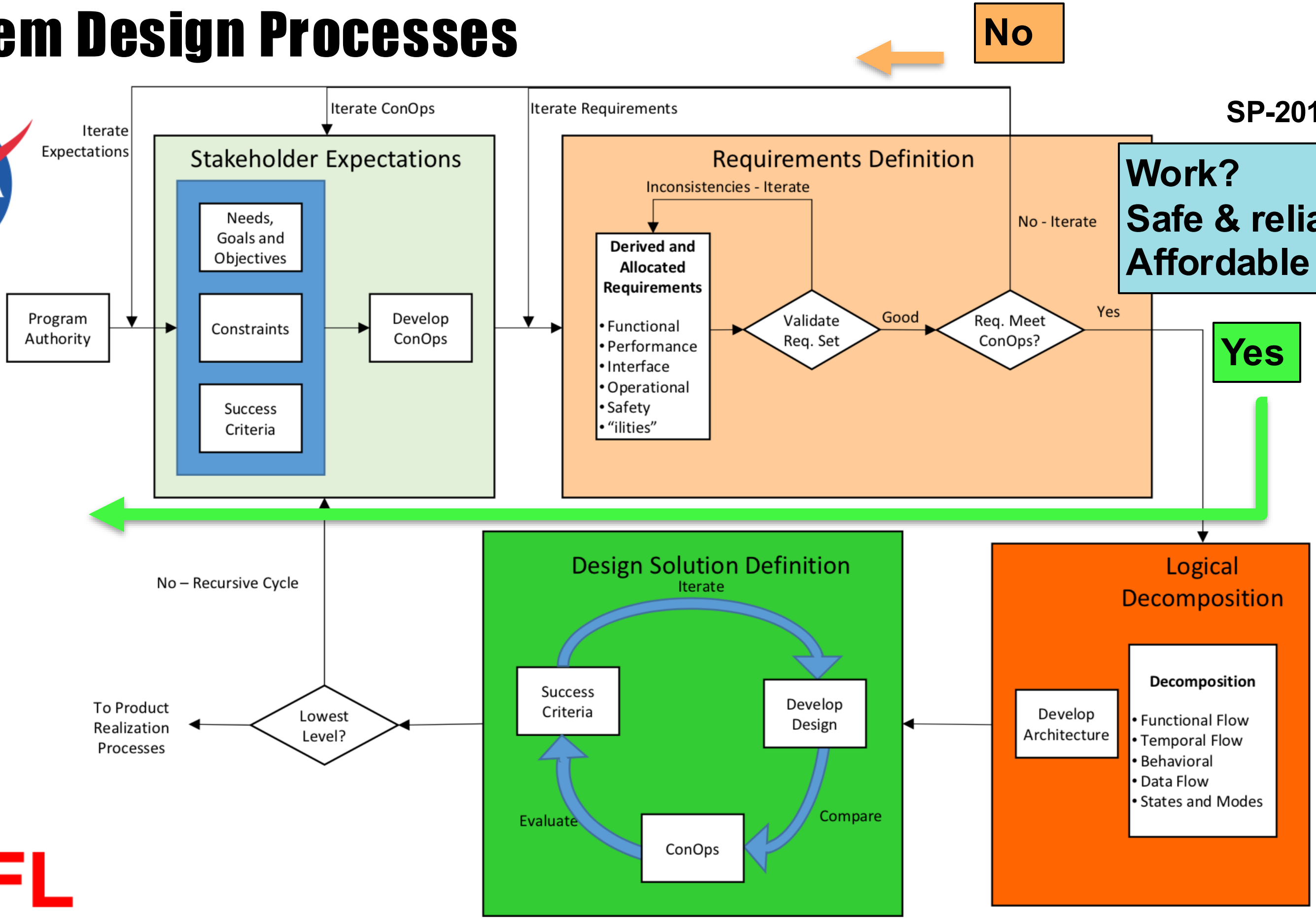
Relationships among the upstream System Design Processes

SP-2016-6105, Figure 4.0-1

Work?
Safe & reliable?
Affordable (incl. Schedule)?



Types of Requirements

- **Functional Requirements define what functions need to be done to accomplish the mission objectives**
  - Example: The Thrust Vector Controller (TVC) shall provide vehicle control about the pitch and yaw axes.
    - This statement describes a high level function that the TVC must perform.
    - Statement has form of Actor – Action Verb – object acted on
- **Performance Requirements define how well the system needs to perform the functions**
  - Example: The TVC shall gimbal the engine a maximum of 9 degrees, +/- 0.1 degree
- **Constraints are requirements that cannot be traded off with respect to cost, schedule or performance**
  - Example: The TVC shall weigh less than 55 kg (mass, power, volume …).
- **Interface Requirements** ∃ Internal and External interfaces
  - Example: The TVC shall interface with the J-2X per conditions specified in the CxP 72262 Ares I US J-2X Interface Control Document, Section 3.4.3.
- **Environmental requirements**
  - Example: The TVC shall use the vibroacoustic and shock [loads] defined in CxP 72169, Ares 1 Systems Vibroacoustic and Shock Environments Data Book in all design, analysis and testing activities.
- **Other -illities requirement types described in the SE Handbook include: human factors, reliability requirements, and safety requirements.**

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Attributes of Acceptable Requirements

- **A complete sentence with a single "shall" per numbered statement**
- **Characteristics for each Requirement Statement:**
  - Clear and consistent – readily understandable
  - Correct – does not contain error of fact
  - Feasible – can be satisfied within natural physical laws, state of the art technologies, and other project constraints
  - Flexibility – Not stated as to how it is to be satisfied
  - Without ambiguity – only one interpretation makes sense
  - Singular – One actor-verb-object requirement
  - Verify – can be proved at the level of the architecture applicable
- **Characteristics for pairs and sets of Requirement Statements:**
  - Absence of redundancy – each requirement specified only once
  - Consistency – terms used are consistent
  - Completeness – usable to form a set of "design-to" requirements
  - Absence of conflicts – not in conflict with other requirements or itself

Requirements Writing “Workshop”

- **Turn to your partner exercise**
- Together write a good requirement that was (possibly) used in the development of one of the following solutions
  - A – Mr. Sticky tape for trapping flies
  - B – New BMW iX2 electric car
  - C – EPFL Rolex Center

A

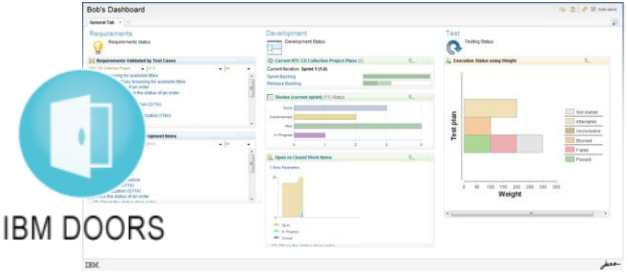
B

Source: BMW AG

C

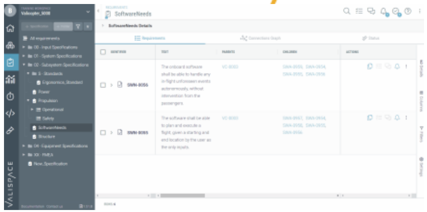
Requirements Capture: Documents vs. Database

- **Where / how are requirements captured?**
  - Low cost "easy" solution: Create a **document** (e.g. in MS Word or Excel) to capture and revise the requirements. Use hyperlinks to link requirements.
  - This works okay for smaller projects with dozens or a few hundred requirements (e.g. about 3 levels of decomposition→ $(7+/-2)^3 = 125$ to 729
  - For larger projects with >1,000 requirements need to use a relational database
  - **Commercial Tools**, e.g. DOORS, Valispace, ReqView… are available (but can be expensive)



https://www.ibm.com/fr-fr/products/requirements-management

VALISPACE



Valispace
https://www.valispace.com

ReqView
https://www.reqview.com

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Requirements Allocation

- **Decompose system requirements into lower levels of design.**
  - Define all the lower level functions which must be performed to satisfy the requirement
  - Create architecture of sub-components to provide those functions
- **Allocate a level of performance to each lower level function**
  - Specify interface requirements to other sub-systems
- **Closure - Ensure that satisfaction of the set of requirements at the lower level will guarantee satisfaction of the higher level requirement.**
- **Keep Traceability** (why, modifications, revisions)

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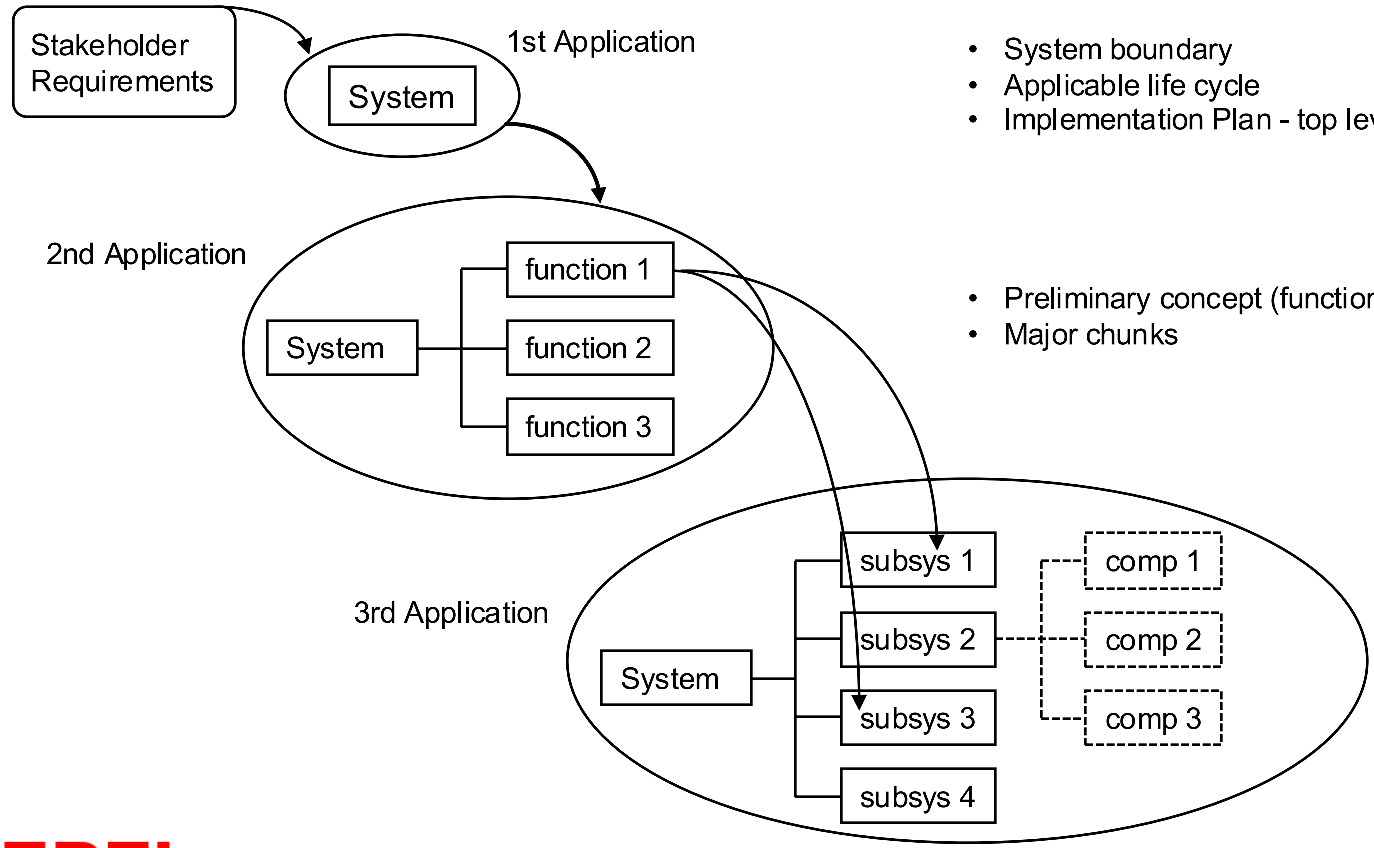
Requirements Allocation Process



- System boundary
- Applicable life cycle
- Implementation Plan - top level

- Preliminary concept (function to form)
- Major chunks

- System key performance parameters
- Subsystems defined
- Notional components

Difficult to decompose requirements to lower levels while staying solution neutral

Common problems with requirements

- **Writing implementations (“How”) instead of requirements (“What”)**
  - Forces the design
  - Implies the requirement is covered

- **Using incorrect terms**
  - Avoid “support”, “but not limited to”, “etc”, “and/or”

- **Using incorrect sentence structure or bad grammar**

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Common problems continued

- **Writing unverifiable requirements**
  - E.g., minimize, maximize, rapid, user-friendly, easy, sufficient, adequate, quick
- **Missing requirements**
  - Requirement drivers include

Functional	Performance	Interface
Environment	Facility	Transportation
Training	Personnel	Reliability
Maintainability	Operability	Safety

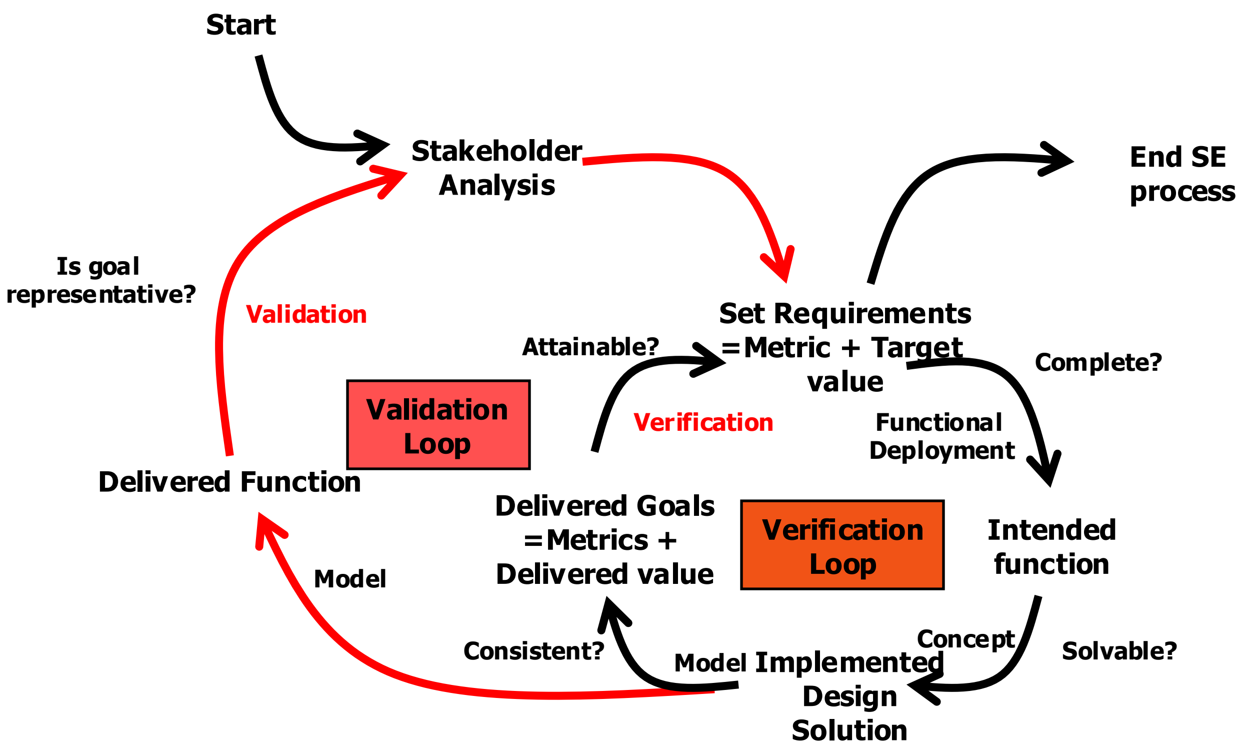
- **Requirements only written for "first use"**
- **Over-specifying**

Verification

- **Every requirement must be verified to ensure that the proposed design actually satisfies the requirement by (ECSS-E-ST-10-02C):**
  - Test (including demonstration)
  - Analysis (including similarity)
  - Review-of-Design (ROD),
  - Inspection

- **Requirements documentation specifies the development phase and method of verification**

Verification and Validation



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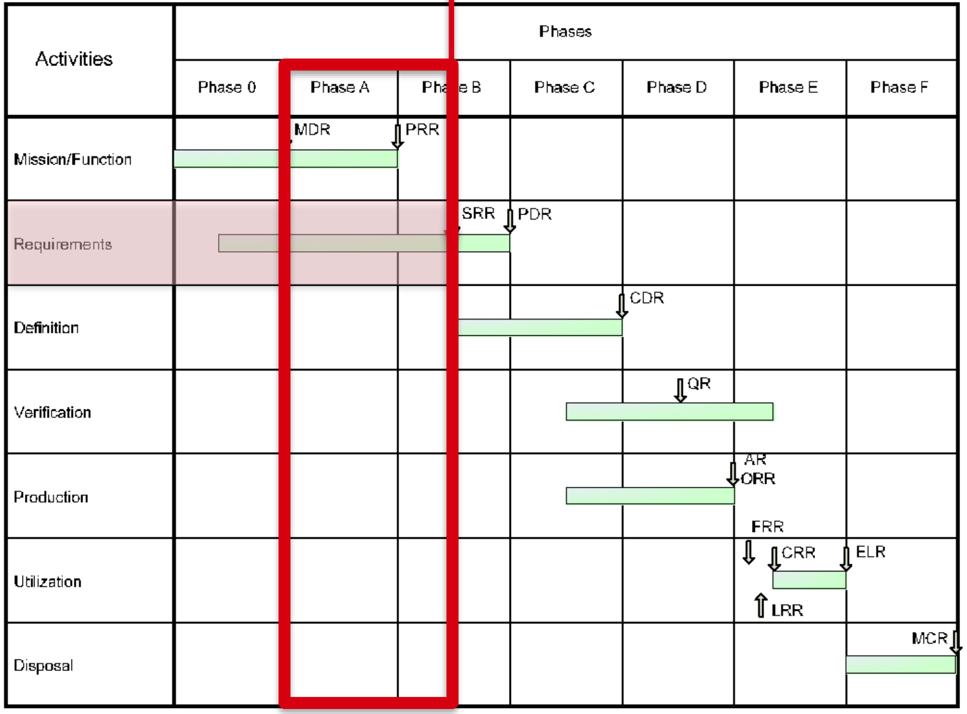
The life cycle of space projects - ESA

SRR

ECSS-M-ST-10C
Project planning and implementation

- Phase 0 - Mission analysis/needs identification
- **Phase A - Feasibility**
- **Phase B - Preliminary Definition**
- Phase C - Detailed Definition
- Phase D - Qualification and Production
- Phase E - Utilization
- Phase F - Disposal



SRR: System Requirements Review
CDR: Critical Design Review
ELR: End-of-Life Review
PDR: Preliminary Design Review
FRR: Flight Readiness Review

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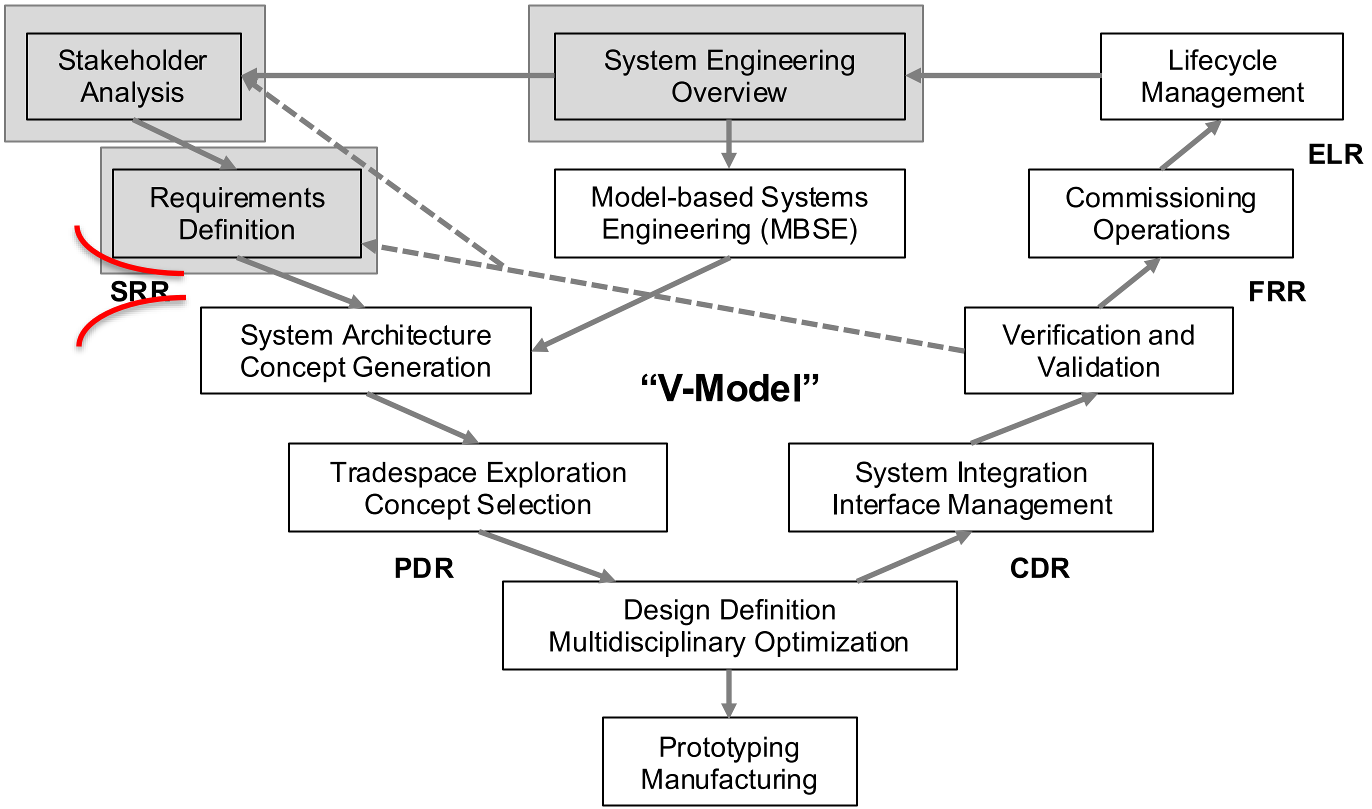
The “V-Model” of Systems Engineering



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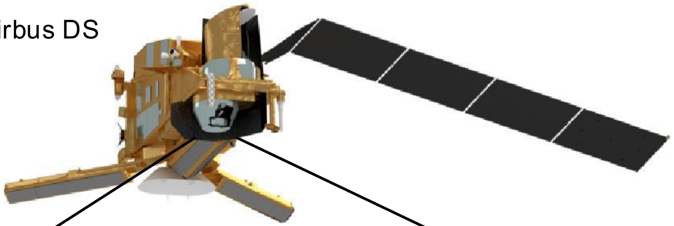
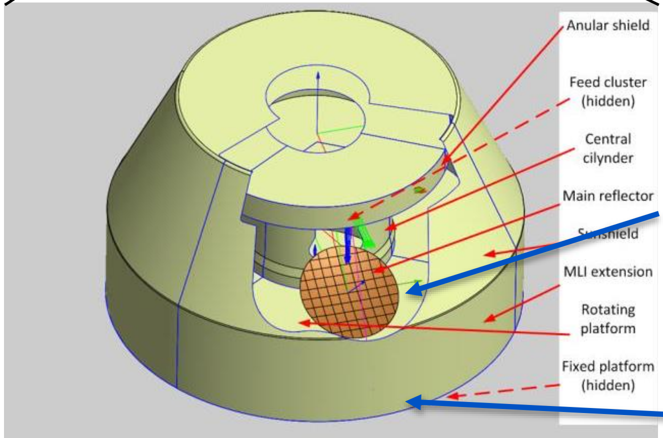
System Requirements Review (SRR)

- **SRR is primarily a human / social peer-review process**
- **Main goal of SRR: Vet the requirements as written. Find any missing, misstated, redundant or otherwise unsatisfactory requirements.**

Ice Cloud Imager Launch Lock Device (MetOp-SG)

© Airbus DS





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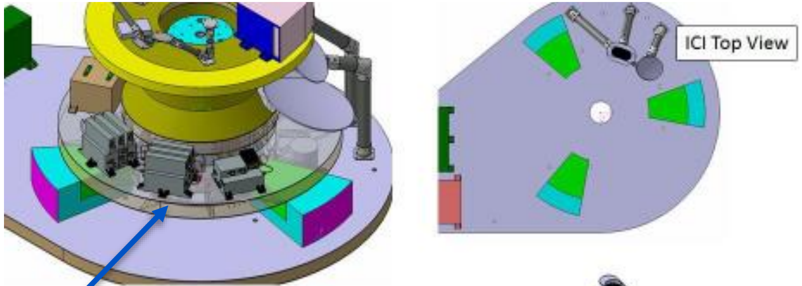

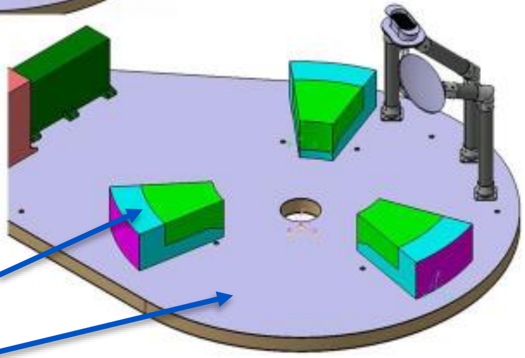

Rotating platform

LLD envelope

Fixed platform

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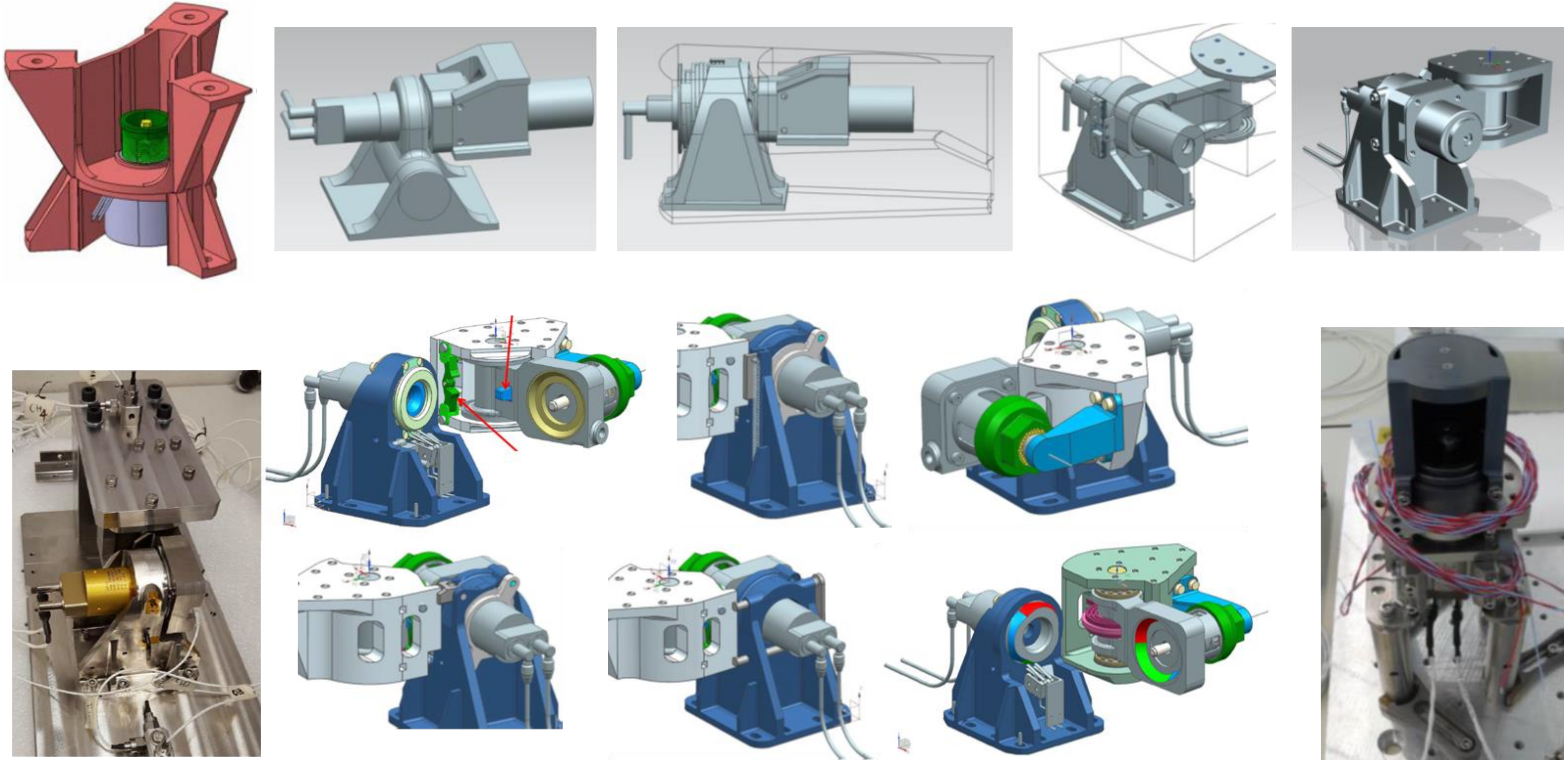
Ice Cloud Imager LLD - Iterations



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Requirements Definition - Summary

- **Good Requirements are essential for driving system design**
  - Basis for cost and schedule estimation
  - Sets up necessary verification and validation activities
- **Requirements flow-down is challenging**
  - Level 0 / Level 1 Requirements from Stakeholder analysis and ConOps
  - Level 2, 3 etc… requirements emerge later during Preliminary Design
- **Some methods and also commercial tools exist for formal requirements management**
  - Isoperformance → requirements allocation given upper level targets
  - DOORS → part of IBM Rational Suite. Professional requirements management