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Systems Analysis, Modeling, and Simulation

Course Objectives

- Present a brief overview of systems analysis using the methods of systems modeling and systems simulation.

- Describe the utility of systems analysis, modeling, and simulation in the context of systems engineering.

Course Overview

- Introductory Material
  1. Systems Analysis
  2. Modeling & Simulation

- Systems Analysis
  3. Systems Life Cycles
  4. Systems Engineering Role of Systems Analysis
  5. Model-Based Systems Engineering

Course Overview
(cont)

- Modeling Techniques & Methods
  6. Symbolic Models
  7. Mathematical Models
  8. Integrated Models
  9. Systems Simulation

- Modeling Applications
  10. Requirements Analysis & Validation
  11. Effectiveness Analysis
  12. Margin Modeling
  13. Risk Analysis

Definitions

- **Tool** – any implement, instrument, utensil, or program used to enhance human physical or intellectual capabilities to accomplish work
  - Example – Excel, Word, Nastran, etc.

- **Model** – a (virtual) imitation of an object or process
  - Example – Geometry, loads, weights, cost, etc.

- **Simulation** – to execute a model using a tool to solve deterministic and non-deterministic problems

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Lesson 1:
Introduction to Systems Analysis

Objectives

- Illustrate the Systems Analysis process
- Describe the context for Systems Analysis

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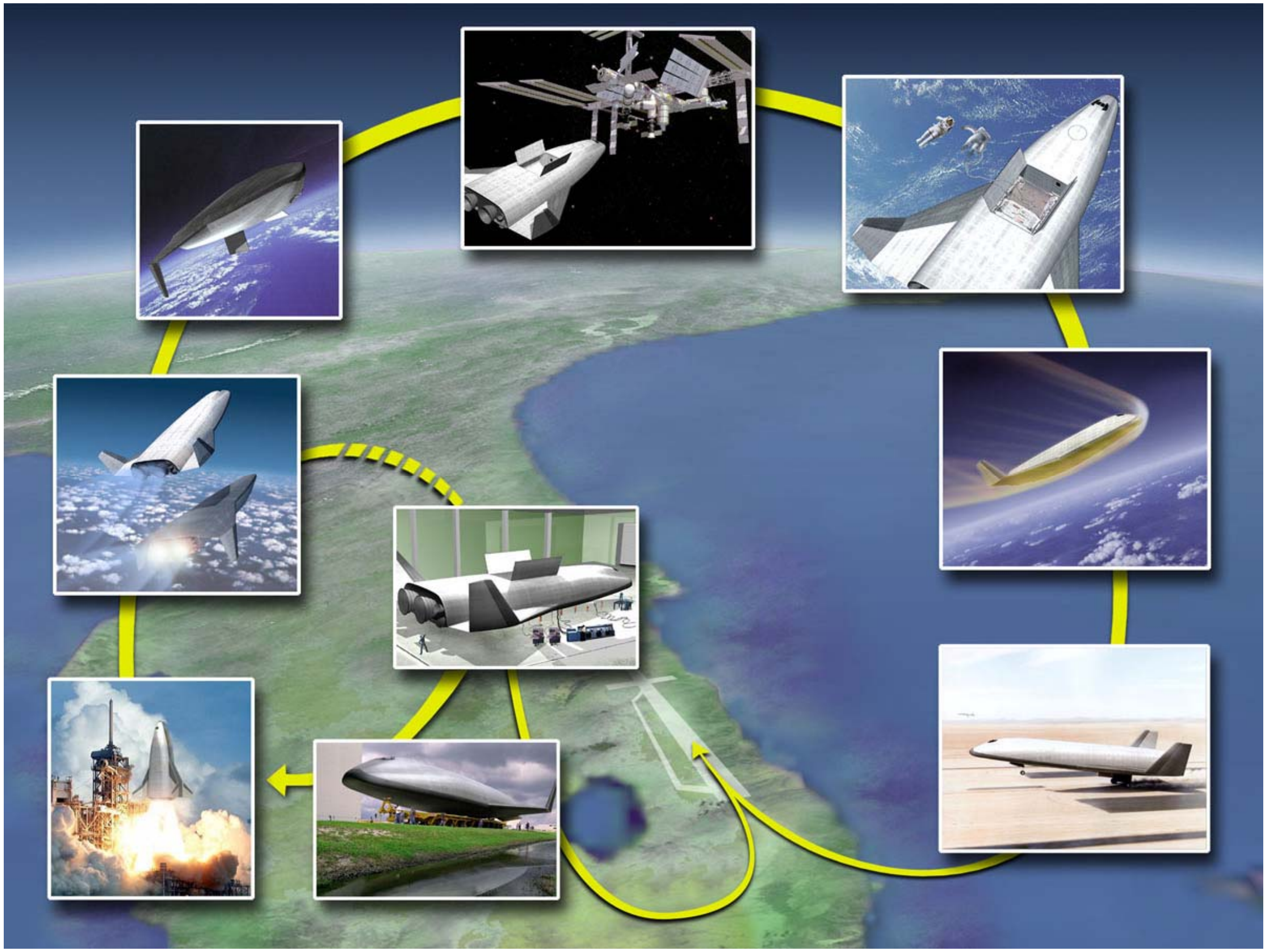
What is a System?



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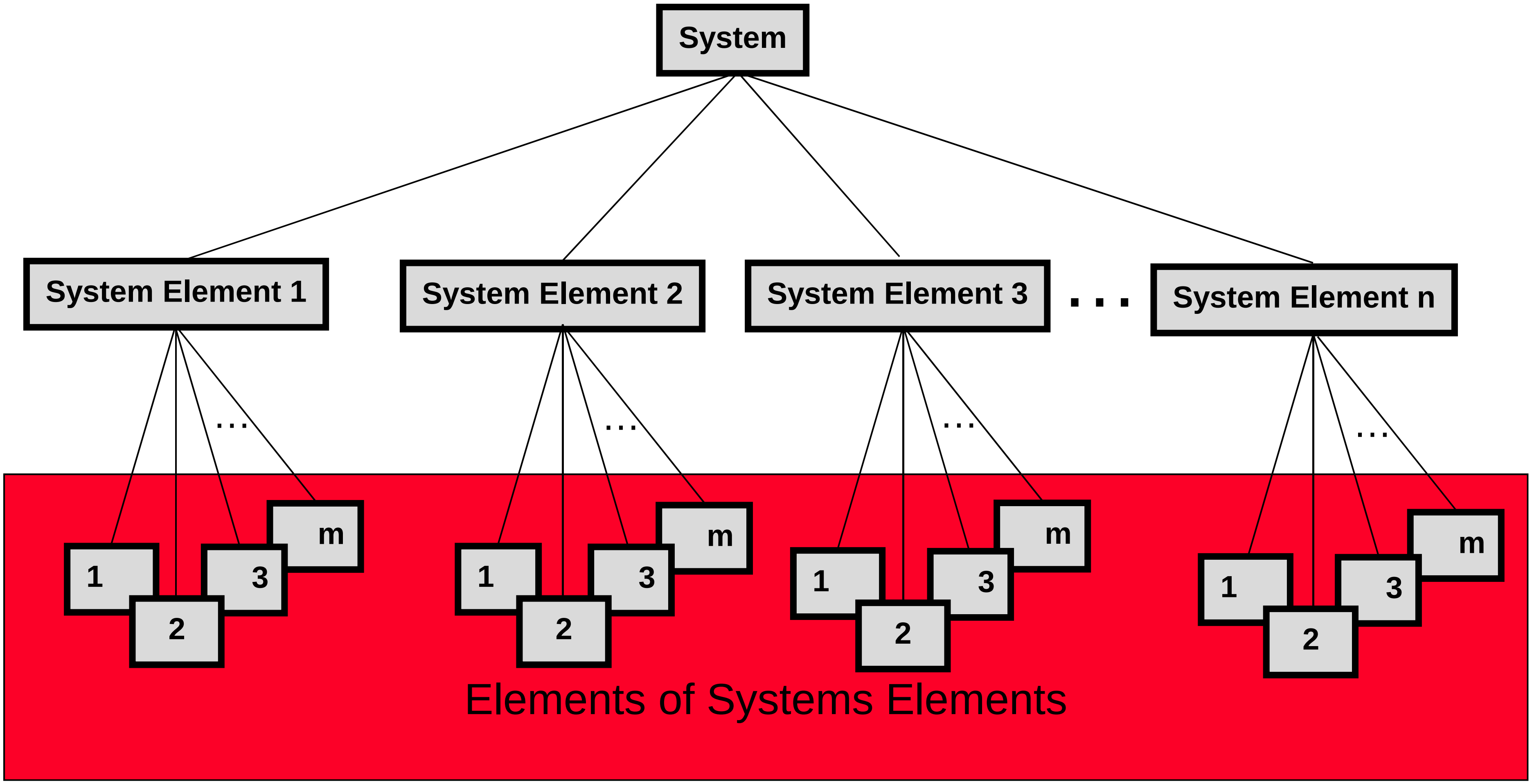
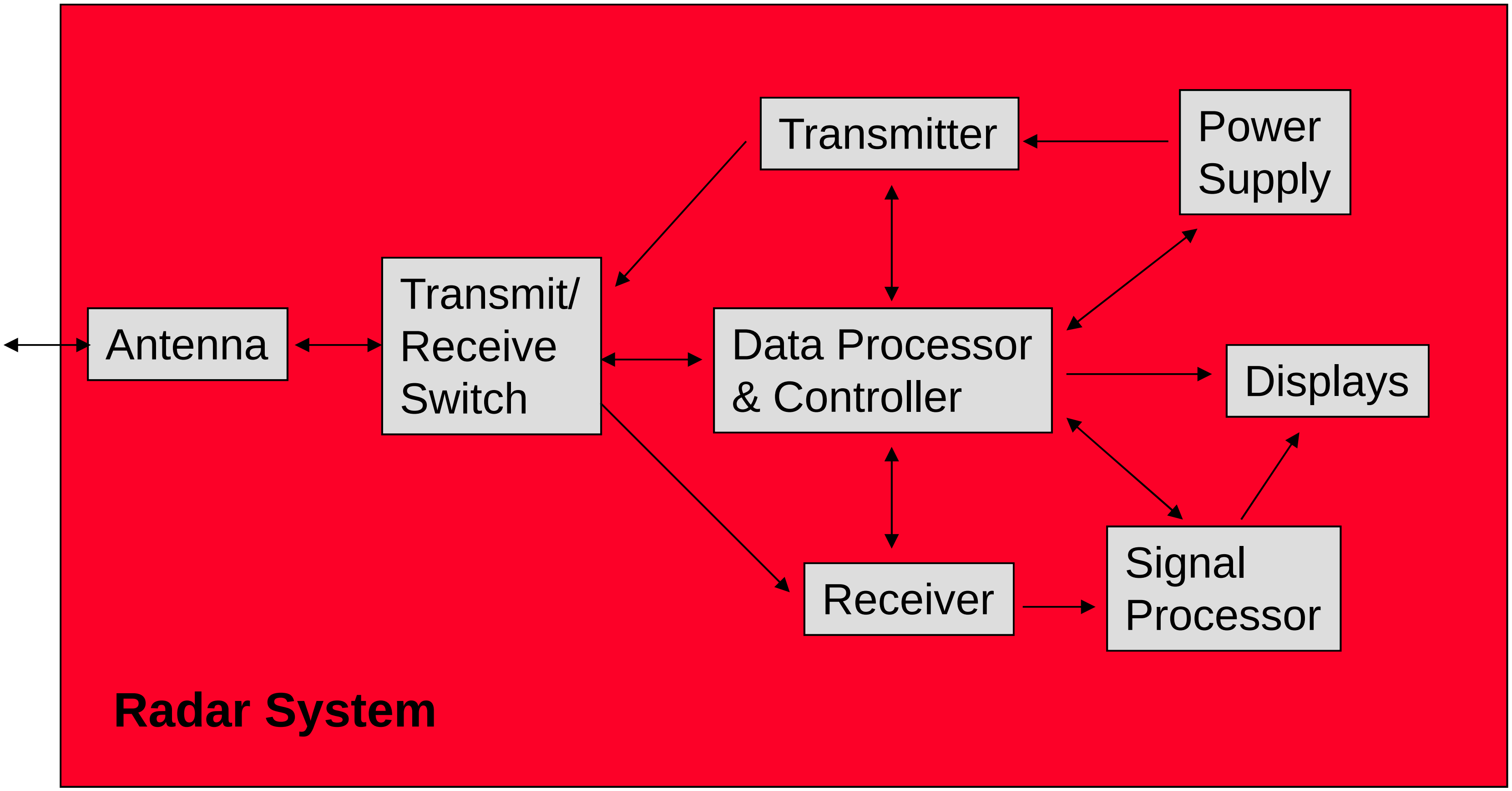
What is Analysis?

- Analysis – the breaking down of a whole into it's parts in order to characterize their nature or function.

System Hierarchy



A Radar System Model



Ref: Systems Engineering Fundamentals

System Breakdown Structure

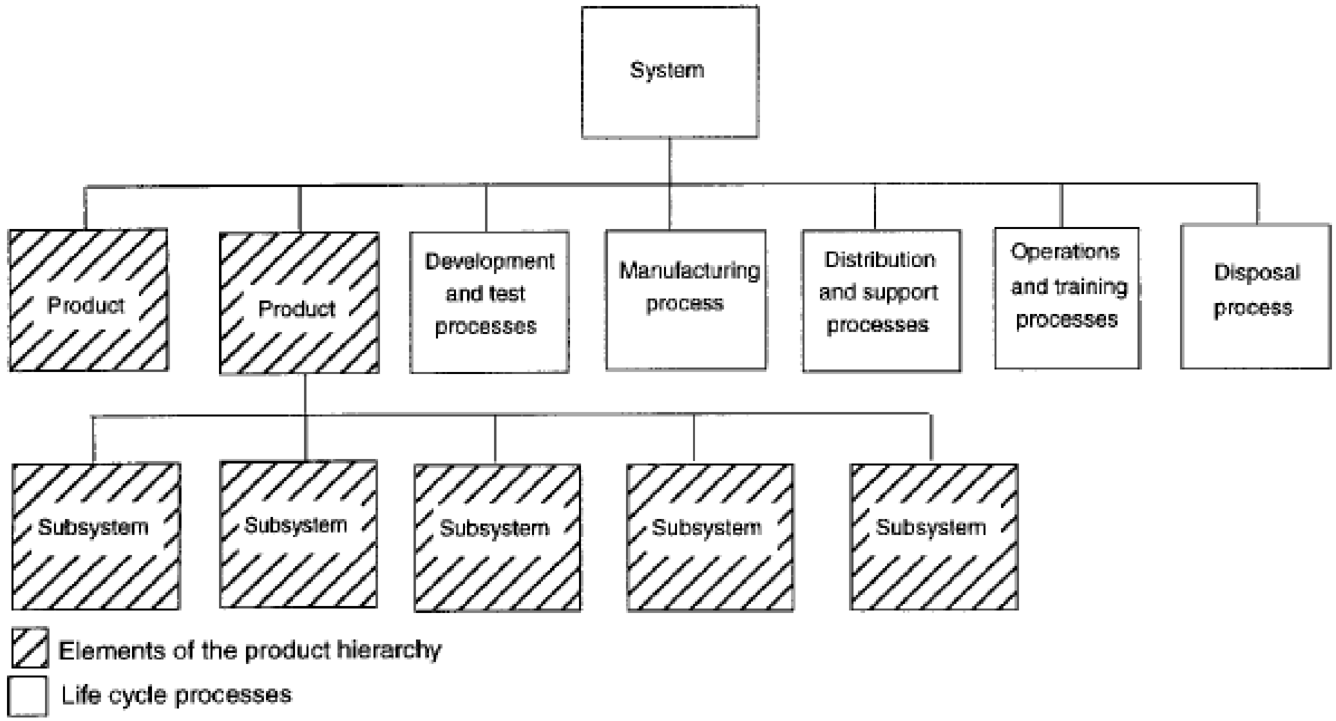
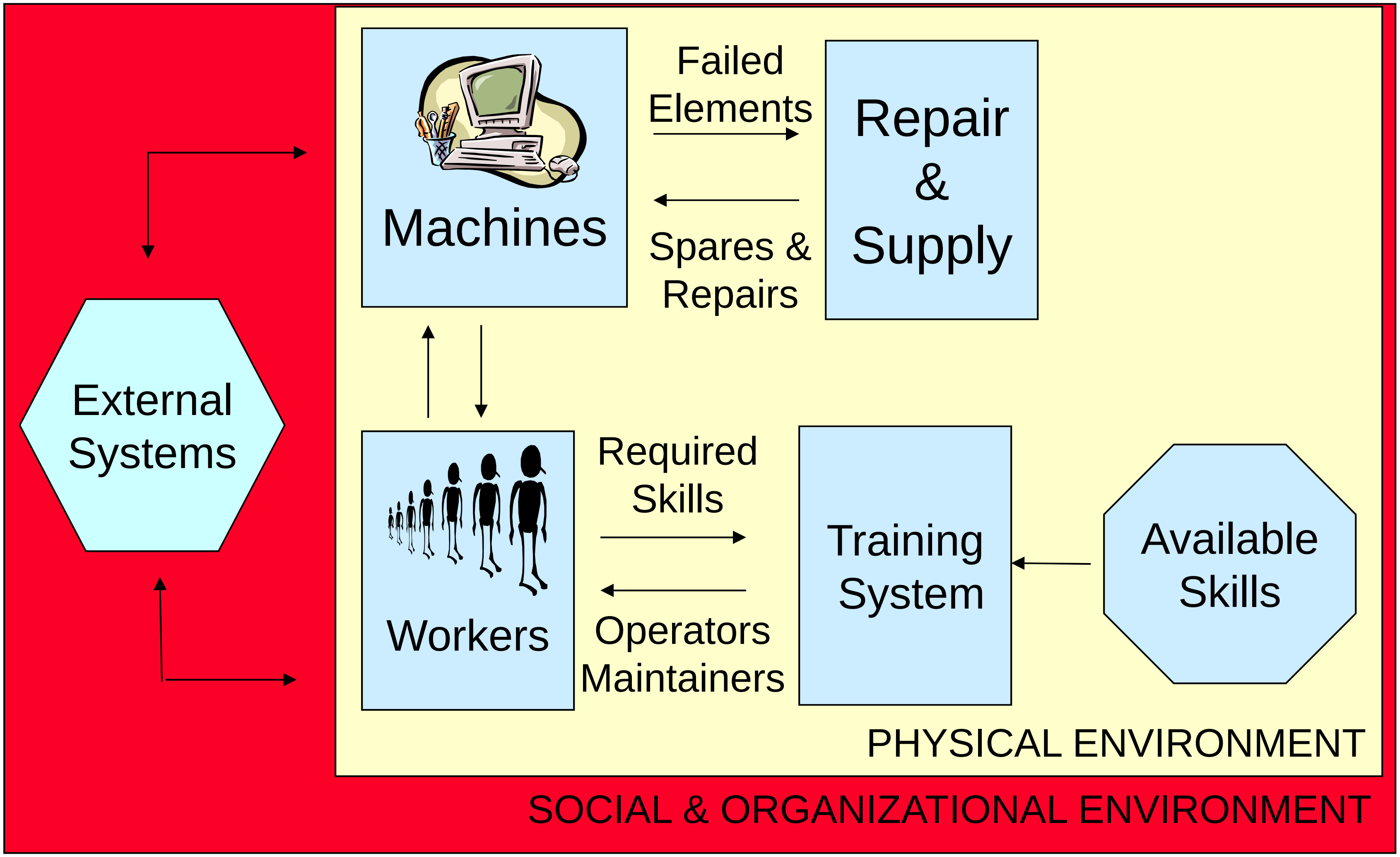


Figure 2—Basic building blocks of a system

The system is more than the product – hence systems analysis must address key processes including test, manufacturing, operations & disposal.

Complex Systems



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The "System of Interest"

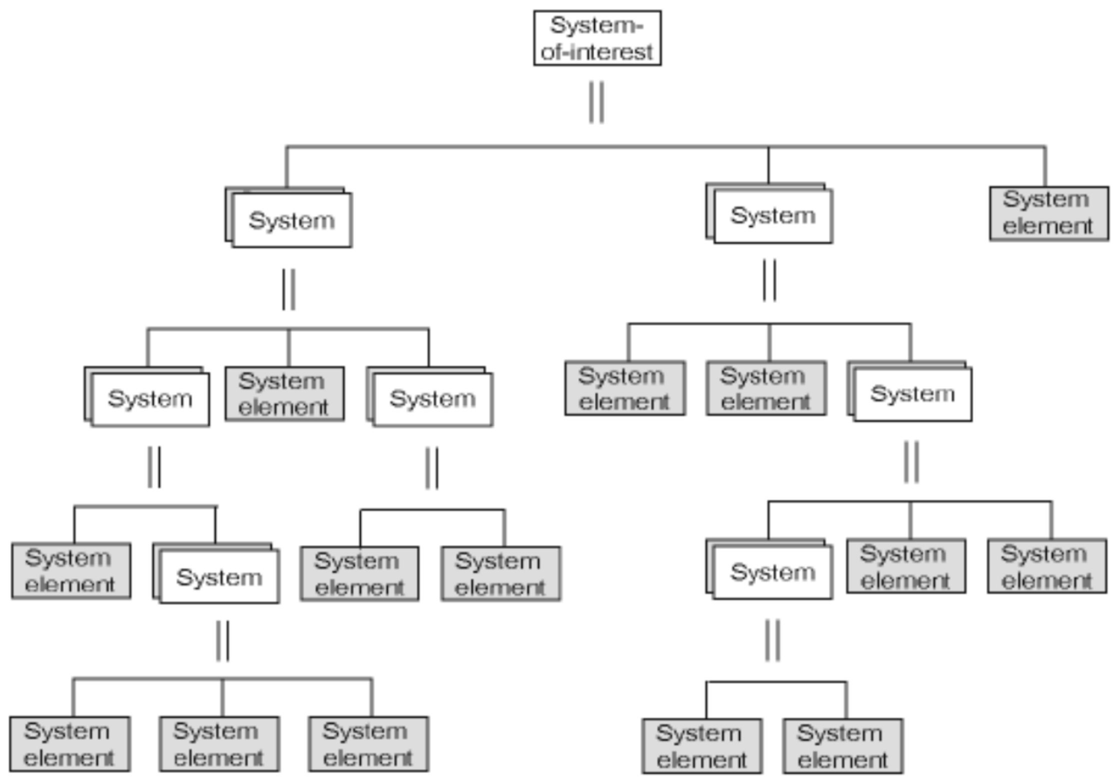

Figure C.2—ISO/IEC 15288 Figure D.3 system-of-interest structure

The "system" is a matter of perspective; a component from an assembly's perspective can be considered to be a system from it's own perspective.

Systems Engineering Process applied to “System of Interest”

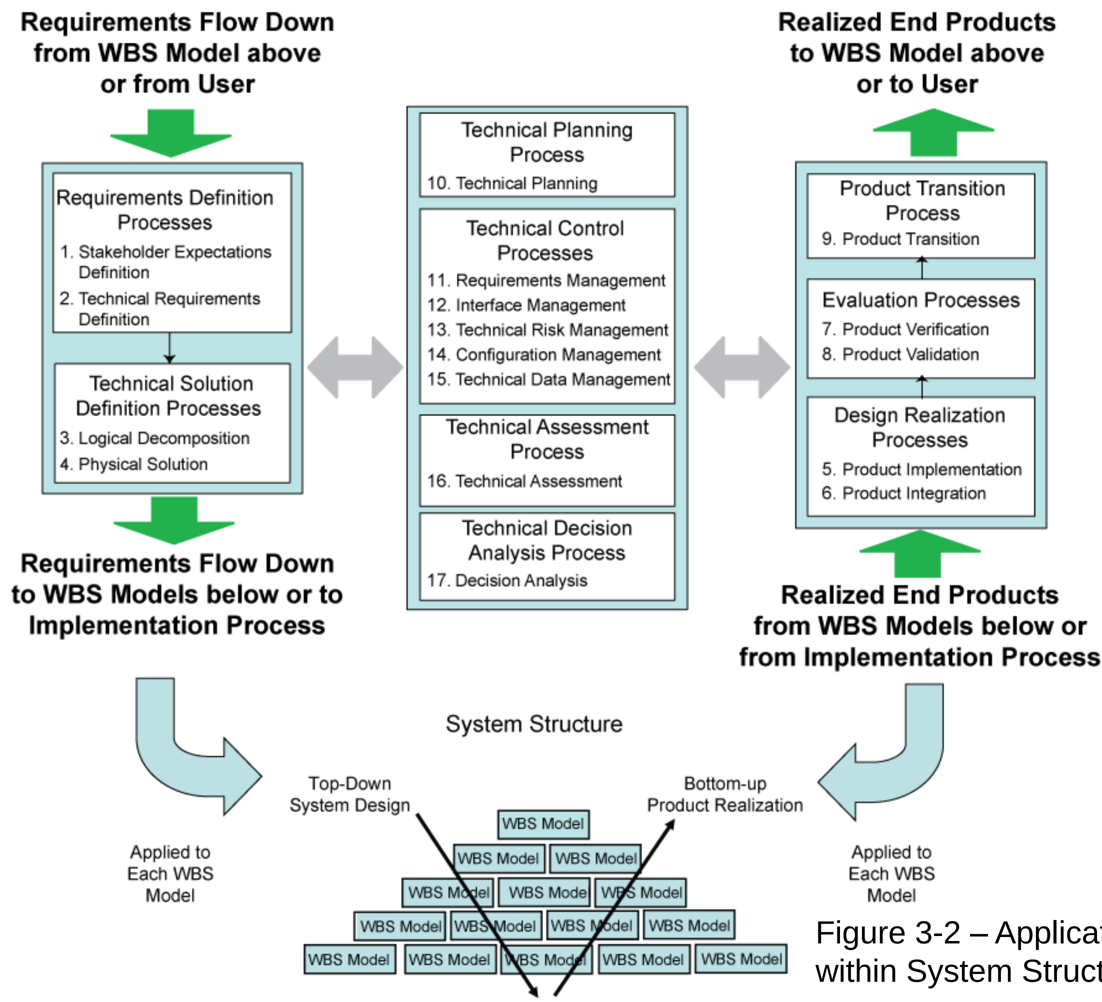

Figure 3-2 – Application of SE Processes within System Structure from NPR 7123

NASA systems engineering process written from the perspective that a “system” can reside anywhere within the SBS; it’s all relative, and the systems engineering process still applies.

Key Points

- Systems analysis allows us to draw inferences concerning systems behavior on the basis of inferences drawn concerning the behavior of the components of the system.

- A system is dependent on perspective; a component of a larger system can itself be considered a system that is, in turn, comprised of components.

- Systems analysis is not just product focused; it must also address the processes & operations of the product.

References

- *IEEE Standard for Application and Management of the Systems Engineering Process*, IEEE Std 1220-2005, September 2005.
- *NASA Systems Engineering Processes and Requirements*, NPR 7123, April 2013.
- *Systems Engineering Fundamentals*, Supplementary Text Prepared by the Defense Acquisition University Press, Fort Belvoir, VA 22060-5565, January 2001.
- *Systems engineering – System life cycle processes*, ISO/IEC 15288, February 2008.

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Lesson 2: Introduction to Modeling & Simulation

Objectives

- Provide an introduction to Modeling
- Provide an introduction to Simulation
- Illustrate modeling and simulation using examples

What is Modeling?

- A model is an abstract, simplified representation of a part of reality and created for a particular purpose.
- The ultimate test of a model is how well it performs when it is applied to the problems it was designed to handle.

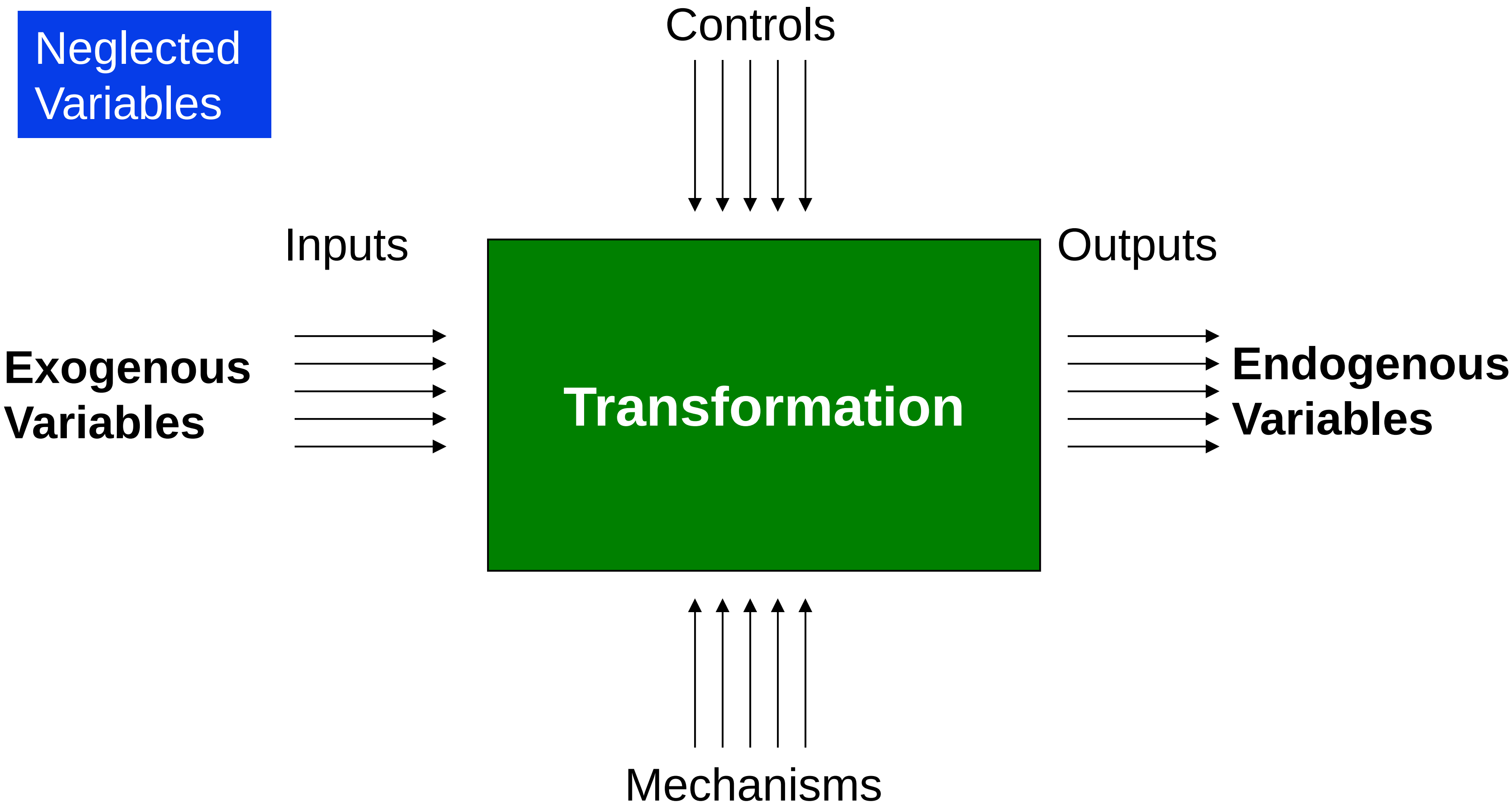
Building a Model – the 4 Step Process

1. **Formulate the Problem**. What is it that you wish to know?
2. **Outline the Model**. Separate the various parts of the system into unimportant, exogenous, and endogenous.
3. **Is it Useful?** If the model fits the situation, will we be able to use it?
4. **Develop and Test the Model.** Use the model to make predictions that can be checked against testing and/or experience.
   - Often a standard process—i.e. NASA-STD-7009.

Types of Models

- Deterministic
  - mathematical models
    - lift of an airplane wing
    - thrust of a rocket engine
- Stochastic
  - random discrete event models
    - wind velocities encountered by a flight vehicle during ascent
    - component failures during system operation
- Hybrid
  - elements of mathematical & random discrete event models
    - ascent performance of a flight vehicle through the atmosphere

The Black Box View of a Model



A Deterministic System Model -- Lorenz Model of Atmospheric Dynamics

$\sigma \quad \rho \quad \beta$ (parameter inputs)

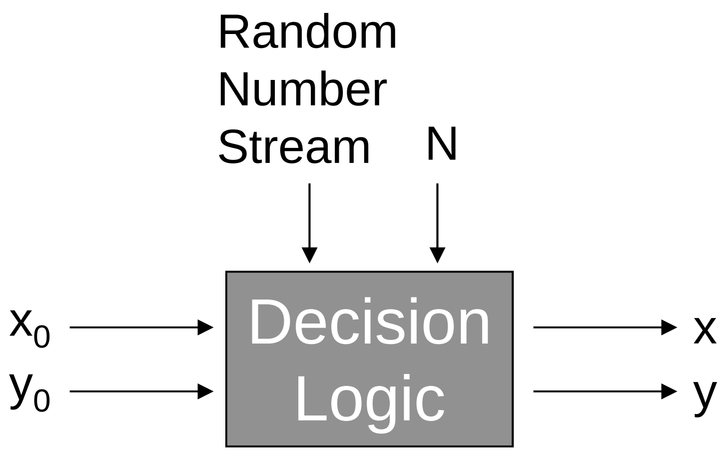
Inputs: x_0, y_0, z_0, t_0

$$\frac{dx}{dt} = \sigma(y-x)$$
$$\frac{dy}{dt} = \rho x - xz - y$$
$$\frac{dz}{dt} = xy - \beta z$$

Outputs: x, y, z, t, dx/dt, dy/dt, dz/dt

x,y,z:	cartesian coordinates for surface coordinates & altitude
t:	time
σ:	ratio of viscosity to thermal conductivity (10)
ρ:	nondimensional temperature gradient (28)
β:	geometric factor (8/3)

A Stochastic System Model -- The Random Walk
(Staggering Drunk)



x & y:	cartesian coordinates of location
N:	number of steps

Properties of Models

- **Generality** – the scope of the model
- **Realism** – the extent to which the model behaves like the system being modeled
- **Precision** – the number of significant digits accommodated & maintained by the model

Typically, generality is traded against precision for a given degree of realism in a model.

What is Simulation?

- Simulation is the process of
  1. Developing a system model
  2. *Conducting experiments* with this model for the purpose of understanding the behavior of the system or evaluating various strategies for the operation of the system

Simulation versus Models

- Model – defined earlier; an abstract representation of a system
- Simulation – an imitation of system performance over time to a predefined degree of fidelity
  - design analyses (model the system & the environment)
  - breadboards (model the system)
  - qualification testing (models the environment)
  - training (models the mission)

Conducting a Simulation – the 4 Step Process

1. **Modeling**. Refer to the 4 Step Model Process.
2. **Strategic & Tactical Planning**. What are the experimental conditions (variable ranges & increments) for using the model?
3. **Experimentation**. Run the model on the specified parameter sets.
4. **Analysis of Results**. What inferences may be drawn from the data and what recommendations for problem resolution can be made?

Remarks

- The three main things to keep in mind when modeling
  - Simplify
  - Simplify
  - Simplify

Key Points

- The four step process for model development
- The four step process for simulation development
- Modeling vs. simulation
- Analysis vs. modeling & simulation

Everything we do for the remainder of this course builds on this foundation.

References

- Bender, Edward A., *An Introduction to Mathematical Modeling*, Wiley, 1978.
- Blanchard, Benjamin S. & Wolter Fabrycky, *Systems Engineering and Analysis, 5th edition*, Prentice-Hall, 2006.
- Buede, Dennis M., *The Engineering Design of Systems: Models and Methods, 2nd edition*, Wiley, 2009
- Pritsker, A. Alan B., & C. Dennis Pegden, *Introduction to Simulation and SLAM*, Wiley, 1979.
- Shannon, Robert E., *Systems Simulation: the Art and Science*, Prentice-Hall, 1975.

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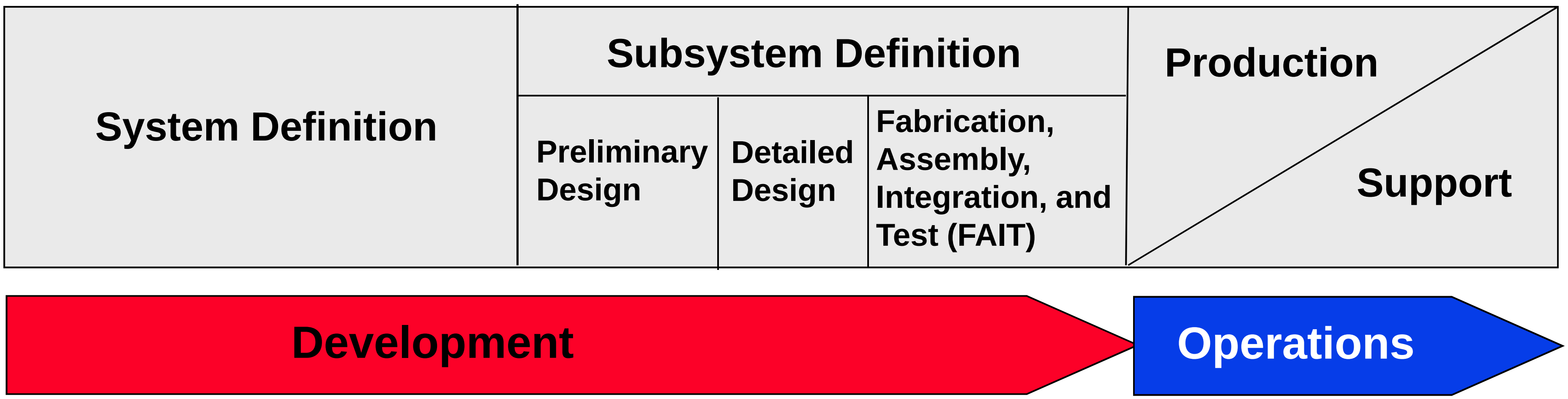
Lesson 3: Systems Analysis and Life Cycles

Objectives

- Review the Systems Engineering Life Cycle
- Describe the Role of Systems Analysis within the context of the overall Systems Engineering Process
- Describe the Role of Systems Analysis over the Systems Engineering Life Cycle

Answer the question: Why do we do systems analysis?

The System Life Cycle per IEEE 1220



Stages of Development

- a) System definition
- b) Subsystem definition
  - 1) Preliminary design of subsystems
  - 2) Detailed design of subsystem components
  - 3) FAIT

Stages of Operations

- a) Production
- b) Support

Ref: IEEE 1220, figure 7.

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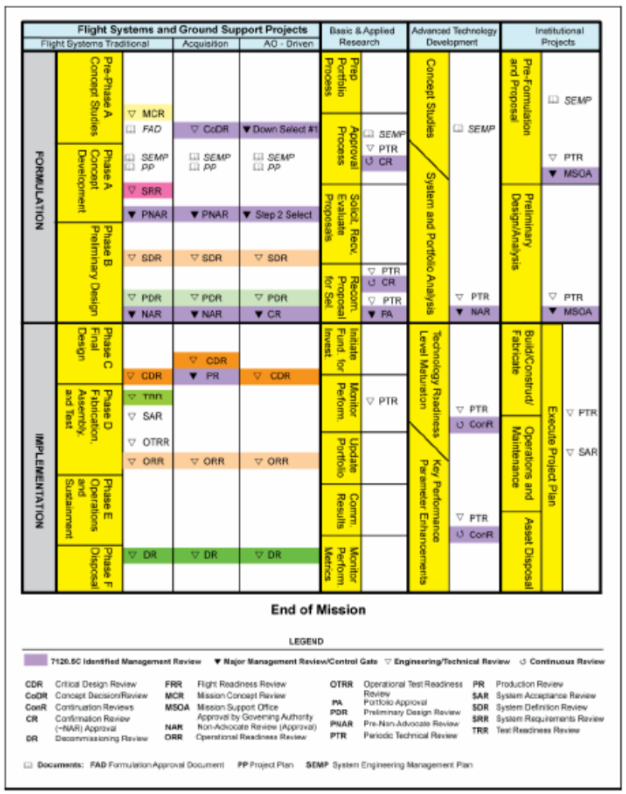
NASA Flight Project System Life Cycle

Formulation			Implementation			
Pre ϕA Concept Studies	ϕA Concept Development	ϕB Preliminary Design	ϕC Detail Design	ϕD Fabrication, Assembly, Integration, & Test	ϕE Operations & Sustainment	ϕF Disposal



- Key Milestone Reviews
  - Mission Concept Review
  - Systems Requirements Review
  - Systems Design Review
  - Preliminary Design Review
  - Critical Design Review
  - Test Readiness Review
  - Systems Acceptance Review
  - Flight Readiness Review
  - Operational Readiness Review
  - Decommissioning Review

The DOD 5000 System Life Cycle - 2003

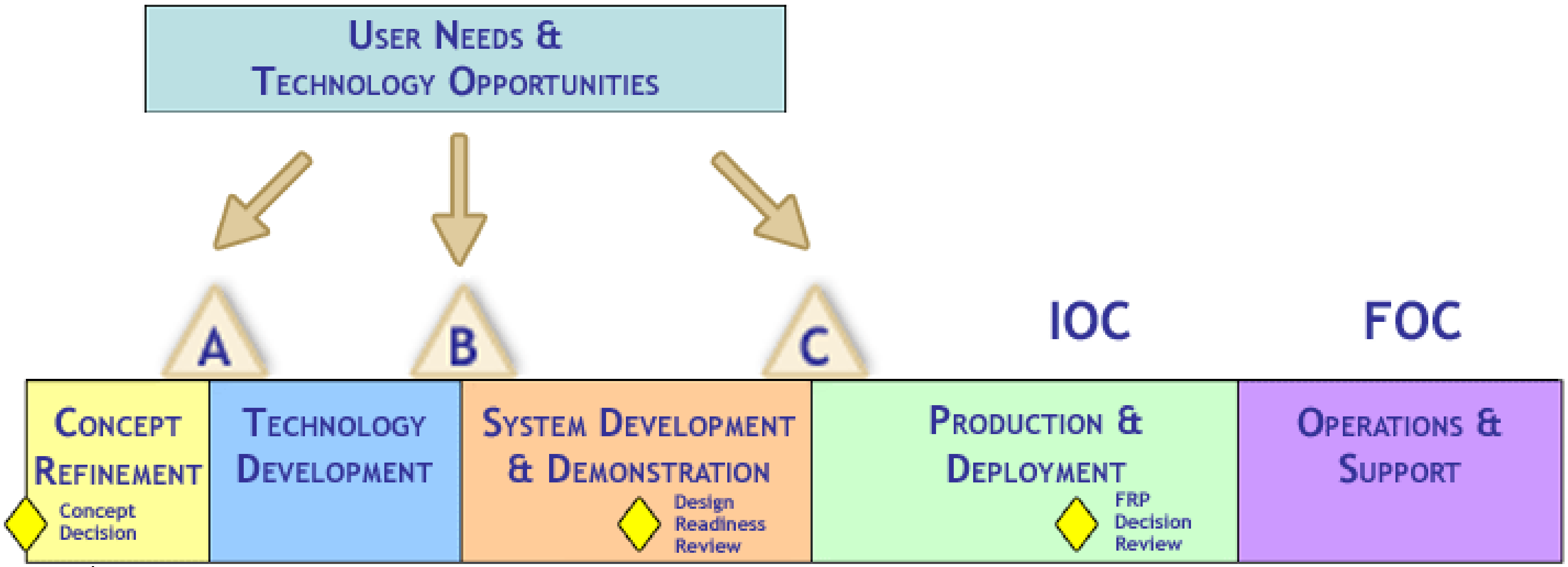


Figure 1. The Defense Acquisition Management Framework

Figure 1 from DOD 5000.2

The DOD 5000 System Life Cycle - 2008

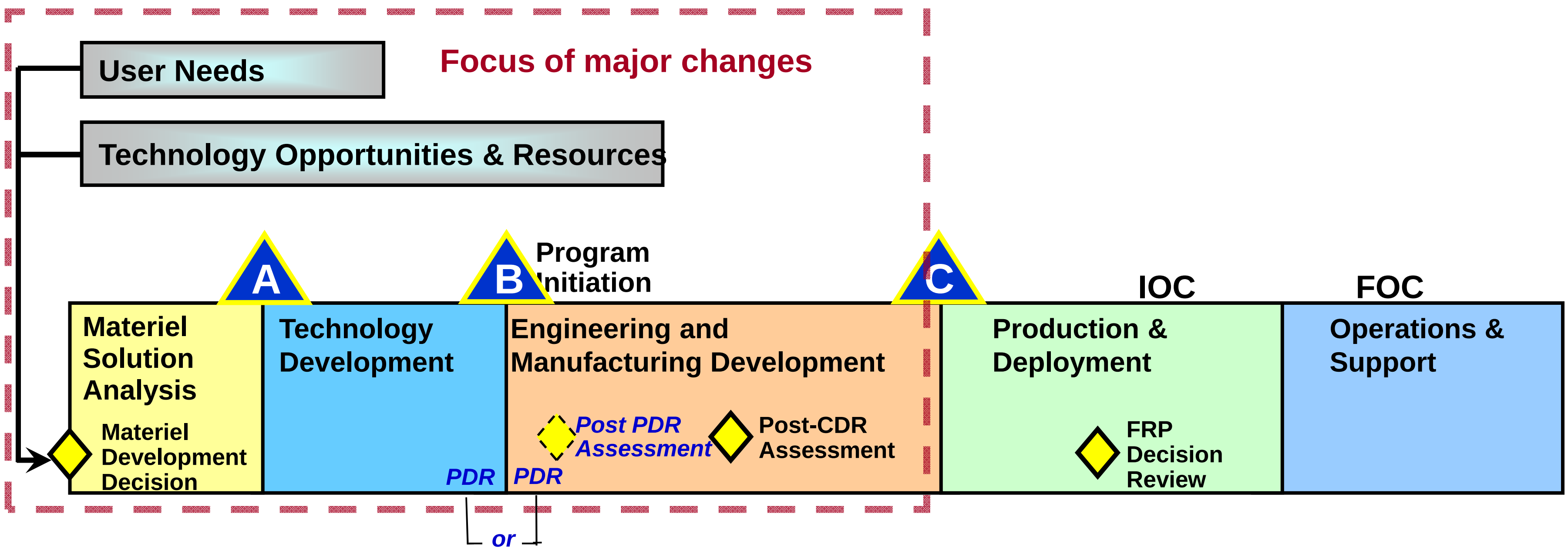
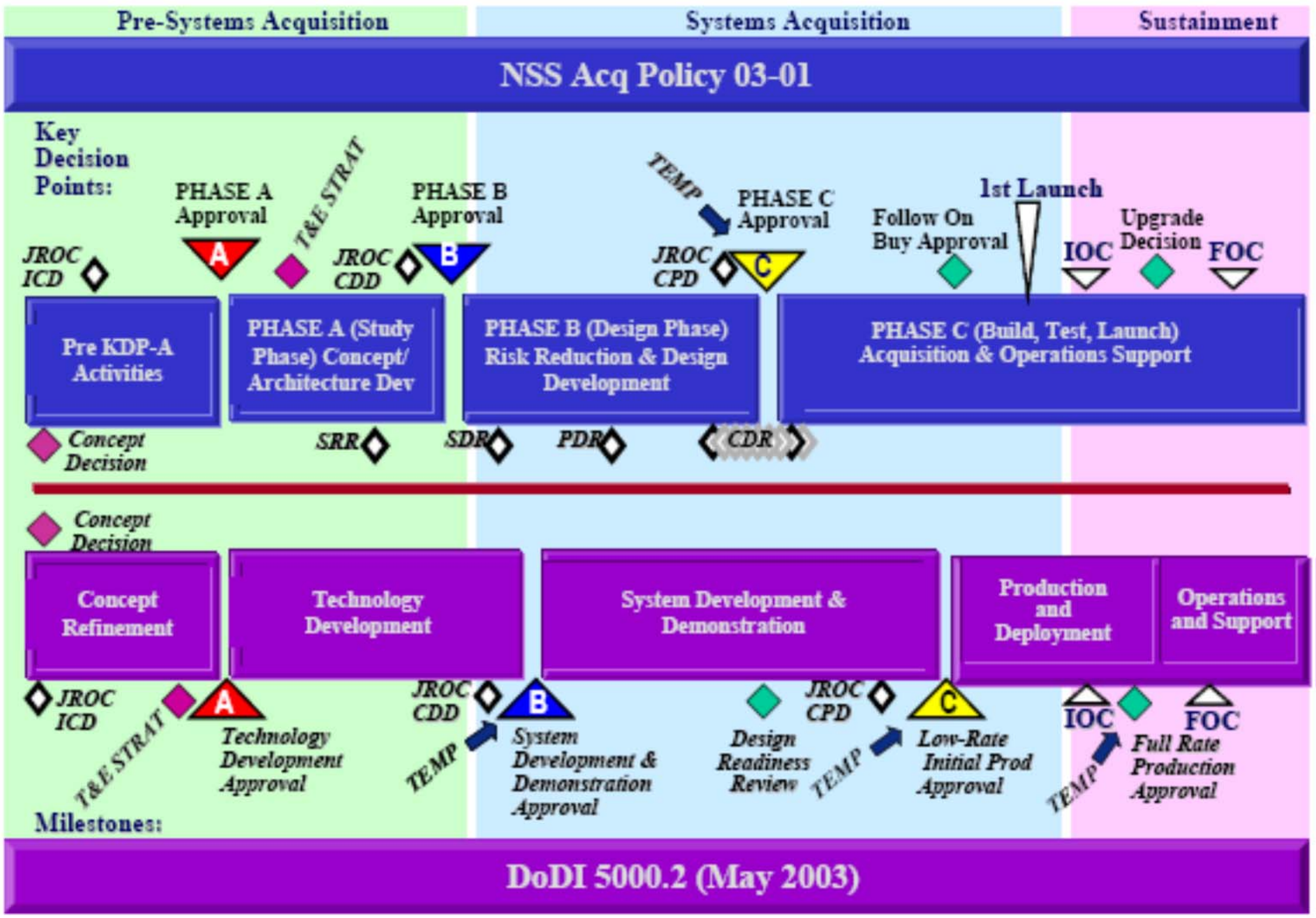


Figure 1. The Defense Acquisition Management Framework

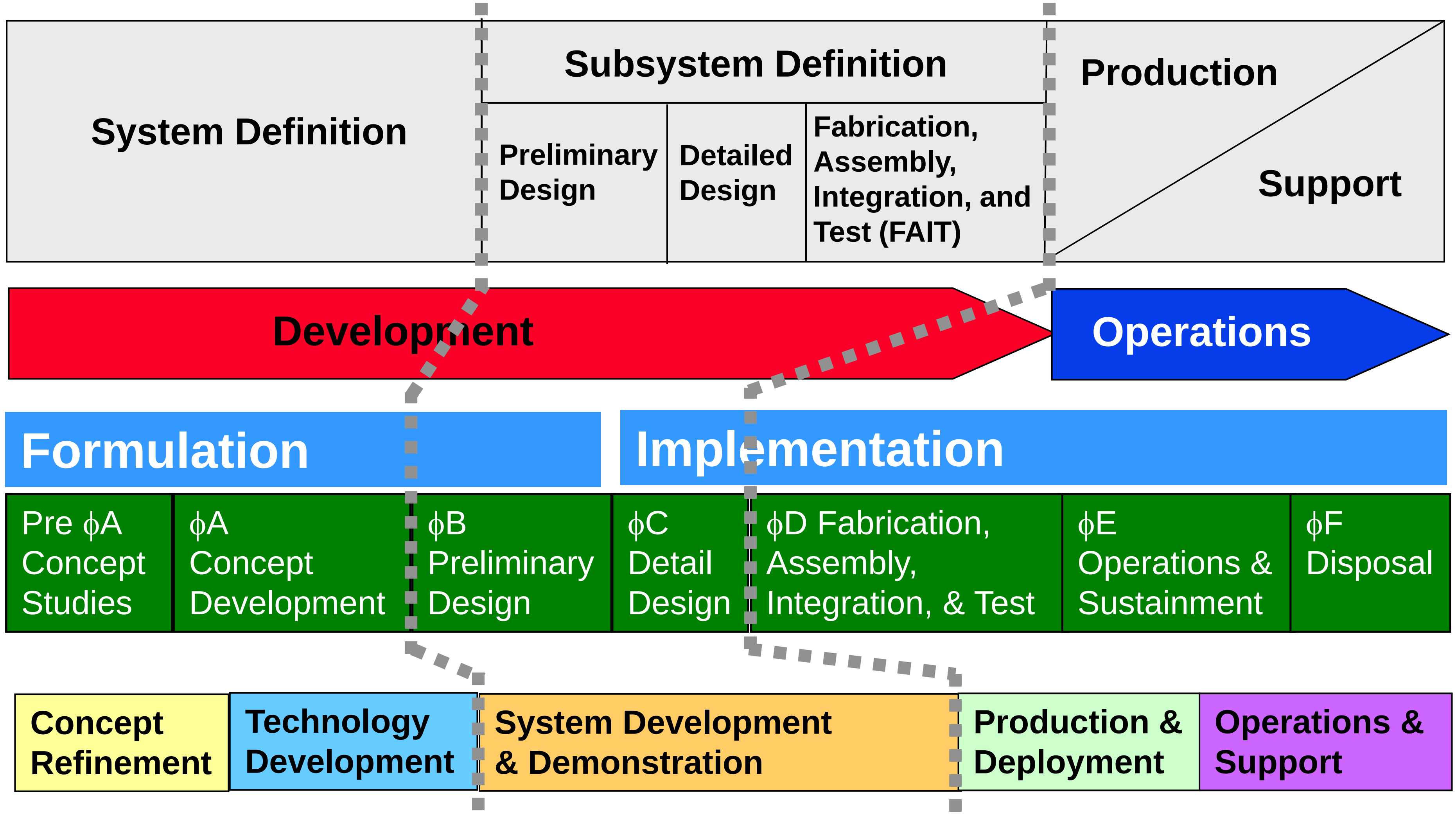
Figure 1 from DOD 5000.2

Tailoring of DoD 5000.2 for National Security Space Programs & Projects

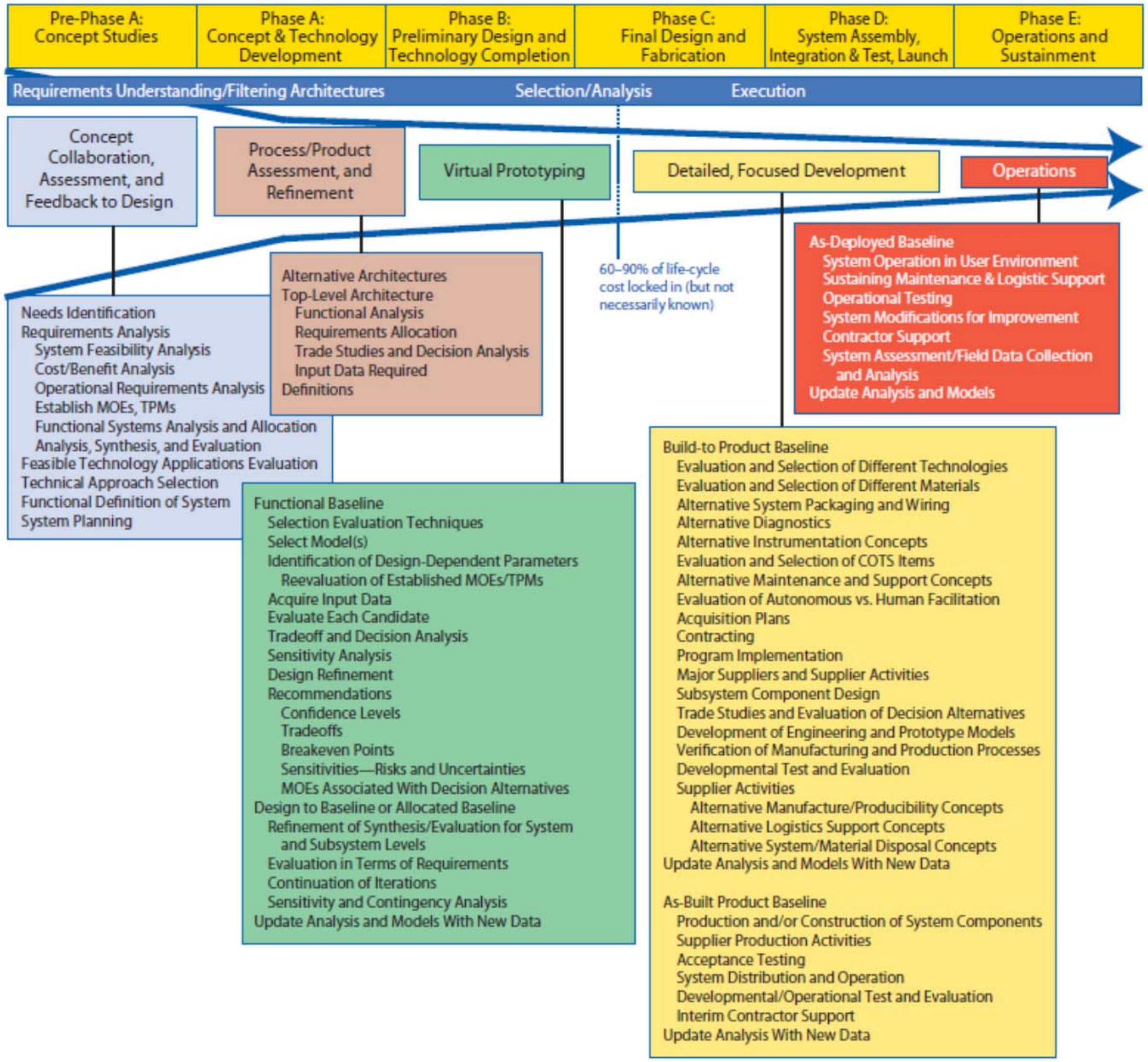


NSS formally tailored DOD 5000.2 to suit small production lots (<50) in highly complex product developments.

Comparison of Life Cycle Models

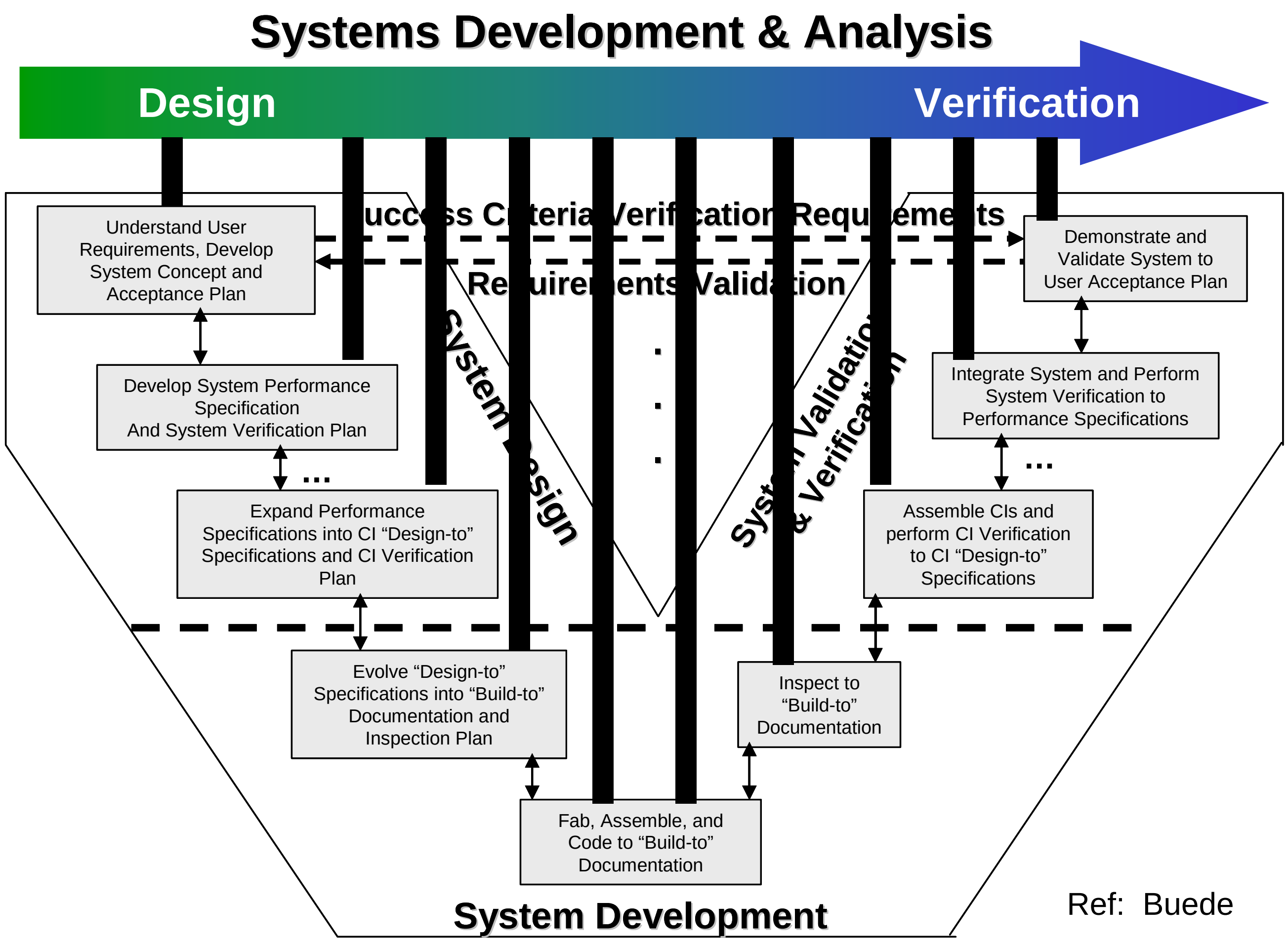


Systems Analysis Across Life Cycle



Systems Analysis Supports Entire Development Cycle

IEEE 1220 provides a process-centric view of the systems engineering process, whereas the "SE Vee" provides a more temporal depiction.



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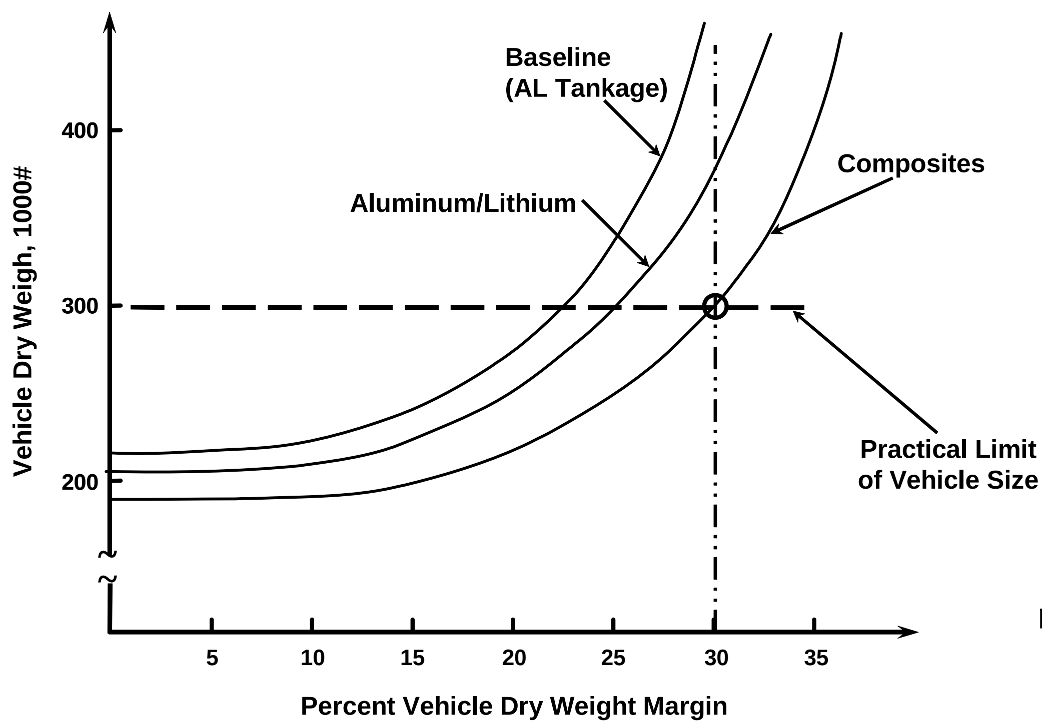
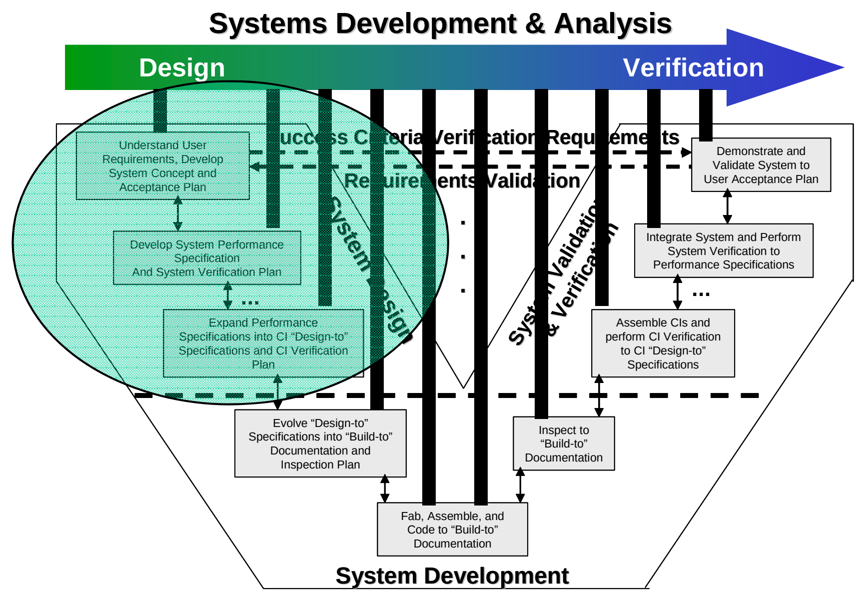
Systems Analysis During Concept Development

Metrics

SSTO Metric Example: Impact of Technologies - ϕA

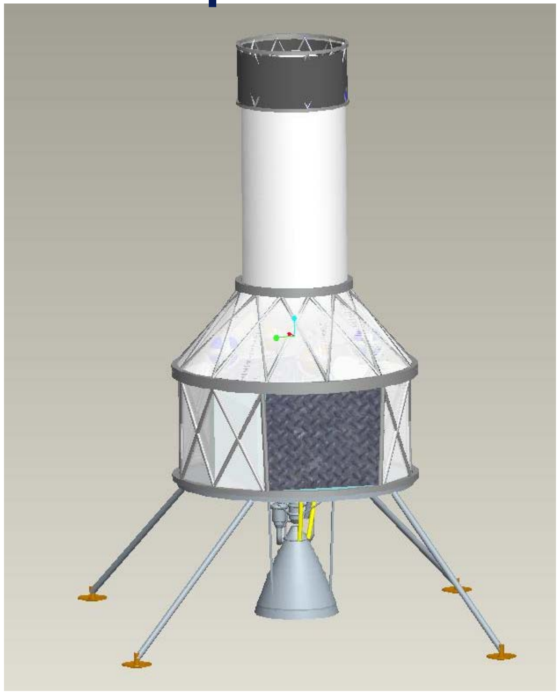
25K to LEO





ref.: Bob Ryan

Concept Trades



- *Lander power supply*
  - *Fuel cells*
  - *Batteries*
  - *Solar arrays*
  - *Nuclear*
  - *Combination*

- *RCS*
  - *Common prop. w/MPS*
  - *Storable*
  - *Cryo*

- *Rover Deployment*
  - *Extendable ramp*
  - *Other*

- *Lander configuration*
  - *Modular vs integrated design*
  - *Horizontal vs vertical*
  - *Multiple ta*

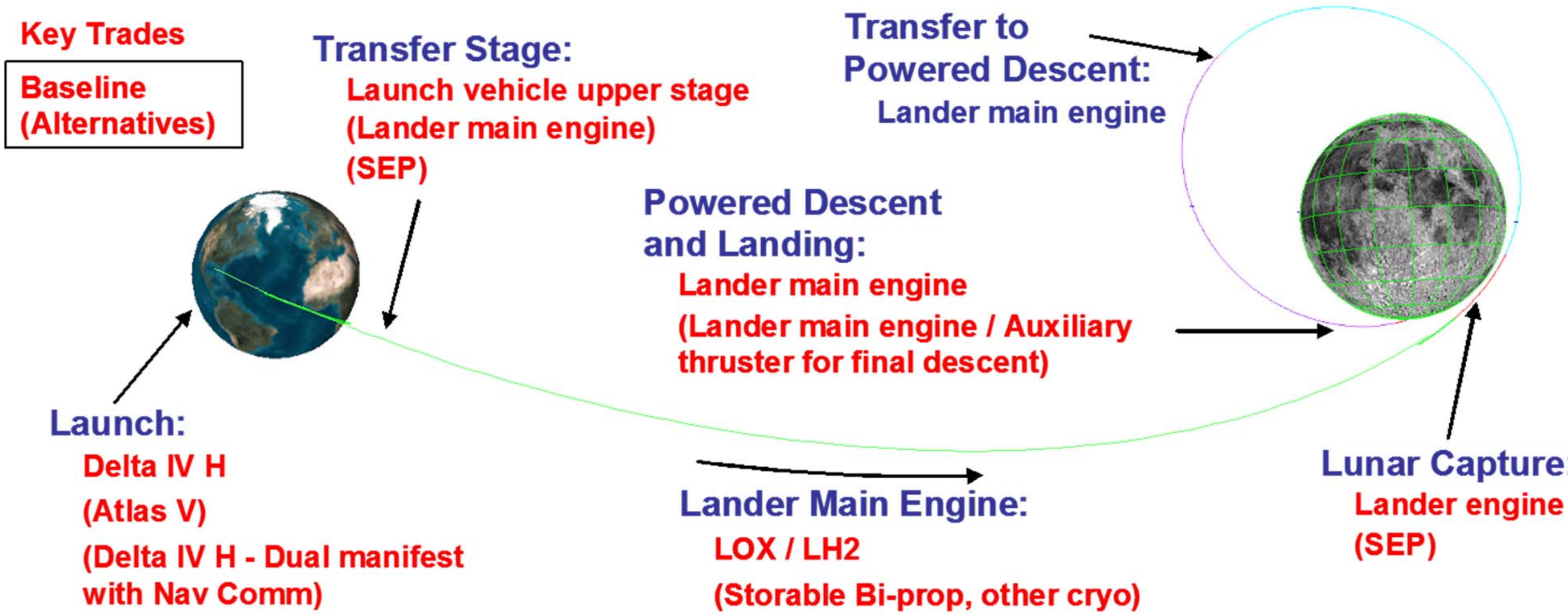
- *Main Propulsion System*
  - *Propellant type*
    - *Storable vs cryo*
    - *Combo*
  - *Engine*
    - *Existing*
    - *New Development*
    - *Modified*

- *Primary Structure*
  - *Construction*
    - *Truss*
    - *Skin-stringer*
    - *Honeycomb*
    - *Isogrid*
  - *Materials*
    - *Composites*
    - *Metallic*

- *Avionics*
  - *Degree of command and contol*
  - *IVHM*

- Communication
  - Direct to Earth vs relay sats
  - High gain antennae vs omni
  - High frequency band trades

Key Mission Events and Associated Trades



- Delta IV H Launch
  - Extensive mass margin for baseline mission;
  - Dual manifest opens cheapest path to full system (lander, rover, Nav/Comm)
- LOX / LH2 main engine
  - Link to potential ISRU; look-ahead to manned systems
- Transfer and capture phases: Lander Main Engine vs. SEP
  - Potential payload increase with SEP is minimal (at best); transfer and capture phases extend to years.
- Powered Descent and Landing: modified RL-10 (5klb thrust, throttle to 10%) alone
  - Alternative (off-ramp) is combination of unmodified RL-10 with lower thrust auxiliary for final descent
  - Development of modified RL-10 deemed less risky than mission and design complexity for alternative

Critical Mission Trades bound the baseline
and point to key Phase 1 studies

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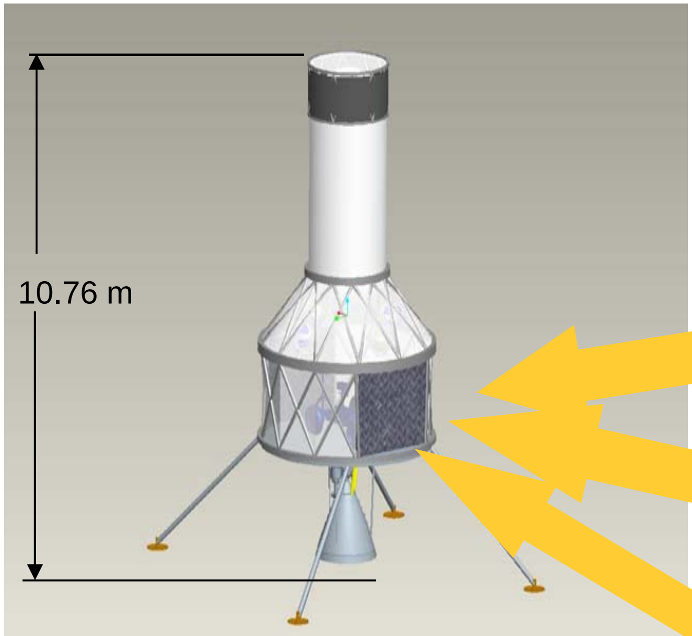
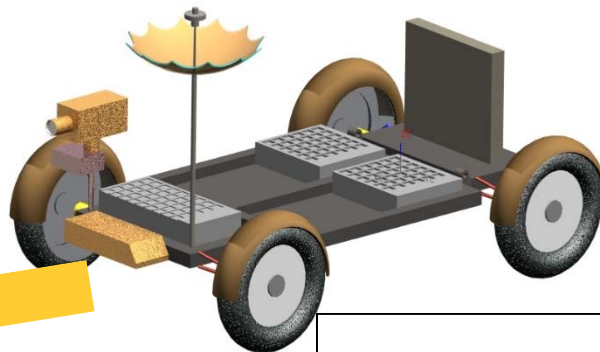
Lander Capability-Current Mission





Lander Payload

Element	Mass (kg)	Power (W)	Volume	Notes
Instrument 1	M1	P1	V1	xyz1
Instrument 2	M2	P2	V2	xyz2
Instrument 3	M3	P3	V3	xyz3
Instrument 4	M4	P4	V4	xyz4

Rover Payload

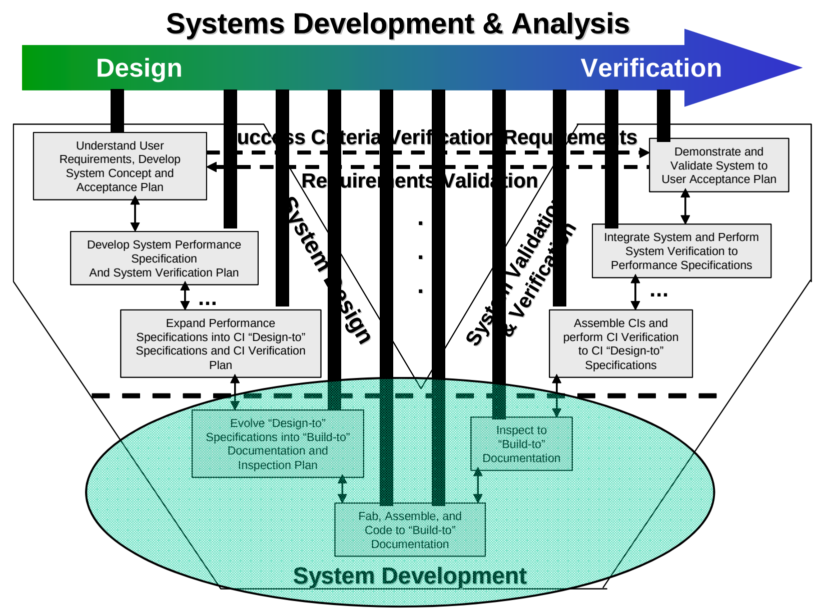
Element	Mass (kg)	Power (W)	Volume	Notes
Instrument 1	M1	P1	V1	xyz1
Instrument 2	M2	P2	V2	xyz2
Instrument 3	M3	P3	V3	xyz3
Instrument 4	M4	P4	V4	xyz4
Instrument n	Mn	Pn	Vn	

Rover+Lander Payloads=1100kg

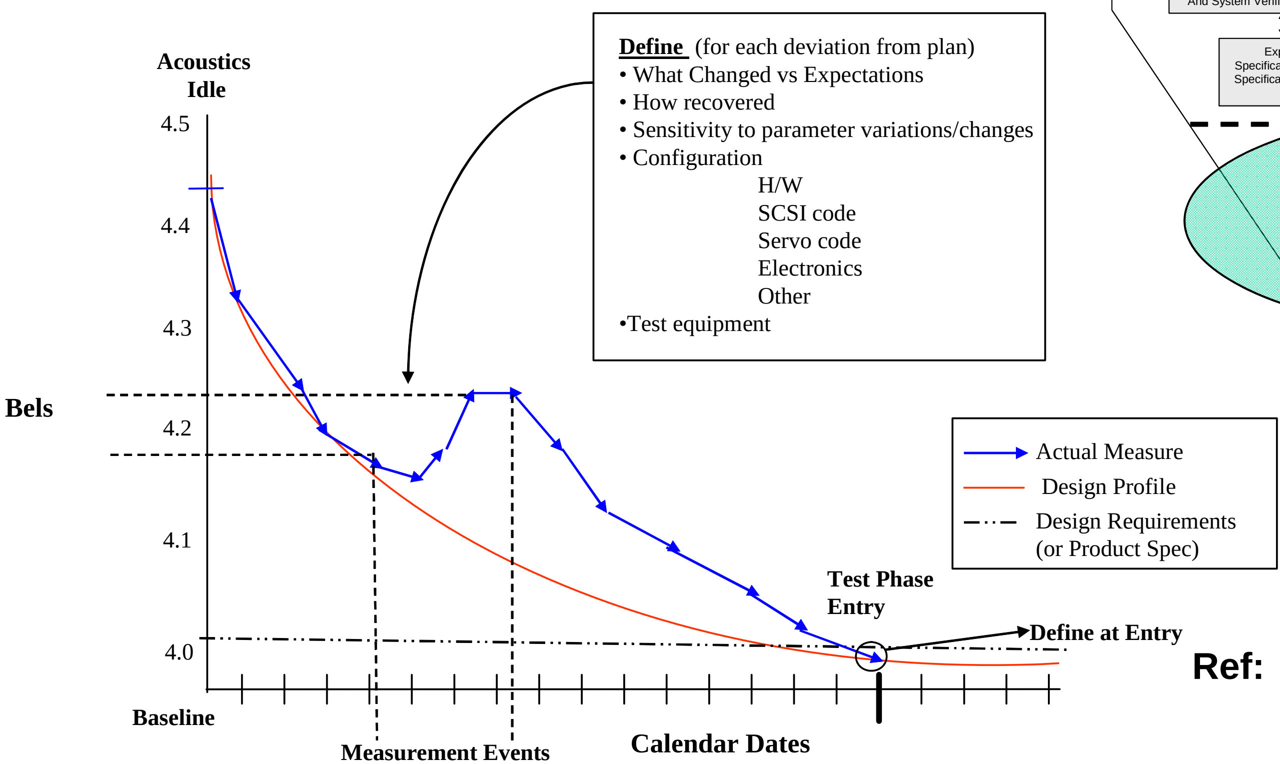
Current concept can land > 1100kg on lunar surface

Common concept has excess capability for currently defined mission

Systems Analysis During Detail Design



TPM Application -- Example



Ref: Alan Ray

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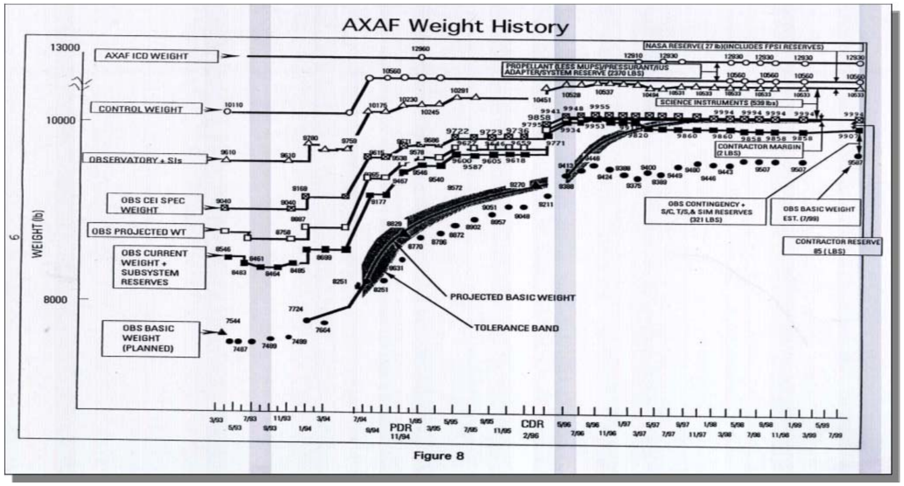
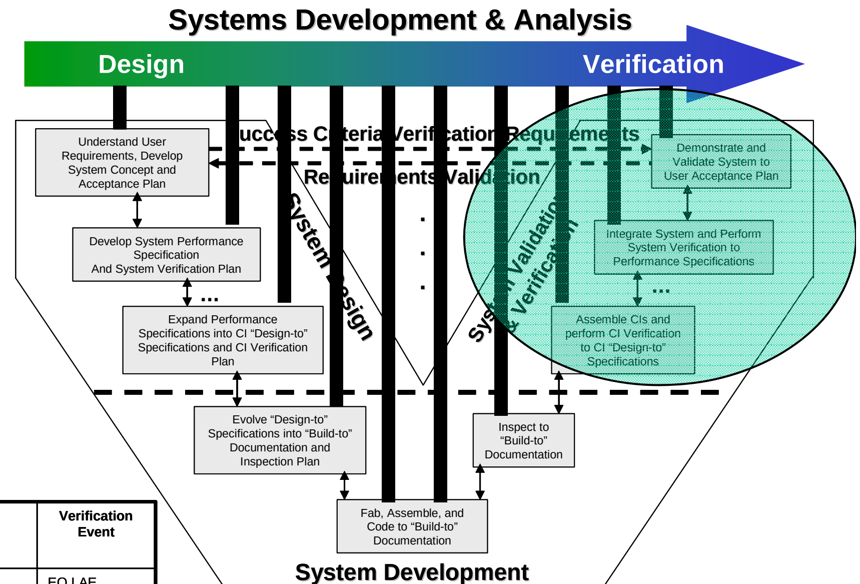
Systems Analysis During Integration





Performance Requirement (Spacecraft Specification Paragraph)	Requirement Source (Parent Requirement)	Capability/Margins (Physical, Functional, Performance)	Planned Method	Verification Requirements	Verification Event
376239 LAE Thrust Vector Alignment Component ± 0.25 degrees	DERVD 3.6 Spacecraft IPS Derived Requirement IOC AXAF.95.350.121 AXSC 3.2.9.1 Structures & Mechanical Subsystem		Analysis	Verified by measurement at the engine level.	EQ.LAE
376240 LAE Location ± 3 inches	DERVD 3.6 Spacecraft IPS Derived Requirement IOC AXAF.95.350.121 AXSC 3.2.9.1 Structures & Mechanical Subsystem		Analysis	Verified by analysis.	SE30.TRW
376241 RCS Minimum Impulse Bit TBD	DERVD 3.6 Spacecraft IPS Derived Requirement IOC AXAF.95.350.121 AXSC 3.2.9.2 Thermal Control Subsystem (TCS)		Analysis	Demonstrated during thruster qualification testing.	EQ.PROP REM
376242 RCS Thrust 21 lbf ± 5% (at 250 psia inlet pressure)	DERVD 3.6 Spacecraft IPS Derived Requirement to be resolved AXSC 3.2.9.2.1 Heaters		Analysis	Demonstrated during thruster qualification testing.	EQ.PROP REM
376243 RCS Minimum Specific Impulse (inlet press. = 250 psia) 225 sec (BOL steady state)	DERVD 3.6 Spacecraft IPS Derived Requirement IOC AXAF.95.350.121 AXSC 3.2.9.2.1 Heaters		Analysis	Demonstrated during thruster qualification testing.	EQ.PROP REM
376244 Total Pulses (each thruster) 50,000	DERVD 3.6 Spacecraft IPS Derived Requirement IOC AXAF.95.350.121 AXSC 3.2.9.2.1 Heaters		Analysis	Demonstrated during thruster qualification testing.	EQ.PROP REM
376245 Propellant Throughput 200 lbm	DERVD 3.6 Spacecraft IPS Derived Requirement IOC AXAF.95.350.121 AXSC 3.2.9.2.1 Heaters	Predicted Throughput: 92.6 lbm Expected Margin: 107 lbm	Analysis	Demonstrated during thruster qualification testing.	EQ.PROP REM

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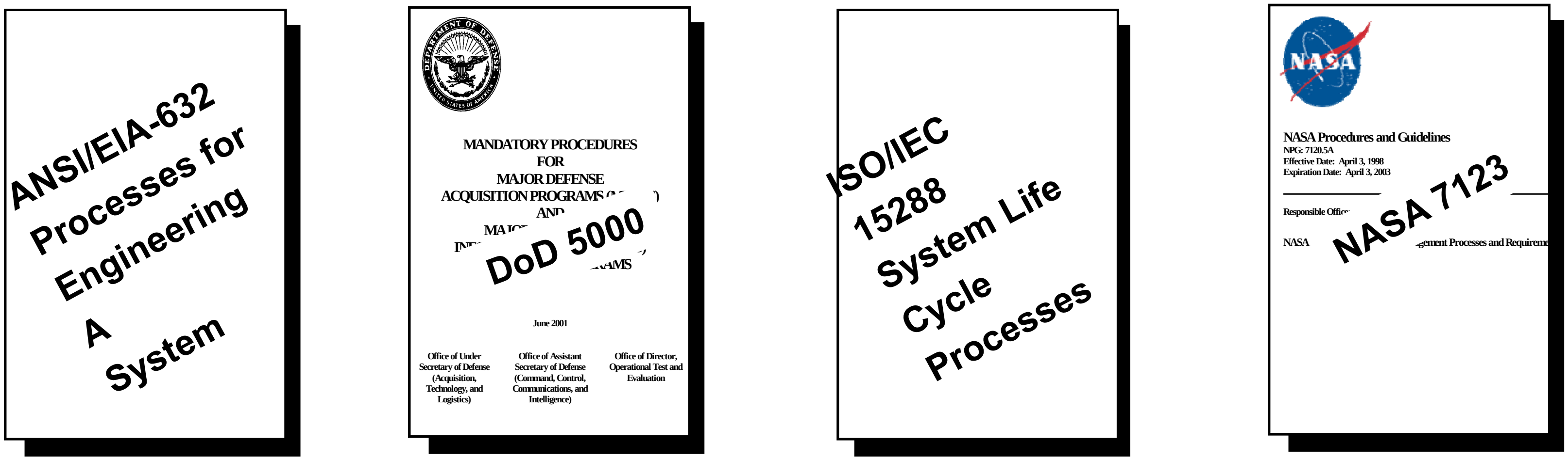
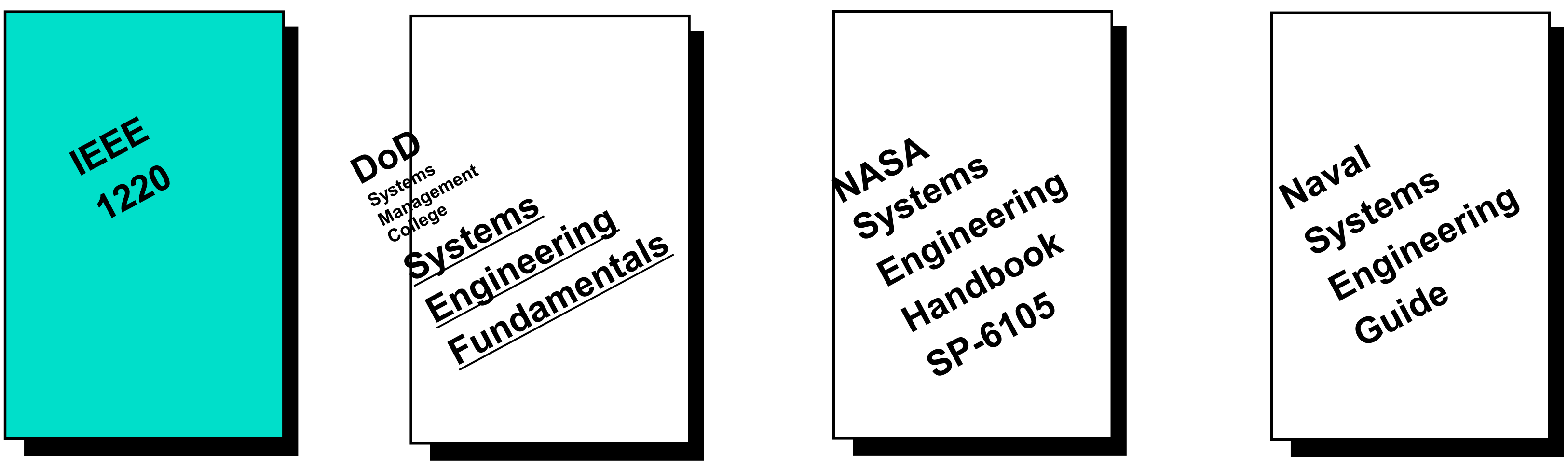
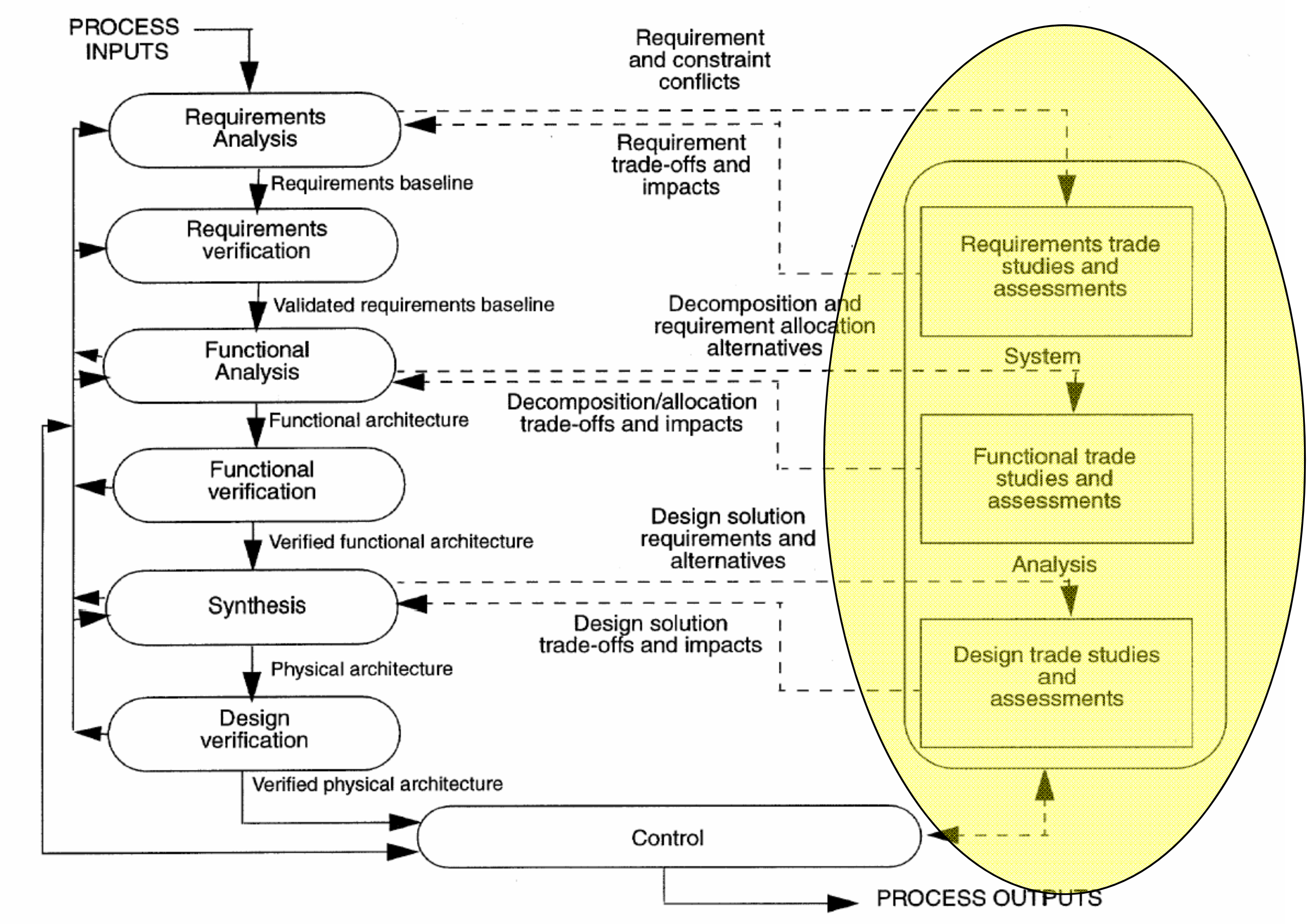


Source books describing systems engineering standards.



Process Relations for Engineering a System



We will examine the role of Systems Analysis in the Systems Engineering Process as defined in IEEE-1220 in the next lesson.

Ref: IEEE-1220, Figure 4

IEEE 1220 SEP Map to “SE VEE”

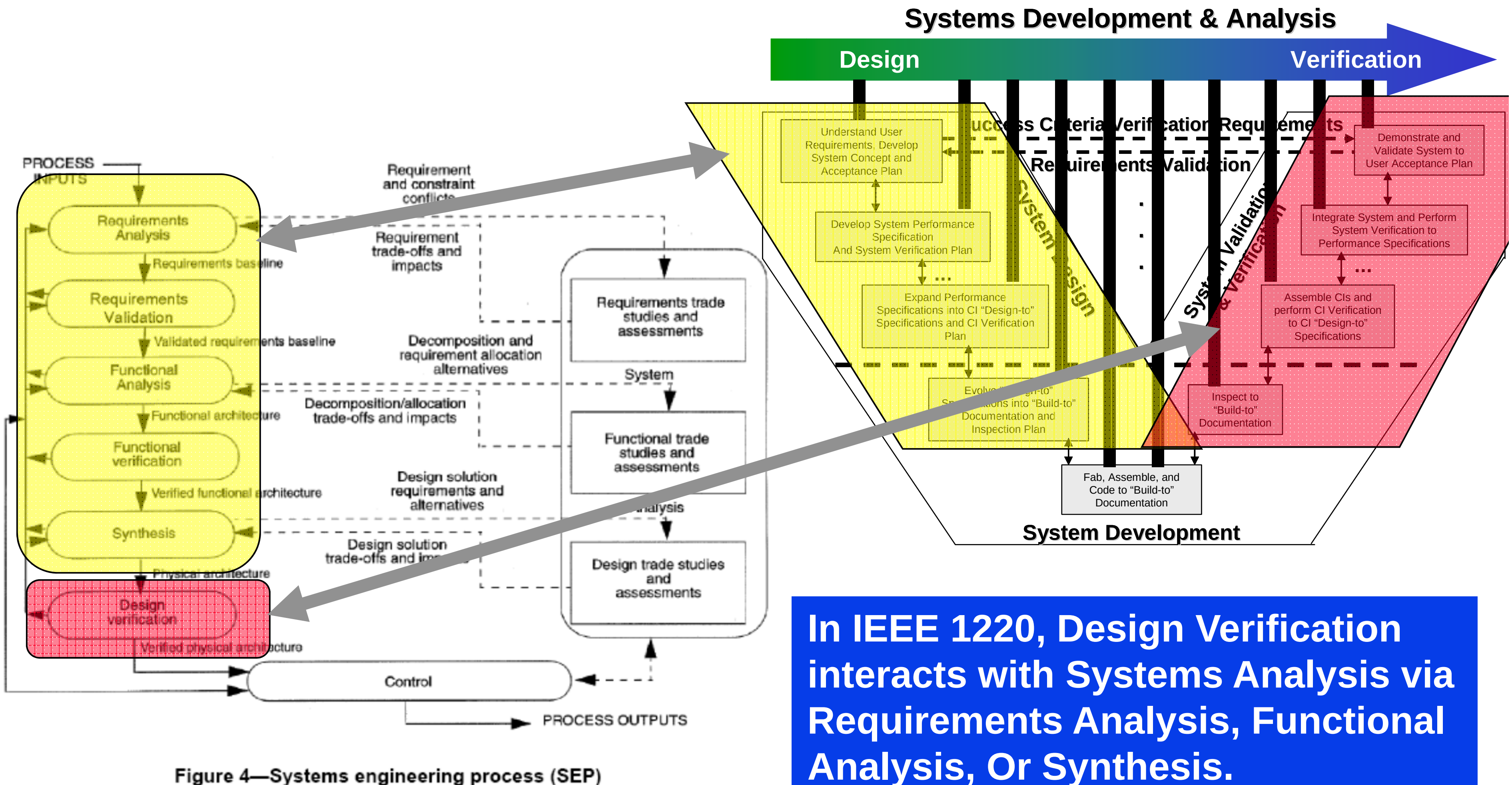


Figure 4—Systems engineering process (SEP)

In IEEE 1220, Design Verification interacts with Systems Analysis via Requirements Analysis, Functional Analysis, Or Synthesis.

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Key Points

- Systems analysis supports the systems engineering process from the very early phases through system operation.

- Early in the development cycle, systems analyses tend to be more broad in scope with less fidelity; over time, the systems analyses tend to more narrow scope and higher fidelity.

References

- Buede, Dennis M. *The Engineering Design of Systems, 2nd edition*, Wiley, 2009.
- *IEEE Standard for Application and Management of the Systems Engineering Process*, IEEE Std 1220-2005, September 2005.
- *NASA Systems Engineering Processes and Requirements*, NPR 7123, April 2013.
- *National Security Space Acquisition Policy*, NSS 03-01, December 2004
- *Systems Engineering Fundamentals*, Supplementary Text Prepared by the Defense Acquisition University Press, Fort Belvoir, VA 22060-5565, January 2001.
- *Operation of the Defense Acquisition System*, DoD Instruction 5000.2, December 2008 (Note: superceded by DoD 5000.02 with a current date of November 2013, but 5000.2 is the correct reference for the information used).

Lesson 4:
Systems Engineering Role of Systems Analysis

Objectives

- Review the formal roles of systems analysis in the execution of the systems engineering process as described in IEEE-1220.
  - Key functions
  - Key interactions

Systems Analysis Process

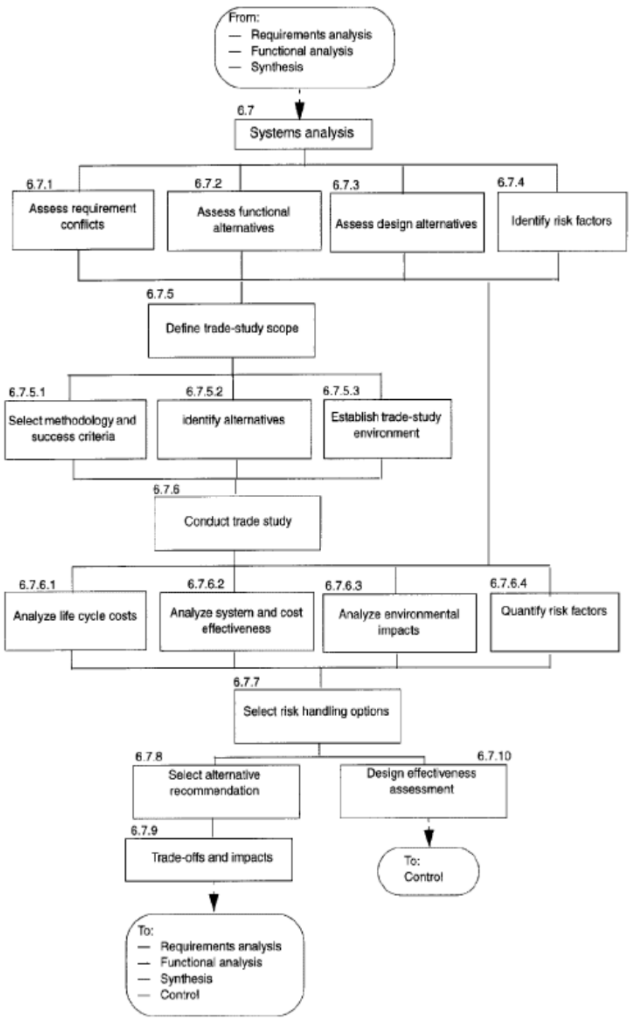
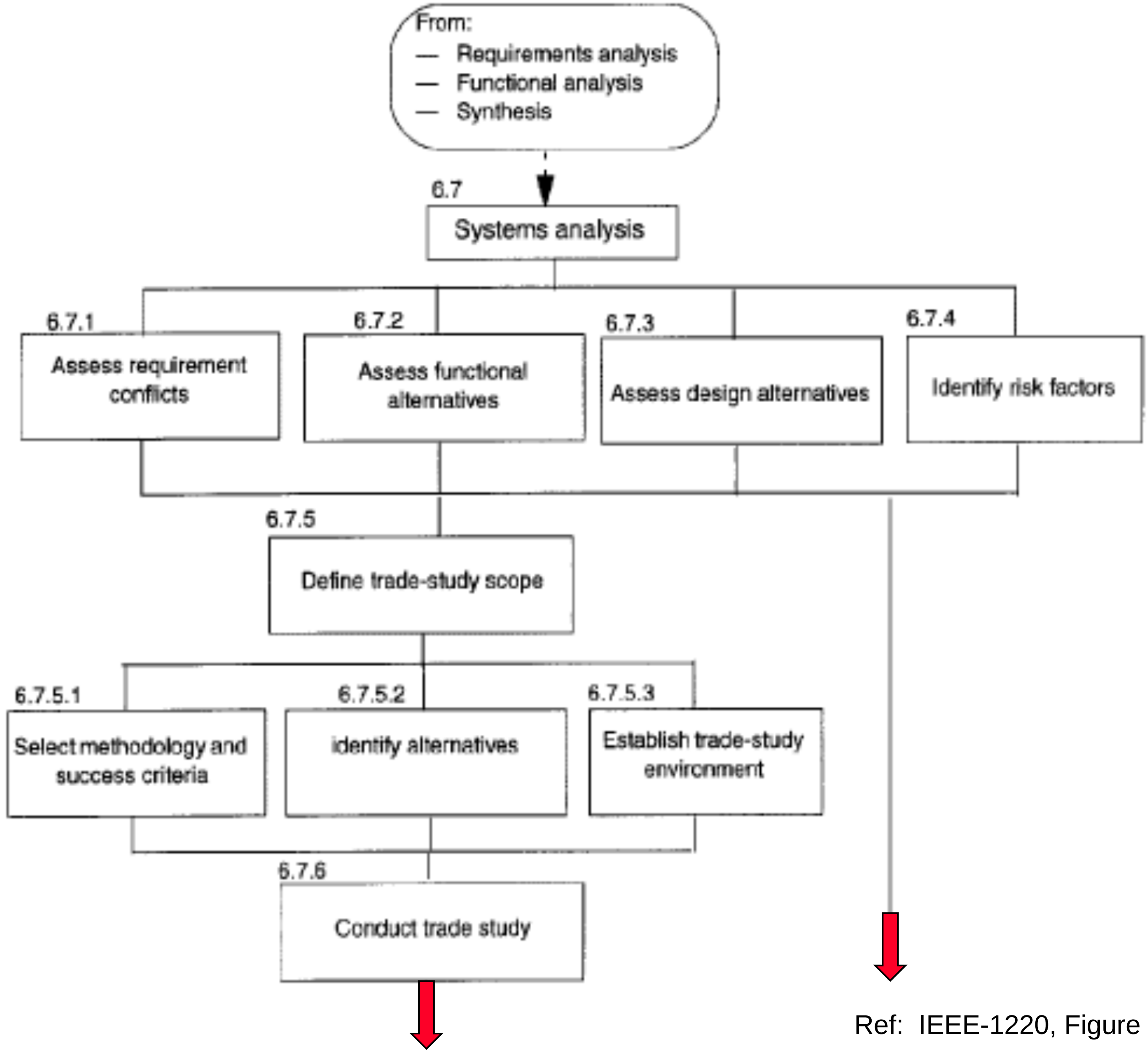


Figure 16—Systems analysis process

The project shall perform the tasks of systems analysis for the purpose of resolving conflicts identified during ***requirements analysis***, decomposing functional requirements and allocating performance requirements during ***functional analysis***, evaluating the effectiveness of alternative design solutions and selecting the best design solution during ***synthesis***, assessing ***system effectiveness***, and managing risk factors throughout the systems engineering effort. ***Systems analysis provides a rigorous quantitative basis for establishing a balanced set of requirements and for ending up with a balanced design.*** The tasks associated with systems analysis are identified in Figure 16. Even if a trade-off analysis is not done, an overall assessment of the system effectiveness should be completed.

Ref: IEEE-1220, Figure 16



Ref: IEEE-1220, Figure 16

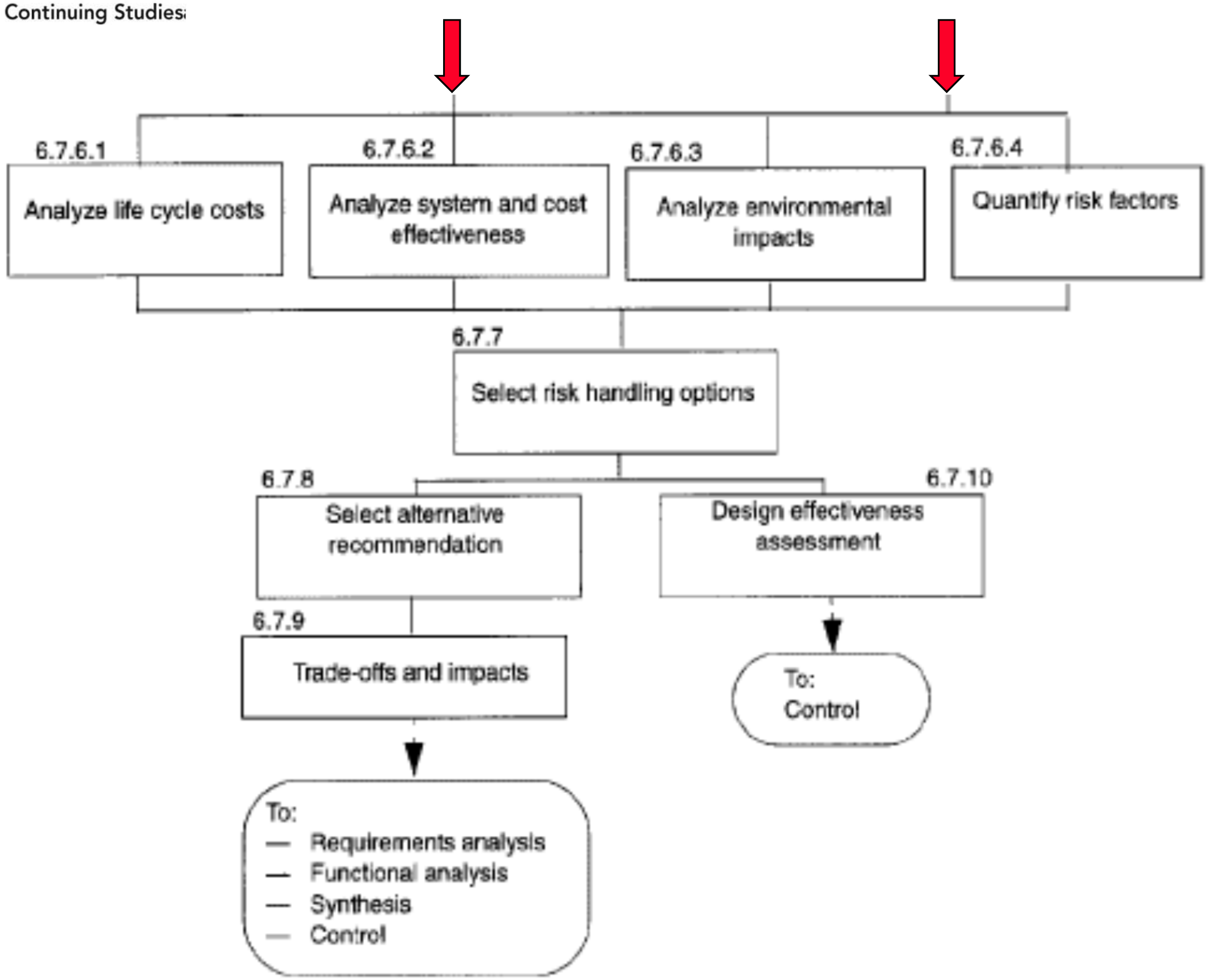


Figure 16—Systems analysis process

Ref: IEEE-1220, Figure 16

6.7.1 Assess Requirement Conflicts

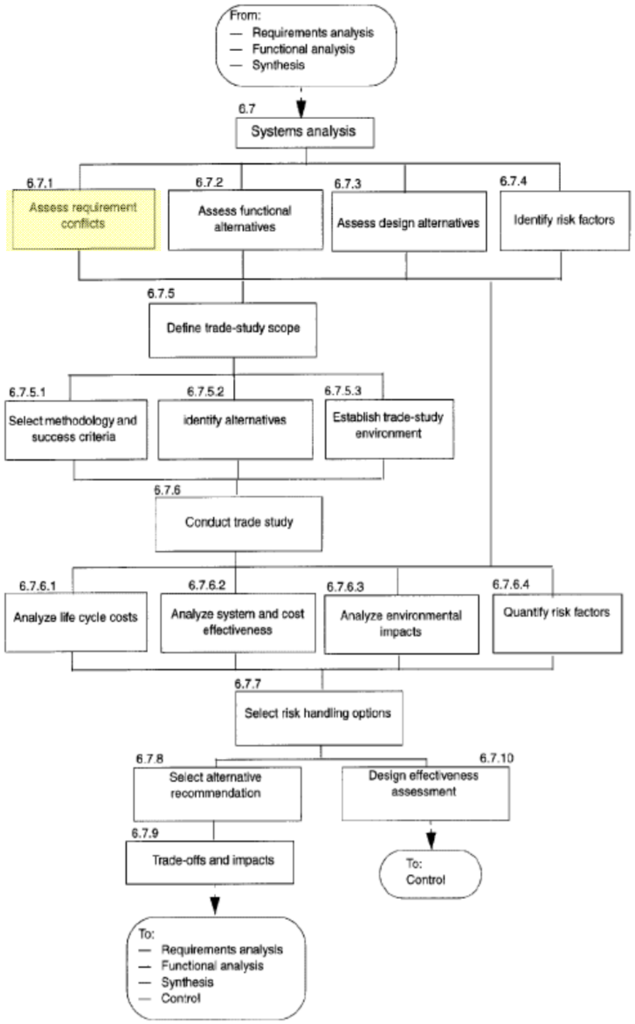


Figure 16—Systems analysis process

The project ***assesses conflicts among requirements and constraints*** identified during requirements analysis to identify alternative functional and performance requirements, where necessary. Requirements trade-off analyses and assessments are performed to ***identify the recommended set of requirements and constraints*** in terms of risk, cost, schedule, and performance impacts.

Ref: IEEE-1220, Figure 16

6.7.2 Assess Functional Alternatives

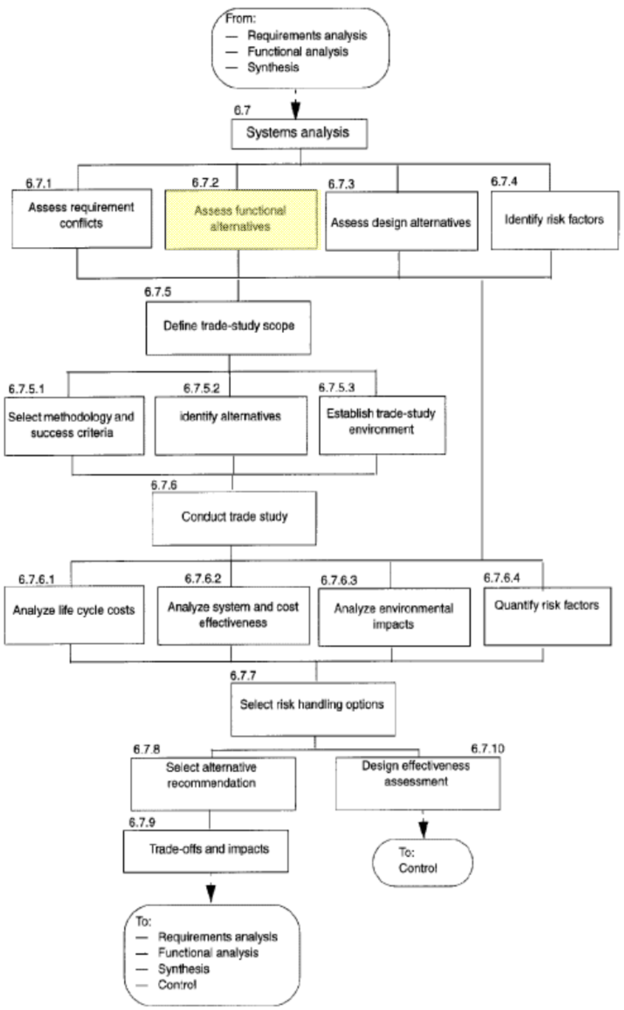


Figure 16—Systems analysis process

The project assesses possible alternative subfunction arrangements for the decomposition of a function and for the ***allocation of allocable performance requirements*** to the subfunctions during functional analysis. Functional trade-off analyses and assessments are performed to ***identify the recommended set of subfunctions for each function and performance requirement allocations*** in terms of risk, cost, schedule, and performance impacts.

Ref: IEEE-1220, Figure 16

6.7.3 Assess Design Alternatives

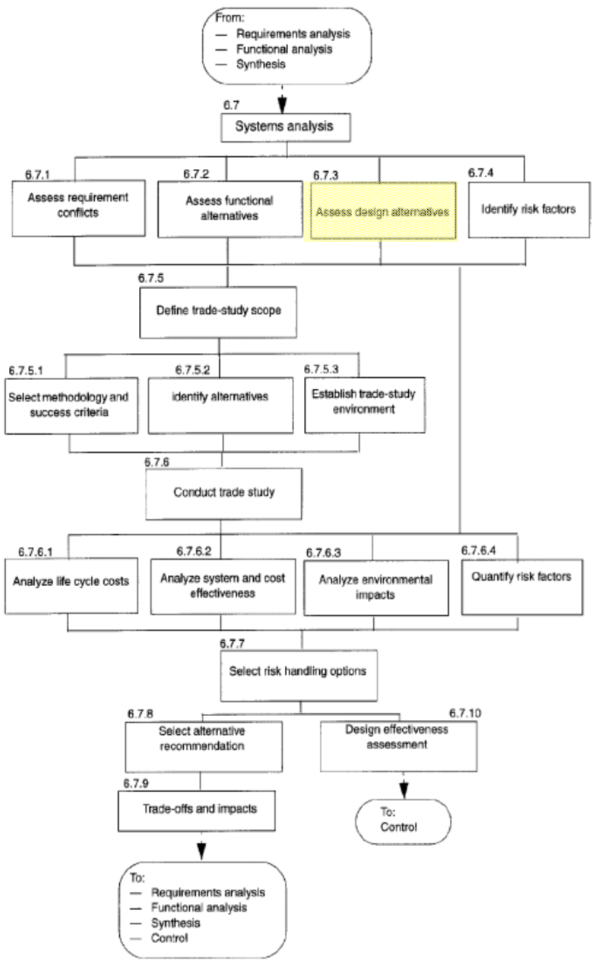


Figure 16—Systems analysis process

The project ***assesses potential groupings and allocations of functions*** from the verified functional architecture and identified design alternatives during synthesis. Design trade-off analyses and assessments are performed to identify the recommended design trade-offs in terms of risk, cost, schedule, and performance impacts.

Ref: IEEE-1220, Figure 16

6.7.4 Identify Risk Factors

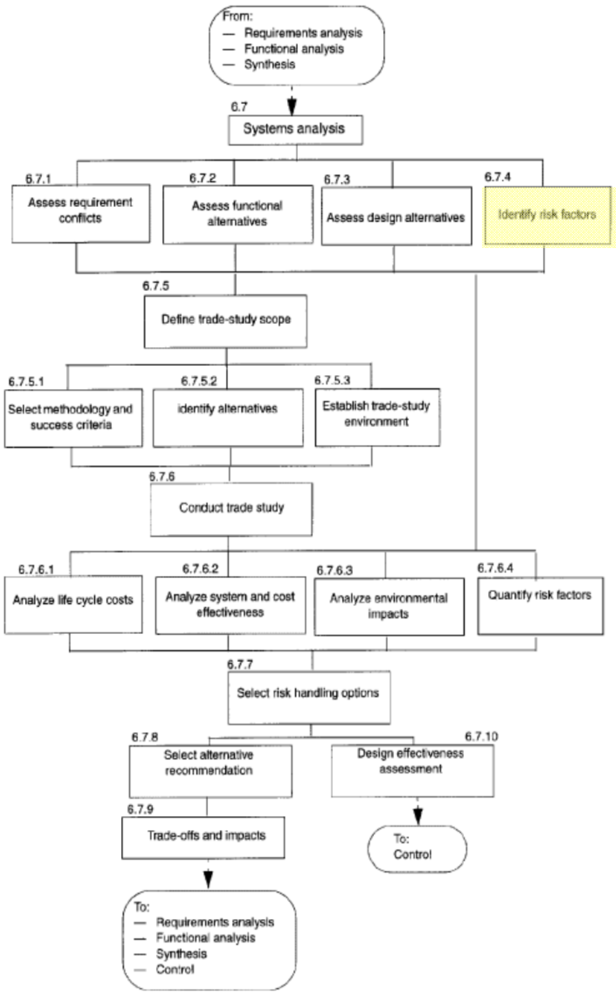


Figure 16—Systems analysis process

The project assesses requirements and constraints from requirements analysis, subfunction arrangements resulting from functional decomposition, allocation of subfunctions to functional elements, design decisions made during synthesis, and design elements of the design architecture, to ***identify the risk factors to successful completion of the project***. These evaluations should be made from an entire life cycle perspective. ***Identification of risk should be in a form to understand the following:***

- ***a) The circumstances that might lead to risk factor occurrence and the probability of occurrence***
- ***b) How the risk factor can be recognized if it does occur***
- ***c) How the risk factor affects cost, schedule, and performance***.

Identified risks are prioritized based upon criticality to the successful development of the system. Acceptable levels of risk should be identified, depending on the stage of development, to provide a basis for establishing and monitoring risk reduction activities and mitigating unacceptable risks.

Ref: IEEE-1220, Figure 16

6.7.5 Define Trade-off Analysis Scope

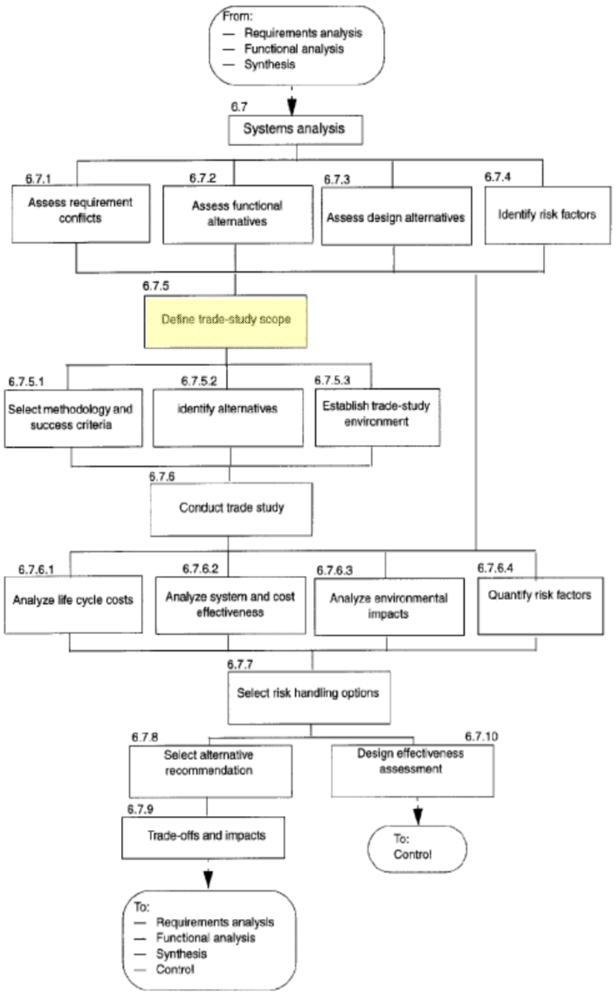


Figure 16—Systems analysis process

The project should define the scope of the trade-off analysis to be conducted. A trade-off analysis can be

a) *Judgmental*—a selection made based on the judgment of the analyst or designer, which does not require the rigor of a more formal study and for which the consequences are not too important; one alternative that is clearly superior to others; and/or time that may not be available for a more formal approach (*most trade-off analyses done in accomplishing the tasks of the SEP are of the judgmental type*);

b) *Informal*—follows the same methodology of a formal trade-off analysis but is not documented as formally and is of less importance to the acquirer;

c) *Formal*—formally conducted with results reviewed at technical reviews.

Informal and formal trade-off analysis objectives, execution, data collection requirements, schedule of activities, analysis of results, and expected outcomes need to be fully defined. *Each trade-off analysis is conducted for the purpose of selecting among competing alternatives to support stakeholder needs, system effectiveness, design to cost, or life cycle cost objectives within acceptable levels of risk.*

Ref: IEEE-1220, Figure 16

6.7.5.1 Select Methodology and Success Criteria

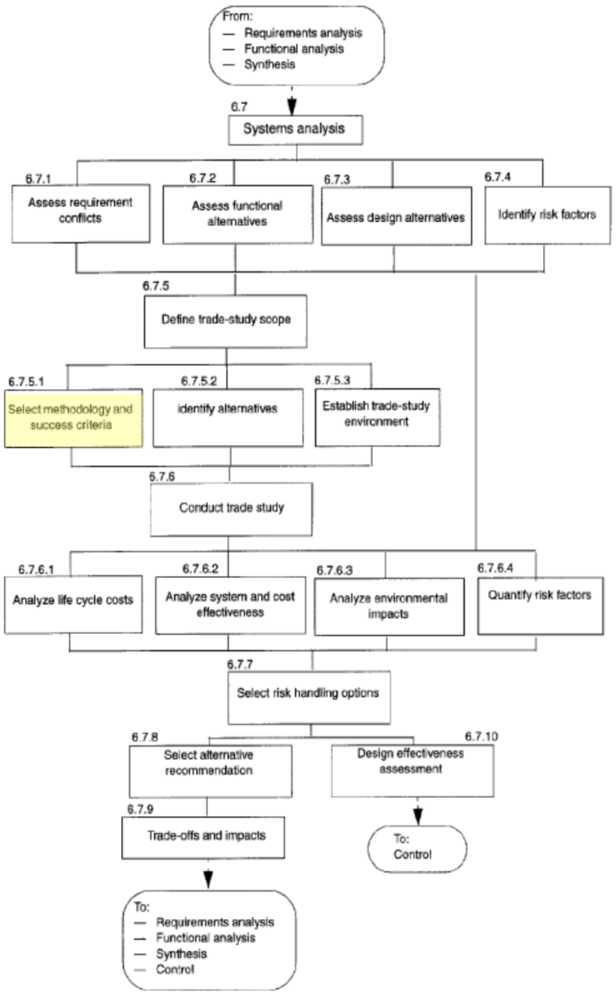


Figure 16—Systems analysis process

The project selects the general approach, resources, and procedures for performing trade studies based upon the trade-study definition, its level of importance, and availability of tools, facilities, special equipment, and related resources. *The project also lists the set of selection criteria, which includes factors that characterize what makes a specific alternative desirable, such as cost, schedule, performance and risk; life cycle quality factors; reuse; and size, weight, and power consumption*. Adverse qualities as well as favorable qualities should be included as criteria.

Ref: IEEE-1220, Figure 16

6.7.5.2 Identify Alternatives

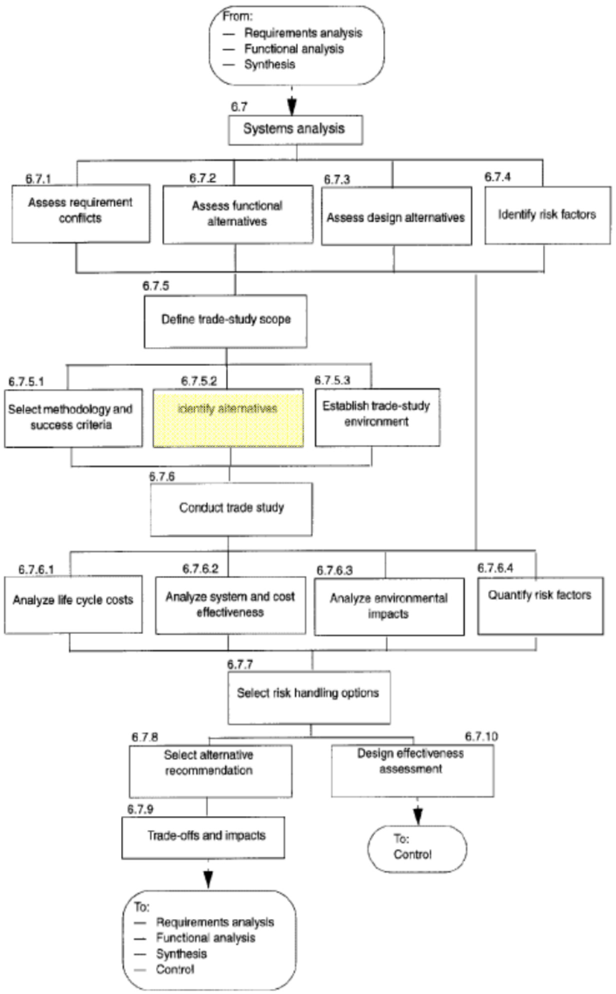


Figure 16—Systems analysis process

The project identifies and lists the viable alternative solutions to be evaluated. Each alternative should be compared with respect to completeness, and *sensitivity analysis should be conducted to understand how each alternative withstands changes in the environment, technology base, or within the bounds of the evolutionary strategy*.

Ref: IEEE-1220, Figure 16

6.7.5.3 Establish Trade-Study Environment

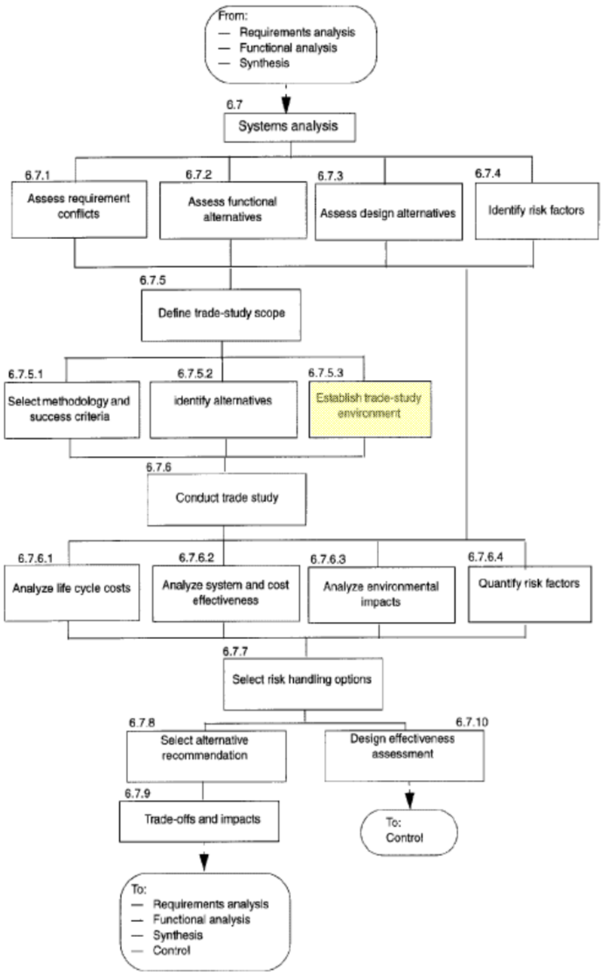


Figure 16—Systems analysis process

The project establishes metrics for each criterion that characterizes how well various alternatives satisfy the criterion. In addition, the project establishes weighting factors for each criterion, which distinguish the degree of importance to the trade-off analysis definition. *Models (representative or simulations) are established, when needed, to support conduct of a formal or informal trade study.* The selection of models depends on the nature of the trade-off analysis, the development stage, the type of information needed, and the characteristics of interest for an alternative. Models should be validated prior to application in a trade-off analysis.

Ref: IEEE-1220, Figure 16

6.7.6 Conduct Trade-off Analysis

Figure 16—Systems analysis process

The project completes tasks 6.7.6.1 through 6.7.6.4, to the degree appropriate, to complete trade-off analyses for the following:

a) Requirements analysis to both resolve conflicts with and satisfy stakeholder/market needs, requirements, and constraints

b) Functional analysis to support decomposition of functions into subfunctions and to *allocate performance requirements*

c) Synthesis to support design decisions

Formal and informal trade-off *analyses are conducted under controlled conditions to generate data pertaining to each alternative*. The results of the trade-off analyses are recorded and analyzed to quantify the impact each alternative has on the system or technical effort. These results are compared against the success criteria to determine which alternative is recommended.

Ref: IEEE-1220, Figure 16

6.7.6.1 Analyze Life Cycle Costs

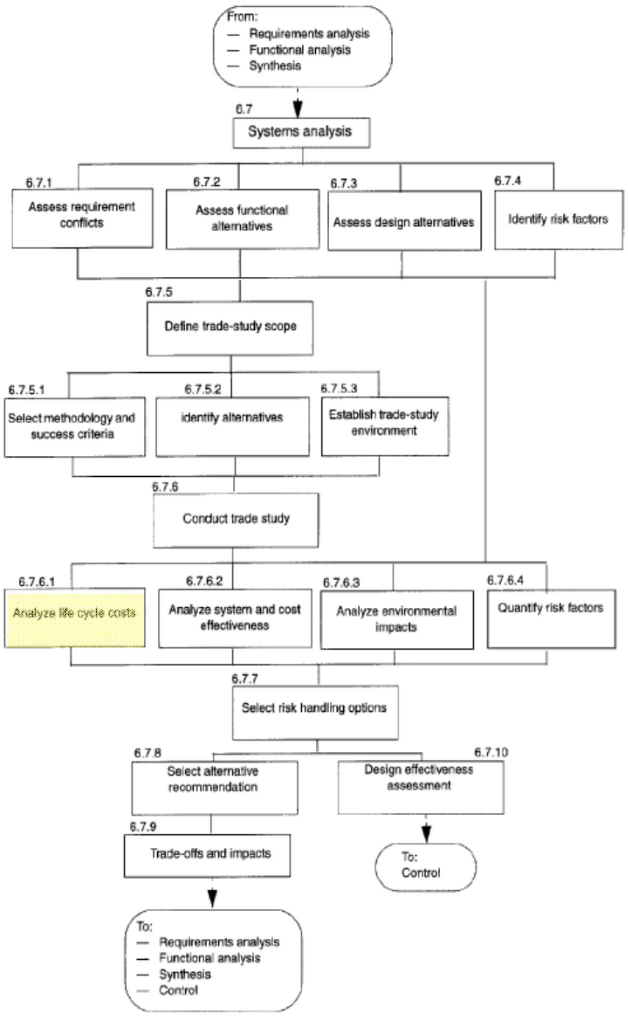


Figure 16—Systems analysis process

The project analyzes the *costs to the project and to the acquirer for alternative system approaches considered in a trade-off analysis or system effectiveness assessment*. Life cycle cost analyses

a) Provide requisite cost information to support trade-off analysis decisions.
b) Provide requisite cost information for system effectiveness assessments.
c) Include the cost of development, manufacturing, test, distribution, operations, support, training, and disposal.
d) Include established design-to-cost goals, a current estimate of these costs, and known uncertainties in these costs.
e) Identify the impacts on life cycle cost of proposed changes.

Ref: IEEE-1220, Figure 16

6.7.6.2 Analyze System and Cost-Effectiveness

Figure 16—Systems analysis process

The project analyzes the *relationships between system effectiveness and life cycle costs* to

a) Determine performance impacts on costs.
b) Understand value added as a function of cost.
c) Support identification of performance objectives and requirements.
d) Support allocation of performance to functions.

System and cost-effectiveness analyses are conducted on life cycle processes of manufacturing, test, distribution, operations, support, training, and disposal to support inclusion of life cycle quality factors into system product designs, and to support the definition of functional and performance requirements for life cycle processes. The results of these analyses are used in evaluating trade-off analysis alternatives and for effectiveness assessments of the system.

Ref: IEEE-1220, Figure 16

6.7.6.3 Analyze Safety and Environmental Impacts

Figure 16—Systems analysis process

The project identifies safety and environmental impacts associated with system implementation. Applicable environmental laws and regulations should be identified, and the project should ensure that these are complied with by any alternative solution. *The project completes an environmental impact and safety analysis to determine the impact on and by system products and the impact of their life cycle processes on the environment or to personnel*. Use of materials or generating by-products that present a known hazard to the environment are to be avoided to the extent feasible. Where not feasible, provisions may be provided for proper handling, storage, and disposal of hazardous materials or by-products. *Results of these analyses influence trade-off analysis recommendations and assessments of system effectiveness*.

Ref: IEEE-1220, Figure 16

6.7.6.4 Quantify Risk Factors

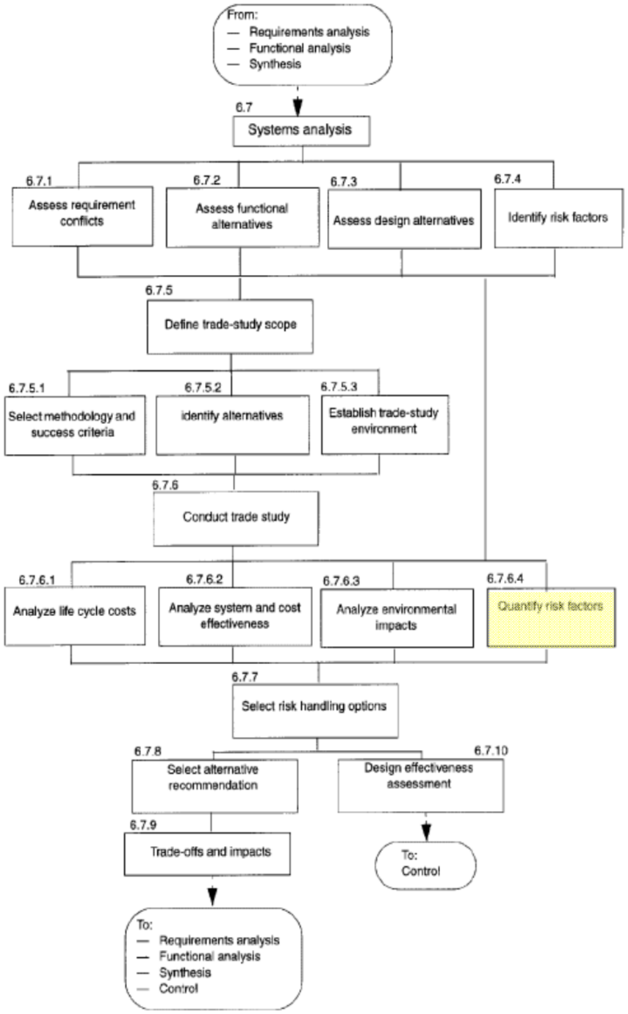


Figure 16—Systems analysis process

The project quantifies the impact of identified risk factors on the system or alternative being considered based on exposure to the probability of an undesirable consequence. *For system effectiveness assessments, each element of the system architecture developed to date is assessed to determine what can go wrong, and if it goes wrong, what impact it may have on the system.* For trade-off analyses, risk levels assessed during life cycle cost, system and cost-effectiveness, and environmental impact analyses are prioritized and reported as part of trade-off analysis recommendations.

Ref: IEEE-1220, Figure 16

6.7.7 Select Risk-Handling Options

Figure 16—Systems analysis process

The project assesses various risk-handling options to select those that may mitigate risks consistent with the current stage of development and risk-management policies set by the project. Risk, which may be reduced by lessening either the likelihood or the impact, or both, may be accepted given the cost, schedule, and performance impacts and planned mitigation approaches. *An analysis of the risk-handling options should be accomplished to quantify costs and effects on the probability and impact of risk.* The project should select those risk-handling options that are feasible and that reduce risks to acceptable levels with the best cost/benefit ratio. The expected remaining risks after risk-handling mitigation efforts are implemented should be identified and quantified. *Throughout risk identification, quantification, and handling, integration is needed from lower levels of the system architecture up through the system level to understand cause-and-effect interactions*. Risk reduction approaches and expected remaining risks are included in a risk reduction plan, which is included in trade-off analysis recommendations and effectiveness assessment reports. The complete risk reduction effort is documented in the engineering plan and integrated into the master schedule for the next stage of development, and briefed at appropriate technical reviews.

Ref: IEEE-1220, Figure 16

6.7.8 Select Alternative Recommendation

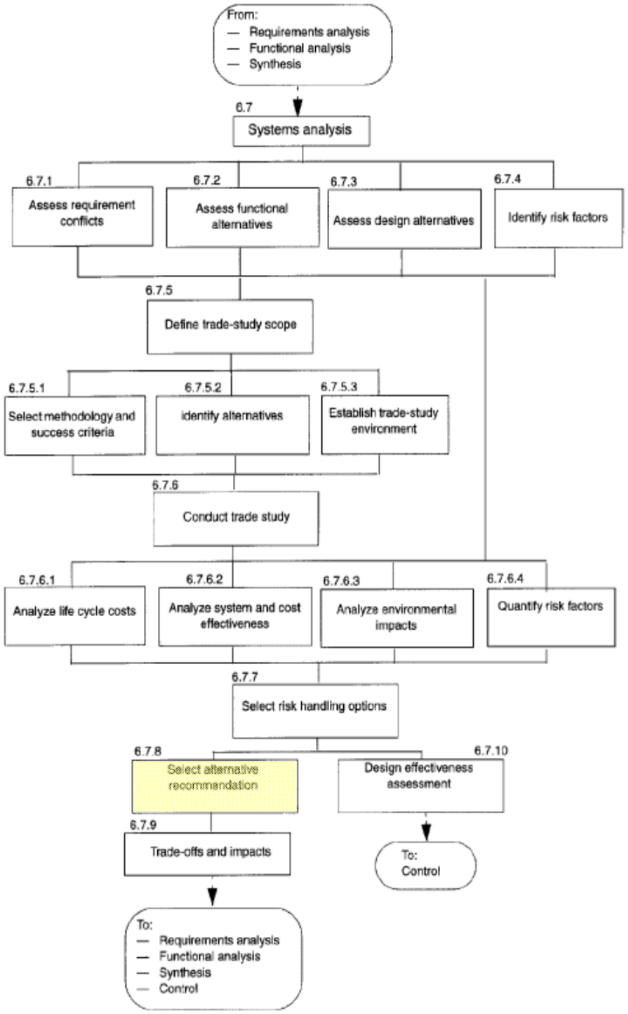


Figure 16—Systems analysis process

The project utilizes the results of trade-off analyses and risk-reduction planning information to recommend a preferred alternative to the decision maker. The project should assess the trade-off analysis to assure that the methodologies and data collection instrumentation were sufficient to support a fair and complete evaluation. *Each recommendation should be presented in terms of configuration and cost, schedule, performance, and risk impact.*

Ref: IEEE-1220, Figure 16

6.7.9 Trade-offs and Impacts

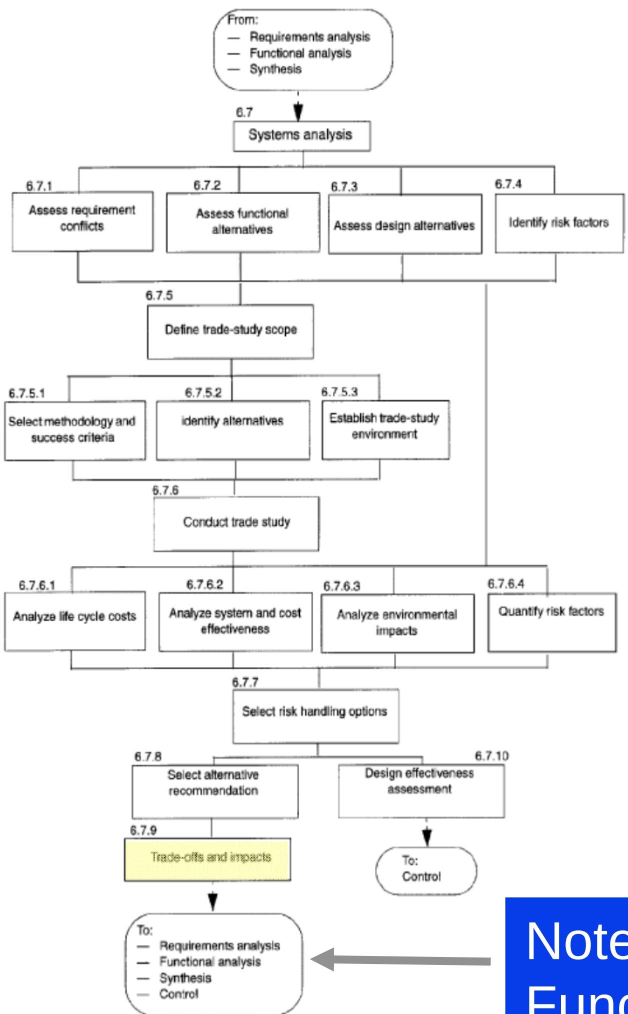


Figure 16—Systems analysis process

The project documents the recommended trade-off alternative(s) with corresponding impacts and *presents the results to the appropriate decision makers within the SEP activity who are making or requesting the trade-off analysis*. The final alternative selection is made based on the criteria established to judge a desirable solution. Key trade-off analysis activities, decisions, rationale, and recommendations are documented in the integrated repository.

Note: key interfaces to the Requirements Analysis, Functional Analysis, Synthesis, & Control processes.

Ref: IEEE-1220, Figure 16

6.7.10 Design Effectiveness Assessment

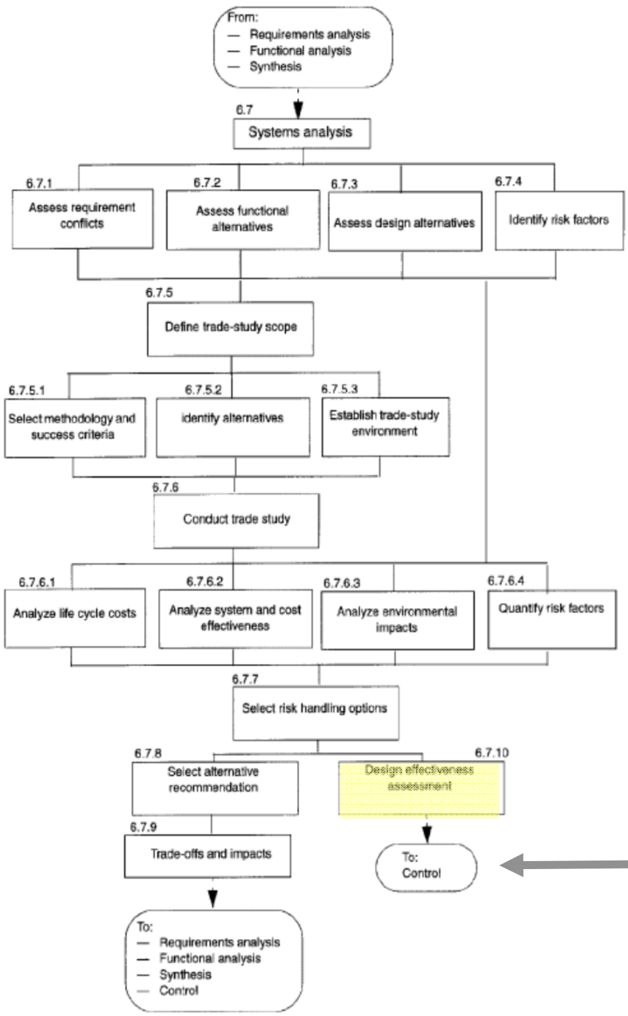


Figure 16—Systems analysis process

The project *determines the effectiveness of the current system design based on the results of the assessments and analyses*. The results of these assessments and analyses are documented in the integrated repository and briefed at appropriate technical and project reviews.

Note: key interface to the Control process.

Ref: IEEE-1220, Figure 16

Process Dependencies

- Requirements Conflicts & Issues
  - Consistency of the system technical requirements with the system being engineered
- Product Characteristics
  - System configuration verified includes manufacturing tolerances & deviations
- Verification Results
  - Requirements, reference standards & calibration data, discrepancies between expected & actual results
- Validation Results
  - Procedures & compliance data

Note the theme of understanding deviation – does it matter?

Key Points

- Systems analysis is a key component of the systems engineering process.
- Per IEEE-1220, systems analysis exists to enable other processes -- Requirements Analysis, Functional Analysis, Synthesis, & Control processes.
- Subsequent modules will address various modeling & simulation methods & techniques employed throughout the system life cycle.

Question: Why do we do systems analysis?

Answer: To provide a basis for execution of the systems engineering process throughout the life cycle.

References

- *IEEE Standard for Application and Management of the Systems Engineering Process*, IEEE Std 1220-2005, September 2005.

Lesson 5:
Model-Based System Engineering

Objectives

- Describe the system engineering process in the context of different types & applications of models.

Modeling & Simulation over the Life Cycle per EIA 632

Assessment of Opportunities	Investment Decision	System Concept Development	Subsystem Design & Pre-Deployment	Deployment, Operations, Support & Disposal

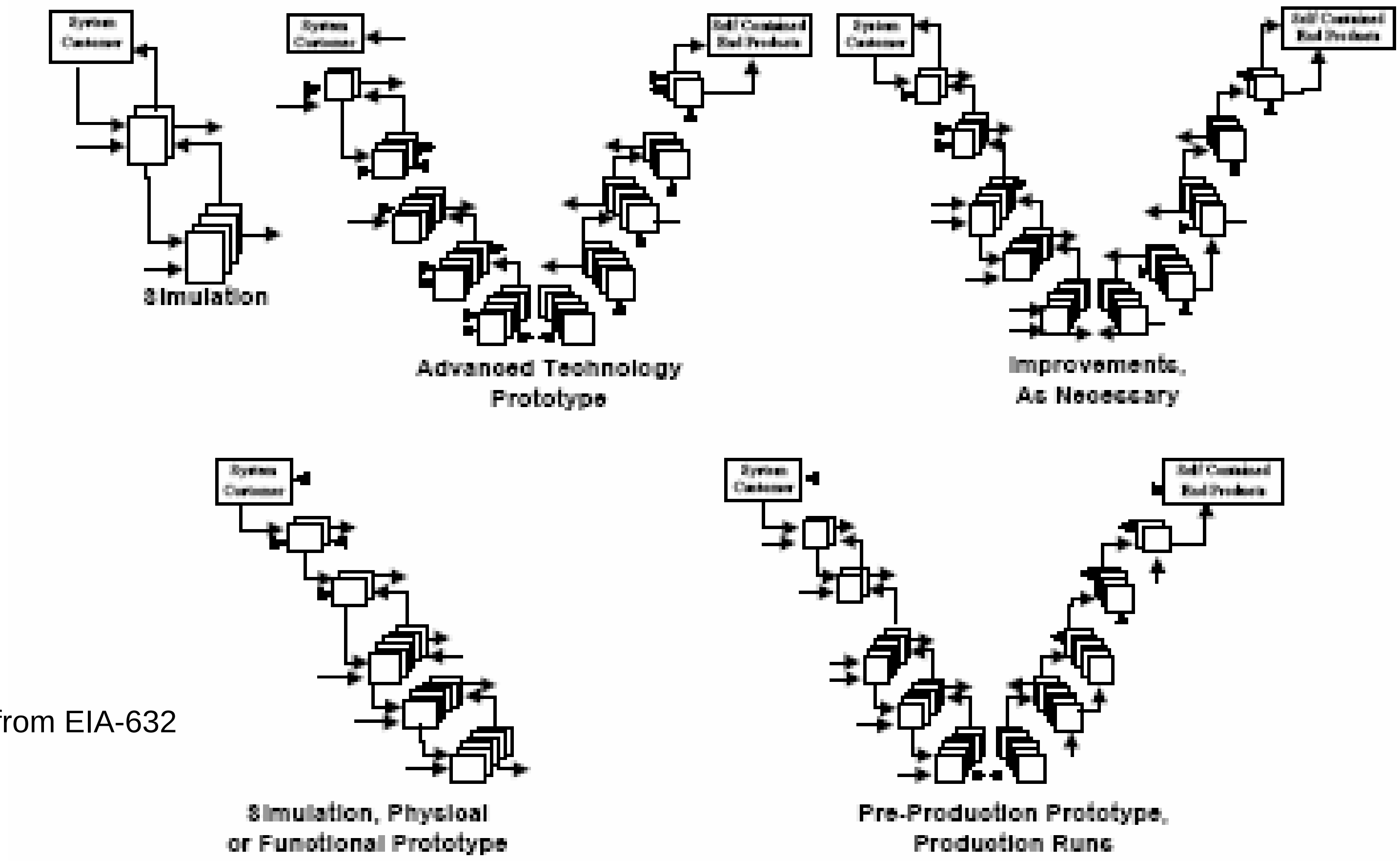
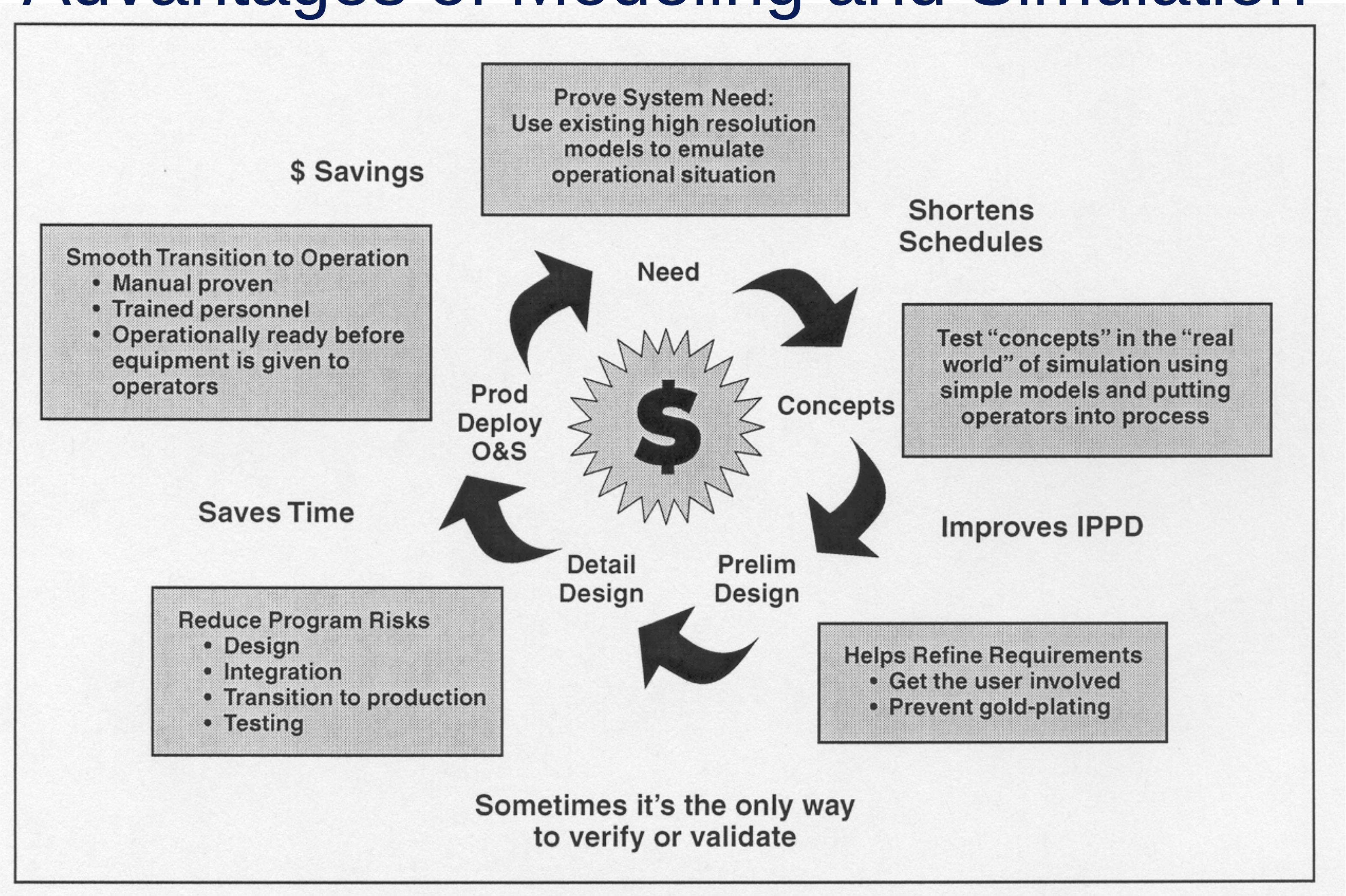


Figure B-1 from EIA-632

Advantages of Modeling and Simulation



Ref. Figure 13-1 from Systems Engineering Fundamentals

Systems Engineering uses of Models

- Creation of a shared vision.
- Communication of the shared vision.
- Testing the shared vision.
- Estimation or prediction of some quantitative measure associated with the system.
- Selection of one design option of other design options.

Models and Modeling

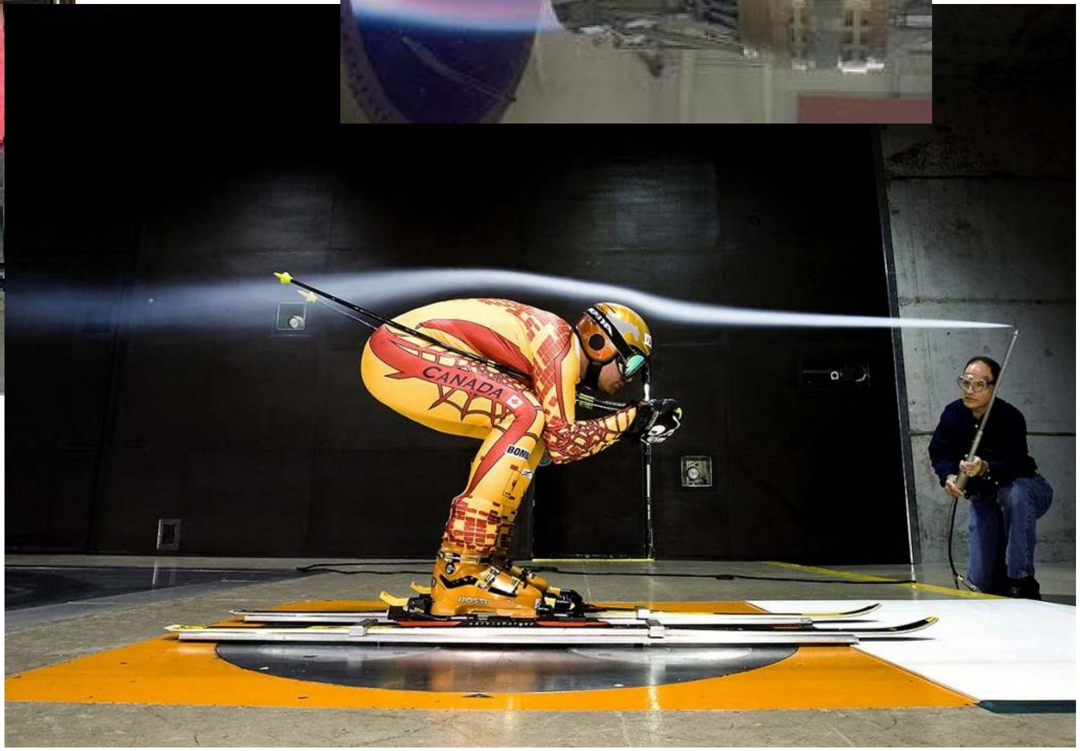
- A model is an incomplete representation of reality. It may be a physical, quantitative, qualitative or mental representation.
- The purpose of a model is to answer questions about a system before it is fully developed. These questions can be:
  - *definitive*, meaning how do we define the system
  - *descriptive*, meaning how will a system perform give a set of inputs
  - *normative*, meaning how an individual or organization ought to think about a product or process

Taxonomy of Models

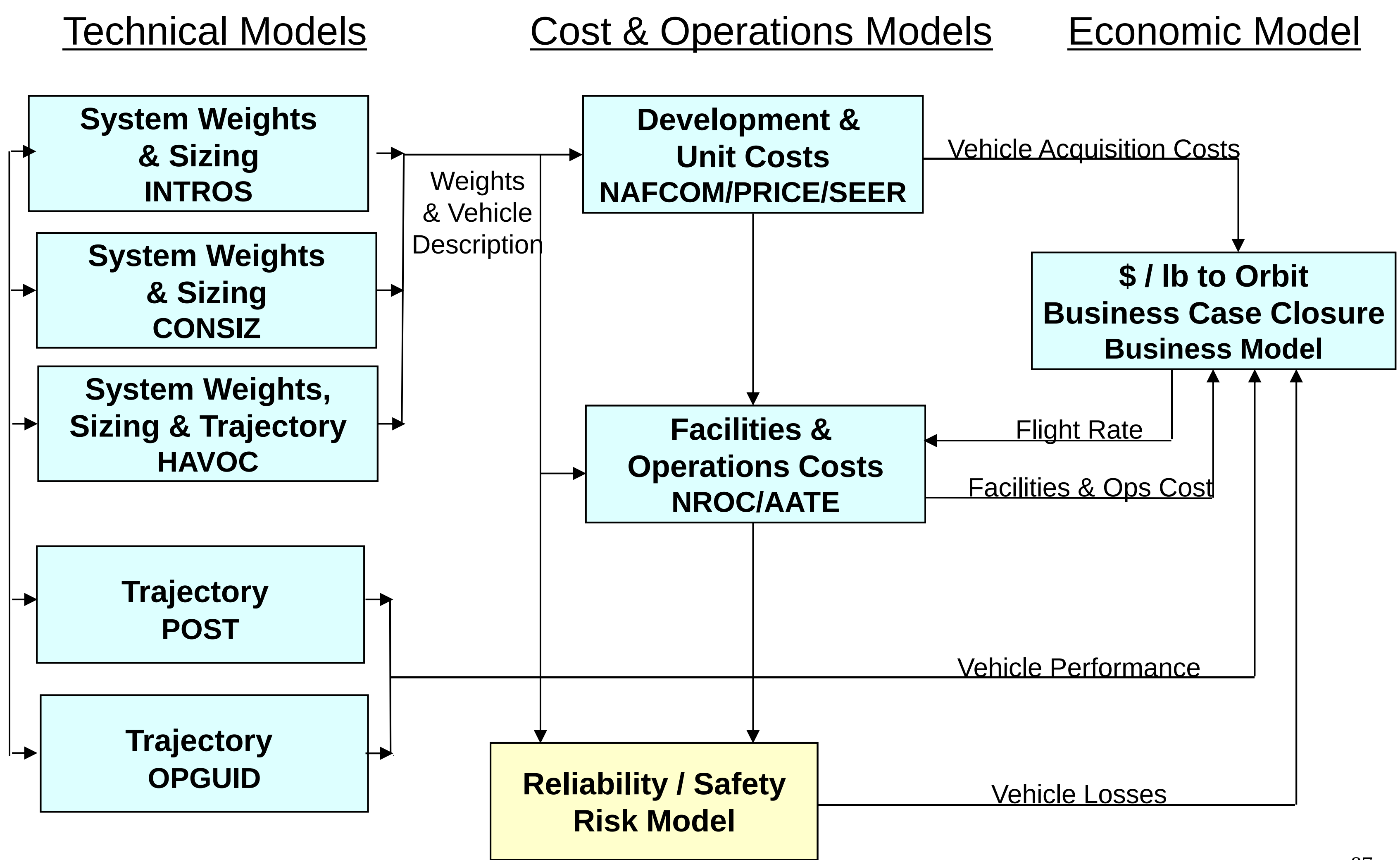
(ref. Table 3.1, Buede)

Model Categories	Model Subcategories	Typical Systems Engineering Questions
Physical	Full-scale mock-up Subscale mock-up Breadboard	How much? How often? How good? Do they match?
Quantitative	Analytic Simulation Judgmental	How much? How often? How good?
Qualitative	Symbolic Textual Graphic	What needs to be done? How well? By what?
Mental	Explanation Prediction Estimation	All of the above!

Physical Models

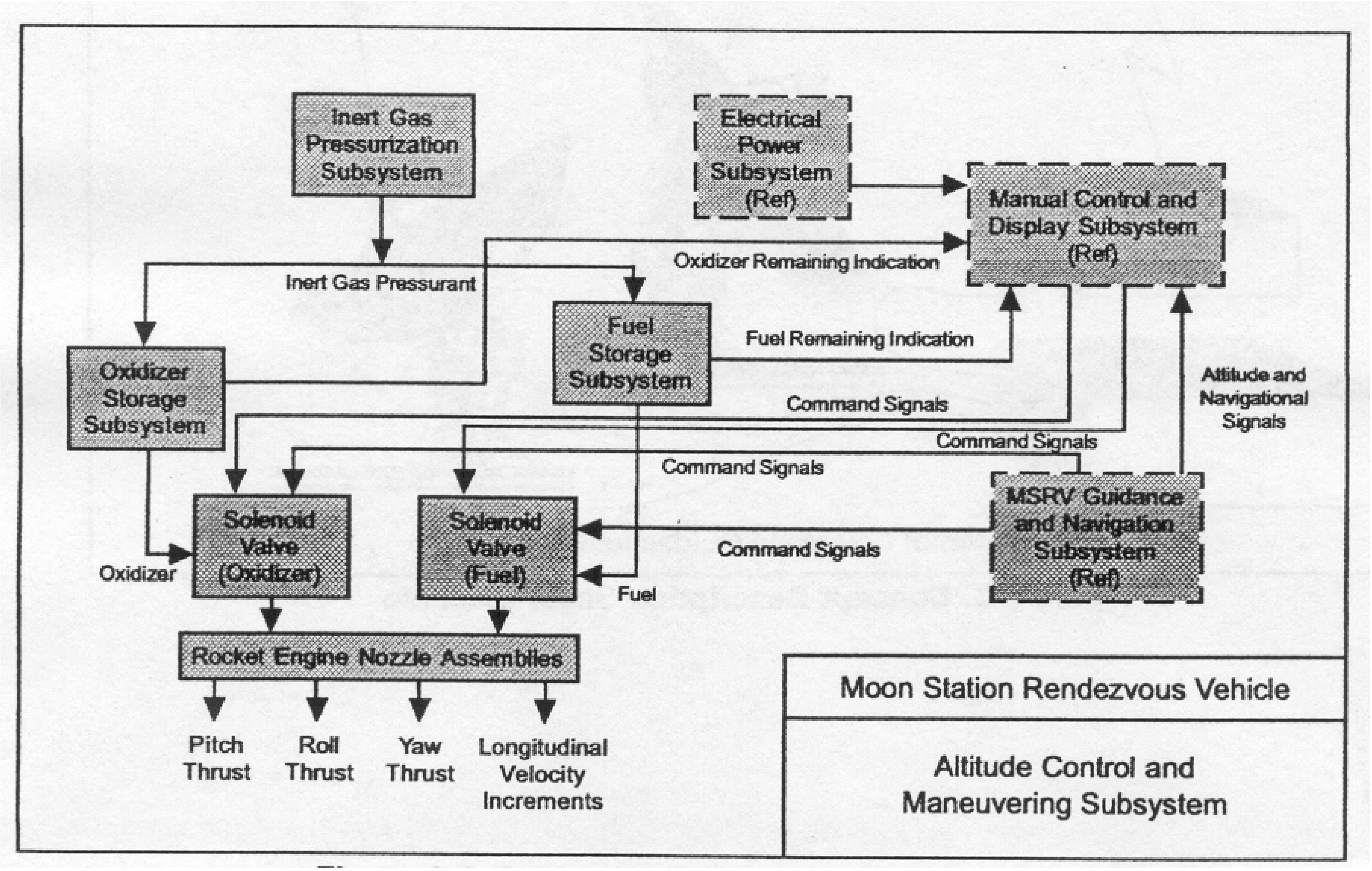


Quantitative Models
Launch Systems Analysis



Qualitative Model -- Schematic Block Diagram

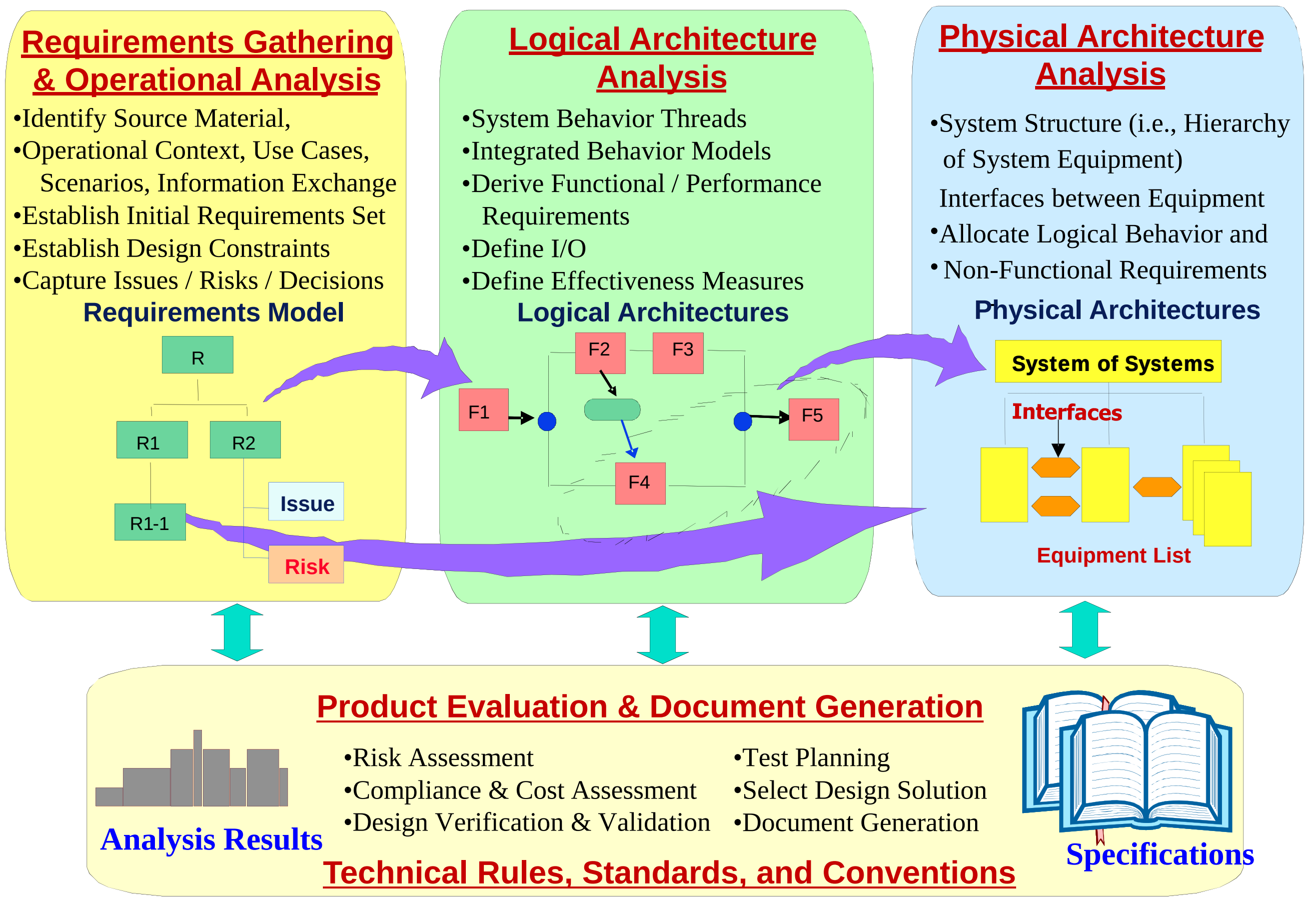
(ref. Figure 6.5, Systems Engineering Fundamentals)



Notes on Modeling

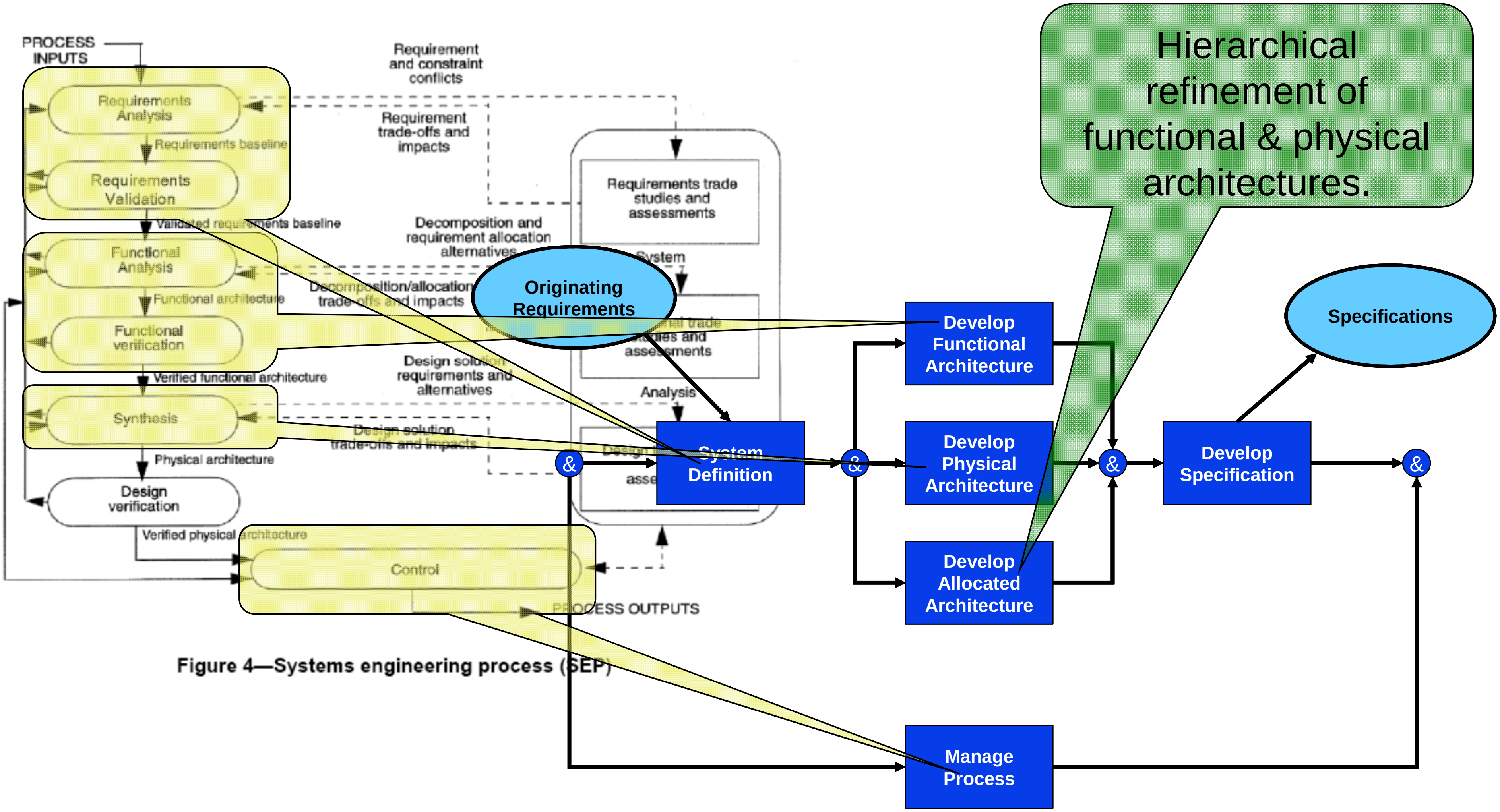
- Begin modeling by defining what question(s) you need to answer.
- Modeling is iterative; this includes development, testing and refinement.
  - Verification checks to see if the model is built correctly—i.e. represents the system as intended .
  - Validation checks to see if the representation matches the real world system.
  - Input pedigree, results uncertainties, results robustness, and model conservatism are all important additional parameters which should be iteratively refined.

Model-Based Systems Engineering Process



These Primary Concurrent / Iterative Activities Are Performed For Each Product/System Architecture Design Layer

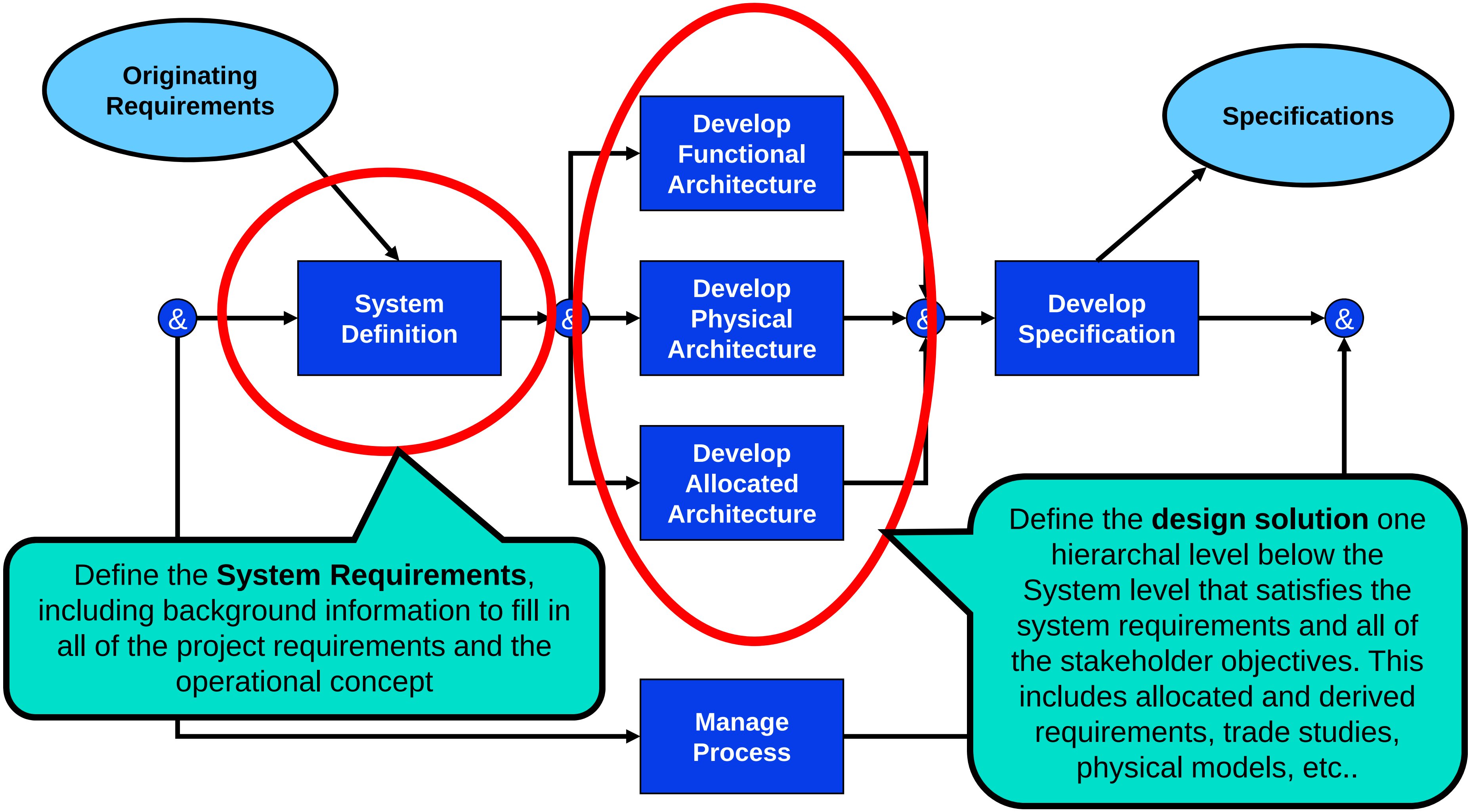
Cross-reference of IEEE 1220 SE Process to a Model-based SE Process



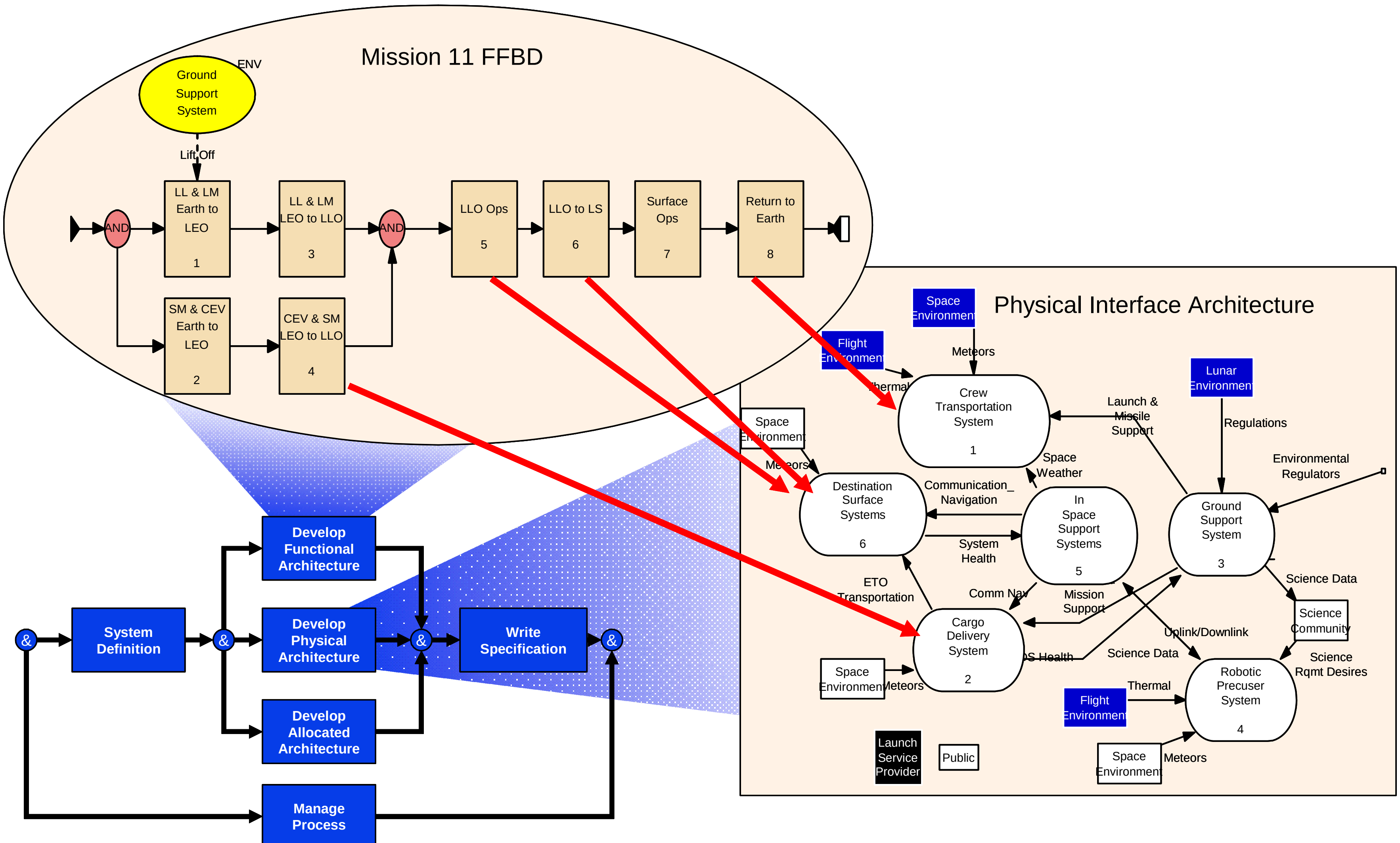
SE Models Are the Infrastructure of the SE Process

- Missions are really top level functions from an operational point of view.
- We acquire assets because we need them to accomplish a mission.
  - Not just hardware, but plans, procedures, etc.
- We specify requirements in order to acquire the assets we need.
- The functional architecture serves as the tie between the operational missions and the design requirements.
- At any given level in the system engineering hierarchy:
  - Start with the Functions allocated to your Component in the allocated architecture.
  - Refine the functional architecture model until each leaf-level function can be allocated to a single child Component.
  - Populate the physical architecture with your new child Components.
  - Specify Requirements for each sub-Component. Link constraints directly to the child Components they affect, and functional requirements to Functions.
  - Link new Requirements to their parents.

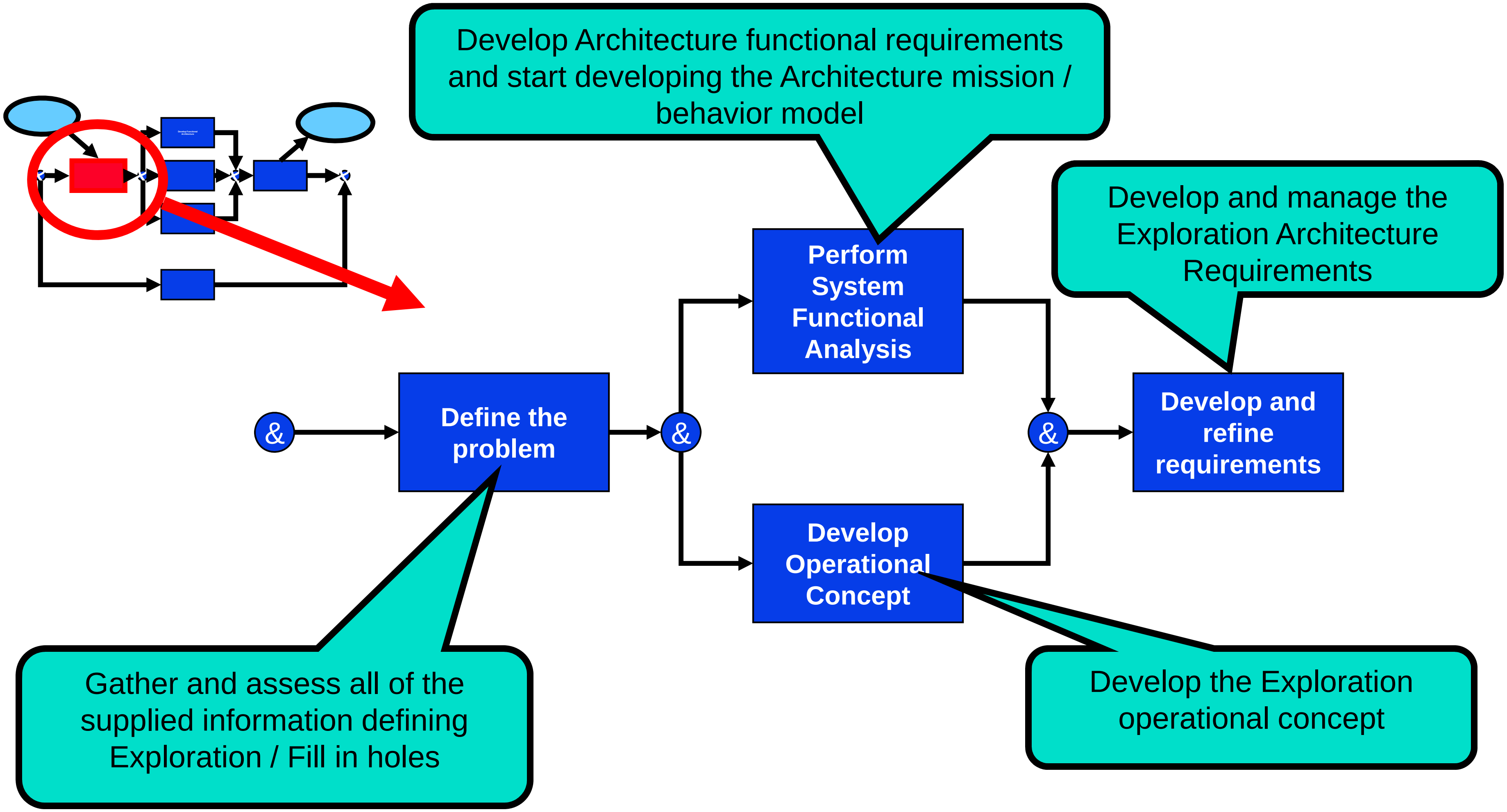
Top Level Systems Engineering Process



Architecture Modeling is Key to Process



System Definition



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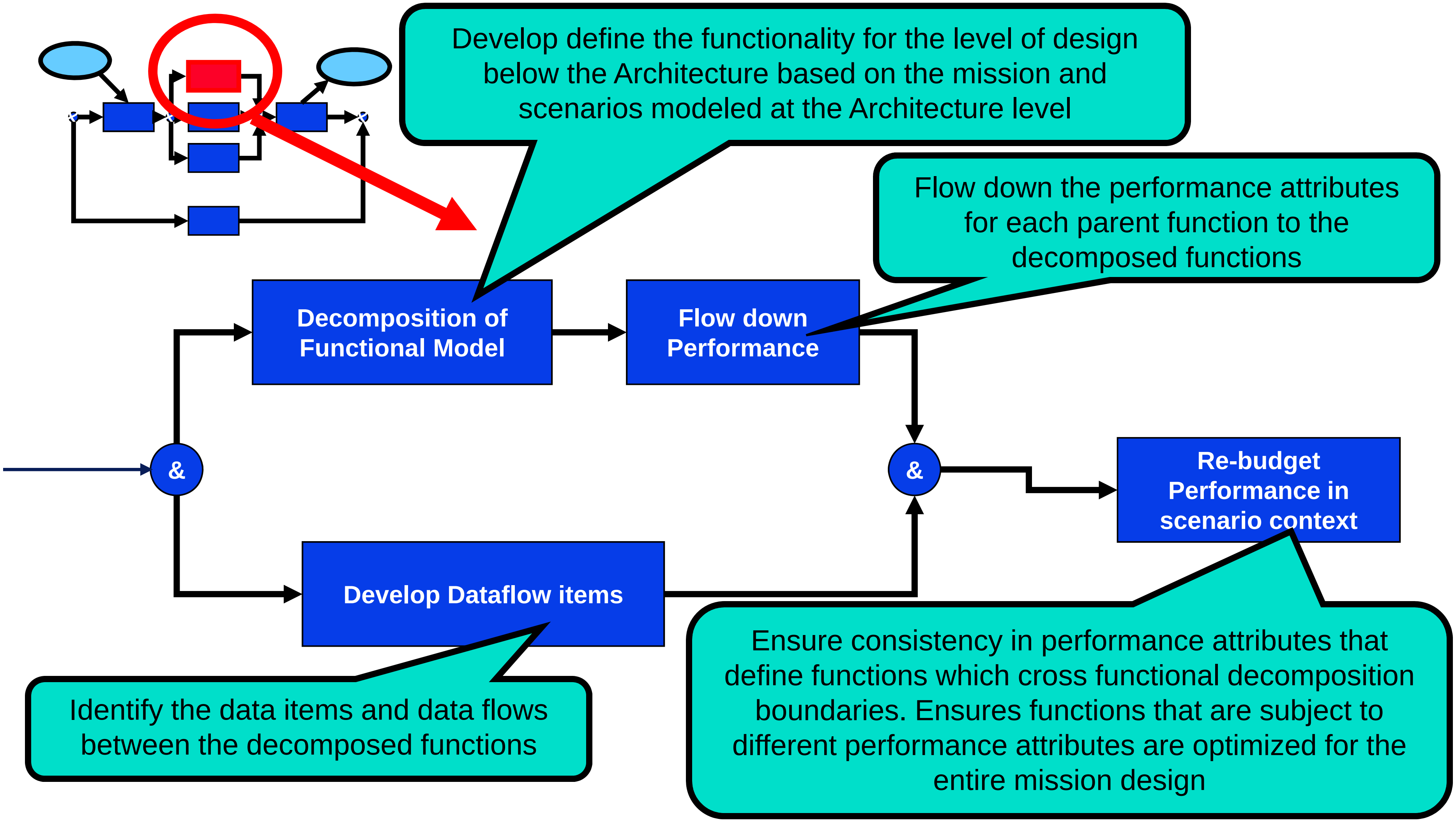
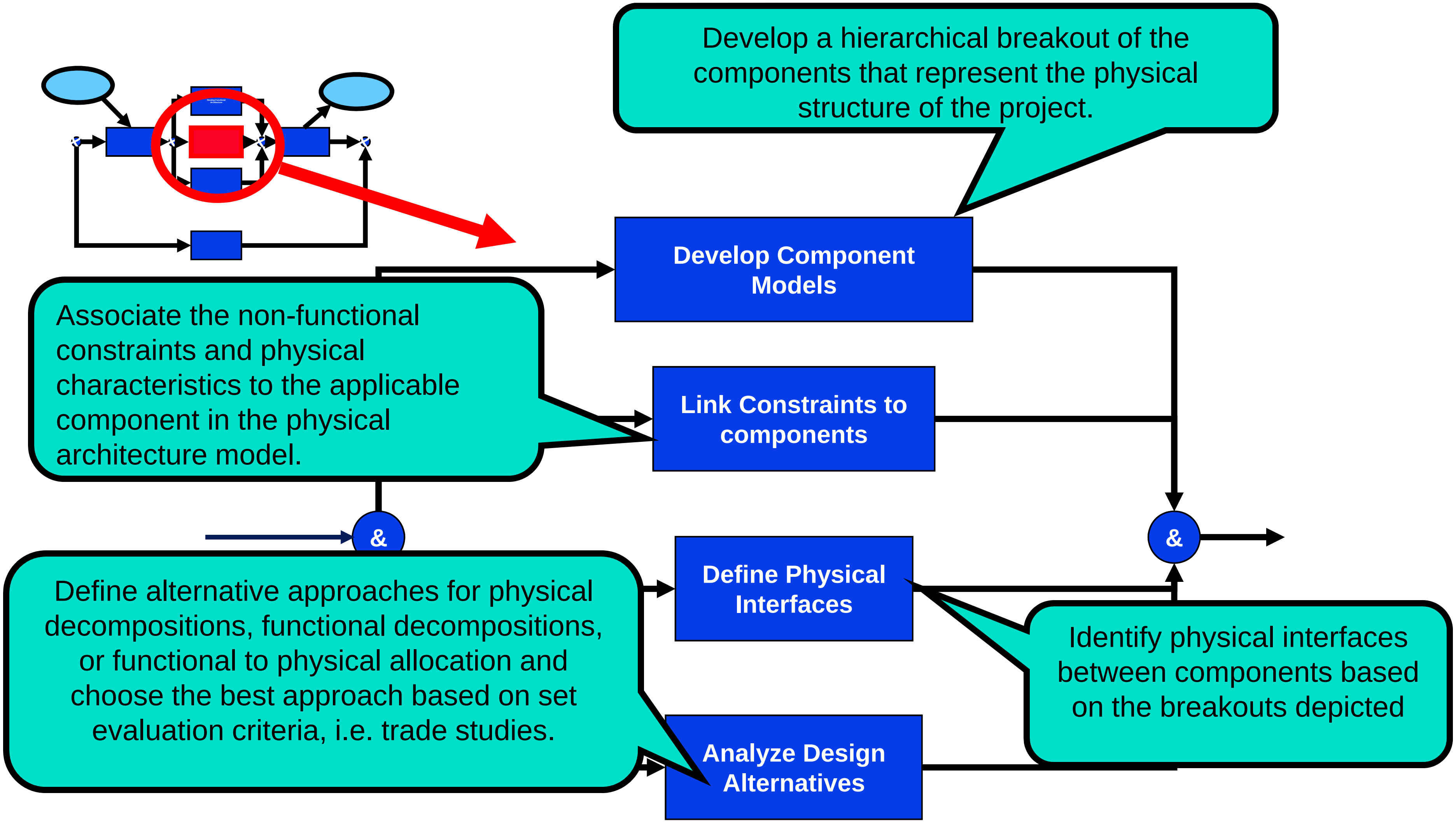
Develop Functional Architecture



Develop Physical Architecture



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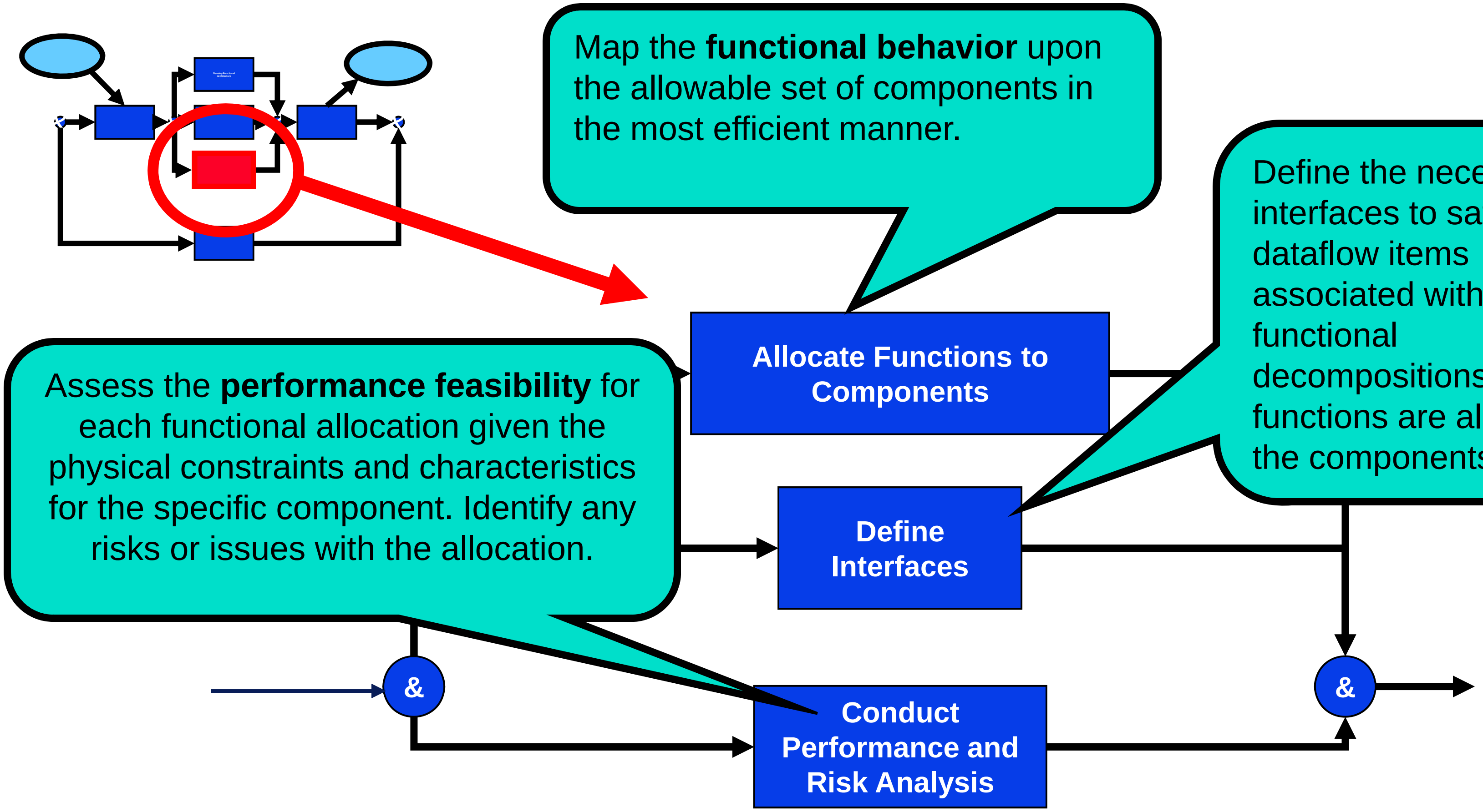
Develop Allocated Architecture



Let Engineering Products Drive Models

- Start with the products you want to produce:
  - Spec Tree, Concept of Operations, Requirements Documents, Data Dictionary, Functional Architecture Model, Risk List, etc.
- Think about the content of these products and how they are related:
  - The Functional Model, for example, is an organizing structure for one section of a Requirements Document.
  - Every Risk in the Risk List should be associated with a Component or Function.
- Use this information to define the structure and content of Models:
  - Items
  - Attributes
  - Relationships
- Don't Repeat Yourself
  - Each piece of information should be kept in one place only.
- The model schema will grow with the product list.

Tie everything to the system breakdown structure.

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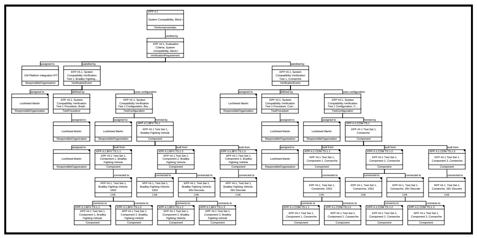
Model Based Systems Engineering

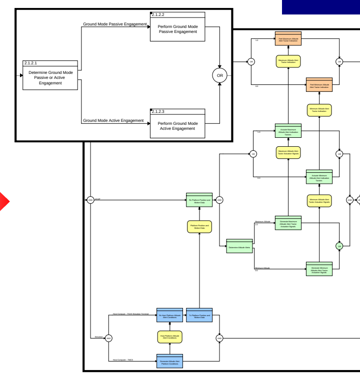
System Definition



Requirements Model

- Establish Source/Originating Requirements
- Structured Hierarchy and Flowdown
- Managed Traceability
    - Level I to Derived Requirements
    - Requirements to Simulation and Verification Elements

Functional Architecture

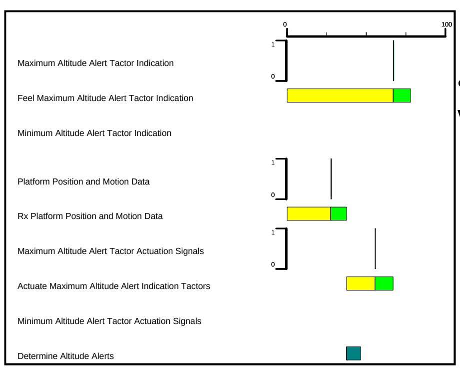


Functional Model

- Translate User Operational Capabilities to System Functional Requirements
- Graphical Analysis Provides Increased Rigor (versus text only)
    - Functions
    - Inputs/Outputs
    - Time Sequence
    - Logic
- Scenario Development
    - Operational
    - Simulation

Allocated Architecture

Analysis Model

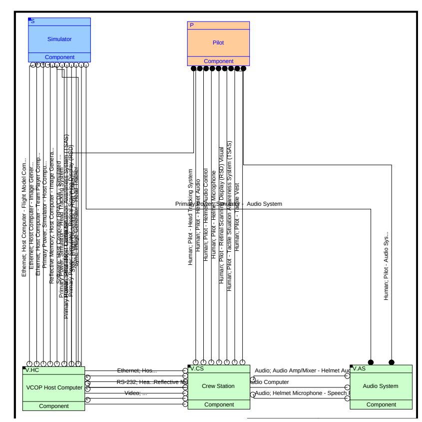


- Validate Performance
    - Requirements Model Update
- Functional Model Execution via Discrete Event Simulation
    - Timeline Analyses
    - Resource Analyses
    - Quantitative Benefits Analyses
    - Validation of Logic

Physical Architecture

Physical Architecture Model

- Candidate Physical Architectures
    - HW, SW, Interfaces
    - Human Operators
- Allocate Functions to Components
- Platform Compatibility ssments
- System Physical Architecture Definition



Key Points

- Models can provide as the foundation for all aspects of the systems engineering process.
  - Requirements analysis & validation
  - Functional analysis & validation
  - Synthesis
  - Control

- ***Keep these modeling applications in mind as we work through systems modeling methods & techniques in subsequent modules.***

References

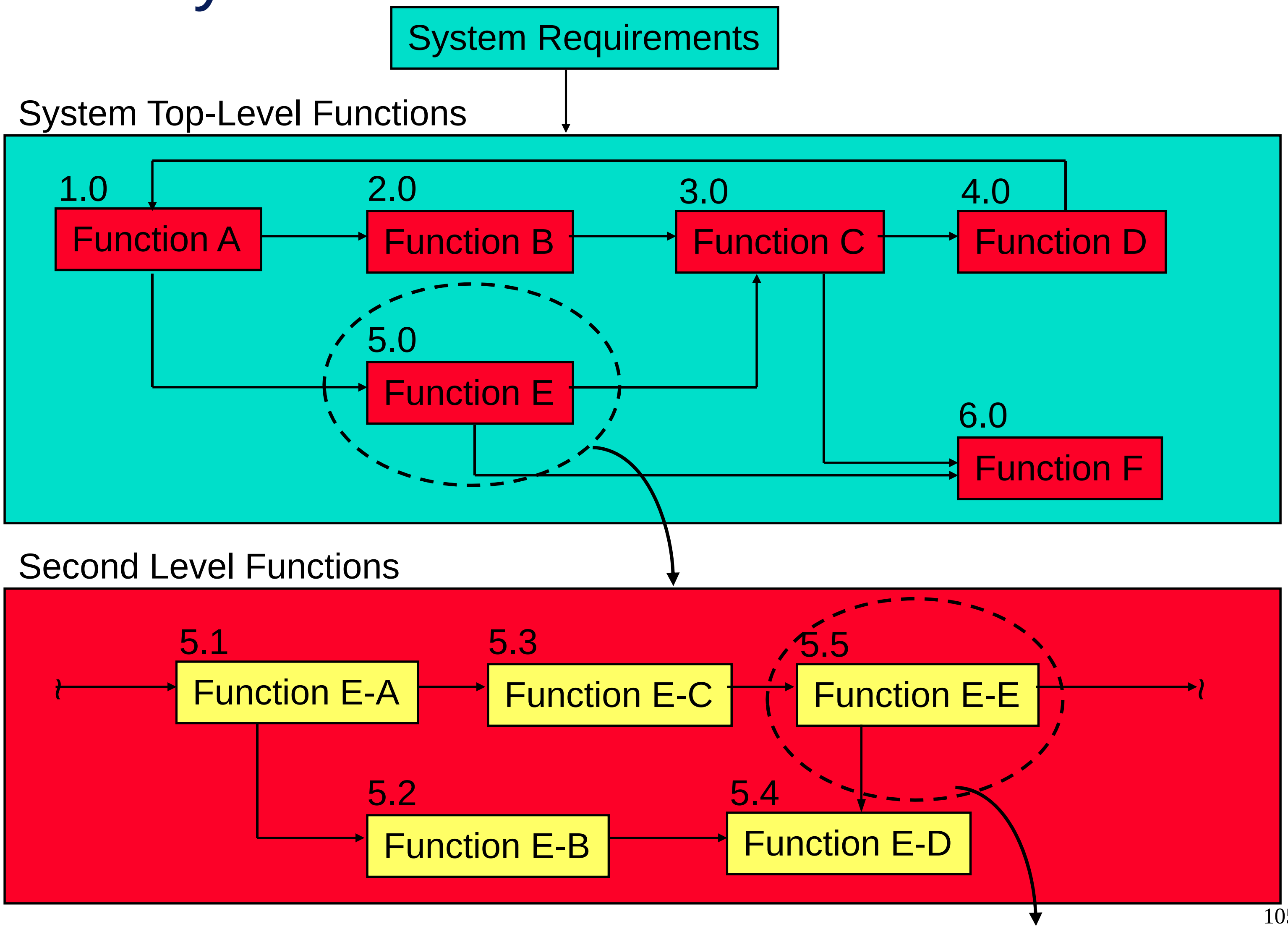
- *Processes for Engineering a System*, ANSI/EIA-632, September 1, 2003.
- *Systems Engineering Fundamentals*, Supplementary Text Prepared by the Defense Acquisition University Press, Fort Belvoir, VA 22060-5565, January 2001.

Lesson 6: Symbolic Models

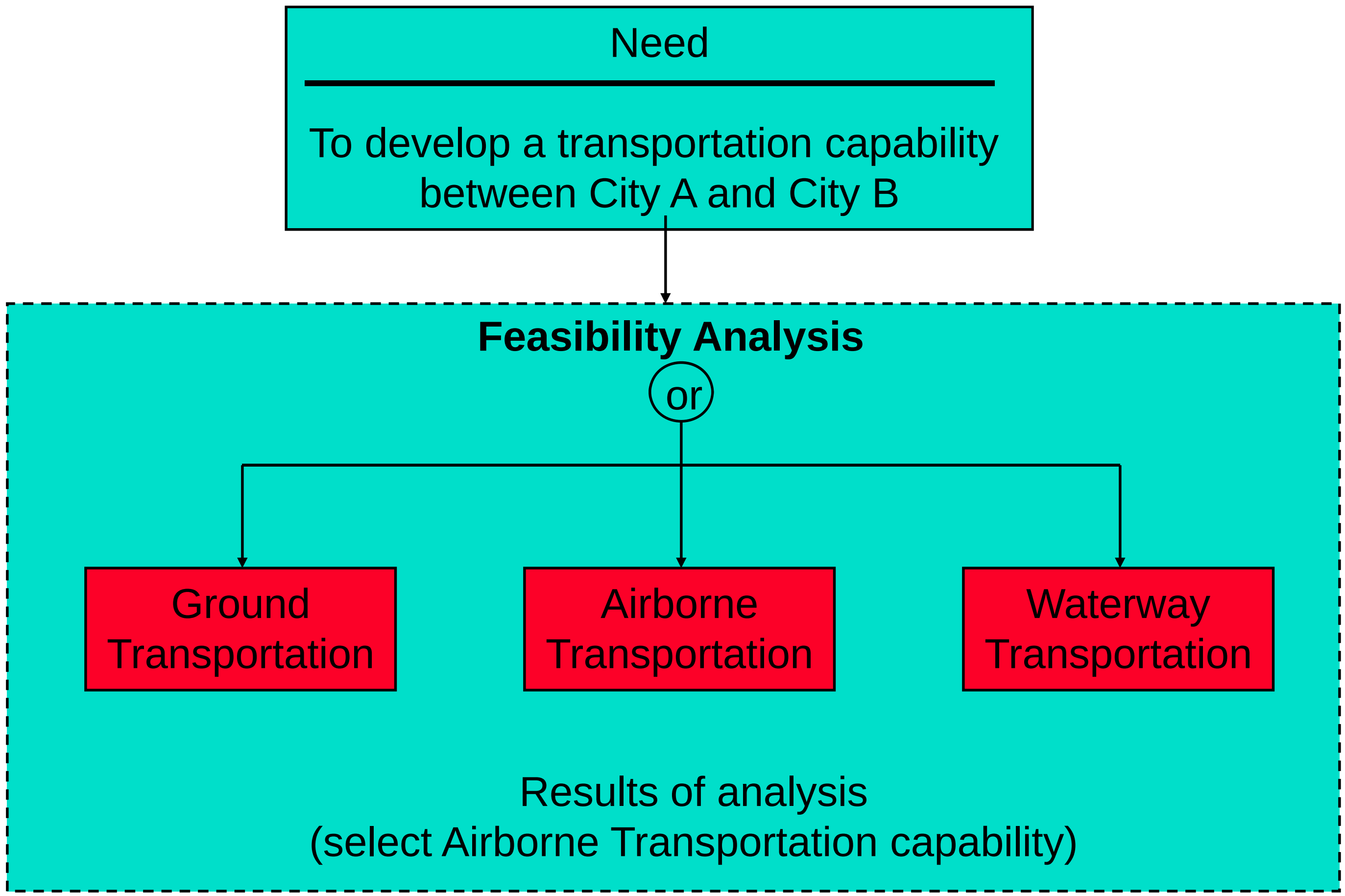
Objectives

- Illustrate basic concepts of symbolic modeling, including functional flow block diagrams (FFBDs).
- Outline functional, physical, and operational architecture representations.
- Provide an overview of IDEF0—an FFBD standard.

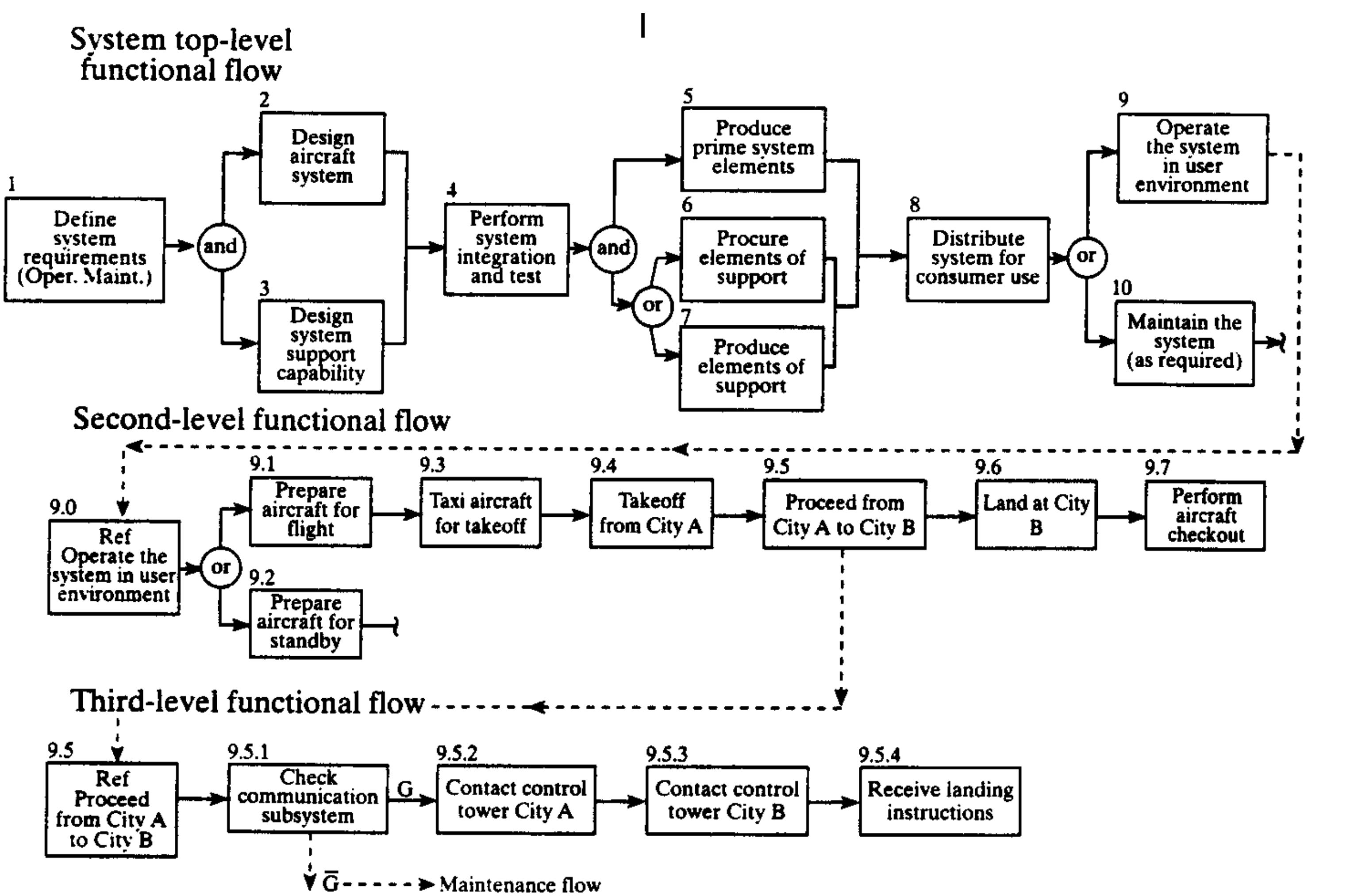
System Functional Breakdown



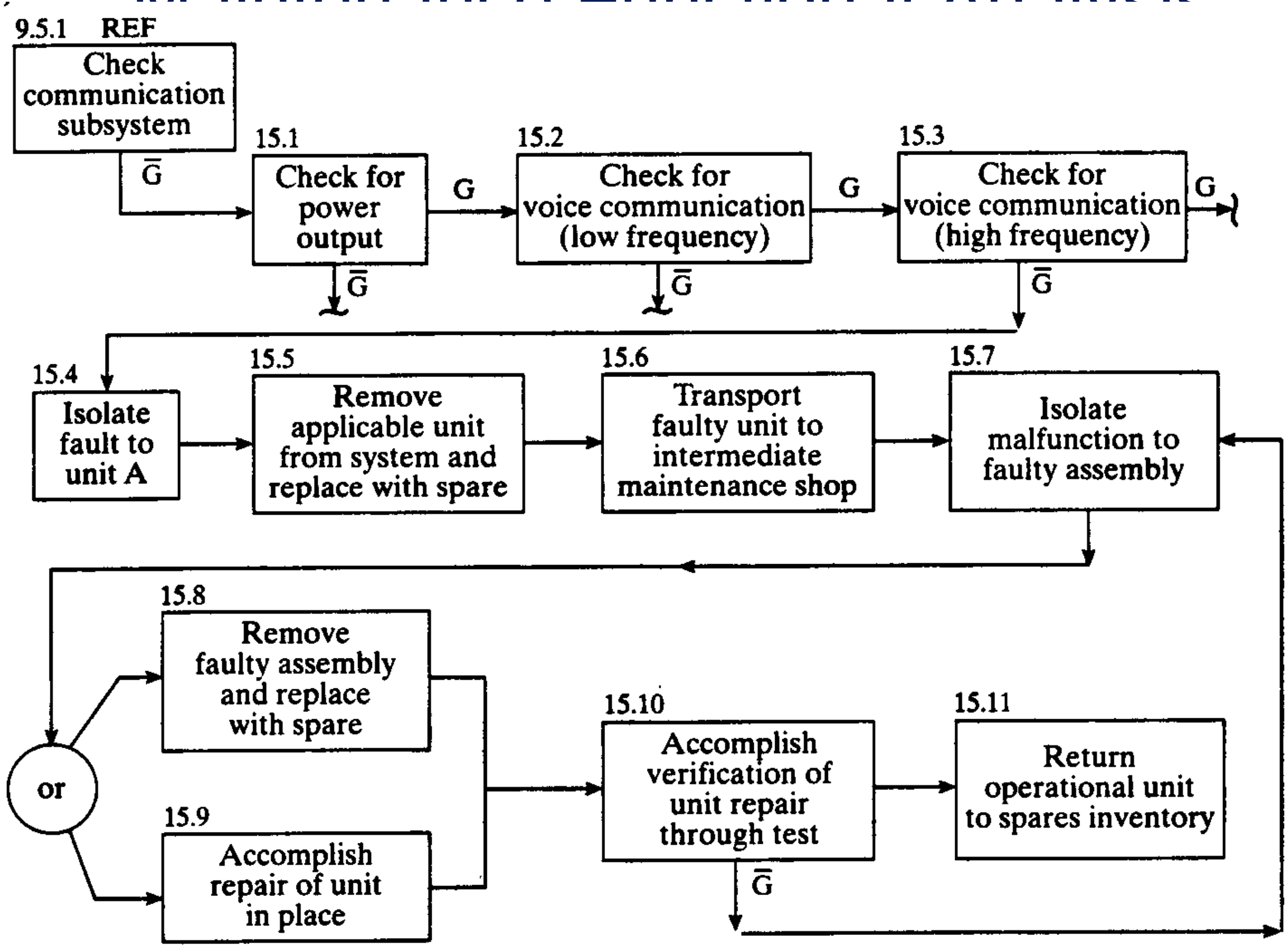
Working From the Operational Need



Progressive Refinement from Need to Functional Analysis Model



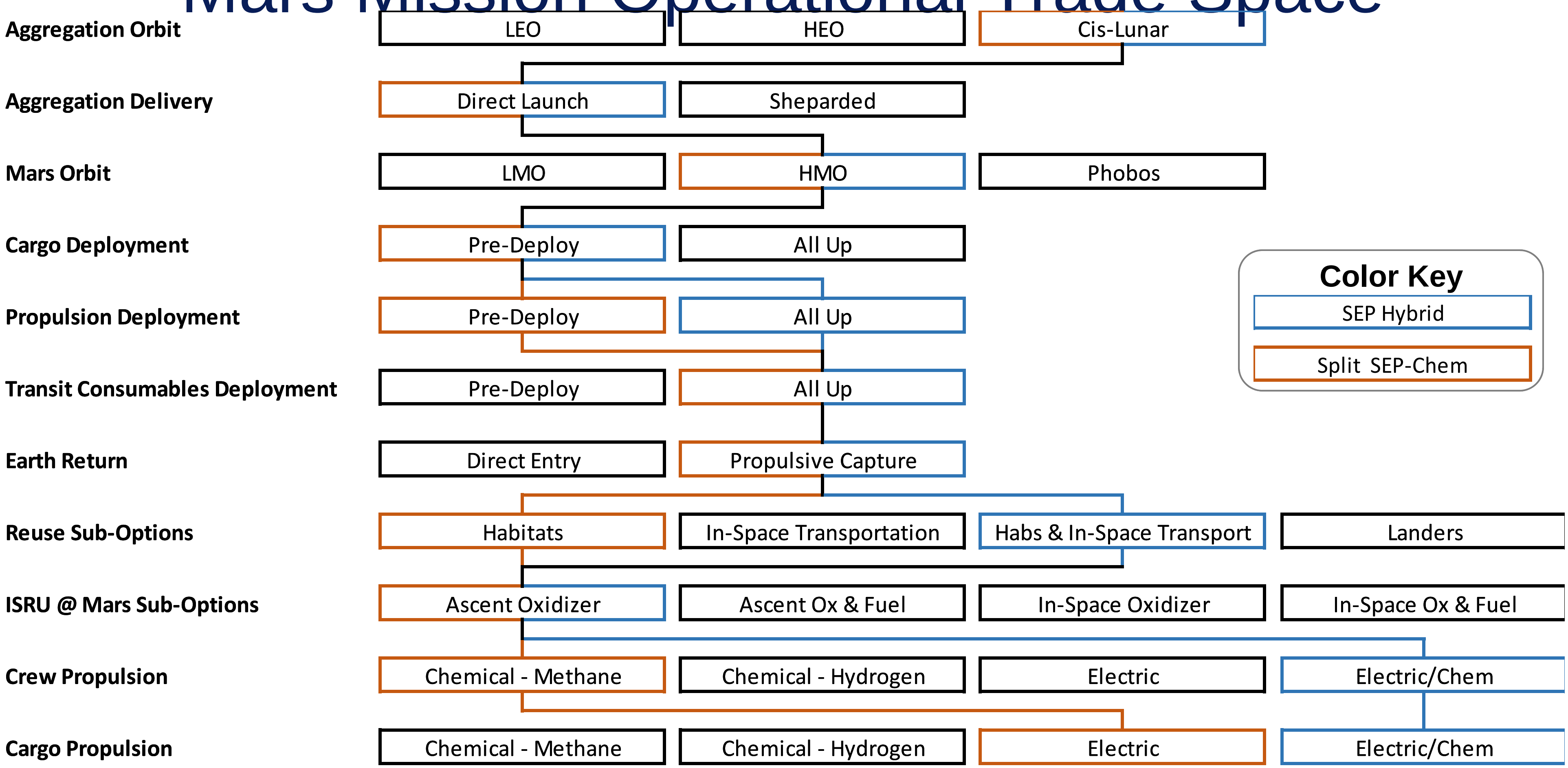
Maintenance Functional Analysis



Top Level Capability/ Mars Mission Def. Trade Space

Mission Type	Flyby	Short Stay	Long Stay	
Surface Mission	None	Minimal	Full	
Surface Campaign	Single-Site, Build-Up	Multi-Site, Independent		
Mars Capture Method	Propulsive Capture All	Aerocapture Some Cargo	Aerocapture All Cargo	Aerocapture All
Reuse	None	Partial	Full	
ISRU	None	At Mars	At Earth	
Primary In-Space Propulsion	Chemical	Electric	Electric/Chem	NTP

Mars Mission Operational Trade Space



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Mars Mission Lower Operational & Element Design Trade Spaces

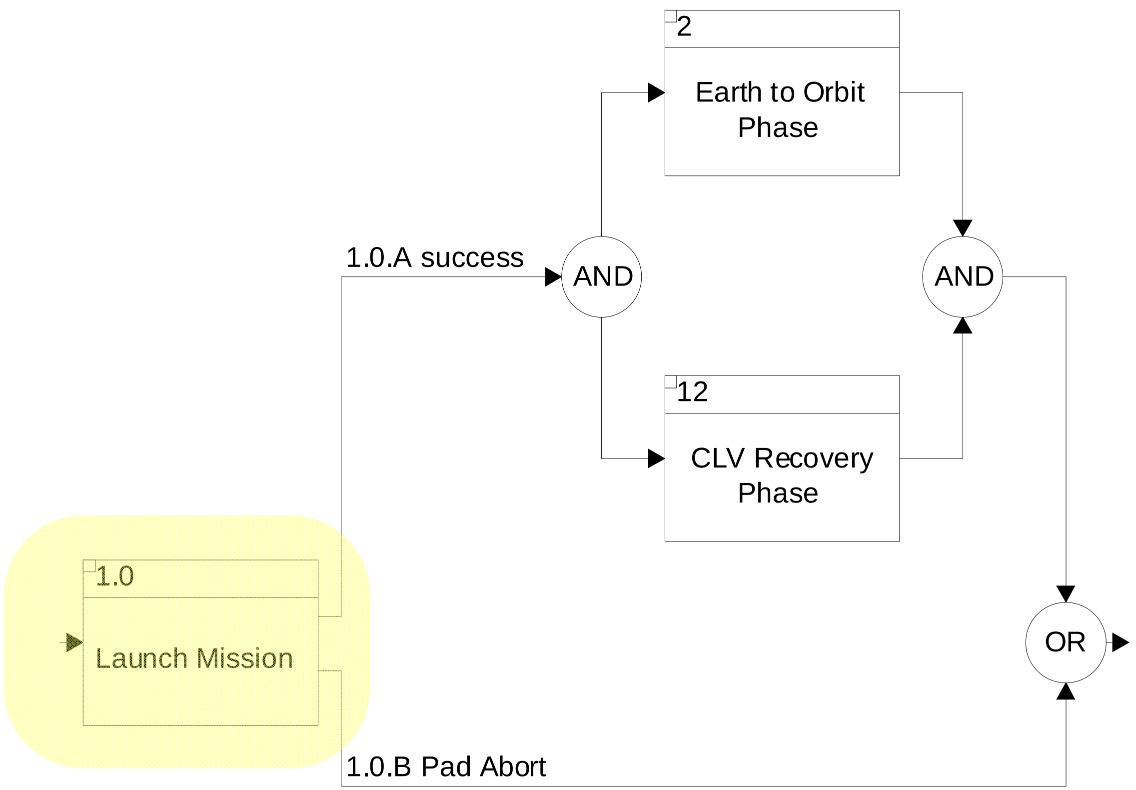
Sample Element Design Trade Space

SEP Heritage	ARM 1a Bus	ARM Component	not from ARM		***TRADE***
SEP Power Level	<500 kWe	500 - 1000 kWe	> 1MWe		***SENSITIVITY***
SEP Thruster	Hall	Hall/Ion	MPD	VASIMR	
SEP Propellant	Xenon	Krypton	H2	Iodine	
PVA System	ROSA	Megaflex	Other		

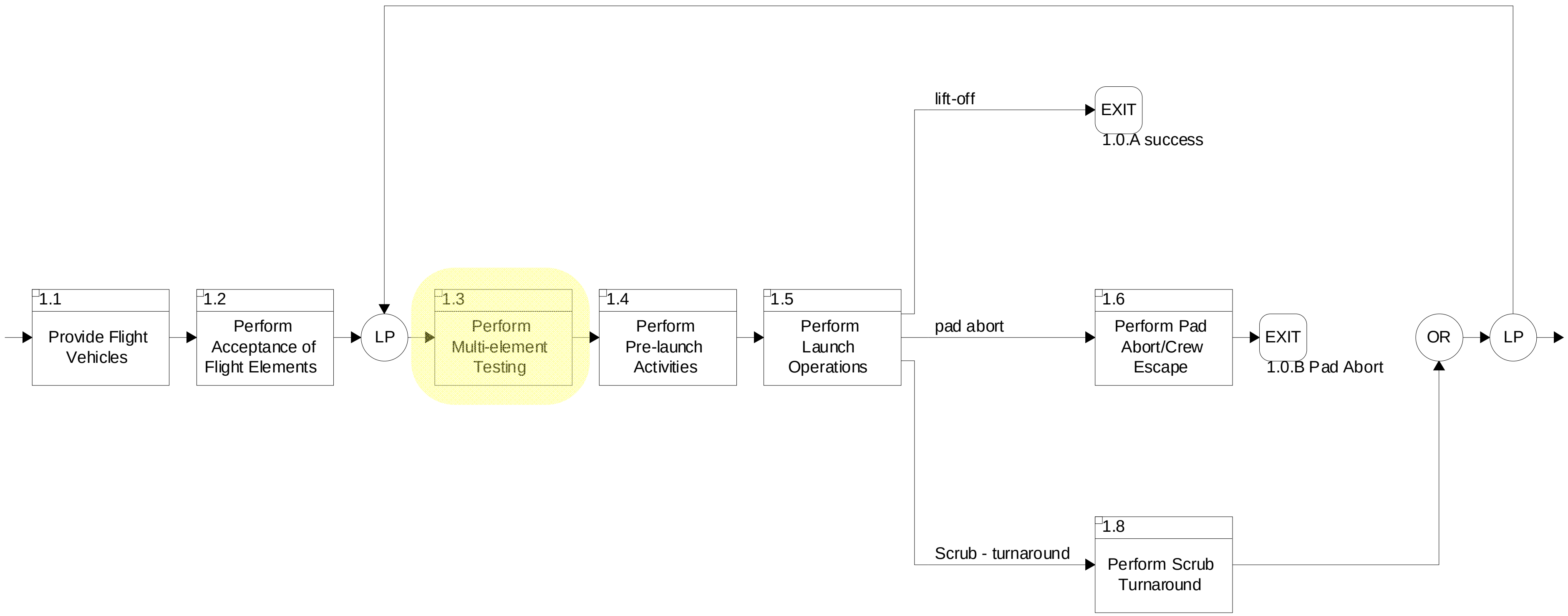
Sample Lower Level Operational Trade Space

Propulsion Stage Pre-Deploy	SEP to 1 Sol	Self-Insertion to 1 Sol	***TRADE***	
Lander Delivery	Single Launch SEP	Dual Launch SEP	Dual Launch Chemical	***TRADE***
Aerocapture Entry Vel.	6.3	7.2	>7.2	***SENSITIVITY***
Phobos Taxi	MAV	PEV	Other	***TRADE***

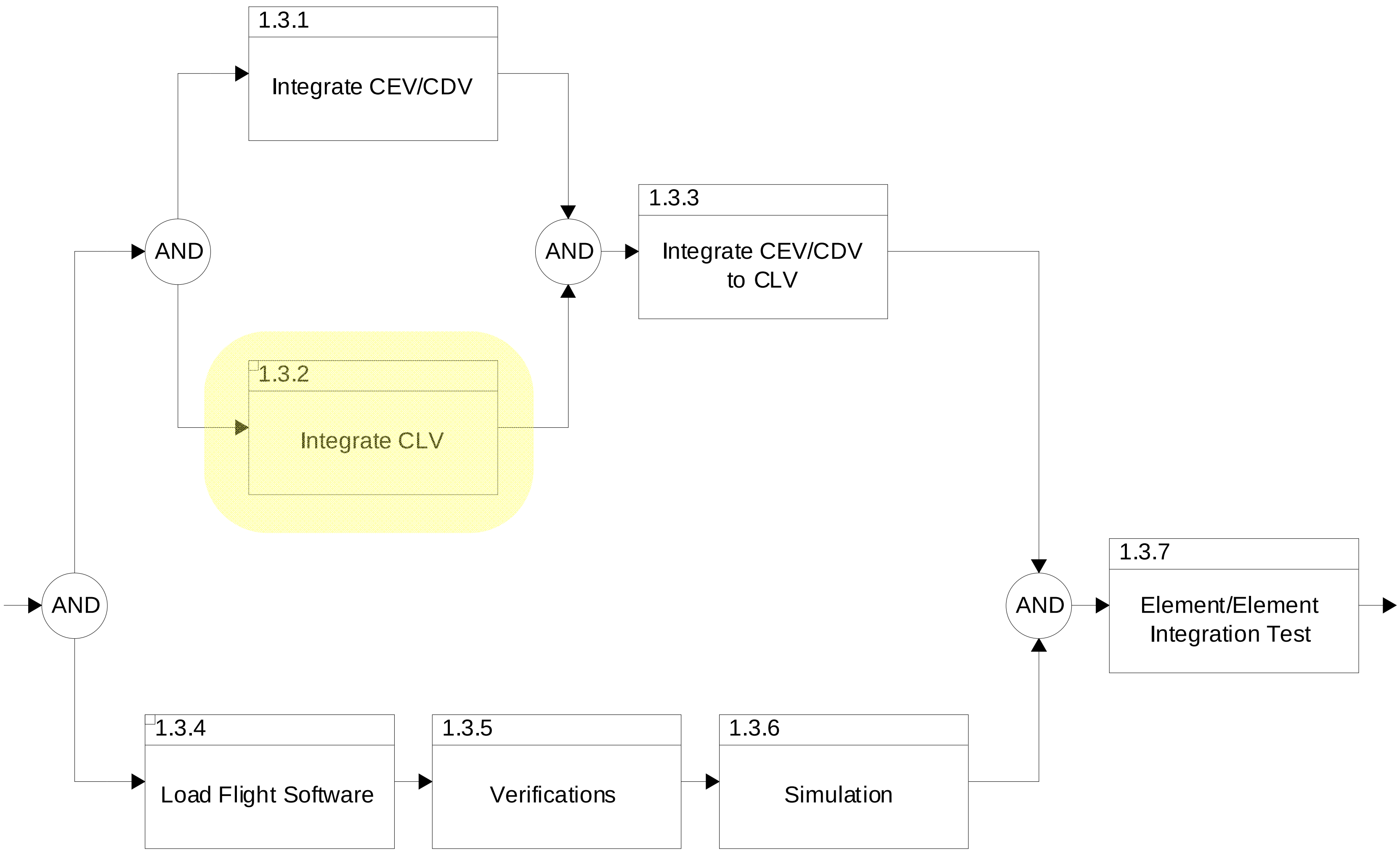
Example – Crew Launch Vehicle Top-level FFBD



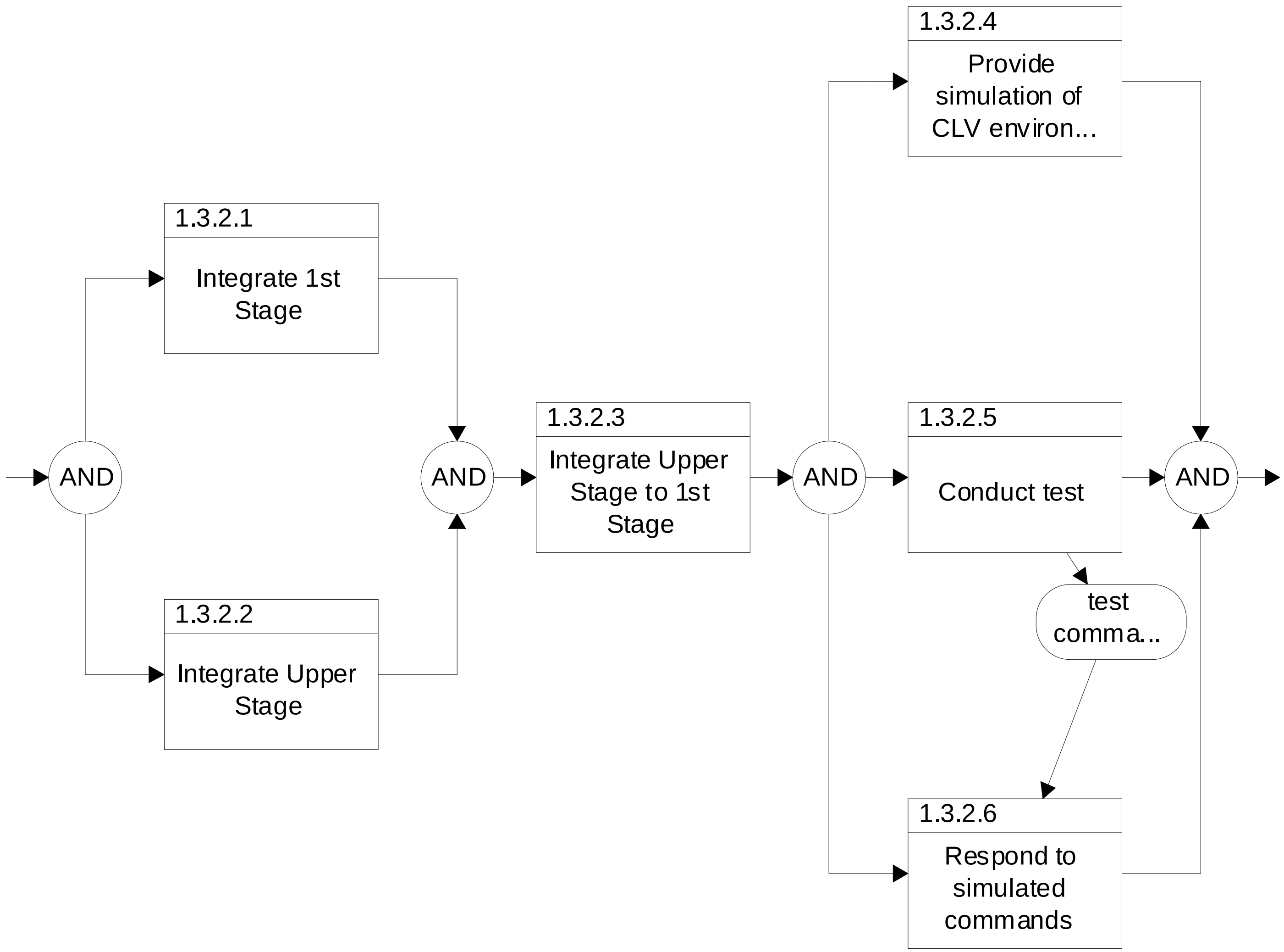
Example – 1.0 Launch Mission



Example 1.3.0 – Perform Multi-element Testing



Example – 1.3.2.0 Integrate CLV



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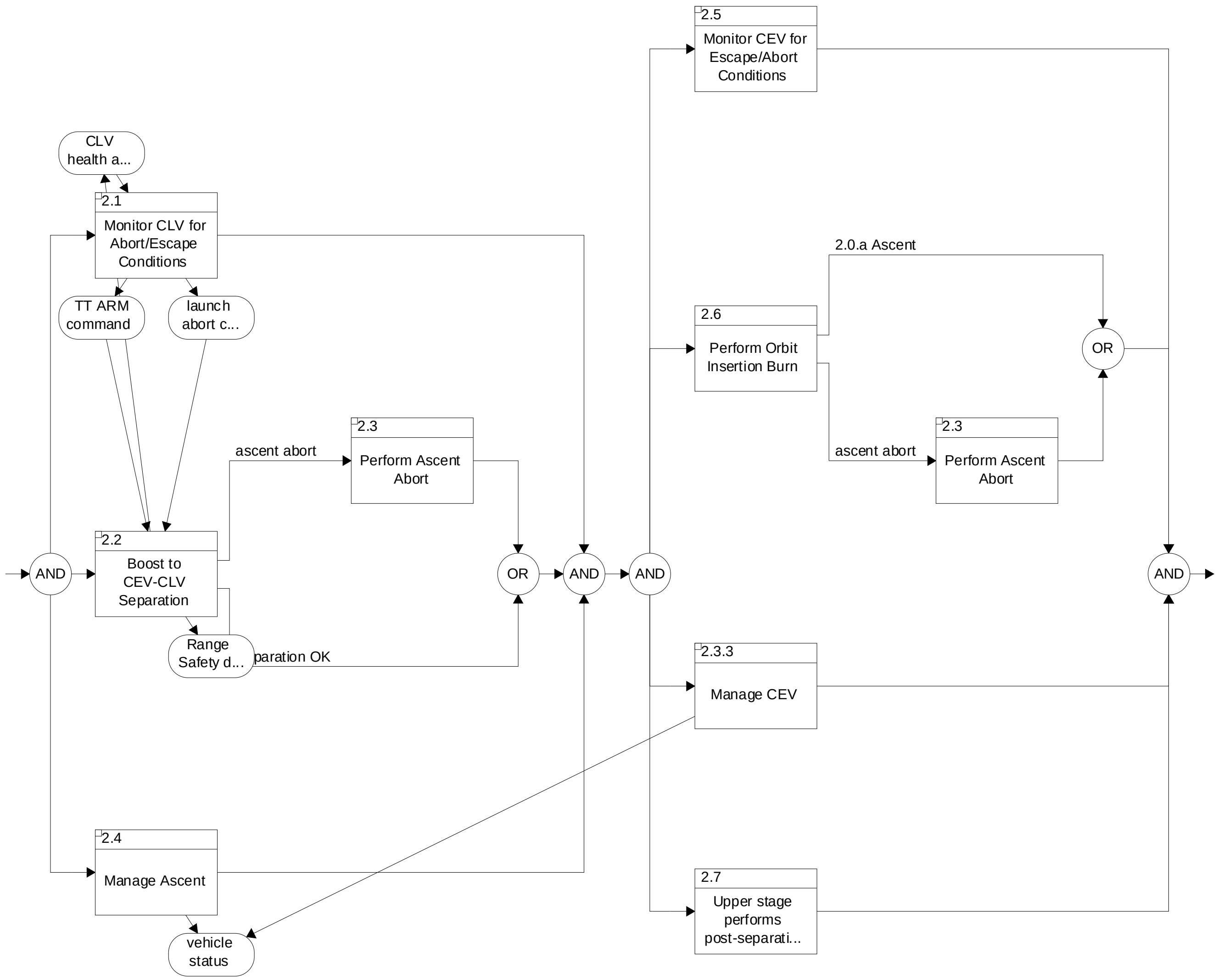
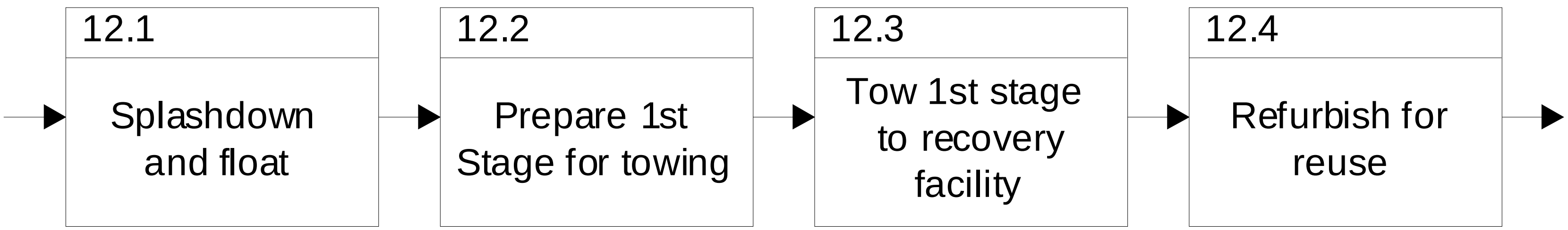
Example – 2.0 Earth to Orbit Phase



Example – 12.0 CLV Recovery Phase



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Introduction to IDEF0

(Integration Definition for Function Modeling)

- IDEF0 is the acronym for the Integrated Definition for Function Modeling.

- Standards maintained through the U.S. Department of Commerce National Institute of Standards and Technology (NIST) publication 183.

- Original roots of IDEF are from the U.S. Air Force’s Integrated Computer Aided Manufacturing (ICAM) program in the 1970s.

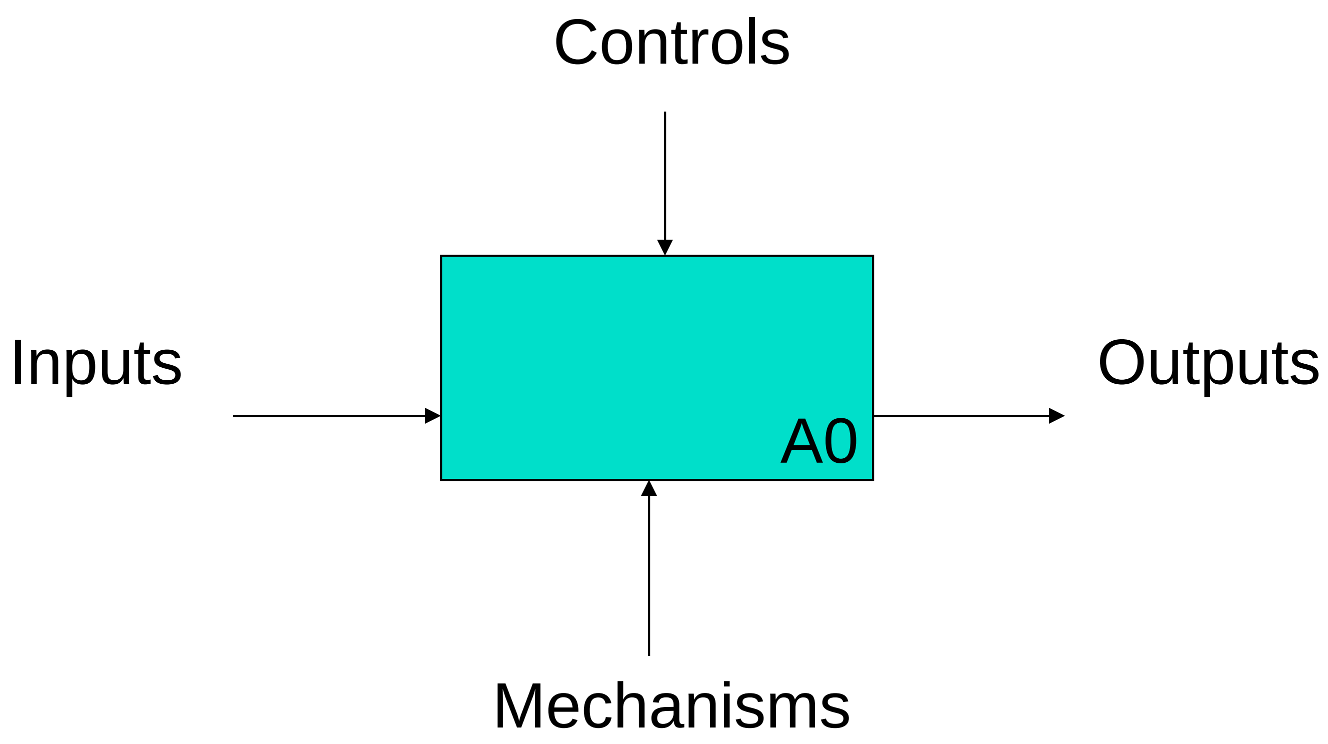
IDEF0 Approach Characteristics

- Comprehensive and expressive
  - Can graphically represent a wide variety of operations to any level of detail.
- Coherent and simple language
  - Provides rigorous and precise expression, promoting consistency of usage and interpretation.
- Enhances communication between system analysts, developers and users.
- Well-tested and proven
  - Years of Air Force and other government agency use.
- Can be generated manually or through a wide range of software packages.
  - CORE
  - DOORS
  - Cradle

IDEF0 Purpose & Viewpoint

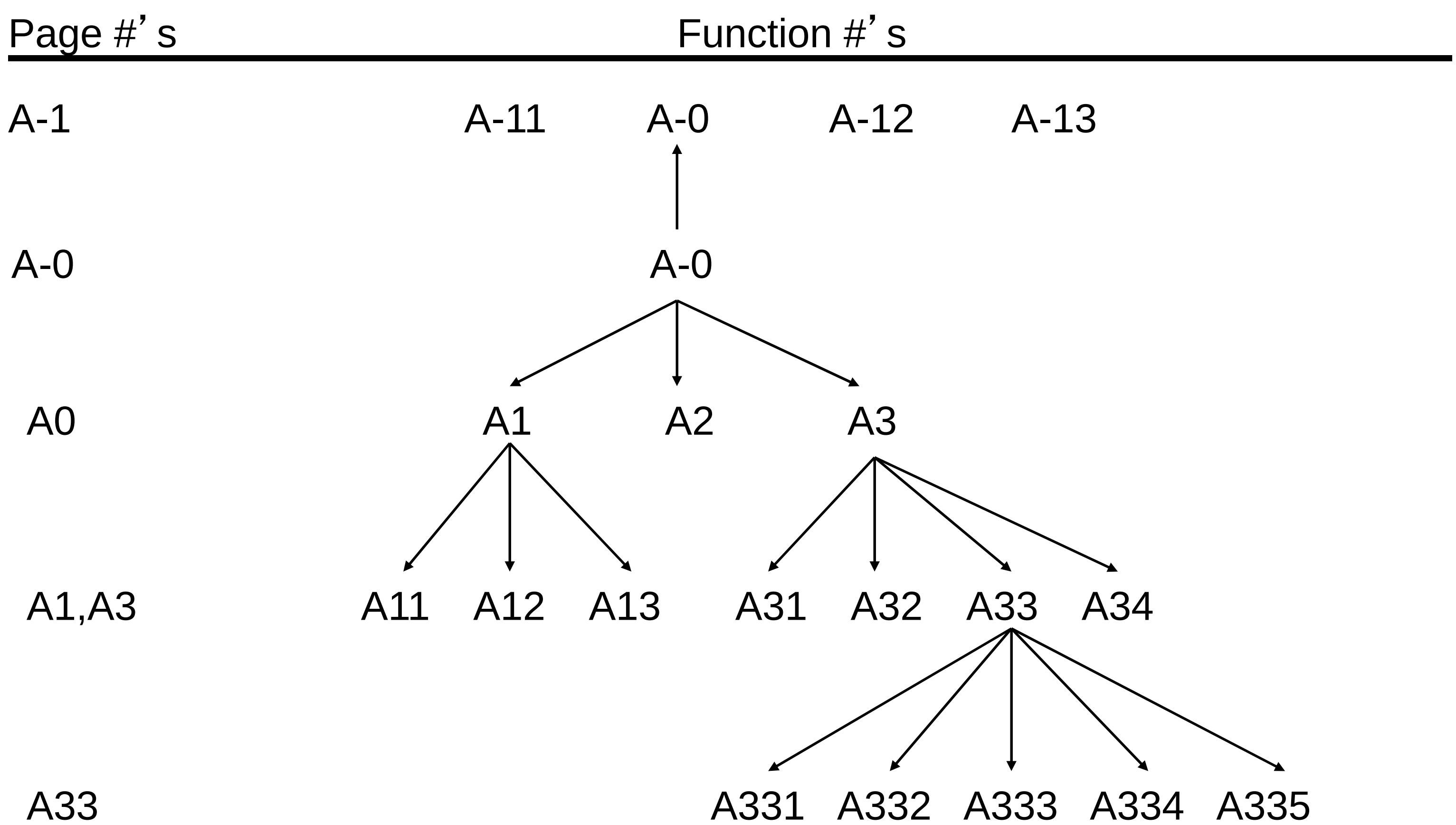
- Answers definitive questions about the transformation of inputs into outputs by the system.
- Establishes the boundary of the system on the context page (A-0).
- Has one viewpoint; the viewpoint is the vantage or perspective from which the system is observed.
- Is a coordinated set of diagrams, using both a graphical language and natural language.

Modeling Systems using IDEF0

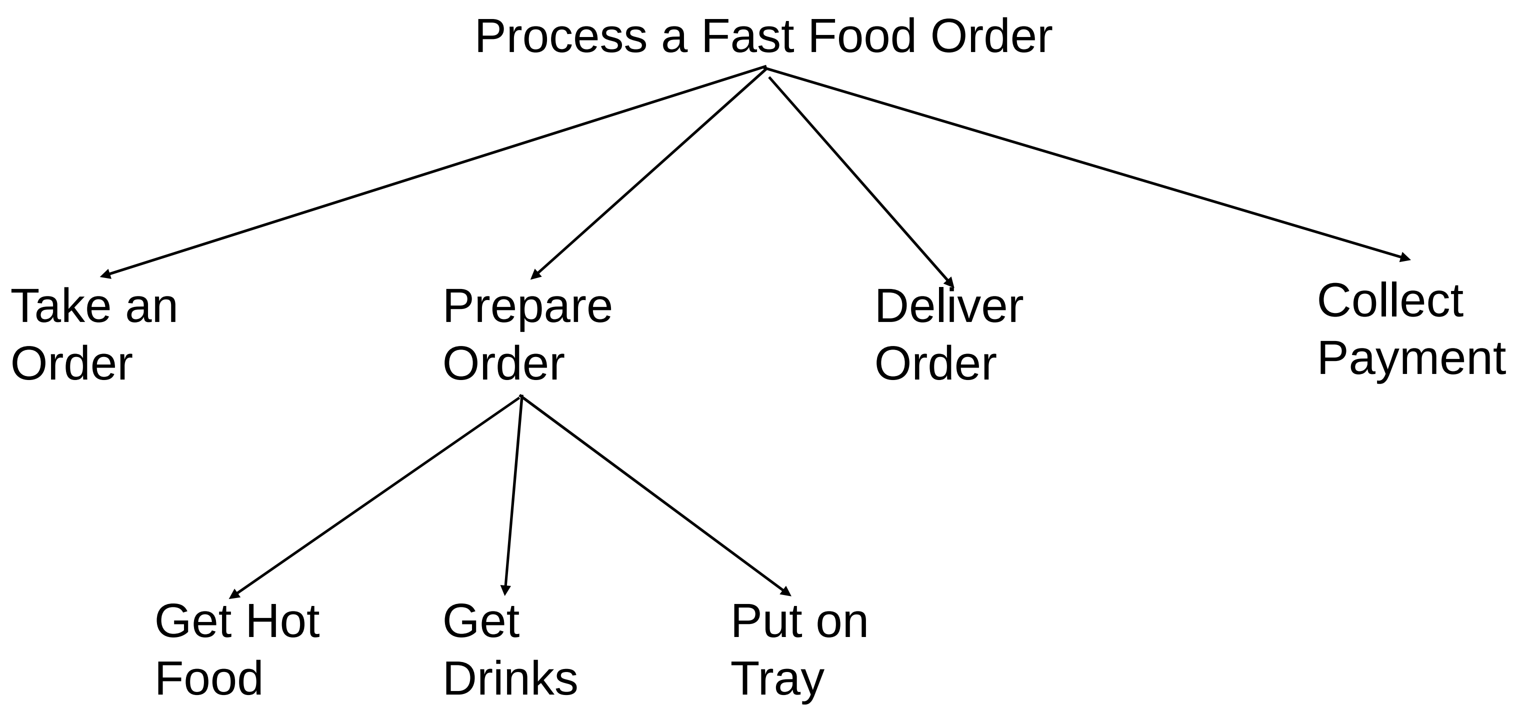


An IDEF0 Functional Decomposition

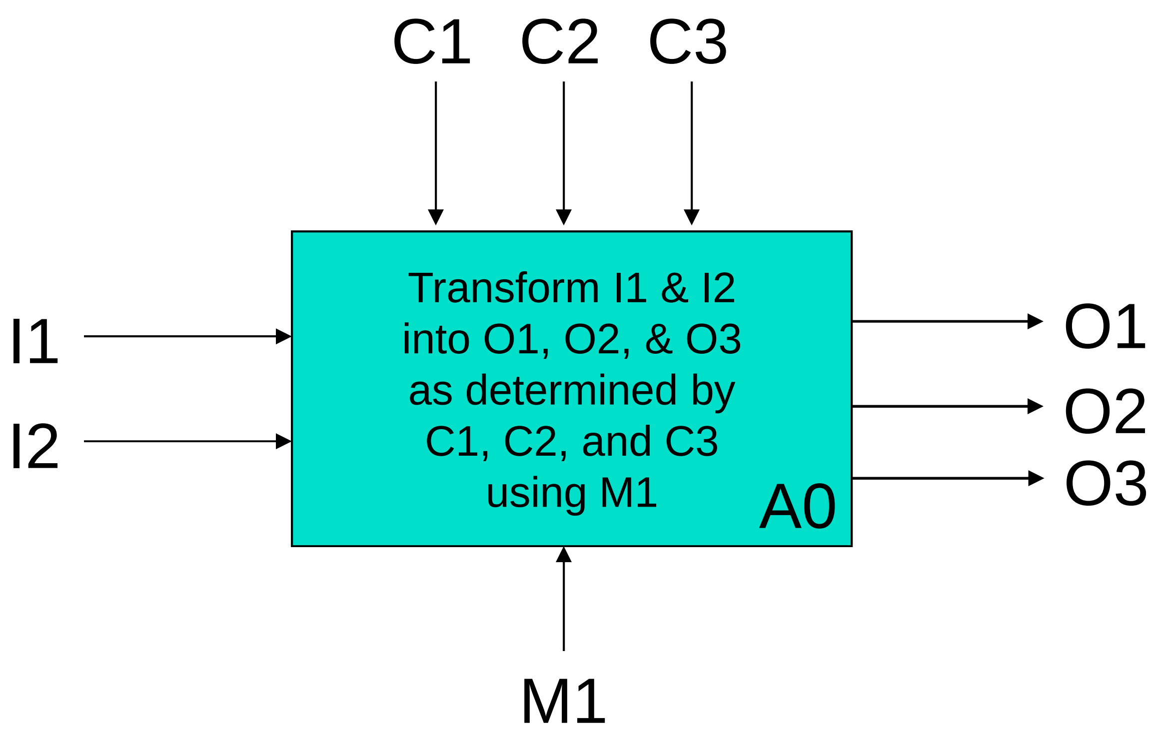
(ref. Figure 3.5, Buede)



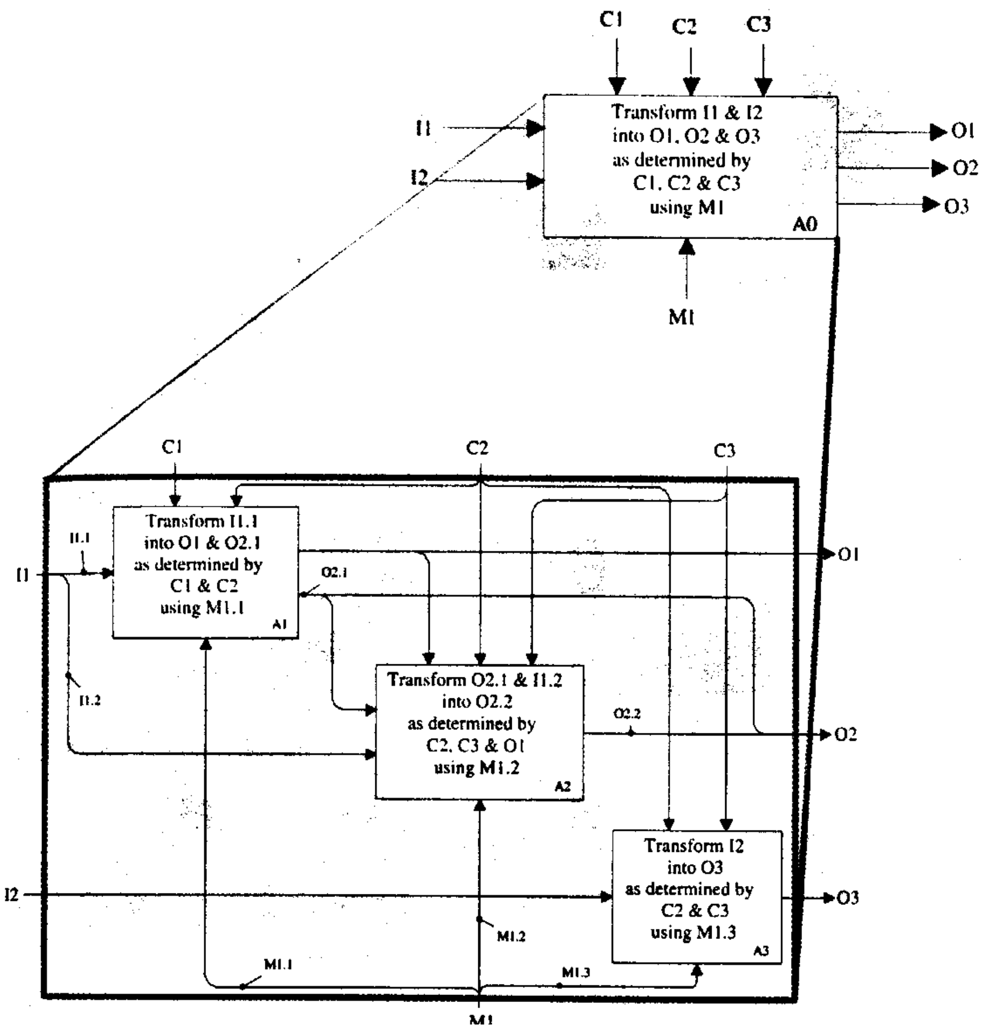
Functional Decomposition



Functional Decomposition in an IDEF0 Model (ref. Figure 3.6, Buede)



A 2-Level IDEF0 Functional Decomposition (ref. Figure 3.6, Buede)



3 Elements of Feedback Control in Functional Design

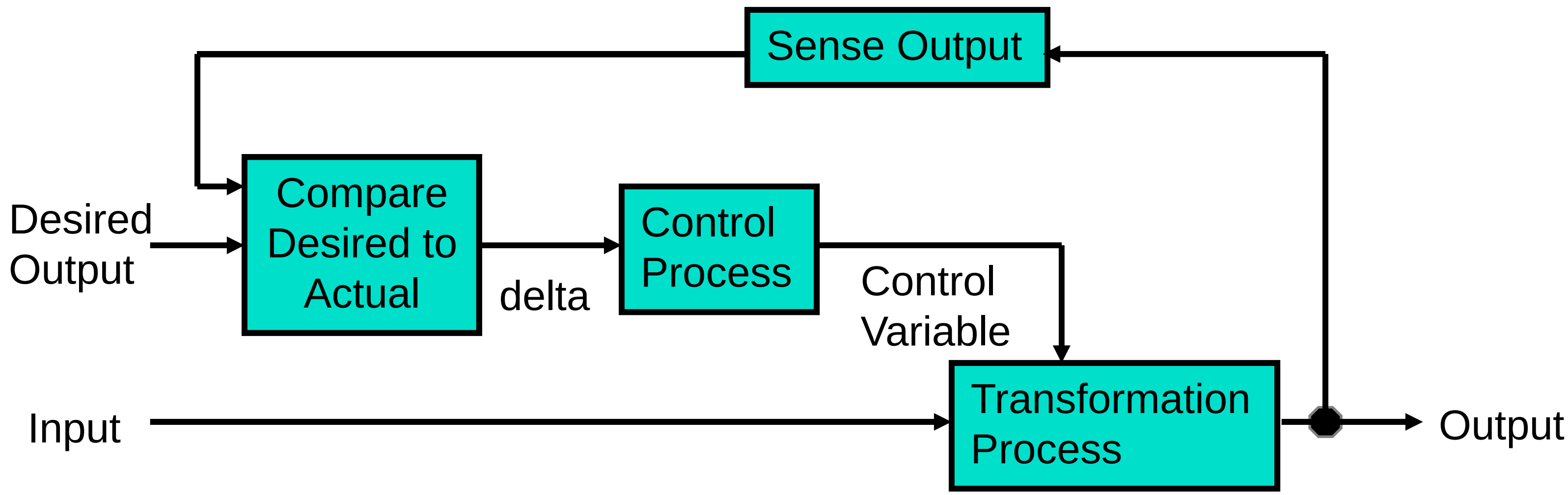
1. *The* *comparison process* in which current values of key variables are compared with desired values of those variables.

2. The *control process* for deciding what to do about the difference between the current value of the output and the desired value of the output.

3. The *transformation process* that is being controlled by the feedback process.

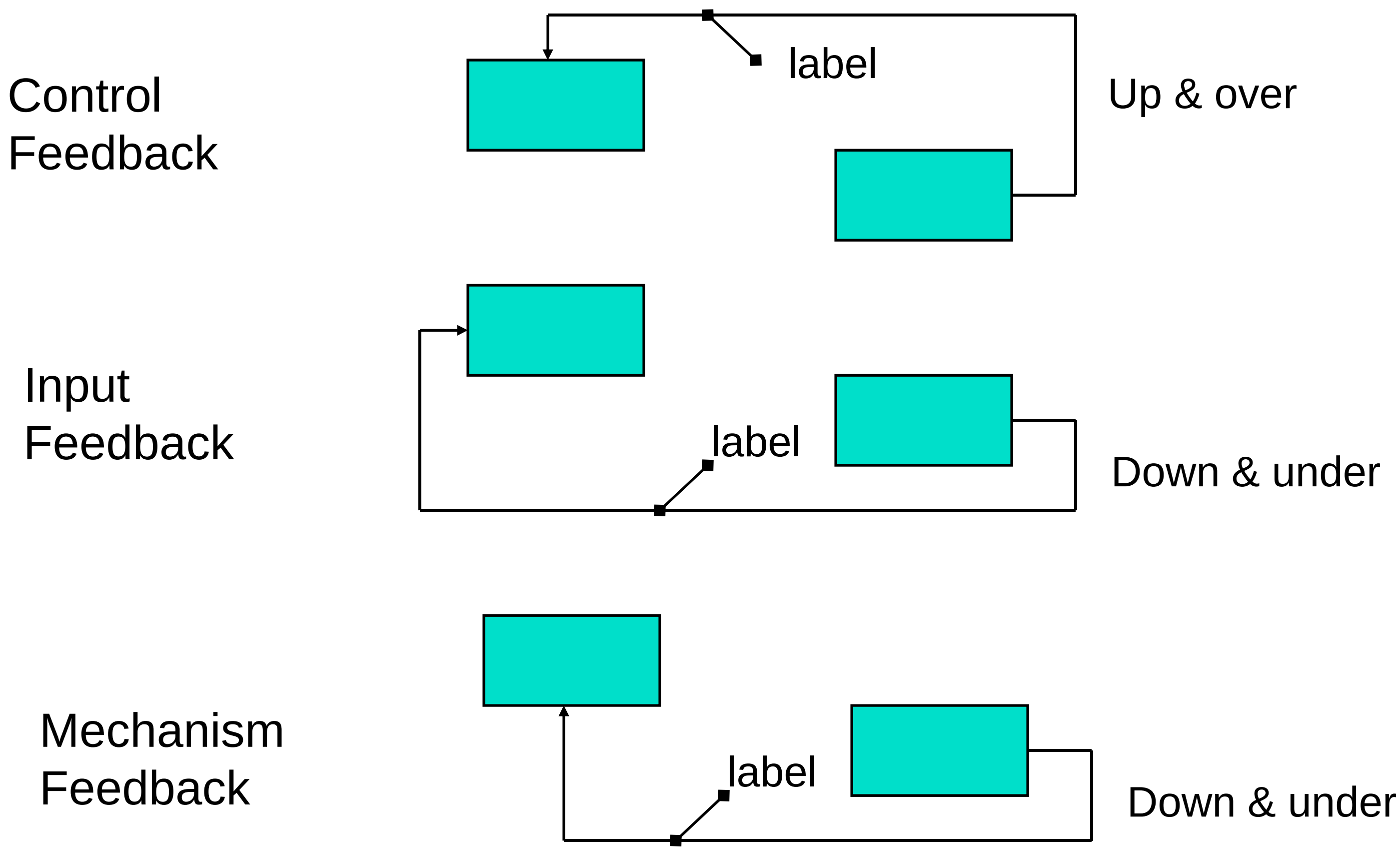
Closed Loop Control Process

(ref. Figure 7.5, Buede, abridged)



IDEF0 Feedback Semantics

(ref. Figure 3.4, Buede)



Mental Models – System Views

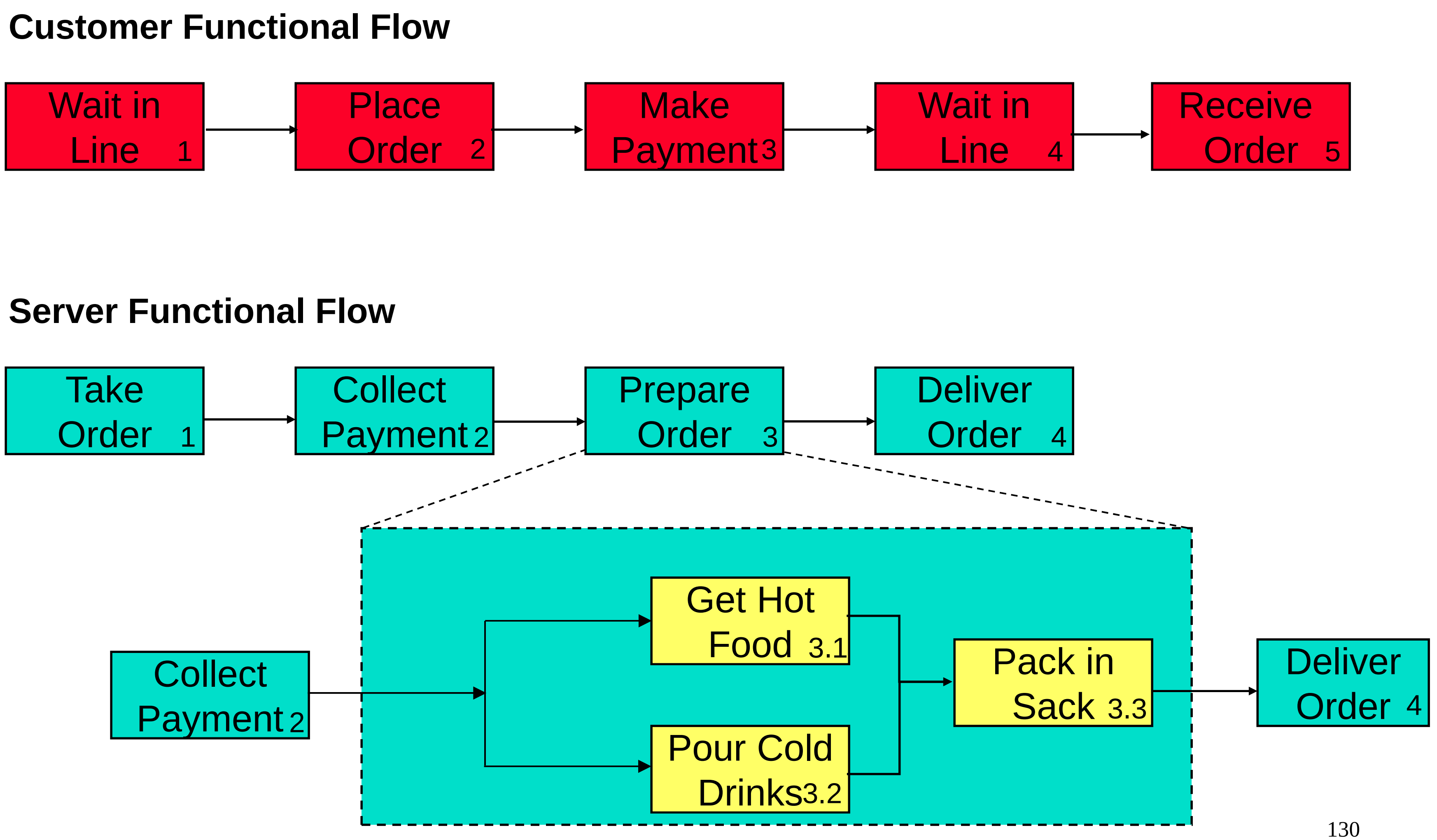
Functional, Physical, & Operational System Views

- The *operational view* describes how the system will serve it's users. It is useful when defining requirements of "how well" and "under what conditions."

- The *functional view* focuses on WHAT the system must do to produce the required operational behavior. It includes the inputs, outputs, states, and transformation rules.

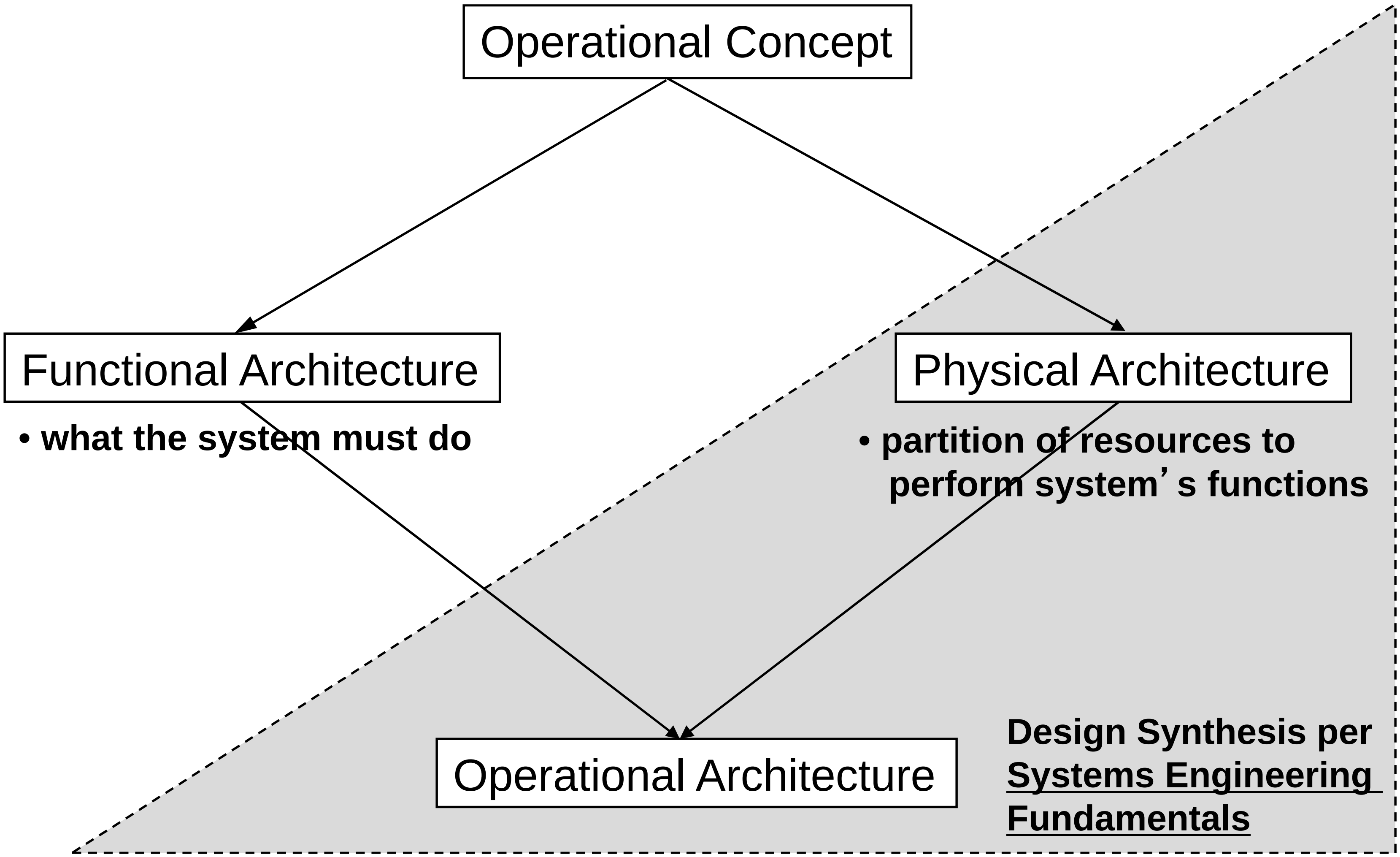
- The *physical view* focuses on HOW the system is constructed. It is key to establishing the physical interfaces among operators and equipment.

A Process Flow from Two Viewpoints



Architecture Development

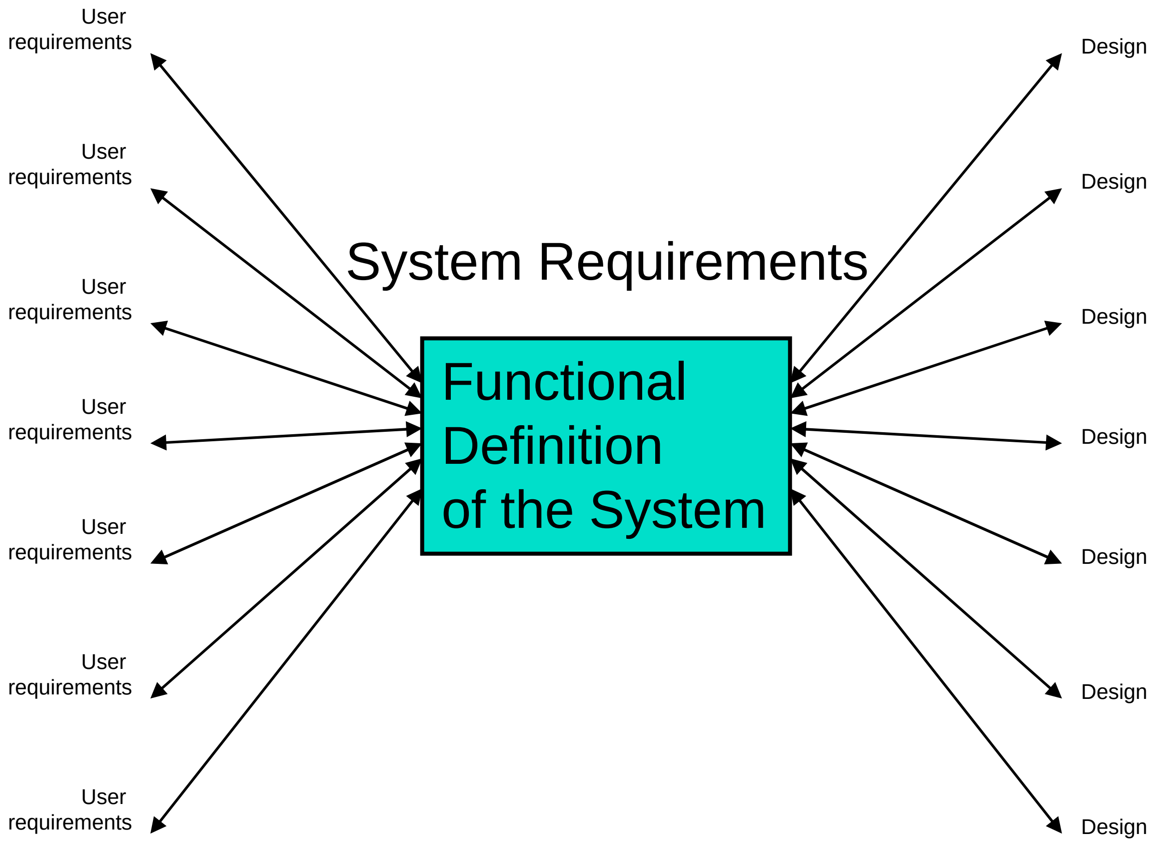
(ref. Figure 1.9, Buede)



Functional Architecture

- Contains a *hierarchical model* of the functions performed by the system, the system's components, and the system's configuration items;
- The *flow* of informational and physical items from outside the system through the transformational processes of the system's functions and on to the waiting external systems being serviced by the system;
- A *data model* of the system's items;
- A *tracing* of the input/output requirements to both the system's functions and items.

What is the Purpose of the Functional Architecture Development?



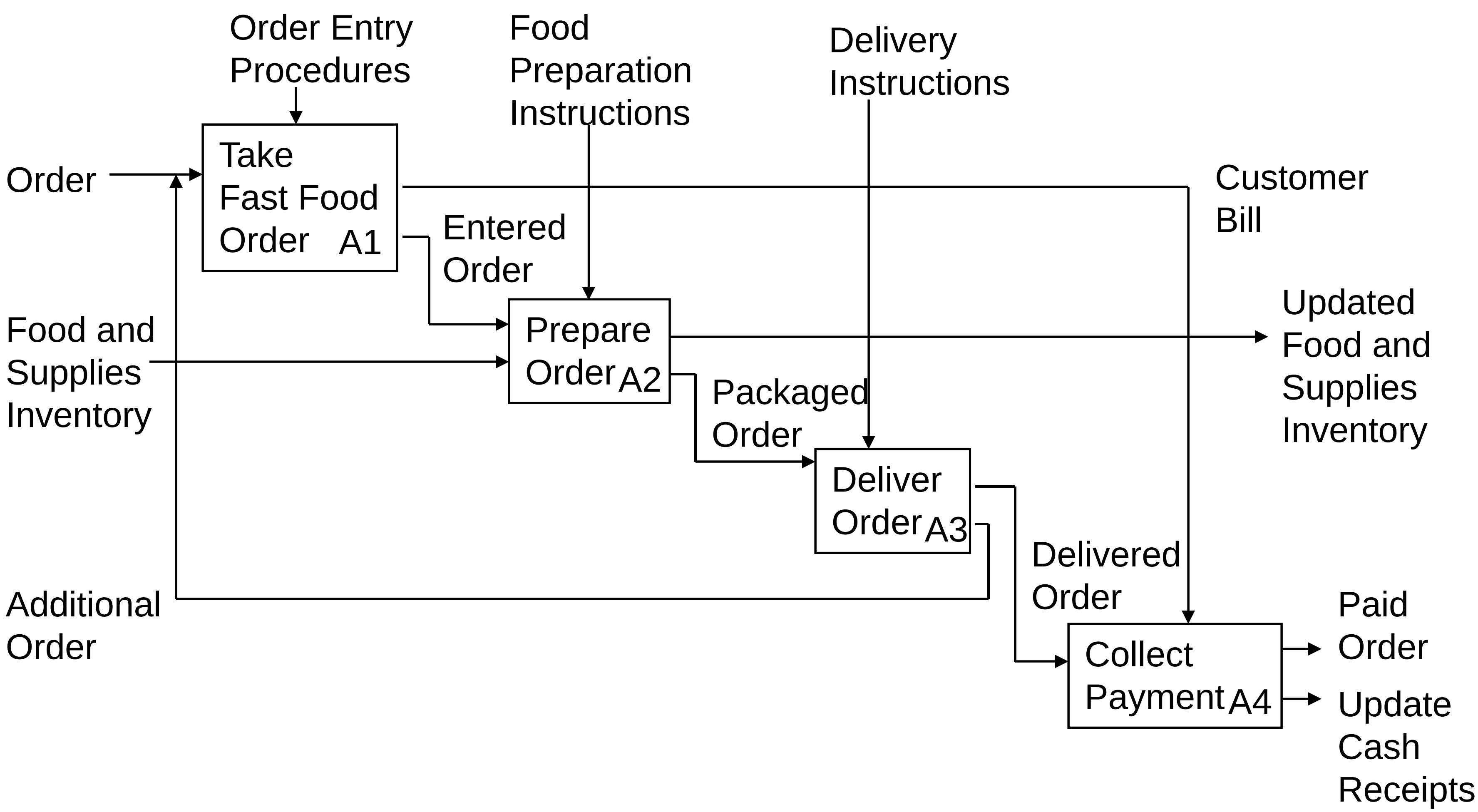
Functional Architecture Terminology

- A system *mode* is a distinct operating capability of the system during which some or all of the system's functions may be performed to a full or limited degree.

- The *state of the system* is a snapshot of the set of metrics or variables needed to describe fully the system's capabilities to perform the system's functions.

- A *function* is a process that takes inputs in and transforms these inputs into outputs.

Process Fast Food Order Functional Architecture



Physical Architecture

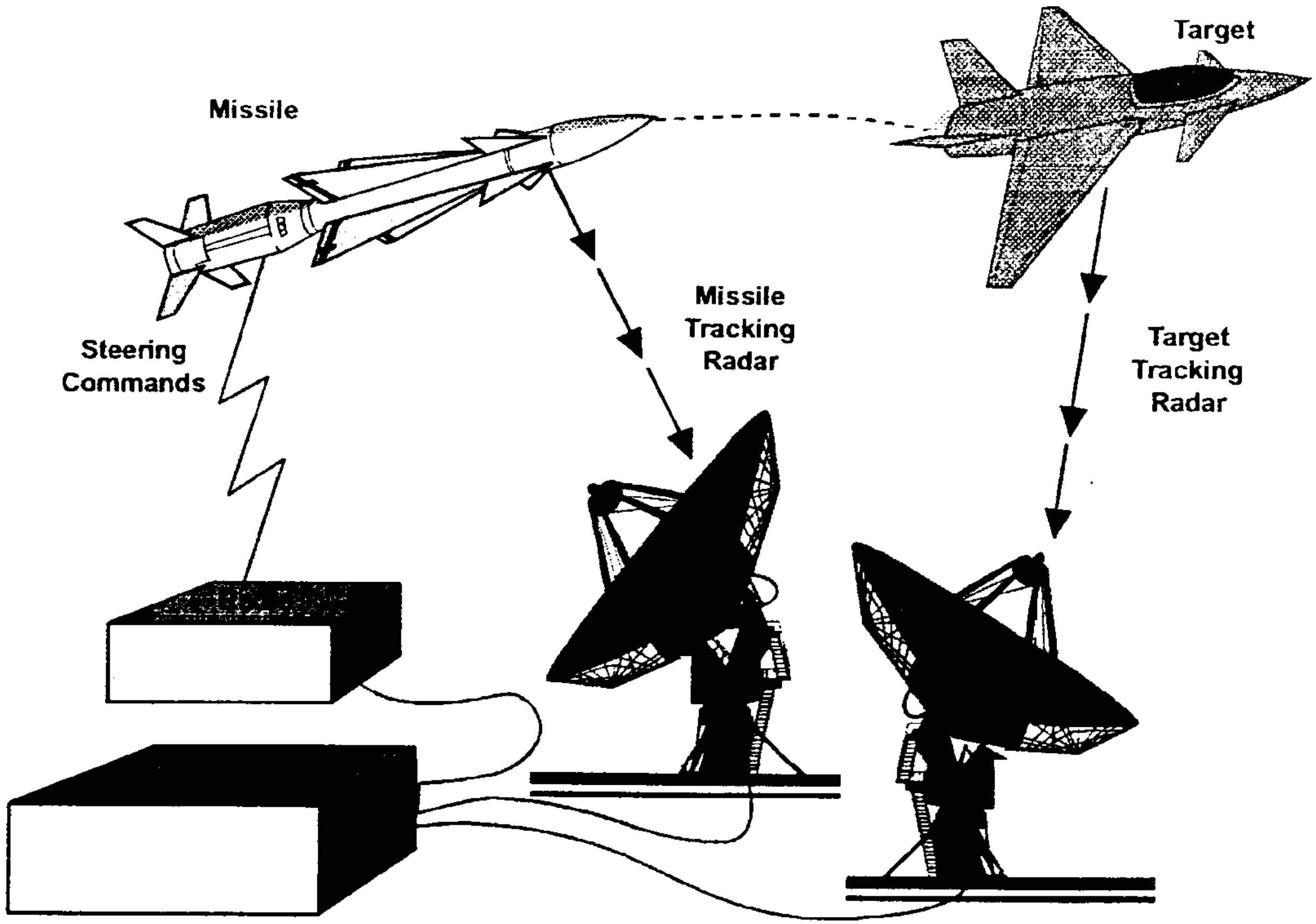
- The physical architecture of a system is a *hierarchical description of the resources* that comprise the system.

- Design synthesis is a creative activity that develops a physical architecture capable of *performing the required functions within the limits of the performance parameters* prescribed.

- The physical architecture forms the *basis for design definition documentation*, such as specifications, baselines, and the Work Breakdown Structure.

Concept Description Sheet

(ref. Figure 6.3, Systems Engineering Fundamentals)



External Command Guidance System

Process Fast Food Order Physical Architecture

- Servers
- Computer Register
- Cooks
- Machines

Operational Architecture

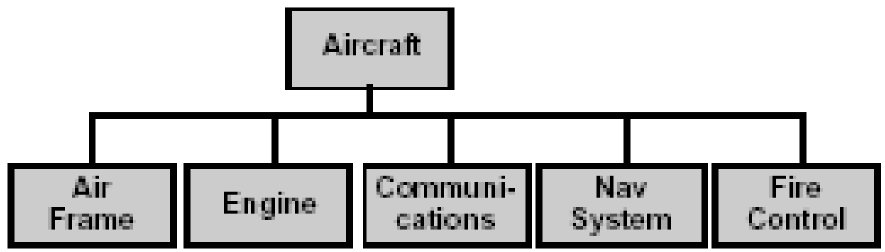
- The operational architecture integrates *requirements decomposition* with the functional and physical architectures.

- Activities involved in developing an operational architecture include:
  - Allocate functions to subsystems
  - *Trace non-input/output requirements & derive requirements*
  - *Define & analyze functional activation & control structure*
  - Conduct performance & risk analysis
  - Document architectures & obtain approval
  - Document subsystem specifications

Functional/Physical Allocation Matrix

(ref. Figure 6.2, Systems Engineering Fundamentals)

PHYSICAL ARCHITECTURE



FUNCTIONAL ARCHITECTURE

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/Physical Allocation Matrix

Fast Food System

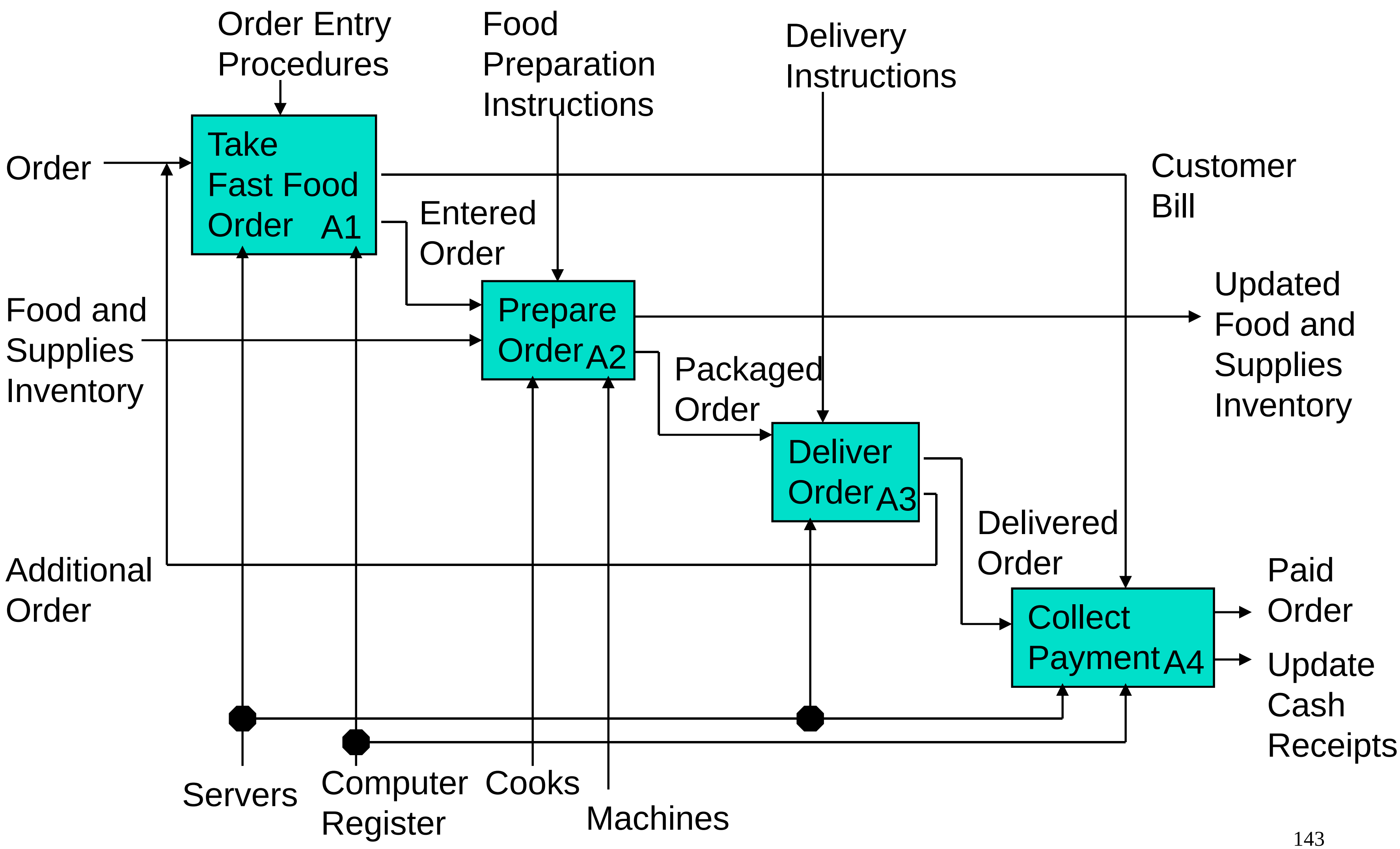
	Computer Register	Cooks	Machines	Servers
Take Fast Food Order	X			X
Prepare Order		X	X	
Deliver Order				X
Collect Payment	X			X

Systems Engineering use of IDEF0 Models

- An IDEF0 model, minus the mechanisms, can be used to define a system's functional architecture.

- By adding the mechanisms to the functional architecture, a description of a system's physical architecture is produced.

Process Fast Food Order Operational Architecture



Key Points

- Symbolic models, including FFBDs as a particular example, provide a basis for requirements generation.

- Symbolic models can represent various system viewpoints.

- IDEF0 is a very adaptable format for depicting symbolic models of various types.

References

- Buede, Dennis M., *The Engineering Design of Systems*, Chapters 8 & 9.
- *Systems Engineering Fundamentals*, Supplementary Text Prepared by the Defense Acquisition University Press, Fort Belvoir, VA 22060-5565, January 2001, Chapter 6.
- *Integration Definition for Function Modeling (IDEF0),* Draft Federal Information Processing Standards Publication 183, National Institute of Standards and Technology, Computer Systems Laboratory, December 1993.

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Lesson 7: Mathematical Models

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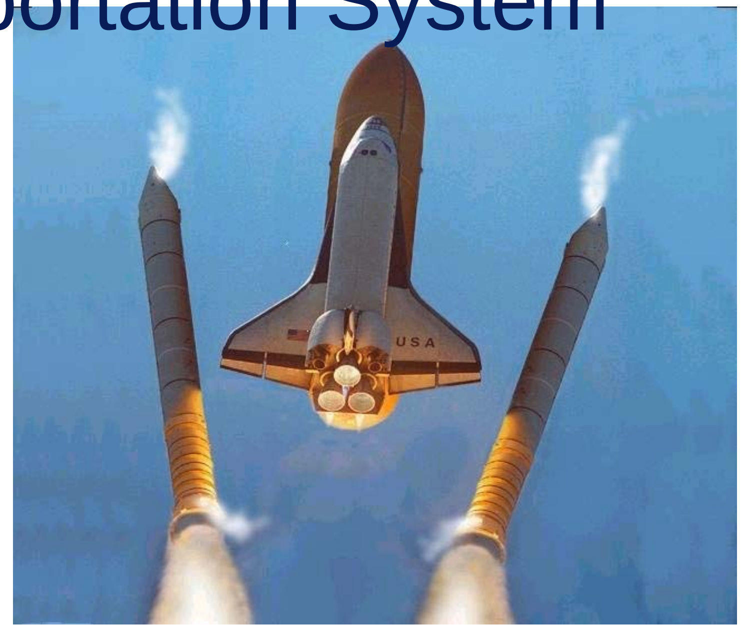
Objectives

- Review the 4-step modeling process.
- Develop a simple mathematical model of ascent performance of a rocket.

Space Transportation System



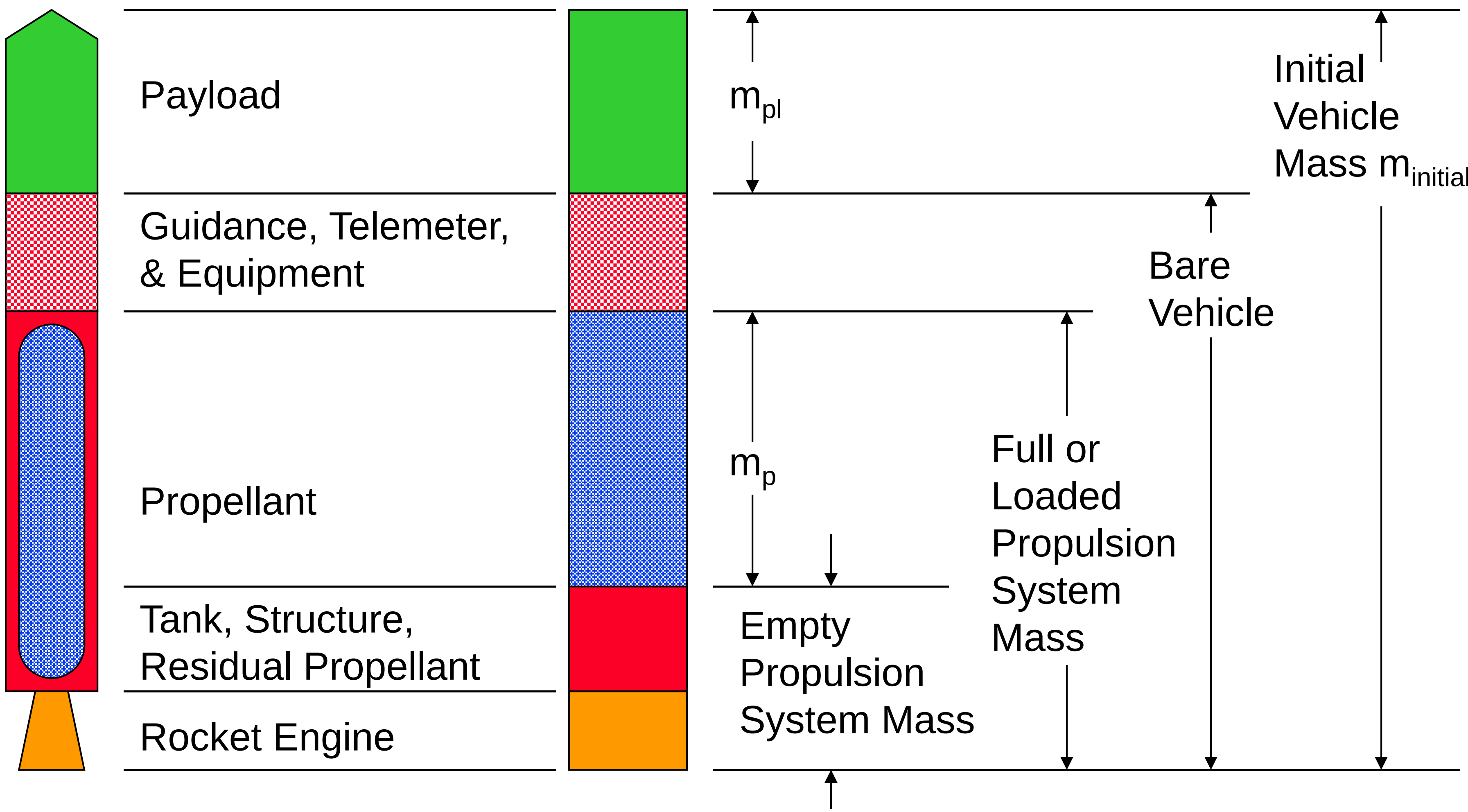
Building a Model – the 4 Step Process

1. **Formulate the Problem**. What is it that you wish to know?
2. **Outline the Model**. Separate the various parts of the system into unimportant, exogenous, and endogenous.
3. **Is it Useful?** If the model fits the situation, will we be able to use it?
4. **Develop and Test the Model.** Use the model to make predictions that can be checked against data and/or common sense.
    - Often a standard process—i.e. NASA-STD-7009.

Exercise

- Step 1. Formulate the Problem. What is it that you wish to know?
  - How do the basic variables of mass, specific impulse, and thrust relate to getting a human payload to Mars?

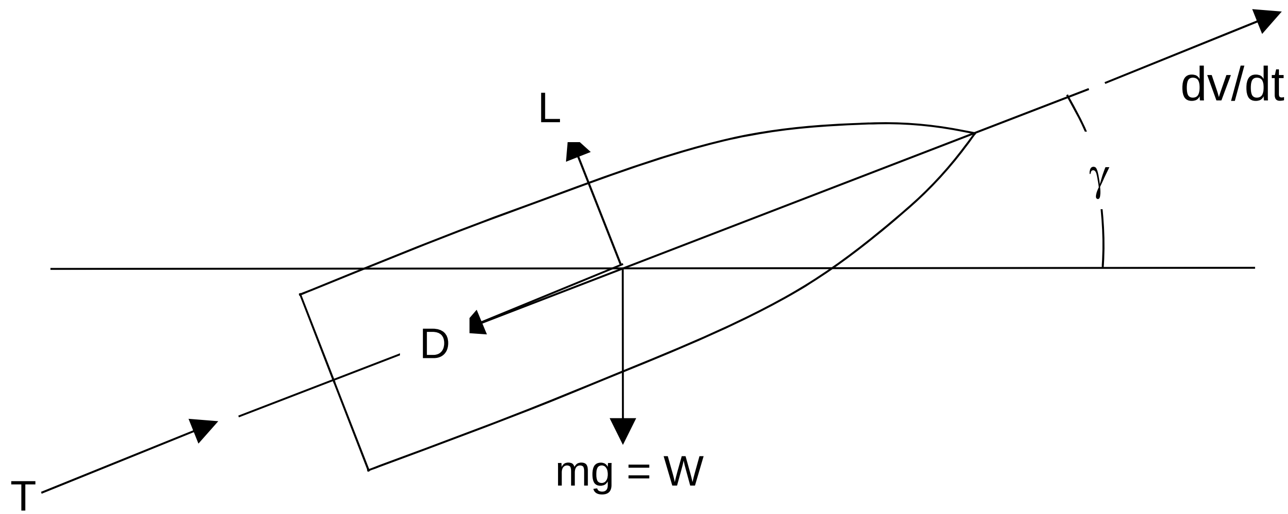
Stage Mass Relations



Exercise

- Step 2. Outline the Model.
  - It can be assumed that the gravitational attraction of all other heavenly bodies may be neglected.
  - Gravity is negligible the trajectory.
  - Flat, non-rotating earth.
  - Point mass.

Derivation of the Rocket Equation



- m is the instantaneous mass of the vehicle
- dv/dt is the vehicle acceleration in the direction of flight
- T is the thrust force of the propulsion unit
- L is the aerodynamic lift force
- D is the aerodynamic drag force
- g is gravity
- γ is the angle of the direction of thrust with the horizontal

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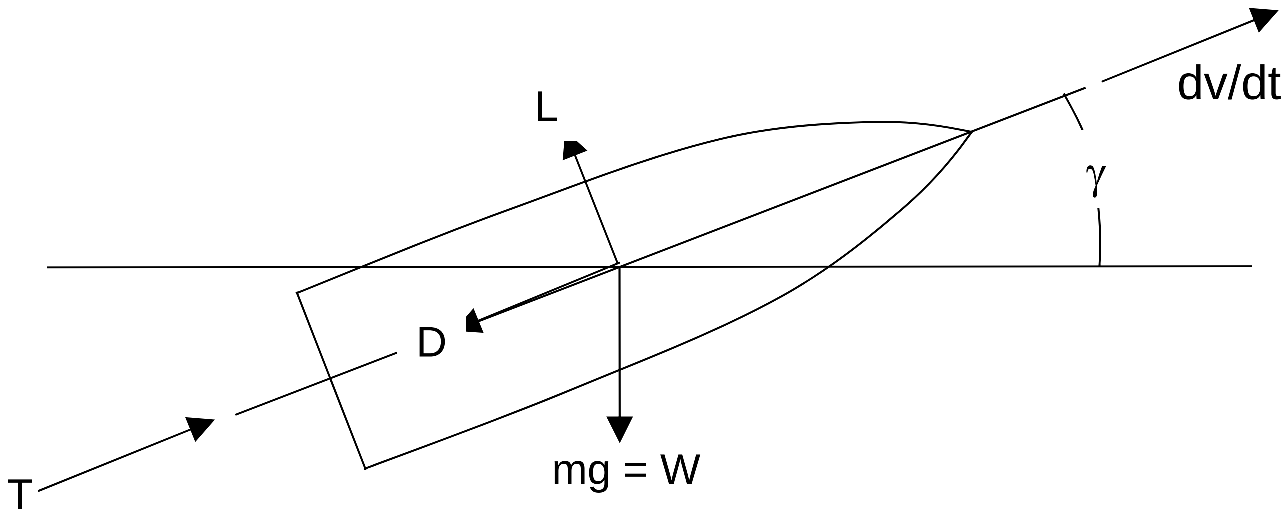
Equation of Motion



$$m\frac{dv}{dt} = T - D - mg\sin\gamma$$

Integration Yields the Rocket Equation

$$\Delta v = gI_{sp}\left(1 - \frac{D}{T} - \frac{mg}{T}\sin\gamma\right)\ln\left(\frac{m_{initial}}{m_{final}}\right)$$

Drag losses

Gravity losses

Mass Ratio (MR)= $m_{initial}$ / m_{final}

= $m_{initial}$ / ($m_{initial}$ – $m_{propellant}$)

Mars In-Space Stage Sizing

Ending with ideal Rocket Equation

$$\Delta v = v_e \ln\left(\frac{m_0}{m_f}\right)$$

Where:

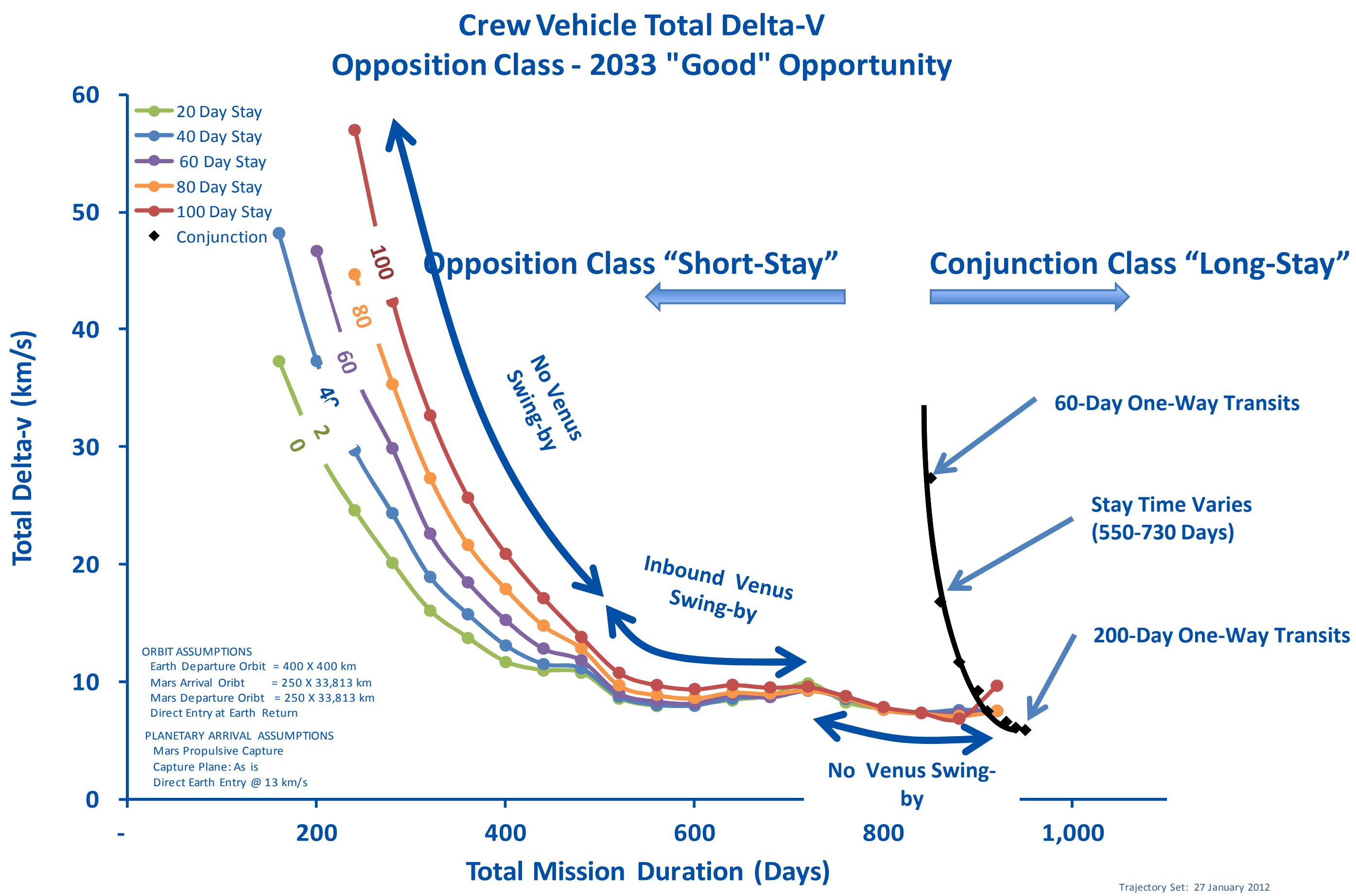
Δv = change in velocity (delta-v) to perform in-space maneuver

V_e = exhaust velocity (engine)

m_0 = stage initial mass – structure mass + propellent

m_f = stage final mass

Example Delta-V for Mars Missions

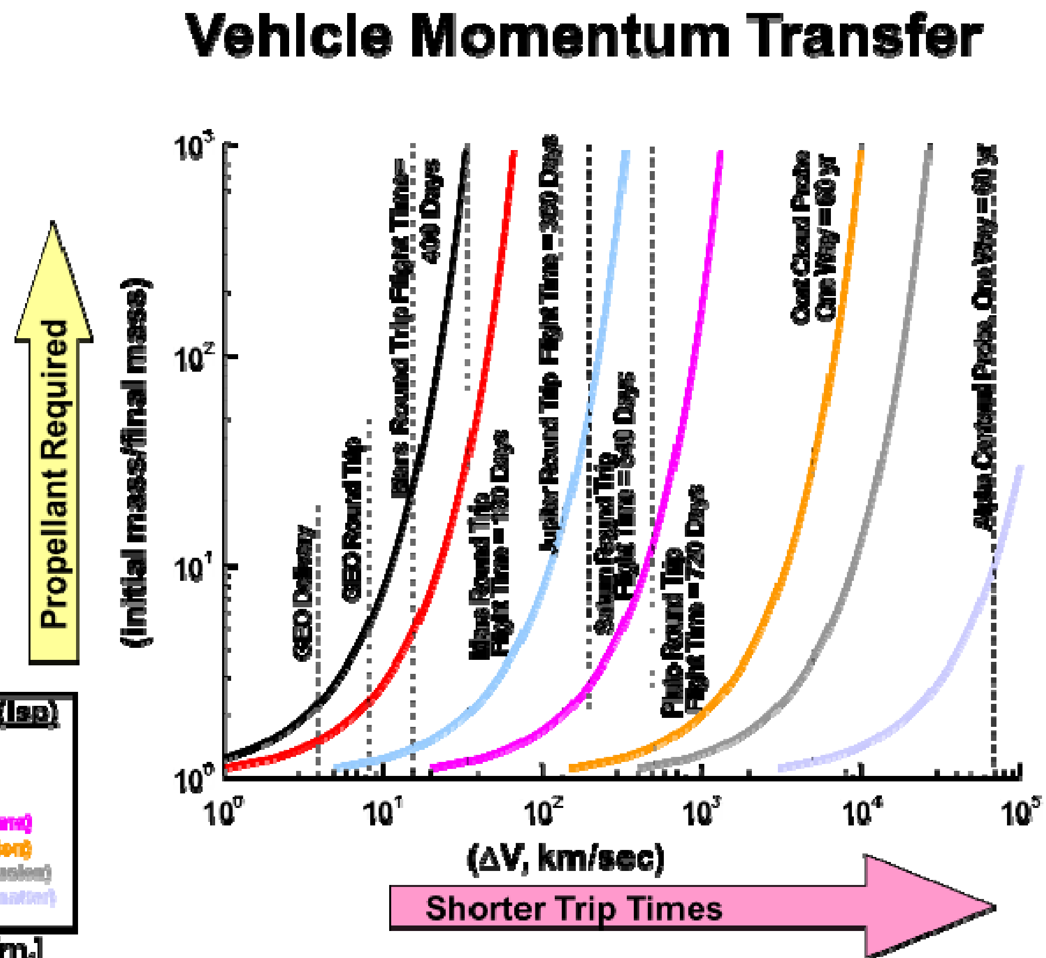


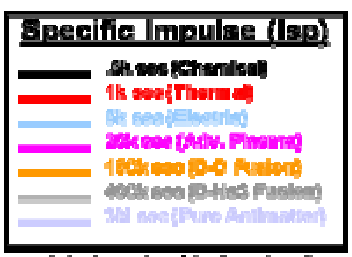
Shorter mission times are related to higher Delta-V, which could be provided with low TRL advanced propulsion

Drake, B. G., et al “Trajectory Options for Exploring Mars and the Moons of Mars”, 2012

Relationship of Delta-V and Isp

Isp	Mp at 7 km/sec	Mp at 11 km/sec
360	6.27mf	21.6mf
522	2.93mf	7.59mf
900	1.21mf	2.48mf
1300	.73mf	1.37mf





$\Delta V = Isp(g_o)\ln(m_i/m_f)$

Higher Delta-V missions require higher Isp (propellant exit velocity) to minimize the amount of propellant required

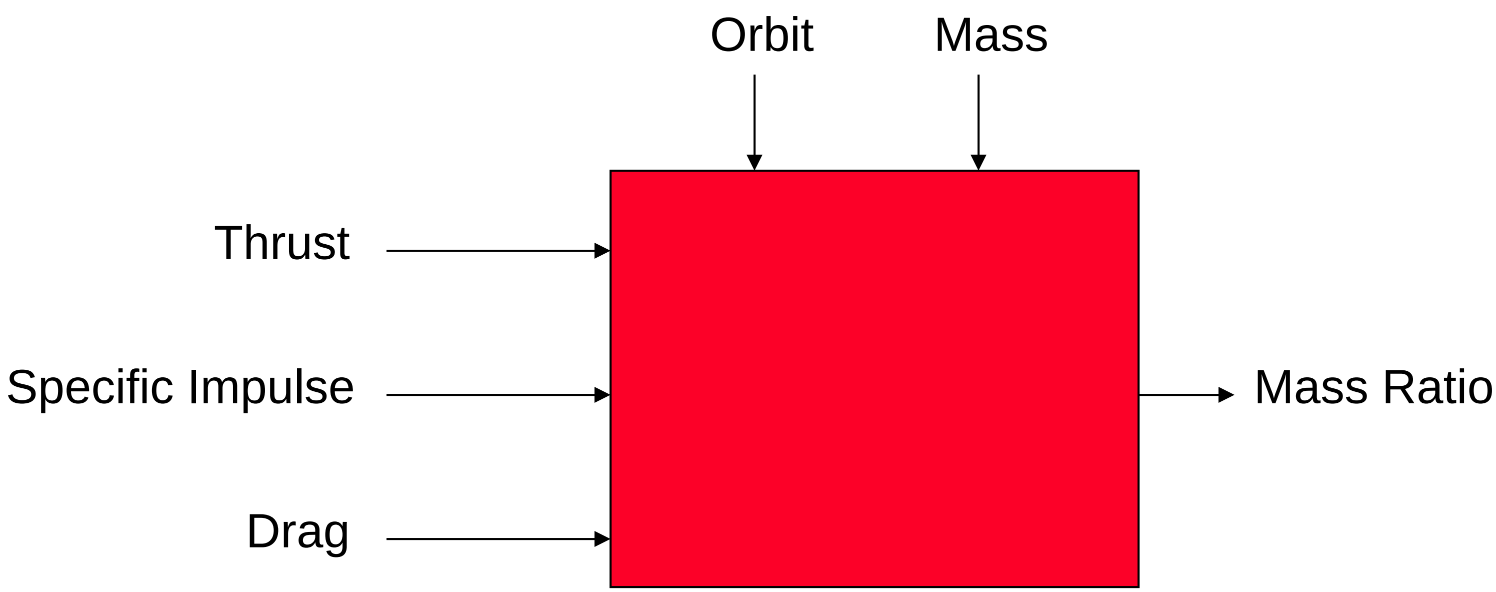
Propulsion System Trades Examples

Chemical Stages	Advanced Propulsion
LO_2/LH_2	Nuclear Thermal (LH_2)
LO_2/LCH_4	Nuclear Electric
NTO/MMH	Solar Electric

Exercise

- Step 3. Is it useful?

Black Box View of Rocket Equation



Exercise

- Step 4. Develop and Test the Model.

Propulsion System Trades Examples

Chemical Stages	Advanced Propulsion
LO_2/LH_2	Nuclear Thermal (LH_2)
LO_2/LCH_4	Nuclear Electric
NTO/MMH	Solar Electric

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Transportation Options for Mars

Standard Exploration Upper Stage

Useable Prop = 118 mt

Engine = RL10-C2

Specific Impulse = 462 s

Total Thrust = 99 klbf

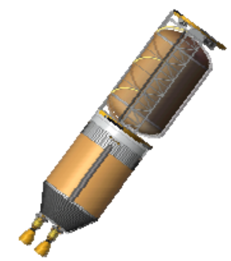
EUS can provide the first TMI burn if it does not have to loiter in Earth orbit for a long duration (i.e. less than 1 week). This drives very aggressive operations assumptions for any multi-launch architecture.

Chemical Propulsion

Varying degrees of technology development required

Leveraging commonality with SLS (EUS) or other Mars elements (methane engines from lander) where possible

Nuclear Thermal Propulsion



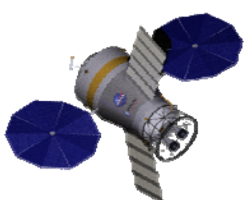
Specific Impulse = 896 s

All LH2 fuel with zero boil-off

Requires 20K cryocoolers for LH2

Implementation requires a "core stage" with engines and nuclear reactors. The core stage is supplemented with in-line tanks and drop tanks to provide the required propellant for the mission.

ZBO Lox/Hydrogen Stage



notional

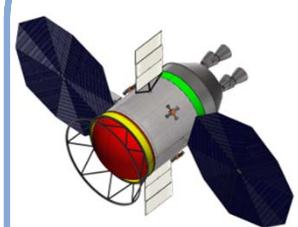
Specific Impulse = 465 s

Total Thrust = 60 klbf

Requires 20K cryocoolers for LH2

EUS cannot be launched full with SLS 2B so this stage would be scaled to fit the mission and lift capabilities of the SLS. With near-ZBO propellant storage, higher specific impulse provides advantages over Lox/Methane

Lox/Methane Stage



Specific Impulse = 360 s

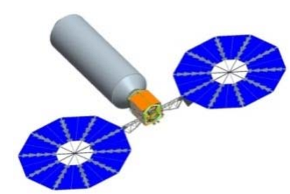
Total Thrust = 90 klbf

Requires 90K cryocoolers for CFM

*Prop Load & Burn Out Mass are scaled to fit mission

Mars architecture balances long term propellant storage with specific impulse for all other propulsive maneuvers by using a Lox/Methane propulsion stage

Solar Electric Propulsion



ARM-derived

100-300 kW

Isp 3000 s

ARM-derived SEP can deliver 35-45mt of cargo to Mars with 3-4 years of flight time. Other, more aggressive trajectories may enable increases is payload delivery but have not yet been fully vetted.

Other Mission Elements

SLS Launch Vehicle

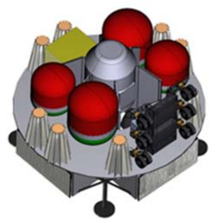
Configuration = Block 2B w/ Advanced Solid boosters and a 10m fairing

Performance data from SLS Mission Planners Guide

Delivery orbit optimized

A 2B SLS is required to provide the necessary lift capability to support human exploration of Mars. 10m fairing is required to package large hydrogen tanks for NTP and Mars landers for surface operations.

Mars Lander



Oxidizer = Liquid Oxygen

Fuel = Liquid Methane

Specific Impulse = 360 s

Lander Payload Capacity	Lander Mars Arrival Mass	Short Surface Stay (30 d) for 2 crew	Set up infrastructure for 4 crew /500 d stay
18t	41t		
27t	59t		
40t	84t		

The mass of the lander can be tailored to fit within the constraints of the transportation systems selected however, the 10m diameter must be accommodated. Smaller landers will result in more landers required for a specified surface mission

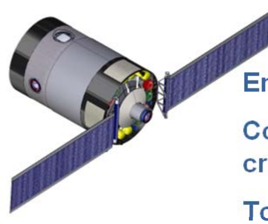
MPCV

Gross Mass = 15.8 mt

Includes Orion capsule and minimum functional SM for ECLSS and power only

Orion can potentially be used in two modes. The first is as a means to deliver the crew to and from an aggregation point in Earth orbit. The second is as a direct re-entry vehicle for crew return directly from a Mars-Earth trajectory.

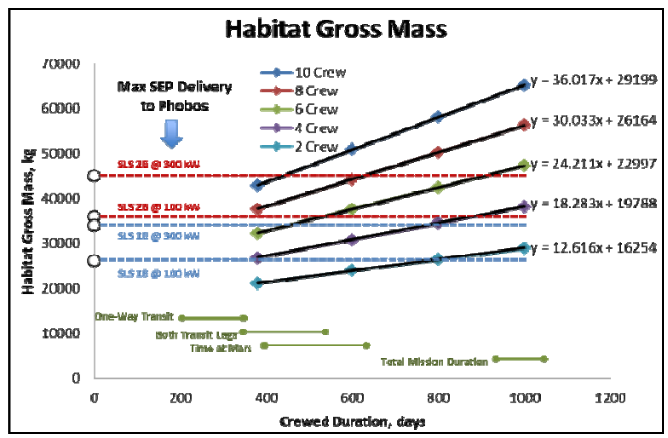
Deep Space Habitat



Empty Mass = 28.24 mt

Consumables = 2.2 kg / crewmember / day

Total 32-40 mt



Coordination between MSFC, LaRC, and JSC habitat teams to develop rules of thumb for consistent habitat sizing as a function of crew size and mission duration.

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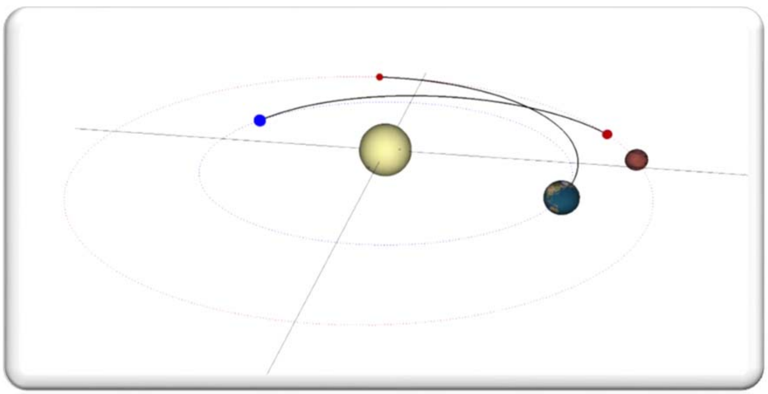
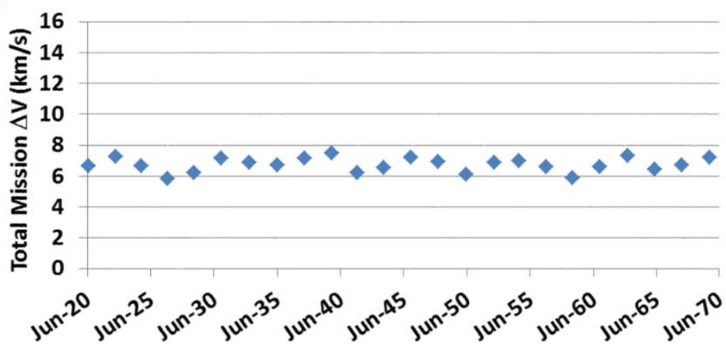
Trajectory Types

Conjunction

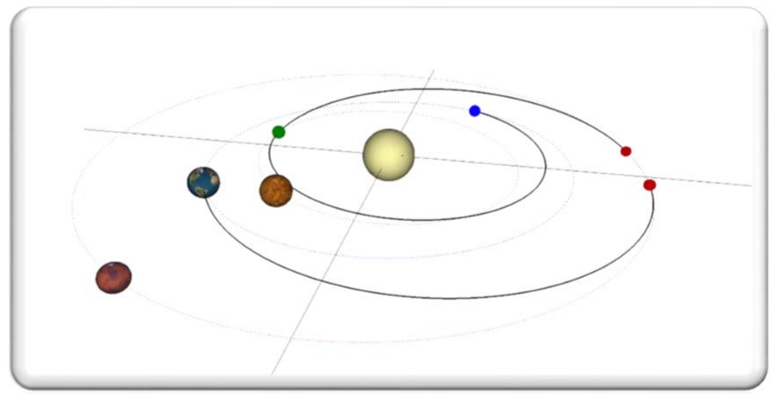
- “Long Stay Mission”
- Typical stay time ~500 days
- Lower energy trajectories

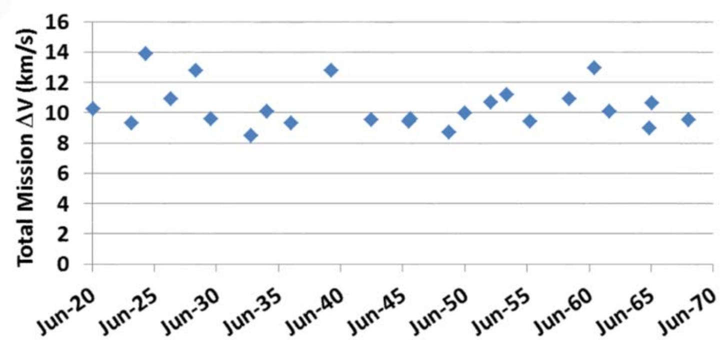




Opposition

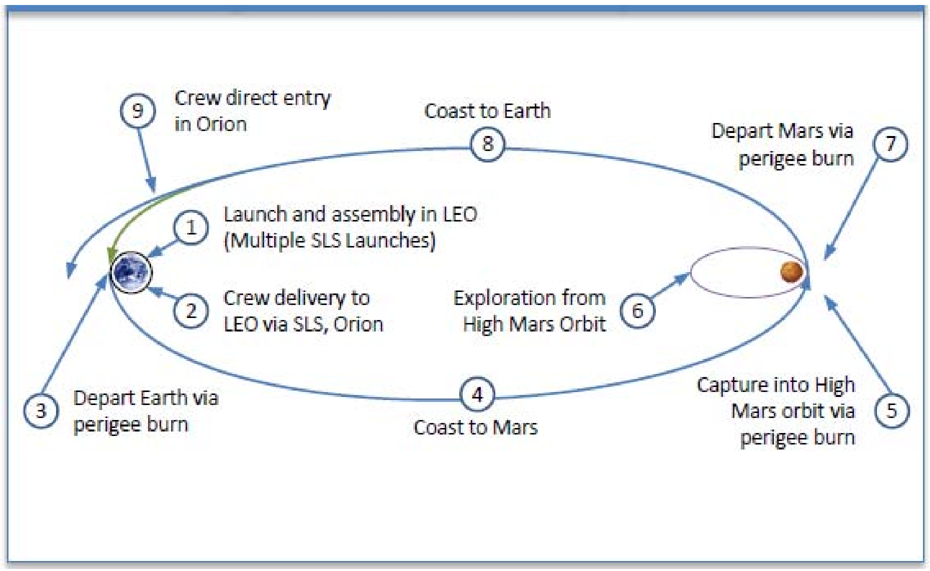
- “Short Stay Mission”
- Typical stay time ~30 days
- Higher energy trajectories
- Many involve Venus swing-by





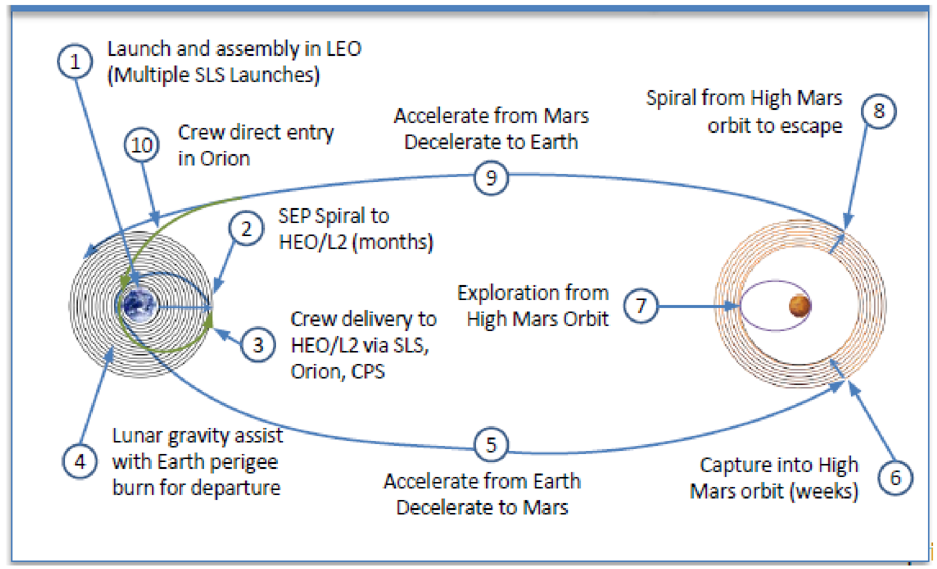
Transportation Tech. Trajectories

High Thrust
(Chemical & Nuclear Thermal)



One-Way Trip Times on the order of 250 days

Low Thrust
(Solar Electric)



One-Way Trip Times on the order of 1400 days

(Near-Term Electric option requires methane chemical propulsion stages for crew delivery; crew trajectories are high-thrust)

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Mathematical Models: Further Exercises

- Overview the deterministic Lorenz Model.
- Describe and demonstrate the stoichastic model of the random walk.
- Describe and demonstrate a hybrid model.

Key Points

- Review the four step modeling process.
- Model output (system performance) does not respond equally to proportionate changes in the input variables.
  - output is much more sensitive to changes in some input variables than to others
  - The model and the system it represents are considered robust for low sensitivities, but non-robust if output is highly sensitive to input parameters.

References

- Sutton, George P. & Donald M. Ross, *Rocket Propulsion Elements*, 8th ed., John Wiley & Sons, 2010.

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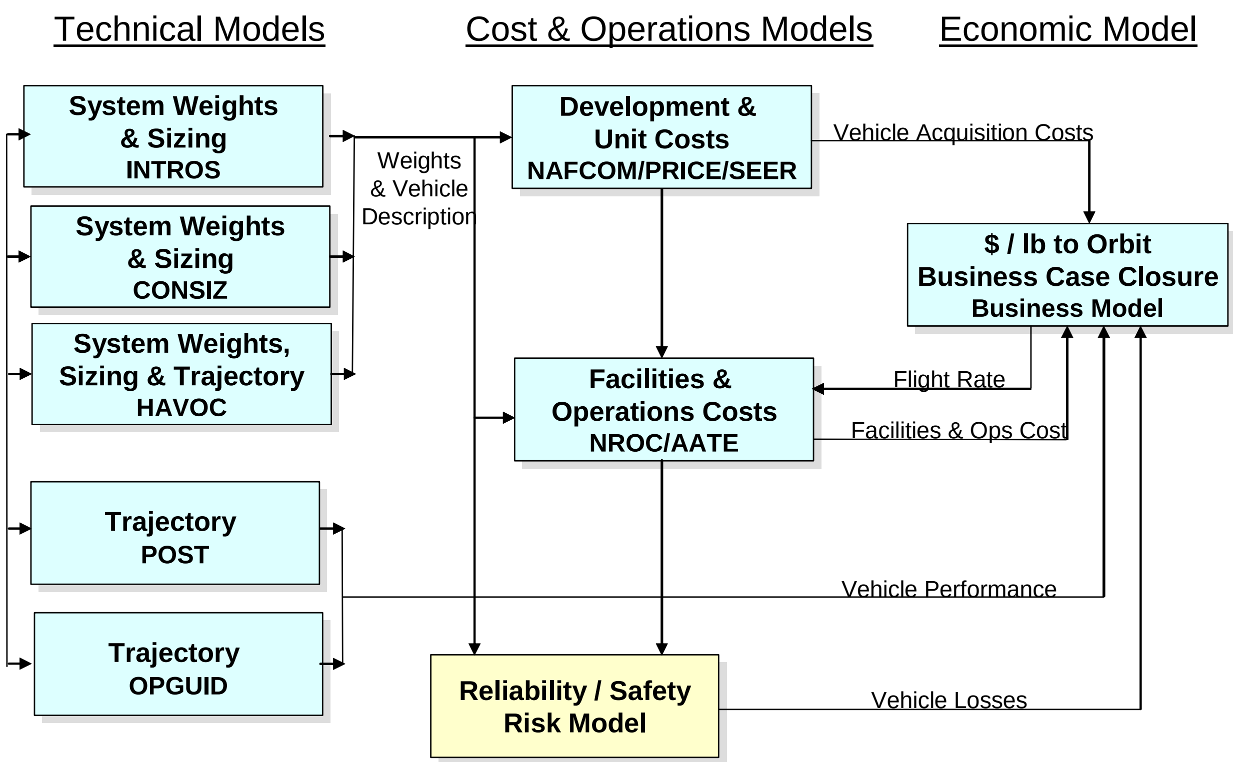
Lesson 8:
Integrated Models

Objectives

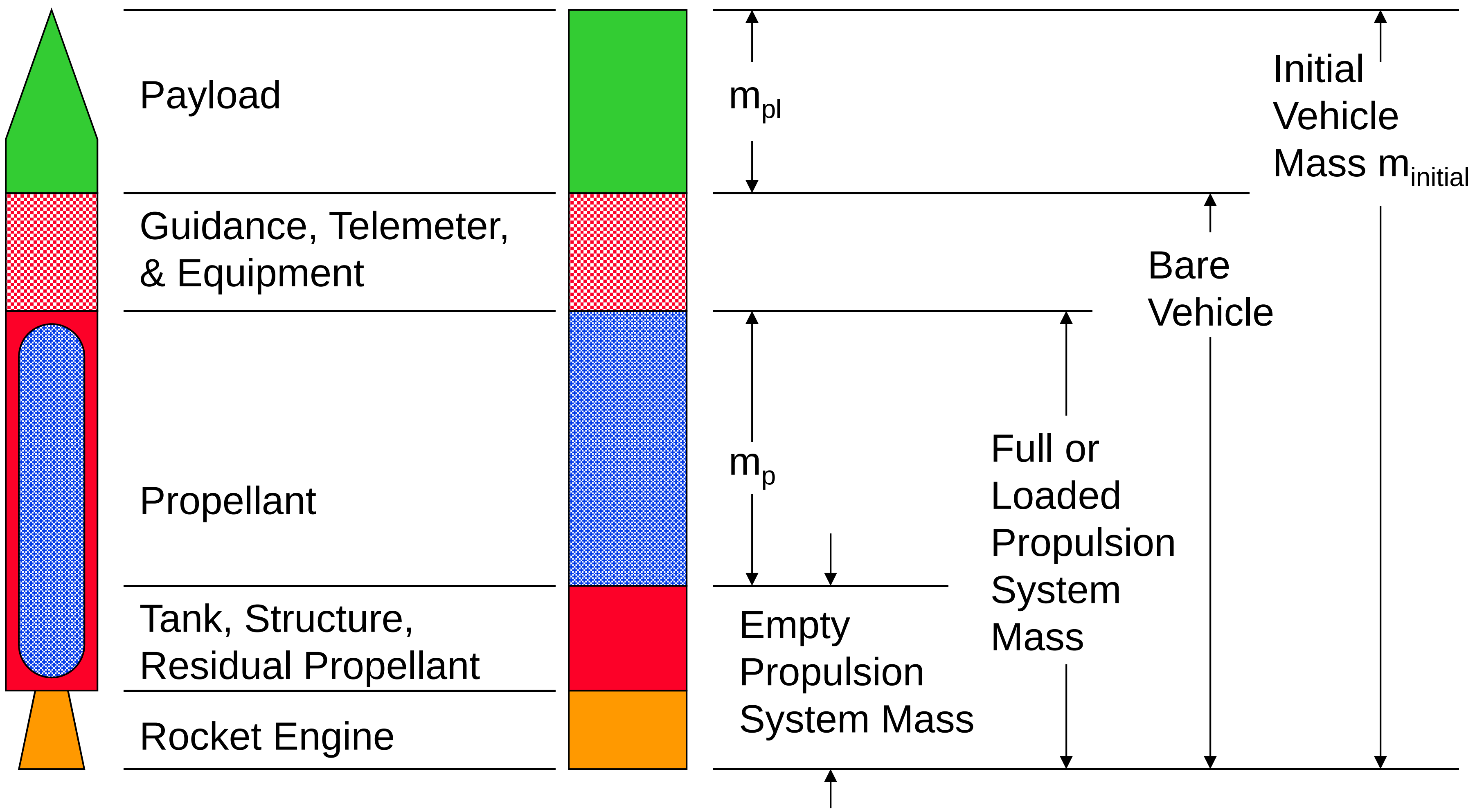
- Illustrate the integration of multiple models to enable comprehensive systems analysis.

Integrated Models

- Often, we wish to know more about a system than a single model can tell us.
- In these cases, we may need a network of integrated models.



Vehicle Mass Relations



Equations of Motion

(1-D Spherical, non-rotating Earth)

$$\frac{dv}{dt} = \frac{T}{m} - \frac{D}{m} - \frac{k}{r^2}\sin\gamma$$

$$where\,\frac{k}{r^2} = g\,(local\,gravitational\,acceleration)$$

$$r = radius\,from\,Earth\,center$$

$$\frac{d\gamma}{dt} = \frac{v}{r} + \frac{t}{vm} + \frac{L}{vm} - \frac{k}{vr^2}\cos\gamma$$

$$\frac{dr}{dt} = v\sin\gamma$$

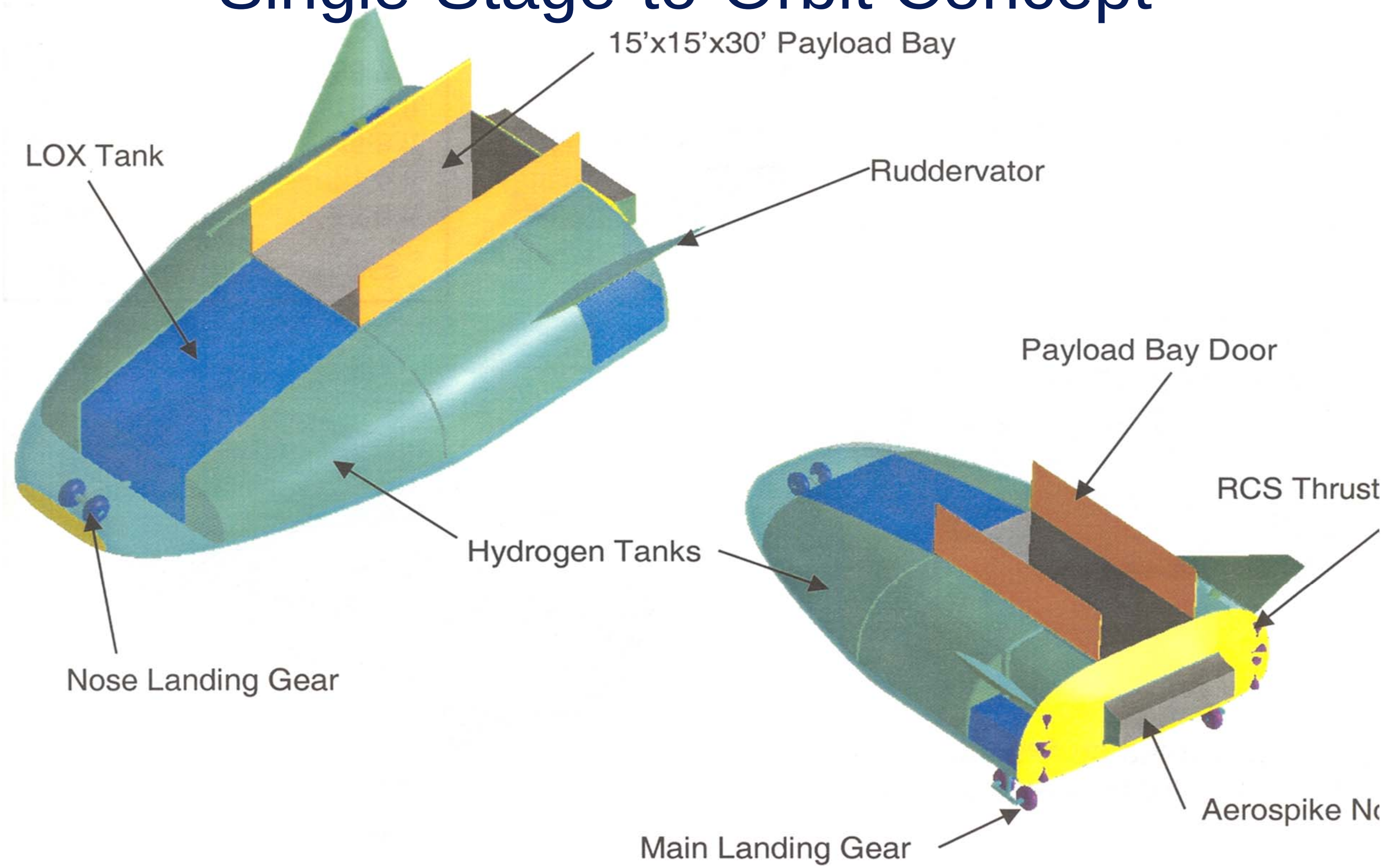
$$\frac{dm}{dt} = \frac{-T}{I_{sp}}$$

Integrate until r = orbit, v = orbital speed, γ = 0 deg solving Mass Ratio (MR)

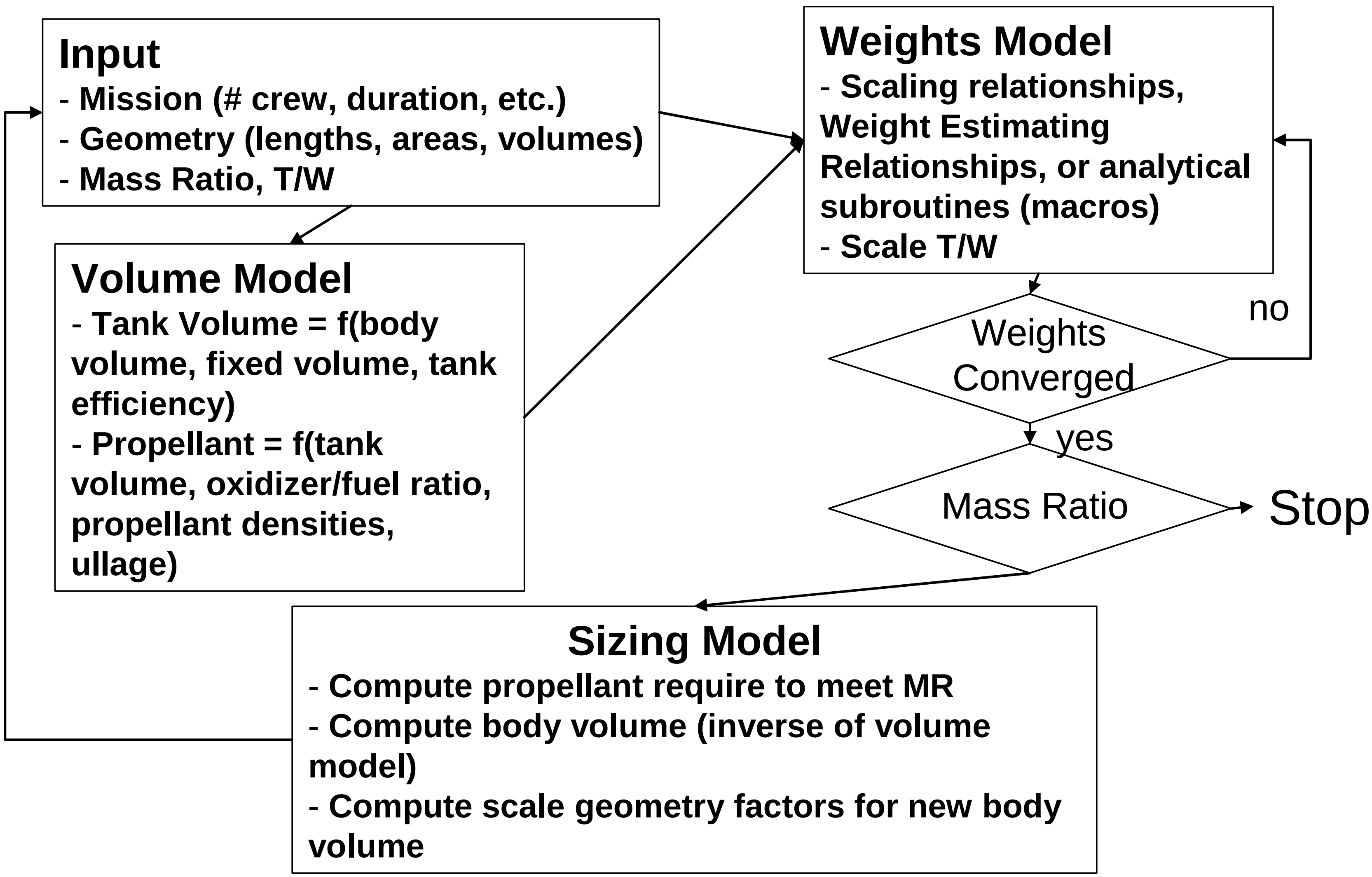
Closure Model

- Vehicle weights, aerodynamics, and thrust (MR, T/W, T/D) must match trajectory result for closure
- Vehicle closure model should include
  - propellant sizing and associated geometry and weights
  - size thrust and associated propulsion and thrust sensitive components
  - size aerodynamic surfaces (especially if landing and/or takeoff speeds are constrained)

Single-Stage-to-Orbit Concept



Launch Vehicle Spreadsheet Sizer (LVSS) Modules



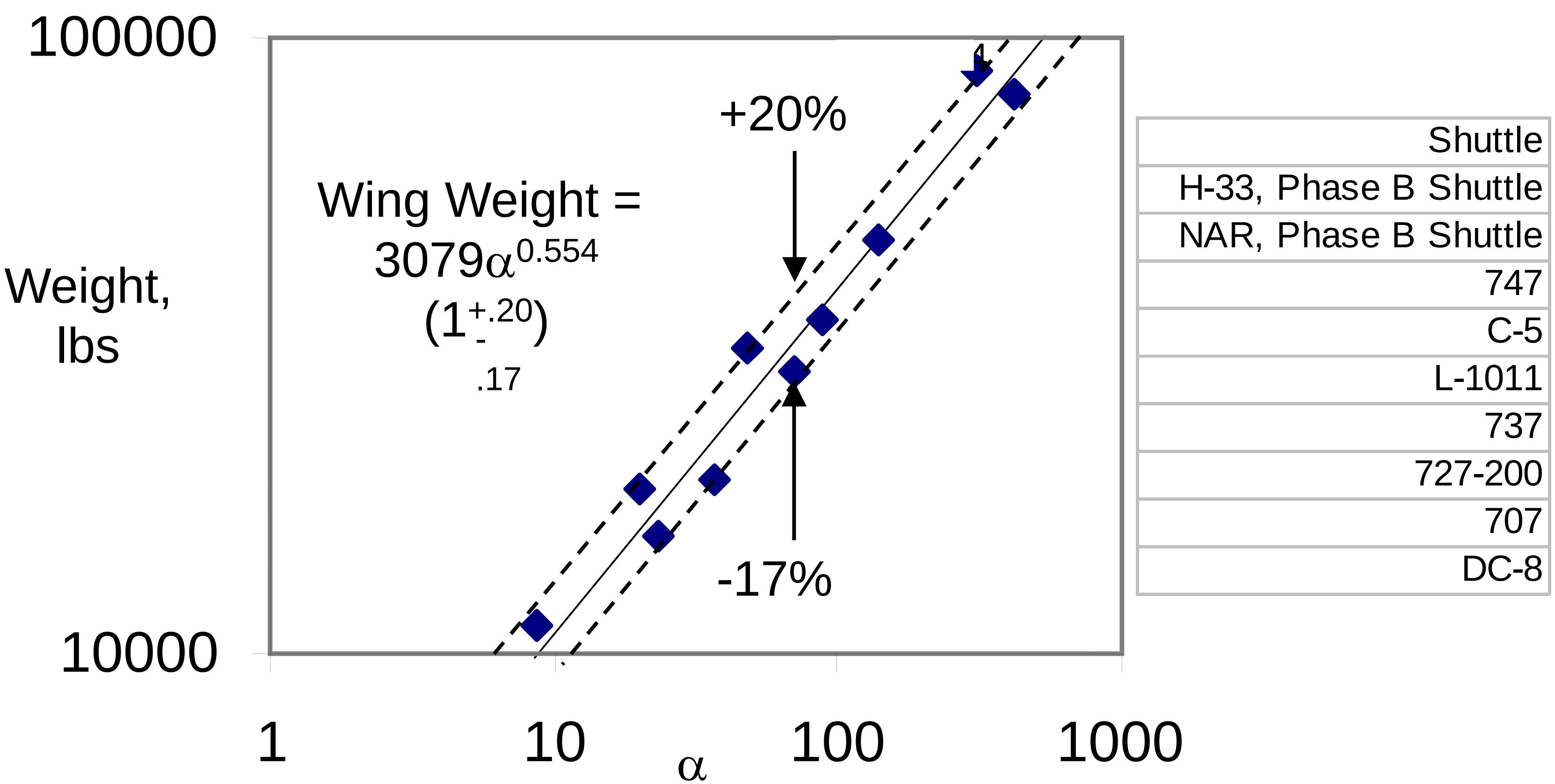
Launch Vehicle Spreadsheet Sizer (LVSS) Output

1.0 Wing		26545	
2.0 Tail		2969	
	LH2 tank		12793
	LO2 tank		9541
	Basic structure		18680
	Secondary structure		12012
3.0 Body		53025	
	TPS		21064
	Internal insulation		1075
	Purge, vent, drn, & hazrd gas det.		941
4.0 Induced environment protectio		23079	
5.0 Undercarriage and aux. syster		8851	
6.0 Propulsion, main		72287	
7.0 Propulsion, reaction control (R		3536	
8.0 Propulsion, orbital maneuver (		3040	
9.0 Prime power		2968	
10.0 Electric conversion and distr.		8710	
11.0 Hydraulic conversion and dis		0	
12.0 Control surface actuation		3648	
13.0 Avionics		6504	
14.0 Environmental control		2839	
15.0 Personnel provisions		0	
16.0 Range safety		0	
17.0 Ballast		3225	
18.0 Payload provisions		0	
EMPTY		199104	

19.0 Growth allowance	69116
20.0 Personnel	0
21.0 Payload accomodations	0
22.0 Payload	1840062
23.0 Residual and unusable fluids	2701
25.0 Reserve fluids	8629
26.0 Inflight losses	9536
27.0 Propellant, main	1663724
28.0 Propellant, reaction control	1070
29.0 Propellant, orbital maneuver	0
PRELAUNCH GROSS	3793942

Historical Weight Estimating Relationship

(Wing)



$$\alpha = \left(\frac{\text{Design Weight*Maneuver Load*Safety Factor*Structural Span}}{\text{Root Chord}}\right)$$

DDT&E Costing Methodology

$$\text{DDT\&E Cost} = \sum a * W^{b} * f1 * f2$$

DDT&E -- (Design, Development, Testing & Engineering)

i = all subsystems
a, b = calibration constants based on STS systems
W = dry weight of subsystem
f1 = new design factor ranging from 0 to 1.0
= 0 for "as is" hardware
= 1.0 for new components, no DDT&E experience, unproven technology (technology levels 4 -5)
f2= design complexity
> 1.0 system functions/specs higher than estimate basis
= 1.0 same function/specs as basis of estimate
< 1.0 fewer functions or lower specs than estimate basis

Weight, W, is a function of concept design maturity

Cost Estimating Process

INPUTS
- Weights
- Technical Parameters
- Complexity Factors

ESTIMATING RELATIONSHIPS

NAFCOM99:
- Cost = A * Wt ^ b * Complexity Factors
- Cost = C * Wt ^ w * New Design ^ x * Technology ^ y * Management ^ z

Other:
- Rocketdyne's Liquid Rocket Engine Cost Model

OUTPUTS
- DDT&E Cost
- First Unit Cost

Cost per Flight

Category	Component
Vehicle Cost	Vehicle recurring cost (fabrication, assembly, and verification), amortization share Refurbishment Cost (including spares)
Direct Operations Cost	Pre-launch ground operations cost, Mission and flight operations cost Propellants, gases, and consumables Ground transportation cost Launch site user fee (per launch) Mission abort and premature vehicle loss charge
Indirect Operations Cost	Program administration and system management Marketing, customer relations, and contracts office Technical support and vehicle improvements Development amortization and royalty or cost recovery of technical changes Profit, taxes, and fees

Production Costs

Production Cost = Theoretical First Unit x Learning Factor

Where

Learning Factor = Number of Units B

And

B = ln(100/Learning curve slope)/ln 2

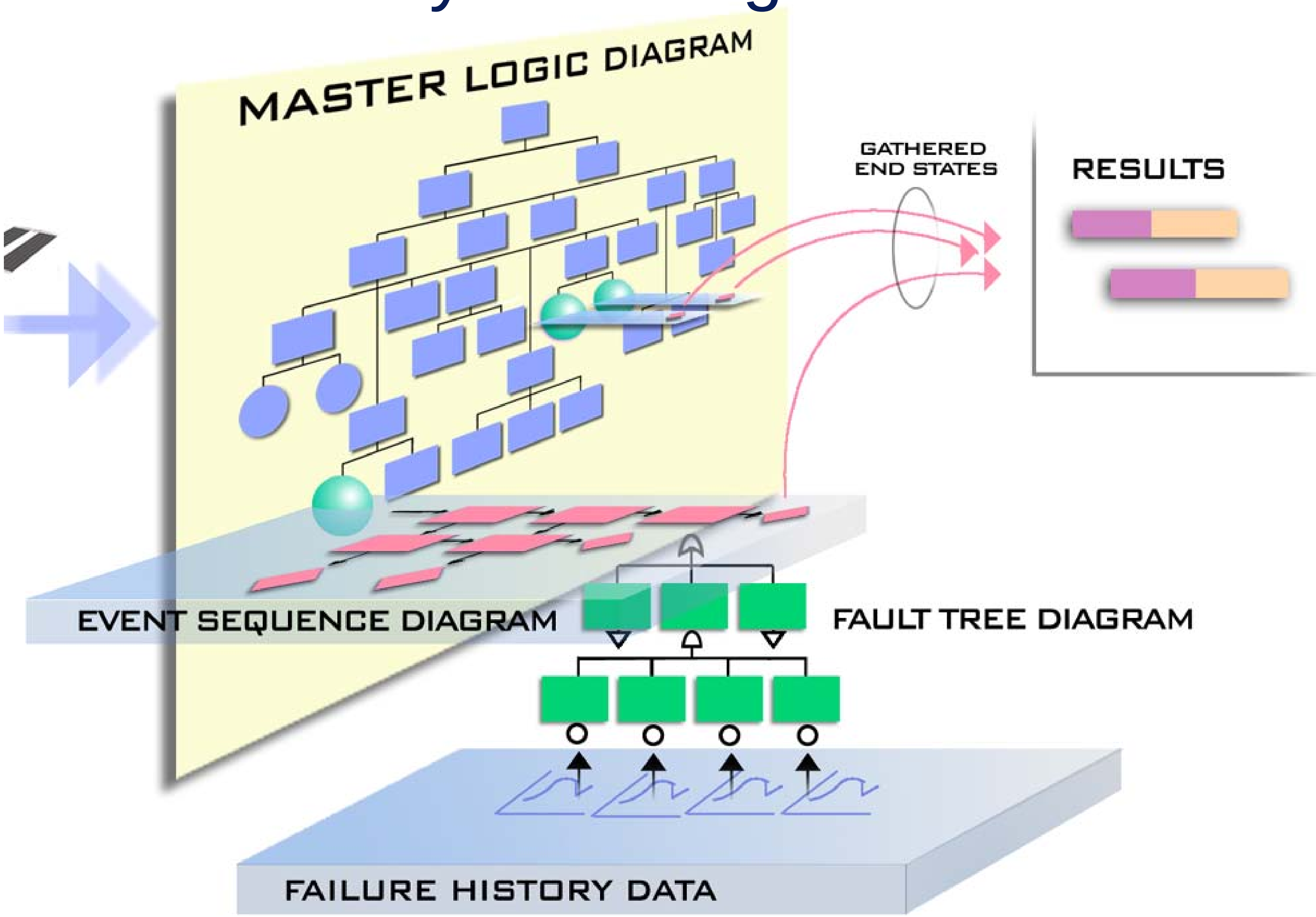
Where

Learning curve slope = percentage reduction in cumulative average cost when the production number of units is doubled.

Unit number	Production cost, TFU x L	Average cost	Unit cost
1	1.00	1.00	1.00
2	1.90	0.95	0.90
3	2.77	0.92	0.87
4	3.61	0.90	0.84
5	4.44	0.89	0.83

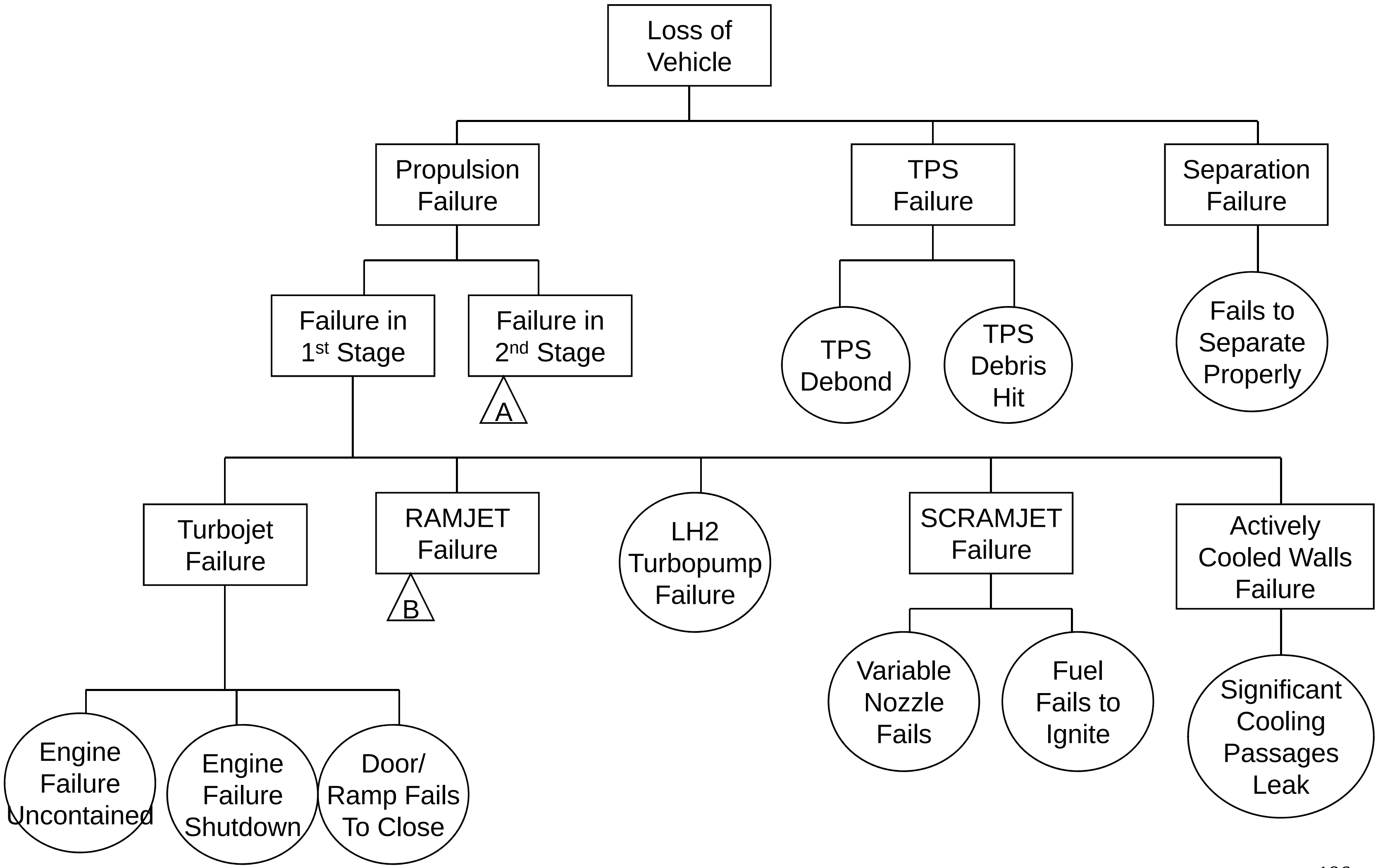
A 95% Learning curve example

Safety Modeling Process

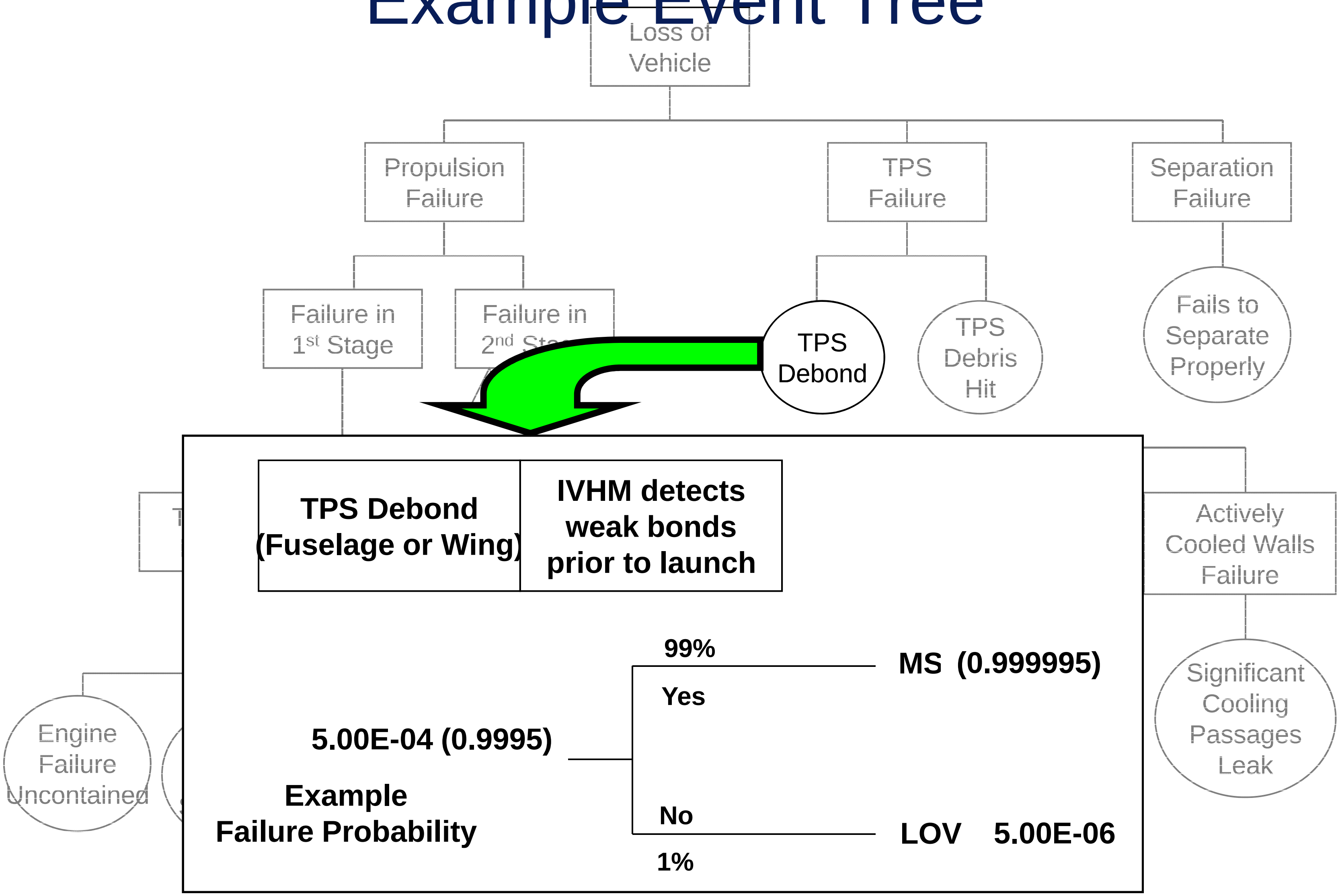


Example Master Logic Diagram

(Fault Tree)



Example Event Tree



Example Safety Analysis Results

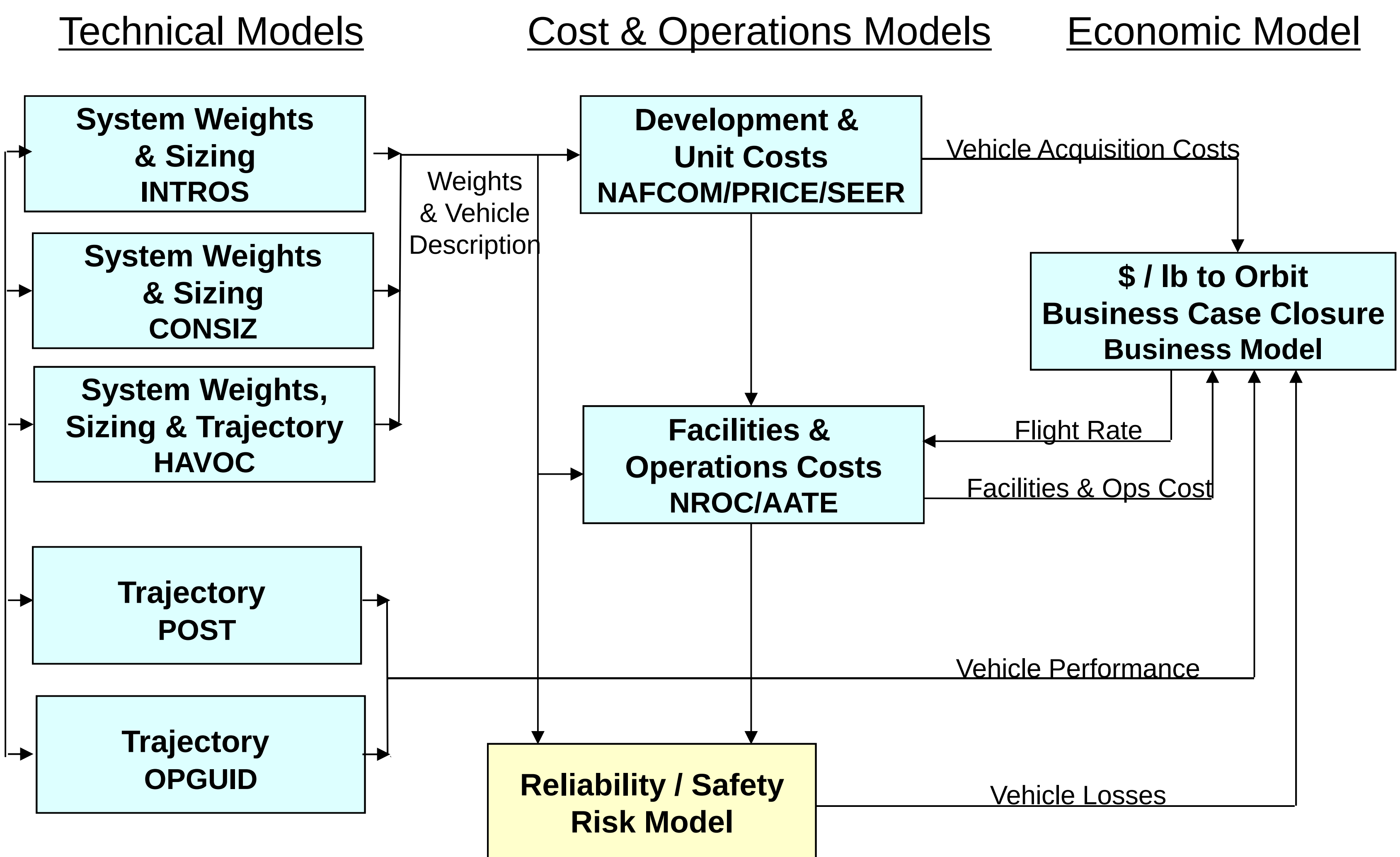
	5th	50th	Mean	95th
Overall LOV Risk	**1.777E-05**	**6.463E-05**	**1.037E-04**	**3.150E-04**
1 in	**56,275**	**15,473**	**9,643**	**3,175**

	5th	50th	Mean	95th
1st StageOverall LOV Risk (MTBF)	371,471	142,227	100,756	40,833
1st Stage Propulsion	753,580	237,699	142,552	50,505
1st Stage TPS - Ascent	3,410,641	915,751	623,441	222,568
1st Stage TPS - Descent	14,545,455	1,752,234	716,332	197,044
1st Stage Landing Risk	12,883,277,506	354,735,722	36,630,037	10,571,942
Separation Risk	< 1 in 10 billion	< 1 in 1 billion	< 1 in 1 billion	843,170,320

	5th	50th	Mean	95th
2nd Stage Overall LOV Risk (MTBF)	96,246	18,986	10,909	3,374
2nd Stage Landing Risk	113,122	19,670	11,128	3,411
2nd Stage Propulsion	11,967,449	1,395,868	560,538	146,929
2nd Stage TPS - Descent	282,953,426	38,639,611	17,621,145	4,997,144
2nd Stage TPS - Ascent	< 1 in 10 billion	< 1 in 10 billion	78,740,157	28,011,204

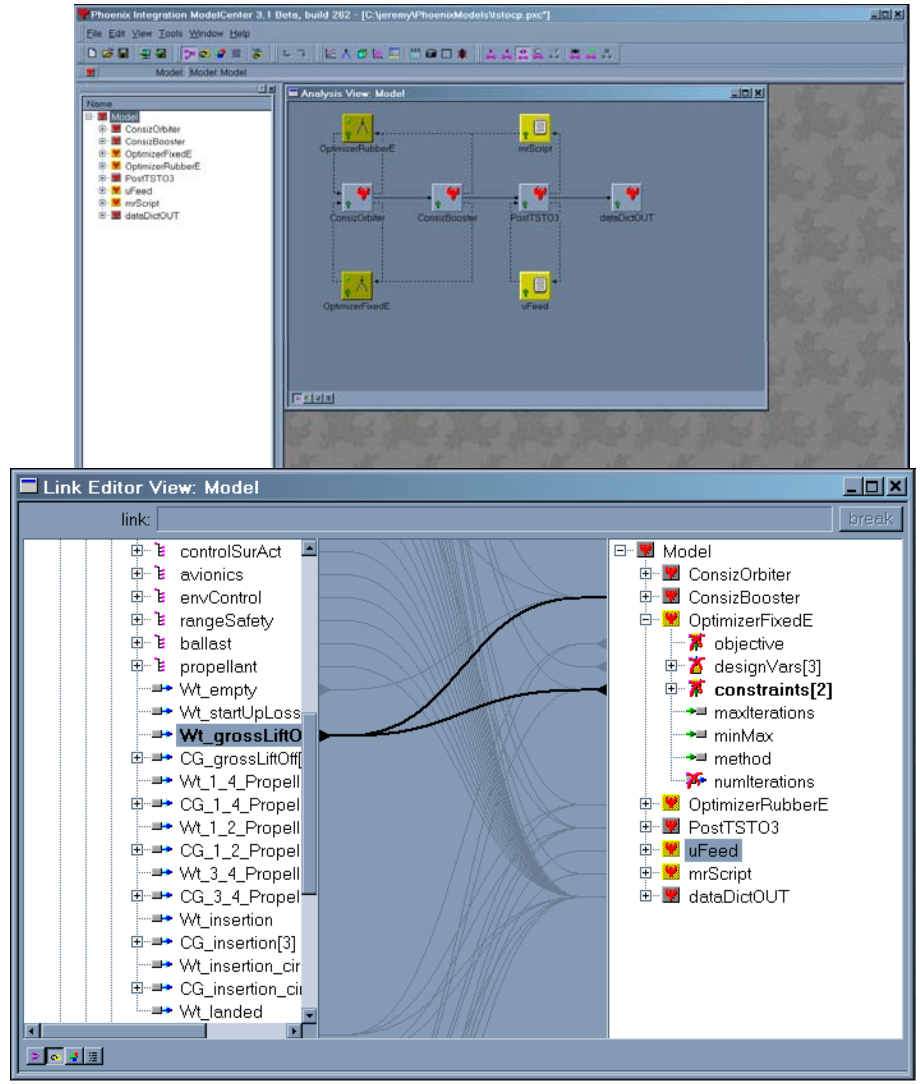
*** Landing Risk associated with an abort are included in LOV risk numbers**

Quantitative Models – Launch Systems Analysis



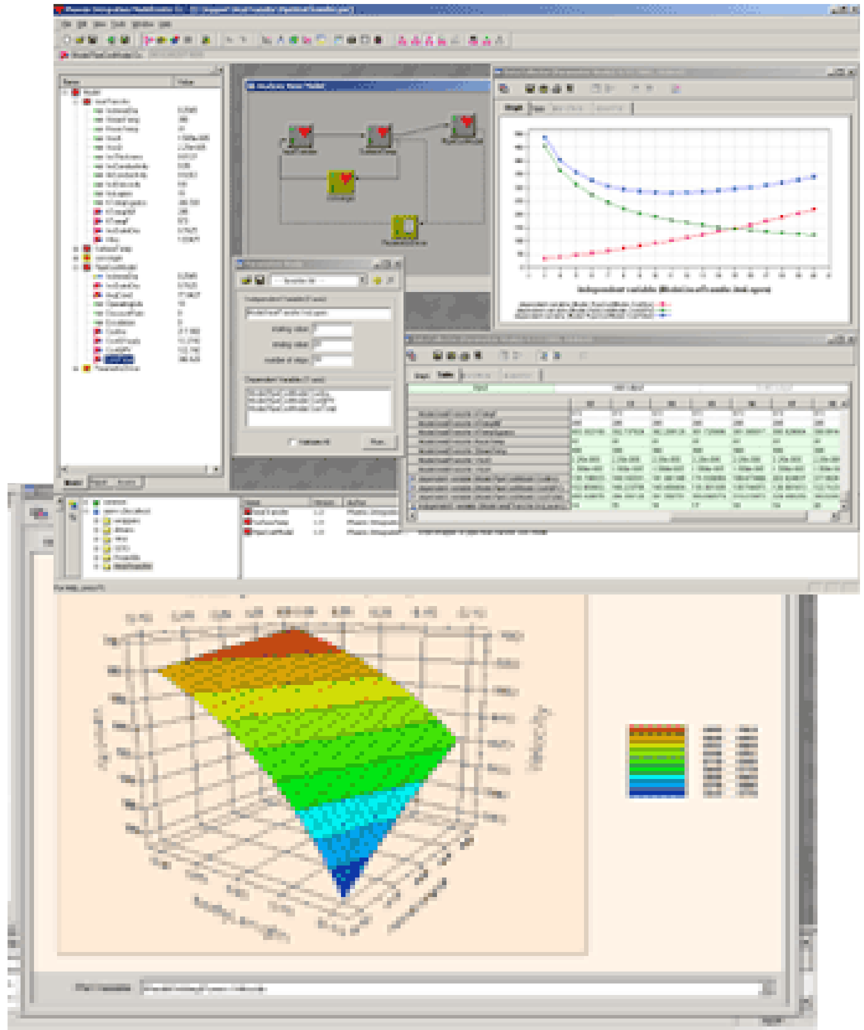
ModelCenter® for Integrated Analysis

- **The Link Editor**
  - Visually link data between different components on different platforms
  - Link data from one component to another
  - Support multi-to-one links and units conversion
  - Algebraic equations can be specified in the link to provide other translation
  - Data types range from simple integers to complex matrices
  - User-defined data types can be constructed and linked



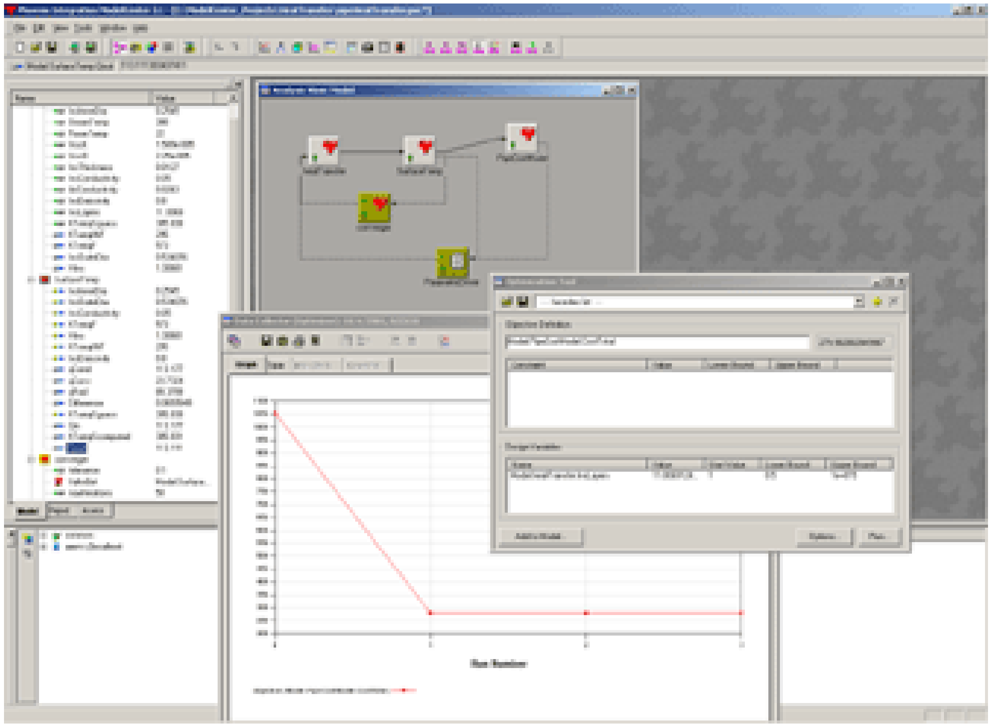
ModelCenter® for Analysis (Design of Experiments)

- DOE Tool
  - The Design of Experiments (DOE) Tool allows users to customize and set up an entire series of runs to measure multiple output responses generated from multiple input data sources.
  - Once the DOE runs are complete in ModelCenter, the user can select any one of the designs for further exploration. The data can be exported for plotting and generation of response surfaces.



ModelCenter® for Analysis (Optimization)

- Optimization Methods include:
  - Variable Metric
  - Conjugate Gradient
  - Feasible Directions
  - Sequential Linear Programming
  - Sequential Quadratic Programming



Key Points

- Models can be networked together if necessary. Excellent tools are available to facilitate model integration.
  - ModelCenter was outlined, but several other tools are available (e.g. Isight with SIMULIA).

- But, be wary of integrating models because it can be done; an unwieldy model may be the result. Rather, use the same discipline in integrating models that is used to develop one model.
  - Recall the 4 step process in model development.
  - Simplify, simplify, simplify

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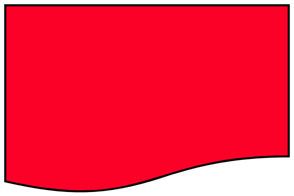
Lesson 9:
Systems Simulation

Objectives

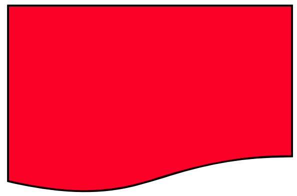
- Review 4 step simulation process.
- Illustrate the simulation process in the modeling of torque & horsepower in an engine simulation.
- Illustrate the simulation planning process using design of experiments (DOE) based approaches.

Vehicle Simulation – Levels of Maturity



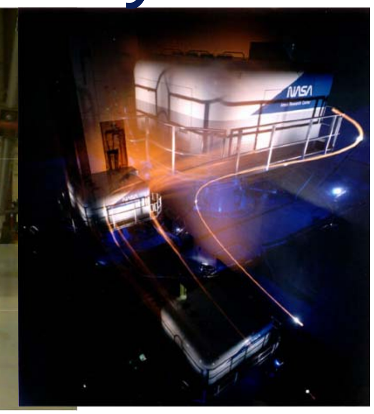
1- to 3-D
Trajectory Simulation

- Performance
- Stability
- Limited Control



6-D
Trajectory Sim

- Stability & Control
- Dynamics
- Control Law Design/ Optimization



Cockpit Simulator

- Human-in-loop
- Dispersion Analysis
- Training

Specialized Simulators

Total In-Flight Simulator

Classes of Simulations

- **Virtual** simulations represent systems both physically and electronically. Examples are aircraft trainers, the Navy's Battle Force Tactical Trainer, Close Combat Tactical Trainer, and built-in training.

- **Constructive** simulations represent a system and its employment. They include computer models, analytic tools, mockups, Flow Diagrams, and Computer-Aided Design/ Manufacturing (CAD/CAM).

- **Live** simulations are simulated operations with real operators and real equipment. Examples are fire drills, operational tests, and initial production run with soft tooling.

Types of Simulations

- **Continuous Simulation**. Exogenous variables change continuously over simulated time, where time may be either discrete or continuous.

- **Discrete Simulation**. Exogenous variables change discretely at specified points in simulated time, where time may be either discrete or continuous.

- **Combined Simulation**. Exogenous variables may change discretely, continuously, or continuously with discrete jumps superimposed.

Recall the 4 Step Simulation Process

1. **Modeling**. Refer to the 4 Step Model Process.
2. **Strategic & Tactical Planning**. What are the experimental conditions (variable ranges & increments) for using the model?
3. **Experimentation**. Run the model on the specified parameter sets.
4. **Analysis of Results**. What inferences may be drawn from the data and what recommendations for problem resolution can be made?

Uses of DOE and Response Surfaces

- Used for screening the sensitivity and design space for large number of variables
- Used for determining the optimum for variable settings in minimum number of trails
- Used for assessing design robustness with 2nd order sensitivities
- Used to represent large-time consuming physics-based or simulation based models for systems integration and/or optimization

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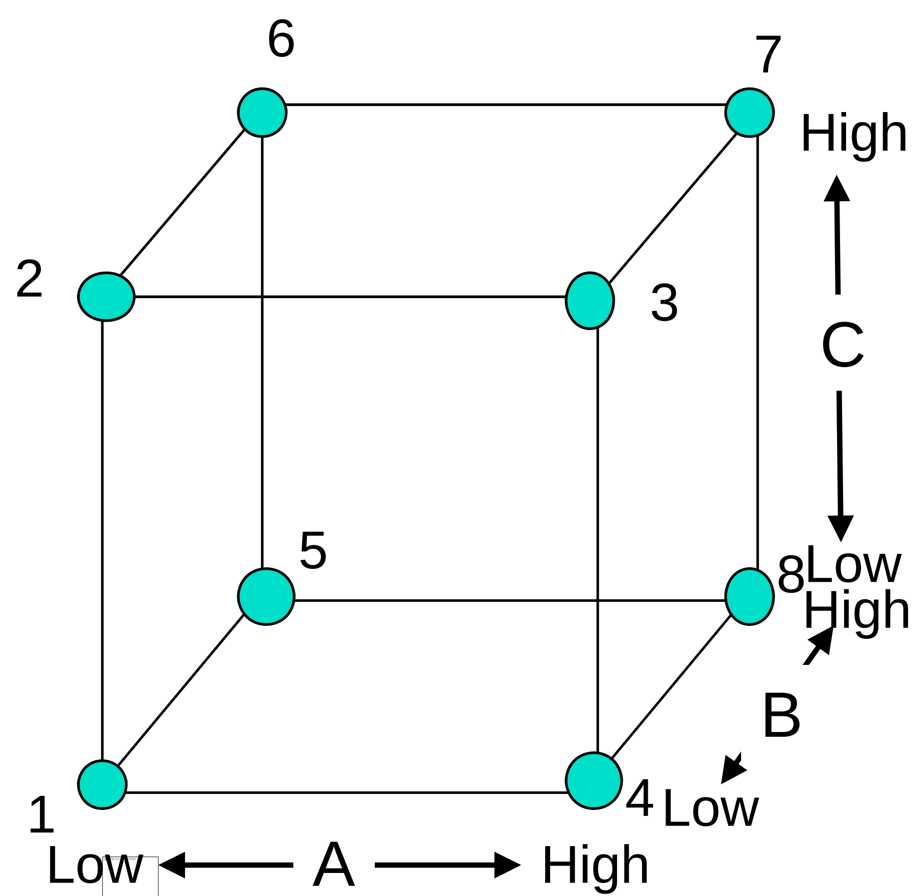
Design of Experiments

- Design Variables and Ranges are Established
- Variables are "Discretized" and Normalized to Fixed Levels [-1, 1]
- Two-level Variables are Most Popular for Simple DoE

Variable	Range	Discretized	Normalized
Engine Thrust	100 - 200 Klb	100 Klb	-1
		200 Klb	+1

Full Factorial Array
(all possible combinations)

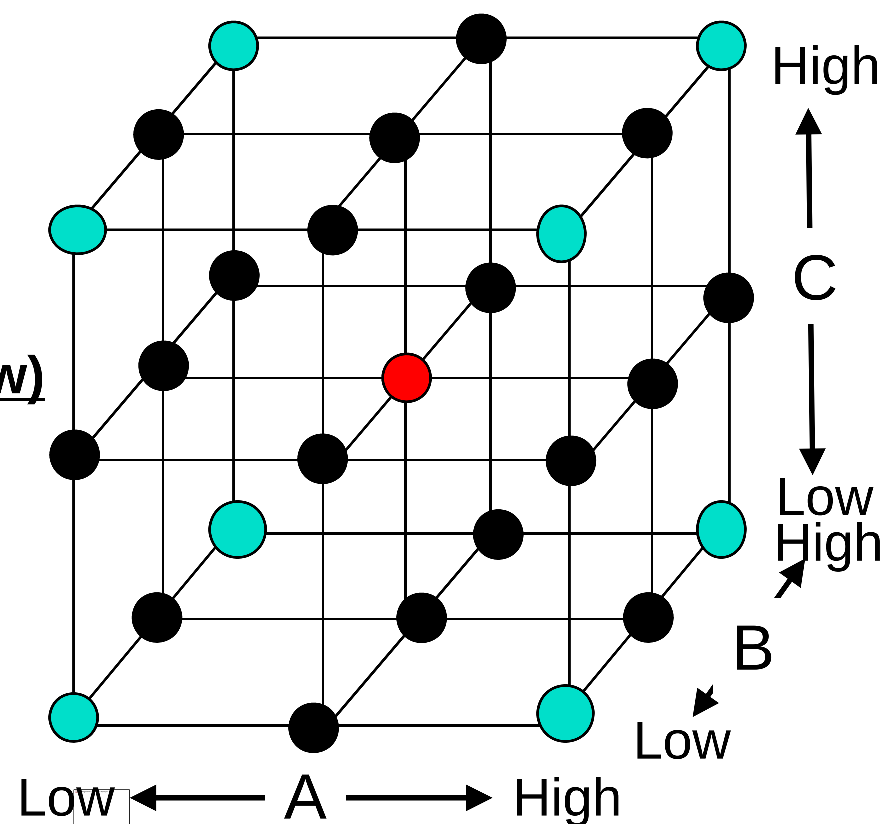
3 Parameters (A, B, C)
<u>2 Variations (High, Low)</u>
8 Experiments



Full Factorial Array for 2nd Order Effects

(all possible combinations)

3 Parameters (A, B, C)
<u>3 Variations (High, Medium,Low)</u>
27 Experiments



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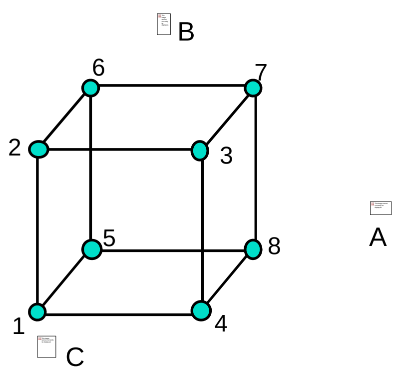
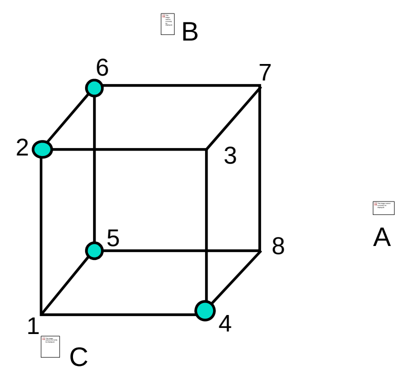
Taguchi Methods

- Based on orthogonal arrays (2, 3, and 5 level)
- Taguchi's orthogonal arrays are fractional DoE's for experimental efficiency
- Orthogonal arrays are balanced and dot product of 2 columns equals 0

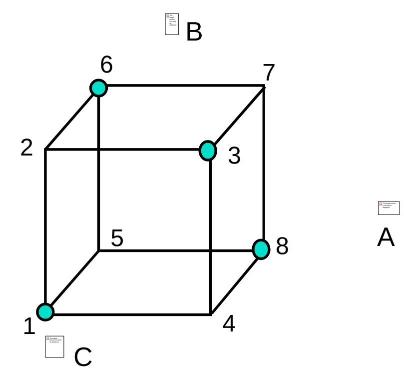


Full Factorial Array

(all possible combinations)



Unbalanced Array



L_4 Orthogonal Array

(each setting is equally represented)

Design Point Requirements for a 2nd Order Model

Number of Variables	Full Factorial Design	CCD Design	D-Optimum Design
3	27	15	11
4	81	25	16
5	243	27	22
7	2187	79	37

Example – Engine Simulation

- Objective is to quantify the relationship between valve lift & duration and average horsepower produced over the 2000-6500 rpm band.

- Use a 350 in^3 small block Chevy,
  - Naturally aspirated using a 600 cfm carburetor
  - Small tube headers & mufflers
  - Performance heads
  - Dual plane manifold
  - 10:1 Compression ratio

Example (continued)

- Two factors – valve lift & duration
- Because we're interested in possible nonlinear relationships, we'll test each factor at three levels
  - A total of nine runs

Example Run Matrix

Variable	Range (Intake/Exhaust)	Discrete Values
Duration	252/258 to 294/300 degrees	252/258
		276/282
		294/300
Lift	0.472/0.480 to 0.540/0.562 in.	0.472/0.480
		0.502/0.510
		0.540/0.562

Example Results – Average Horsepower

	Valve Duration		
Valve Lift	252/258	276/282	294/300
0.472/0.480	306.7	317.3	291.5
0.502/0.510	308.4	319.2	293.3
0.540/0.562	309.4	320.9	294.9

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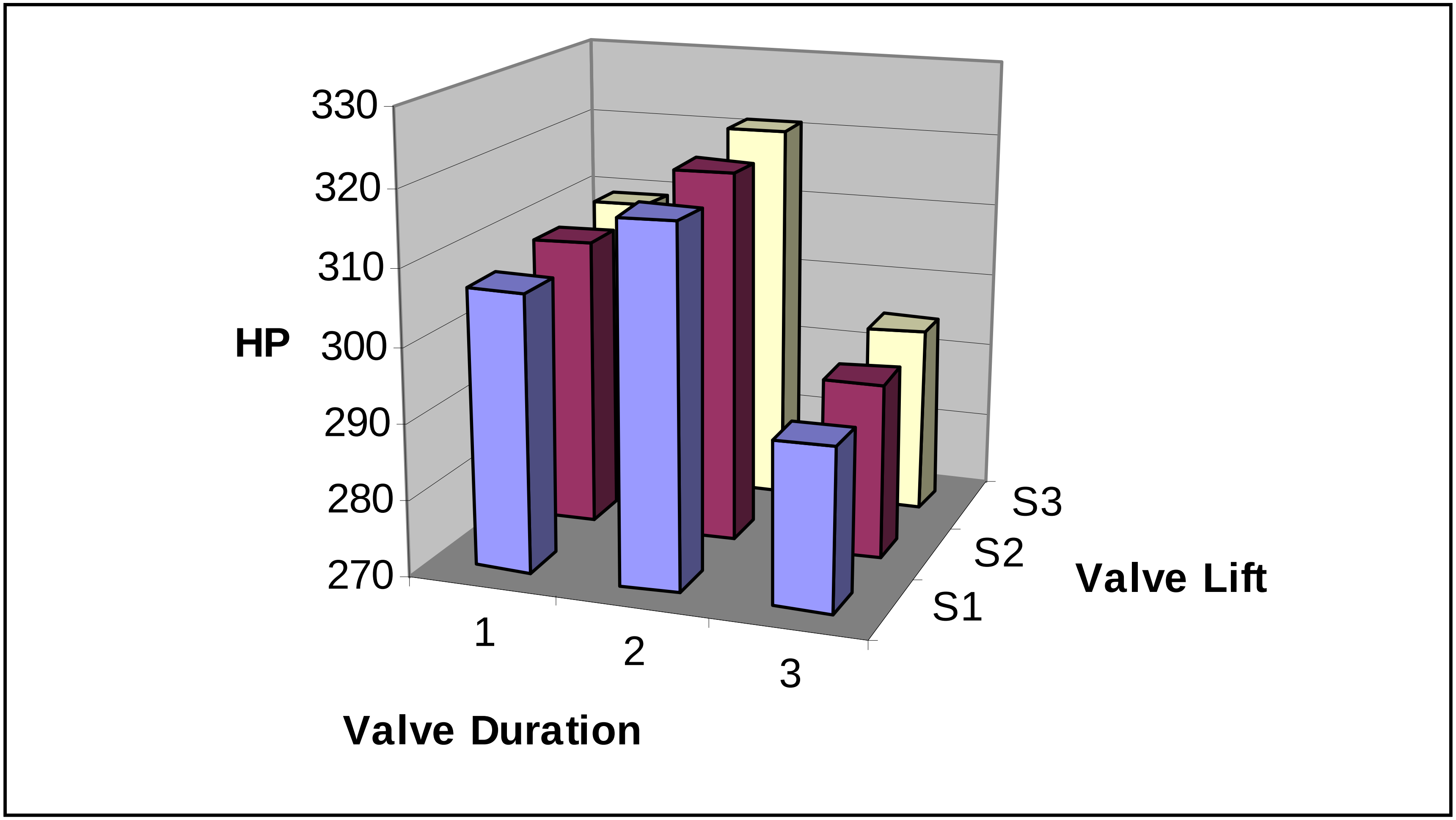
Example – Plot of Experimental Results



Use of Response Surface Methods (RSM)

- Obtain polynomial approximations to relationships between performance characteristics and design parameters.

$$y = \beta_o + \beta_1{*}A + \beta_2{*}B + \beta_3{*}C + \beta_4{*}AB + \beta_5{*}AC + \beta_6{*}BC + \beta_7{*}ABC$$

- Response surface model captures individual effects, parameter/discipline interactions, and non-linearity (curvature).
- These models are then used to determine optimum values and for sensitivity studies.

Constructing the Response Surface Model

- One way is to sample from the design space using Design of Experiments (DOE) techniques.

Efficient DOE Methods

- Utilize fractional factorial DOE designs for efficiently constructing non-linear approximation models.
  - Central Composite Designs
  - D-Optimal Designs for Computer Experiments
- The response surface model coefficients can be estimated efficiently by sampling the design space using these techniques.

Fitting a Simple Model From DOE

The following mathematical model for the 2^3 array can be determined...

$$y = \beta_o + \beta_1{*}A + \beta_2{*}B + \beta_3{*}C + \beta_4{*}AB + \beta_5{*}AC + \beta_6{*}BC + \beta_7{*}ABC$$

$$\bar{y} = [X]\ \bar{\beta}$$

$$\bar{y} = \begin{bmatrix} 1 & -1 & -1 & -1 & 1 & 1 & 1 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ 1 & -1 & 1 & 1 & -1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 & -1 & 1 & -1 & -1 \\ 1 & 1 & 1 & -1 & 1 & -1 & -1 & -1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \bar{\beta}$$

The solution to the unknown coefficients (b's) can be solved by linear regression on the experimental data.

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Example Response Surface

$$y = 257.1 + 66.27x_1 + 1.617x_2 - 18.43x_1^2$$

Where: y = predicted average horsepower
x_1= valve duration (coded 1,2,3)
x_2= valve lift (coded 1,2,3)

Example – Optimization

- Response Surface Model Prediction
  - 321.5 HP at 1.8 duration & 3.0 lift (coded)
    - Duration = 269/275
    - Lift = 0.540/0.562

- Dyno Simulation
  - 323.7 HP at 270/276 degrees duration & 0.540/0.562 inches lift

Key Points

- Systems Simulation is the usage of models to conduct experiments.
- DOE methods are very useful in strategic & tactical planning for simulation runs.
- Care must be exercised in planning simulations such that the behavior of the system to input variable & parameter variations is evaluated.

Lesson 10:
Requirements Analysis & Validation

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Objectives

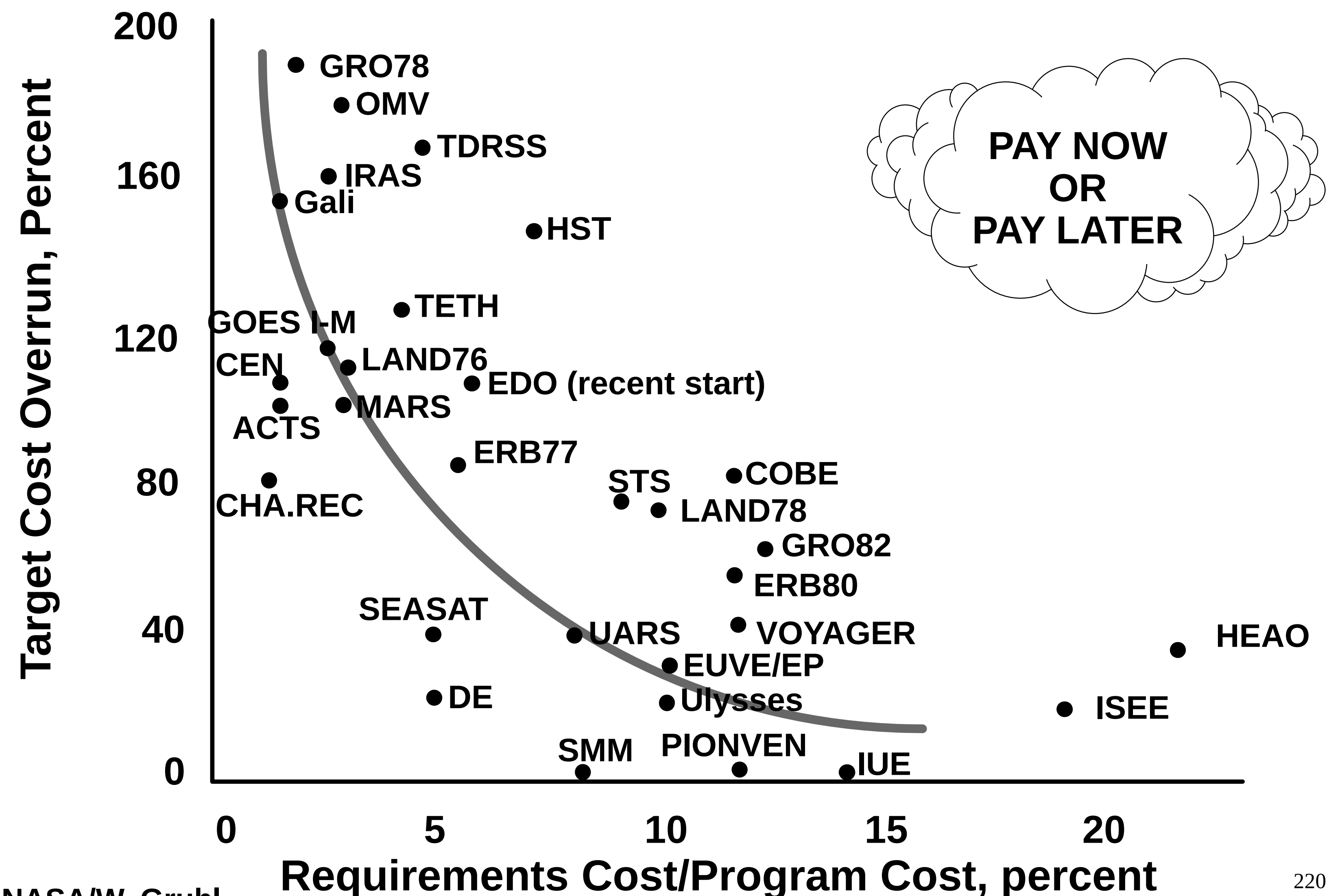
- Reference to IEEE-1220 processes
  - 6.7.1 Assess Requirement Conflicts
  - 6.7.2 Assess Functional Alternatives
- Illustrate systems analysis support of requirements analysis & requirements validation processes

Requirements Analysis

- In the first stages of systems development we use systems analysis to help develop requirements

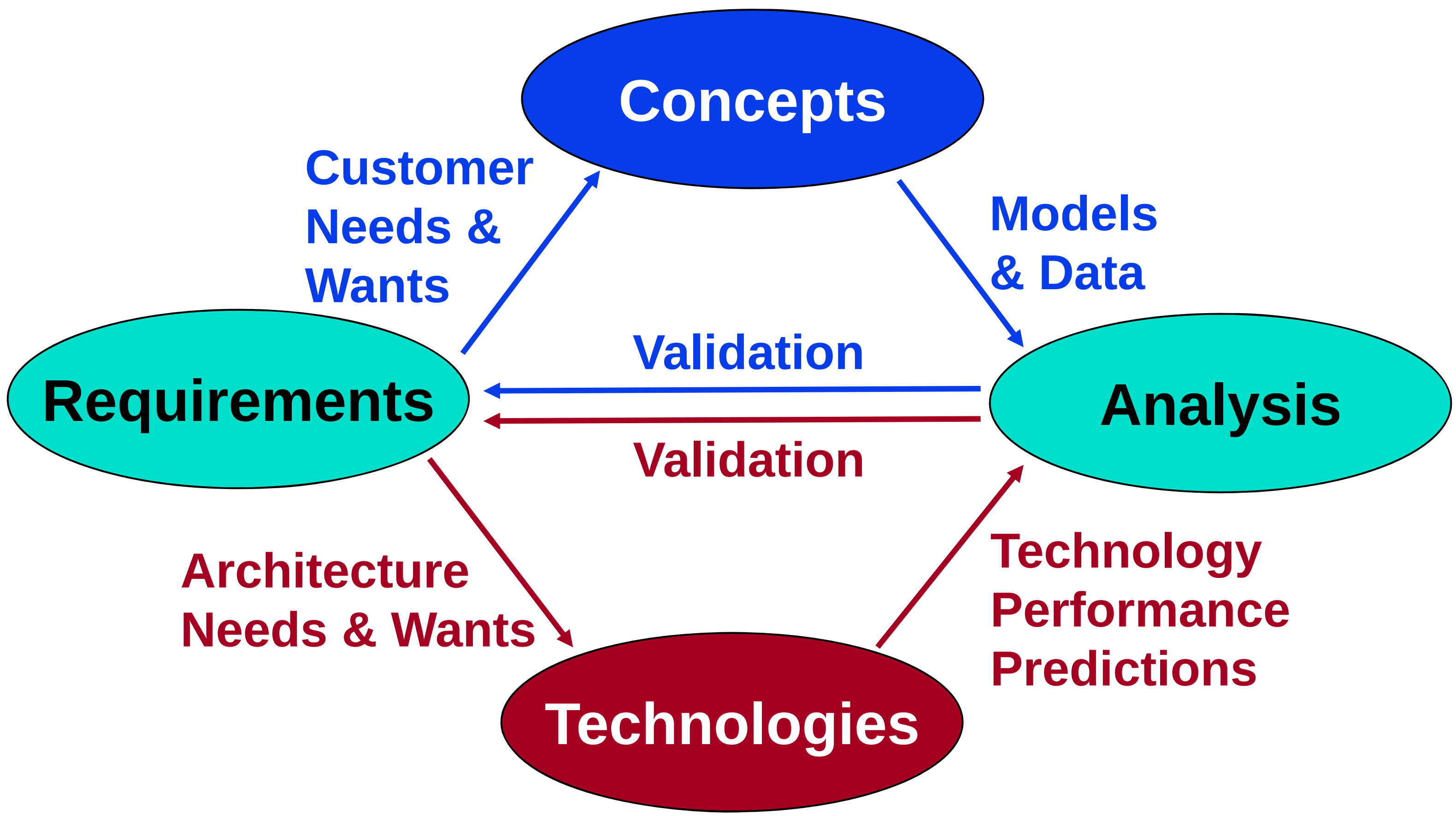
- Answers the questions
  - What functions will the system perform?
  - When will the system perform?
  - Where will the system perform?
  - How will the system accomplish its objective?

Effect of Requirements Definition Investment on Program Costs



Ref: NASA/W. Gruhl

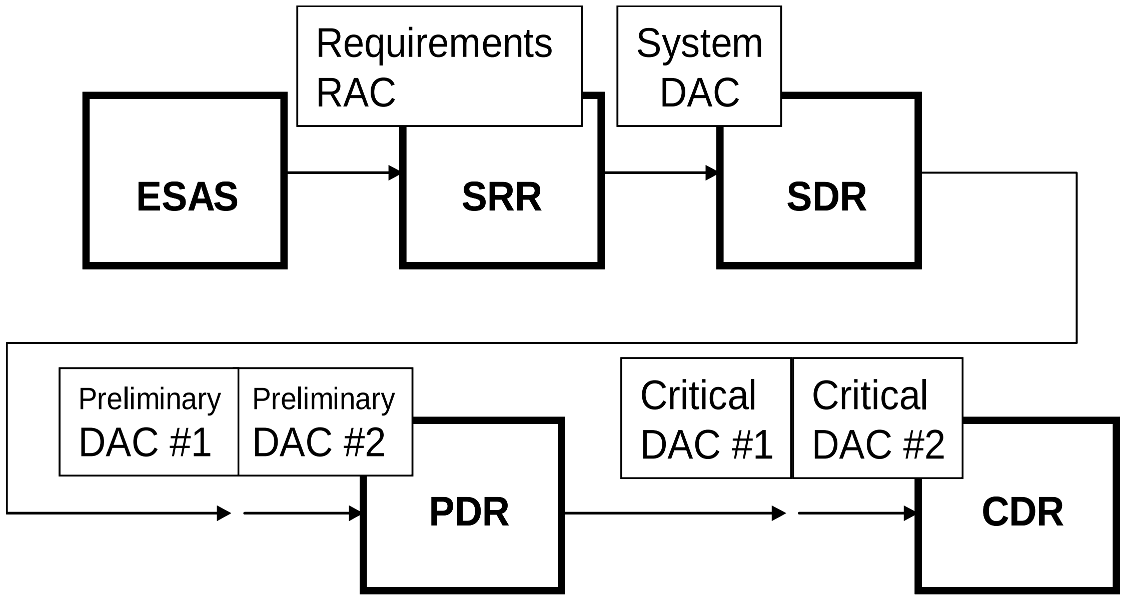
Design Feasibility



- Analysis cycles validate requirements and foster mutually consistent architectures and technologies.

Analysis Cycle Roadmap

- For a Program based on NASA's Life Cycle Program Plan, Analysis Cycles should be planned to support the schedule and objectives of Program reviews
- This Program is using the ESAS activity as the Pre-Phase-A (MCR) and Phase-A (MBR) milestones. We are now in Phase-B, Definition.
- Regardless of Program Phase, all analyses should be driven by requirements
  - Requirement Definition
  - Requirement Validation
  - Operational Concept refinement or resolution
  - Requirement Verification



Top Level Analysis Cycle Roadmap

The rest of this lesson will use the term DAC as a generic term for an analysis cycle

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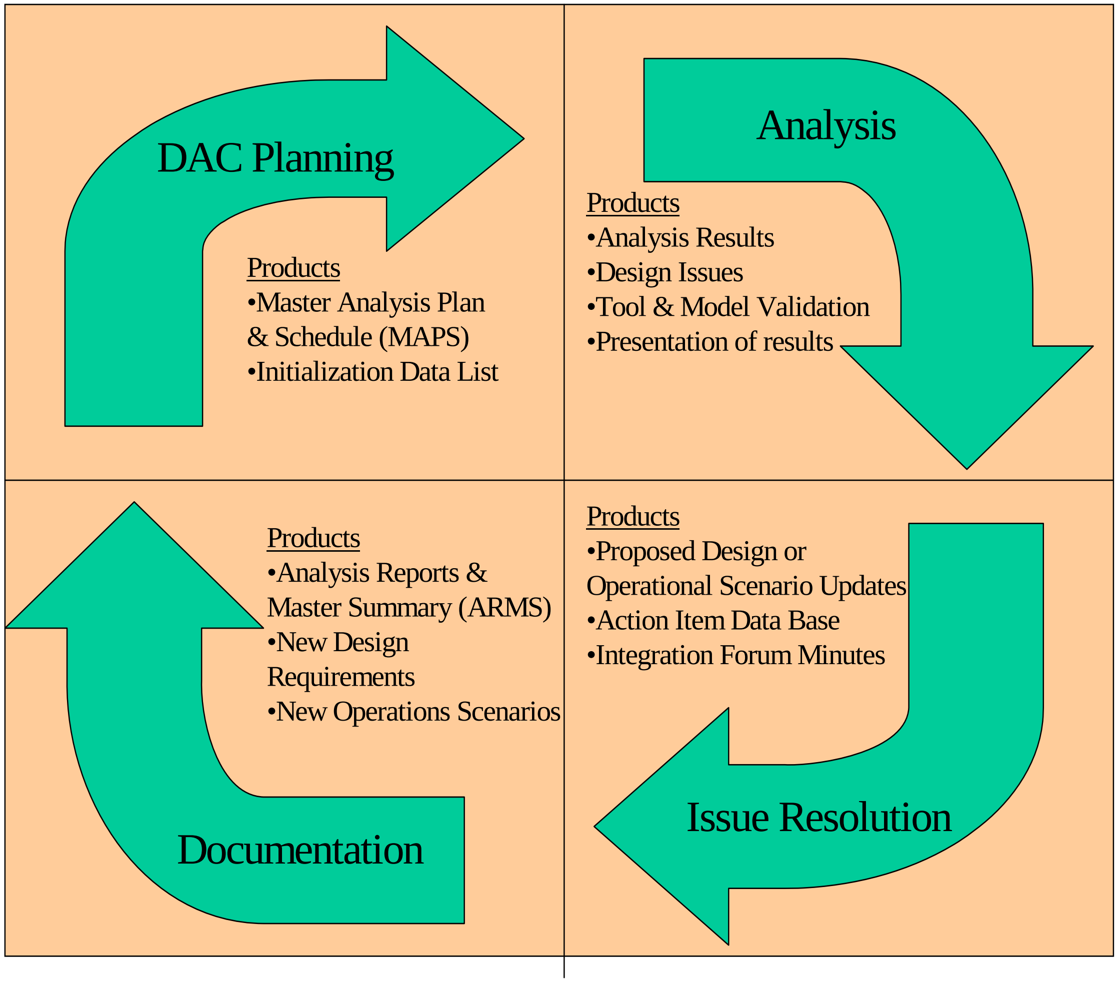
DAC Process Overview

- The essence of the Design Analysis Cycle process is the cyclical execution of a planned set of complementary engineering analyses and trade studies to characterize the capability and functionality of a system.
- The objective is to ensure that the system will perform the intended mission.
- The process is divided into four main functions: DAC planning, analysis, issue resolution, and documentation.



Coverage Matrix

- Validate Coverage
  - Are all requirements properly covered by this cycle ? Enables a cognizant decision on each requirement
- CM Elements
  - Requirement – from respective Spec
  - Analysis – Task associated with TDS
- Coverage Stages
  - Requirements (this example) – analysis to solidify requirements
  - Design – analysis to develop and mature the design to a stated level
  - Verification – analysis to verify that the design meets the requirements
- Example Issues
  - ① No coverage – no analysis being performed in support of a requirement – may be intentional (not required)
  - ② Duplicate coverage – multiple analyses working same requirement – may be intentional (validation of results)
  - ③ Unnecessary coverage – analysis against a requirement that needs no work to meet the goals of this cycle
  - ④ Missing requirement – analysis cannot be mapped to a current requirements – may need to add

Example Coverage Matrix

Requirement	AN #1	AN #2	AN #3	AN #4	AN #5
Rqmt #1 - TBR	X				
Rqmt #2 - TBR			1		
Rqmt #3 - TBR	X	2	X		
Rqmt #4 - Baselined			X	3	
Rqmt #5 - TBR					X
No Rqmt				4 X	

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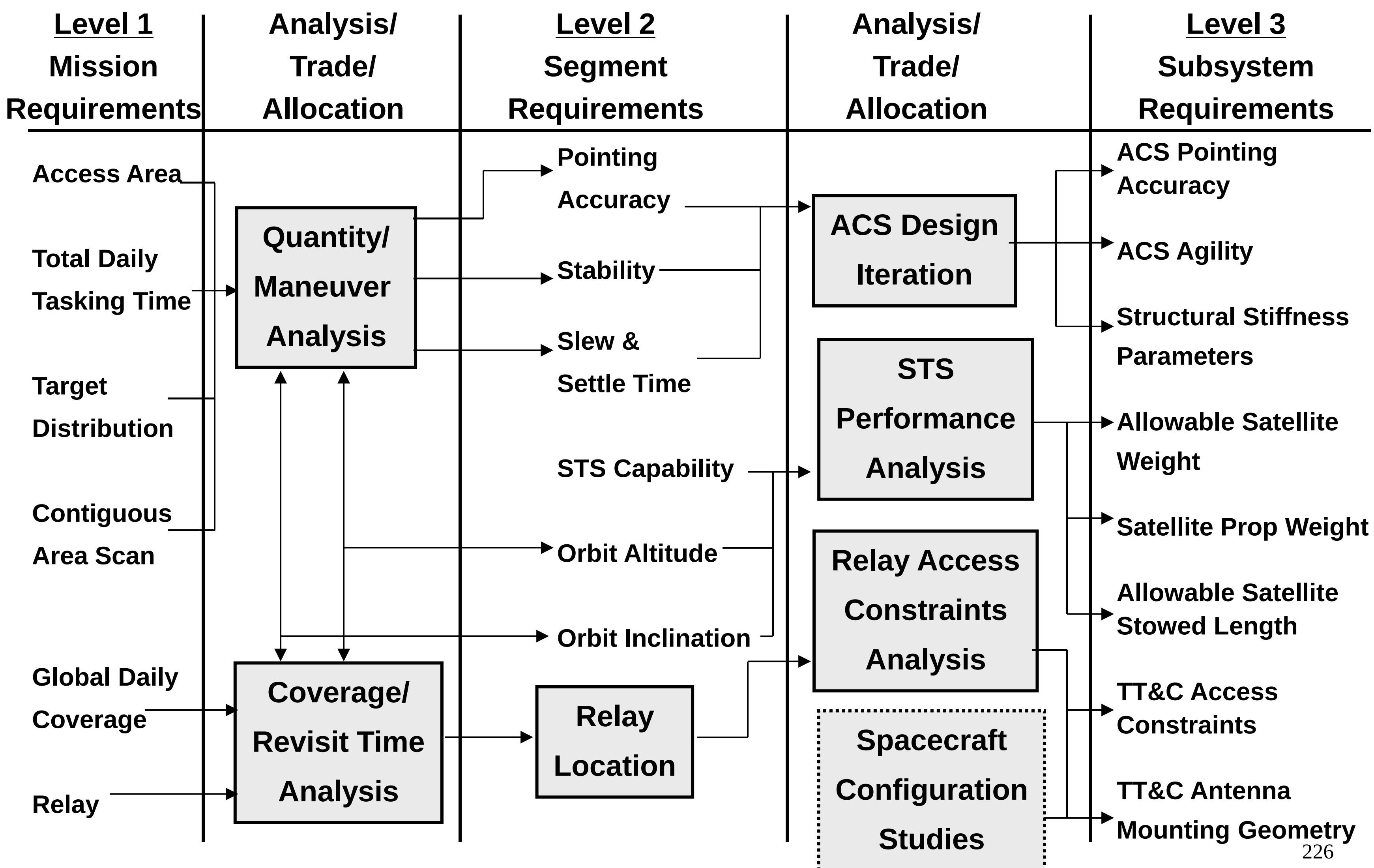
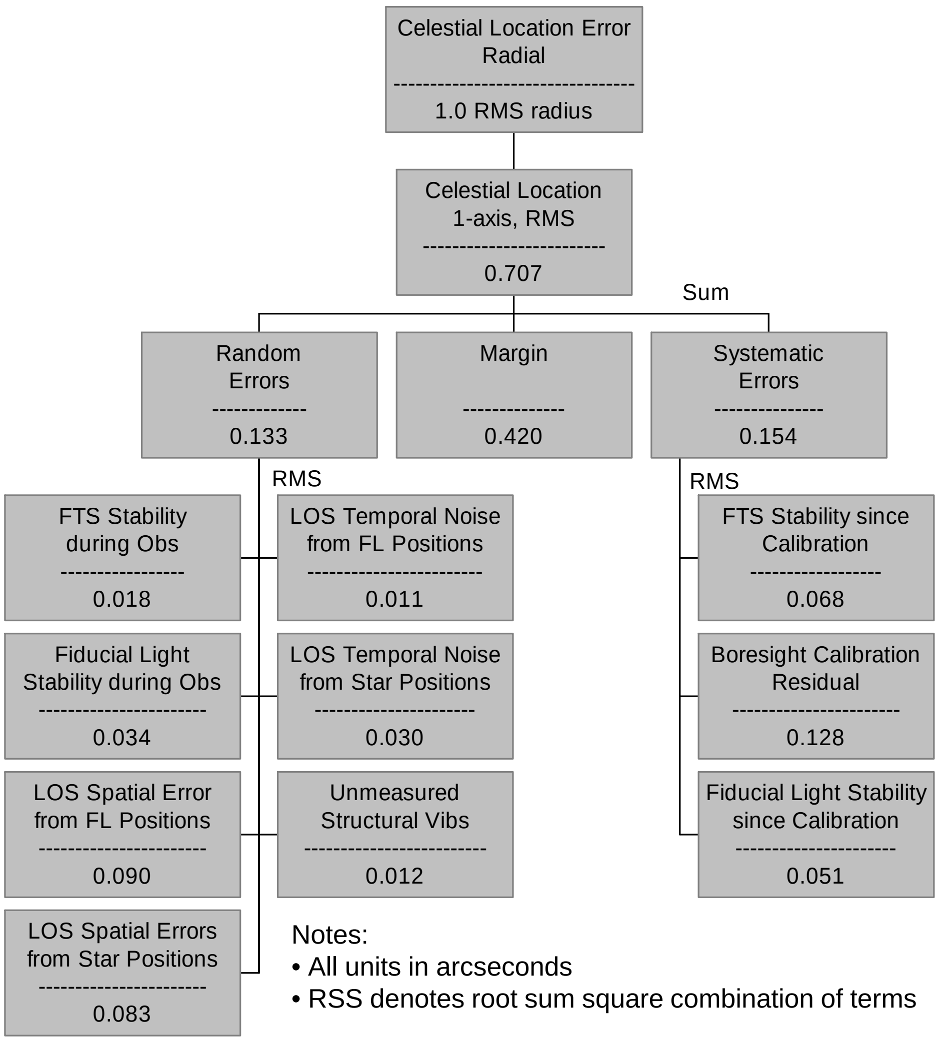
Example: CEV Project RAC 1 Coverage Matrix

Req. #	Requirement	Feasibiliy			Requirement Definition	
		Feasibility Approach	Feasibility Method (TDS)	Feasibilty Organization	Requirement Definition (Correctness) Approach	Definition Organization
CV0001	The CEV shall transport crews of 2, 3, and 4 crew members between Earth and lunar orbit in accordance with Table 1, Total Lunar DRM Crew, Destination Cargo, and Equipment Definition. [CV0001]	Analysis	1	S/C SE&I	CARD	Level 2
CV0002	The CEV shall have a lunar mission rate of no less than three per year. (TBR-002-106) [CV0002]	Analysis	5	Operations	CARD	Level 2
CV0003	The CEV shall be capable of conducting a lunar mission within 30 days (TBR-002-003) following a failed mission attempt.[CV0003]	Assessment	7	Ground Ops	CARD	Level 2
CV0034	The CEV hatch shall be capable of being opened and closed by ground personnel. [CV0034]	Previous Programs/ Engineering	7	Ground Ops	7	Ground Ops
CV0042	The CEV Launch Abort System shall provide a thrust of not less than 15 (TBR-002-12) times the combined weight of the CM+LAS for a duration of 2 (TBR-002-149) seconds. [CV0042]	Analysis	1	S/C SE&I	9	AFSIG
CV0062	The CEV shall provide pressurized transfer of crew and cargo between mated habitable elements in orbit. [CV0062]	Agency Decision / CARD	1	S/C SE&I	CARD	Level 2
CV0063	The CEV shall equalize pressure between CEV pressurized volume and the transfer vestibule prior to opening the CEV transfer hatch. [CV0063]	Previous Programs/ Engineering	1	S/C SE&I	4	Operations
CV0064	The CEV shall monitor the pressure of the mated vestibule volume when the CEV docking hatch is closed. [CV0064]	Previous Programs/ Engineering	4	Operations	4	Operations
CV0065	The CEV shall provide not less than two (TBR-002-007) vestibule pressurization cycles per mission. [CV0065]	Analysis	1	S/C SE&I	6	Operations

Requirements Allocation & Flowdown



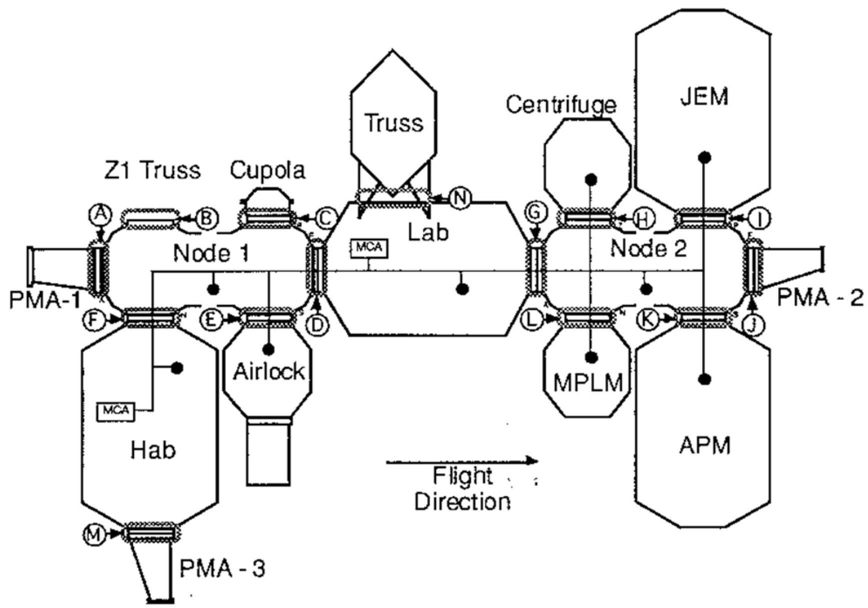
Resource Allocation



Notes:
- All units in arcseconds
- RSS denotes root sum square combination of terms

Systems Analysis enables prudent allocation of requirements/ resources and margin from system to component.

ISS Atmosphere Control Systems Analysis



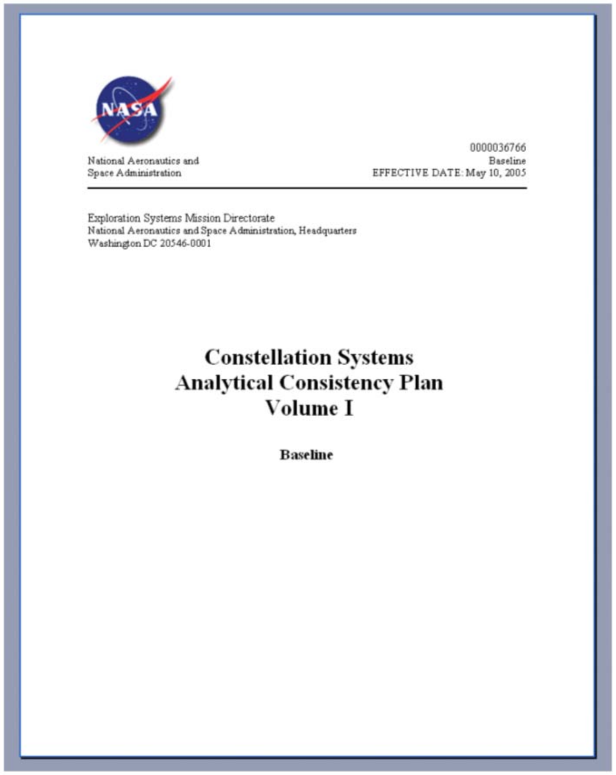
Interface Conditions*					
Interface Point	ICD	Pressure Drop (psid)	Pressure (psia)	Press. Point	Flow Rate (scc/min)
N1 probe to F	41140	0.40	13.50 to 14.80	F	600
N1 probe to D	41141	0.40	13.50 to 14.80	D	600
D to F	41140	0.25	12.60 to 14.80	F (All cases)	600
E to D	41141	0.40	13.30 to 14.60	D (From A/L)	600
E to F	41140	0.40	13.30 to 14.60	F (From A/L)	600
F to D	41141	0.25	13.35 to 14.65	D (From Hab)	600
F to Hab MCA	41140	0.15	N/A	N/A	600
Hab probe to F	41140	0.30	13.60 to 14.90	F	600
Airlock to E	41145	0.20	13.70 to 15.00	E	600
D to Lab MCA	41141	0.60	N/A	N/A	600
Lab probe to D	41141	0.60	13.30 to 14.60	D	600
G to Lab MCA	41143	0.60	N/A	N/A	600
G to D	41141	0.40	12.85 to 14.15	D (All cases)	600
K to G	41143	0.50	13.25 to 14.55	G (From APM)	600
I to G	41143	0.35	13.25 to 14.55	G (From JEM)	600
H to G	41143	0.50	13.25 to 14.55	G (From Cntr)	600
L to G	41143	0.50	13.25 to 14.55	L-From MPLM	600
N2 probe to G	41143	0.50	13.40 to 14.70	G	600
JEM to I	41151	0.30	13.60 to 14.90	I	600
MPLM to L	42007	0.15	13.75 to 15.05	L	600
APM to K	41150	0.15	13.75 to 15.05	K	600
Centrifuge to H	41147	0.15	13.75 to 15.05	H	600

What are the requirements for each module such that the air is safe for the crew and can support the experiments?

Systems Analysis Planning

- Planned, deliberate evolution & maturation of key systems models over the life cycle

- Drivers include risk mitigation, verification, & operations such as training & anomaly resolution



National Aeronautics and
Space Administration

0000036766
Baseline
EFFECTIVE DATE: May 10, 2005

Exploration Systems Mission Directorate
National Aeronautics and Space Administration, Headquarters
Washington DC 20546-0001

**Constellation Systems
Analytical Consistency Plan
Volume I**

Baseline

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Verification Compliance Matrix

Performance Requirement (Spacecraft Specification Paragraph)	**Requirement Source** (Parent Requirement)	**Capability/Margins** (Physical, Functional, Performance)	**Planned Method**	**Verification Requirements**	**Verification Event**
376239 LAE Thrust Vector Alignment Component ± 0.25 degrees	DERVD 3.6 Spacecraft IPS Derived Requirement IOC AXAF.95.350.121 AXSC 3.2.9.1 Structures & Mechanical Subsystem		Analysis	Verified by measurement at the engine level.	EQ.LAE
376240 LAE Location ± 3 inches	DERVD 3.6 Spacecraft IPS Derived Requirement IOC AXAF.95.350.121 AXSC 3.2.9.1 Structures & Mechanical Subsystem		Analysis	Verified by analysis.	SE30.TRW
376241 RCS Minimum Impulse Bit TBD	DERVD 3.6 Spacecraft IPS Derived Requirement IOC AXAF.95.350.121 AXSC 3.2.9.2 Thermal Control Subsystem (TCS)		Analysis	Demonstrated during thruster qualification testing.	EQ.PROP REM
376242 RCS Thrust 21 lbf ± 5% (at 250 psia inlet pressure)	DERVD 3.6 Spacecraft IPS Derived Requirement to be resolved AXSC 3.2.9.2.1 Heaters		Analysis	Demonstrated during thruster qualification testing.	EQ.PROP REM
376243 RCS Minimum Specific Impulse (inlet press. = 250 psia) 225 sec (BOL steady state)	DERVD 3.6 Spacecraft IPS Derived Requirement IOC AXAF.95.350.121 AXSC 3.2.9.2.1 Heaters		Analysis	Demonstrated during thruster qualification testing.	EQ.PROP REM
376244 Total Pulses (each thruster) 50,000	DERVD 3.6 Spacecraft IPS Derived Requirement IOC AXAF.95.350.121 AXSC 3.2.9.2.1 Heaters		Analysis	Demonstrated during thruster qualification testing.	EQ.PROP REM
376245 Propellant Throughput 200 lbm	DERVD 3.6 Spacecraft IPS Derived Requirement IOC AXAF.95.350.121 AXSC 3.2.9.2.1 Heaters	Predicted Throughput: 92.6 lbm Expected Margin: 107 lbm	Analysis	Demonstrated during thruster qualification testing.	EQ.PROP REM

Sample Analysis Fidelity Definitions

Fidelity Level	Geometry & Packaging	Structures & Materials	Sizing & Closure	Trajectory & Performance
Beginning	Documented vehicle from literature with similar technology	Mass fraction estimate	Weight closure only	Rocket equation/mass ratio estimate
0	Parametric, empirical or analytical geometry model	Parametric or historical equations adjusted to level 1 or higher for similar technology and vehicle configuration	Weight & volume closure w/ consistent bookkeeping of all propellants & fluids based on commensurate fidelity level inputs from other disciplines; As-Flown vehicle photographic scale factor < +/- 15% from As-Drawn	Rocket equation or energy methods (path following) simulation
1	External & major internal components modeled such as propellant tanks. Payload bay, propulsion, etc… for volume, area, and key linear dimensions	1D bending loads analysis based on structural theory of beams, shell, etc… with non-optimums based on level 2 or higher results	Weight & volume closure w/ consistent bookkeeping of all propellants & fluids based on commensurate fidelity level inputs from other disciplines; As-Flown vehicle photographic scale factor < +/- 10% from As-Drawn	Optimized ascent, flyback & re-entry 3-DOF simulation (un-trimmed)
2	All components modeled, packaged, and analyzed for geometric properties including center of gravity. Geometry re-drawn and packaged to match closure model	Limited 3D FEA (<20,000 nodes) for all major load cases, structure sized to allowables, non-optimums determined empirically or analytically	Weight & volume closure w/ consistent bookkeeping of all propellants & fluids based on commensurate fidelity level inputs from other disciplines; As-Flown vehicle photographic scale factor < +/- 5% from As-Drawn	Optimized ascent, flyback & re-entry 4-DOF (pitch trim) simulation; Longitudinal stability & control evaluation

Sample Analysis Fidelity Definitions (con't)

Fidelity Level	Geometry & Packaging	Structures & Materials	Sizing & Closure	Trajectory & Performance
Beginning	Documented vehicle from literature with similar technology	Mass fraction estimate	Weight closure only	Rocket equation/mass ratio estimate
3	All components modeled, packaged, and analyzed for geometric properties including center of gravity. Geometry re-drawn and packaged to match closure model	3D FEA (>20,000 nodes) for all major load cases, structure sized to allowables, non-optimums determined empirically or analytically	Weight & volume closure w/ consistent bookkeeping of all propellants & fluids based on commensurate fidelity level inputs from other disciplines; As-Flown vehicle photographic scale factor < +/- 3% from As-Drawn	Optimized ascent, flyback & re-entry 6-DOFsimulation; Longitudinal, lateral & yaw stability & control evaluation
4	All components modeled, packaged, and analyzed for geometric properties including center of gravity. Geometry re-drawn and packaged to match closure model	3D FEA (>100,000 nodes) for all major load cases, structure sized to allowables, non-optimums determined empirically or analytically	Weight & volume closure w/ consistent bookkeeping of all propellants & fluids based on commensurate fidelity level inputs from other disciplines; As-Flown vehicle photographic scale factor < +/- 1% from As-Drawn	Optimized ascent, flyback & re-entry 6-DOFsimulation; Longitudinal, lateral & yaw stability & control evaluation

Other Disciplines for Which Fidelity Levels have been Defined for Launch System Development

- Aerodynamics & Aerothermal
- Avionics & Software
- Propulsion Design & Performance
- Aerothermal & TPS Sizing
- Thermal Management & Design
- Airframe & Engine Subsystems
- Safety & Reliability
- Operability, Supportability & Maintainability
- Cost & Economics

Progressive Fidelity over Time

Systems Analysis Fidelity	0	1	2	3	4
Geometry & Packaging	■				
Structures & Materials	■				
Sizing & Closure	■	■			
Trajectory & Performance	■	■			
Aerodynamics & Aerothermal	■				
Avionics & Software	■				
Propulsion Design & Performance	■				
Aerothermal & TPS Sizing	■				
Thermal Management & Design	■				
Airframe & Engine Subsystems	■				
Safety & Reliability	■				
Operability, Supportability & Maintainability	■				
Cost & Economics	■				

MCR

Systems Analysis Fidelity	0	1	2	3	4
Geometry & Packaging	■	■			
Structures & Materials	■	■			
Sizing & Closure	■	■	■		
Trajectory & Performance	■	■	■		
Aerodynamics & Aerothermal	■	■			
Avionics & Software	■	■			
Propulsion Design & Performance	■	■	■		
Aerothermal & TPS Sizing	■	■			
Thermal Management & Design	■	■			
Airframe & Engine Subsystems	■	■			
Safety & Reliability	■	■	■		
Operability, Supportability & Maintainability	■	■			
Cost & Economics	■	■	■		

PDR

Systems Analysis Fidelity	0	1	2	3	4
Geometry & Packaging	■	■	■	■	
Structures & Materials	■	■	■	■	■
Sizing & Closure	■	■	■	■	■
Trajectory & Performance	■	■	■	■	■
Aerodynamics & Aerothermal	■	■	■	■	■
Avionics & Software	■	■	■	■	
Propulsion Design & Performance	■	■	■	■	■
Aerothermal & TPS Sizing	■	■	■	■	■
Thermal Management & Design	■	■	■	■	
Airframe & Engine Subsystems	■	■	■	■	
Safety & Reliability	■	■	■	■	■
Operability, Supportability & Maintainability	■	■	■	■	
Cost & Economics	■	■	■	■	

CDR

Note the progression of fidelity throughout the life cycle.

General Fidelity Level Descriptions

Fidelity Level	Assembly Level	Program Phase	Analyses Type	TPM Level
0	System	Pre-Phase A	rapid assessment of system architectures	definition of system level TPM's
1	Subsystem	Pre-Phase A	initial assessment of as-drawn system design	definition of subsystem level TPM's
2	Assembly	Phase A	refined assessment of as-drawn system & subsystem design	definition of assembly level TPM's
3	Component	Phase B	preliminary assessment of as-drawn system, subsystem & assembly design	definition of Component level TPM's
4	Part	Phase C	detailed assessment of as-drawn system, subsystem, component & part design	definition of part/material/property level TPM's

Key Points

- Systems analysis methods illustrated previously can be used for requirements development & allocation.
  - Symbolic models including FFBDs in particular

- Systems analysis planning strategically ties systems analysis activity to requirements validation and continued requirements analysis during the development cycle.

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Lesson 11:
Effectiveness Analysis

Objectives

- Reference to IEEE-1220 processes
  - 6.7.5.1 Select Methodology and Success Criteria
  - 6.7.6.2 Analyze System and Cost-Effectiveness
  - 6.7.10 Design Effectiveness Assessment

- Describe & illustrate development & application of technical performance metrics to assess system effectiveness.

Technical Metrics

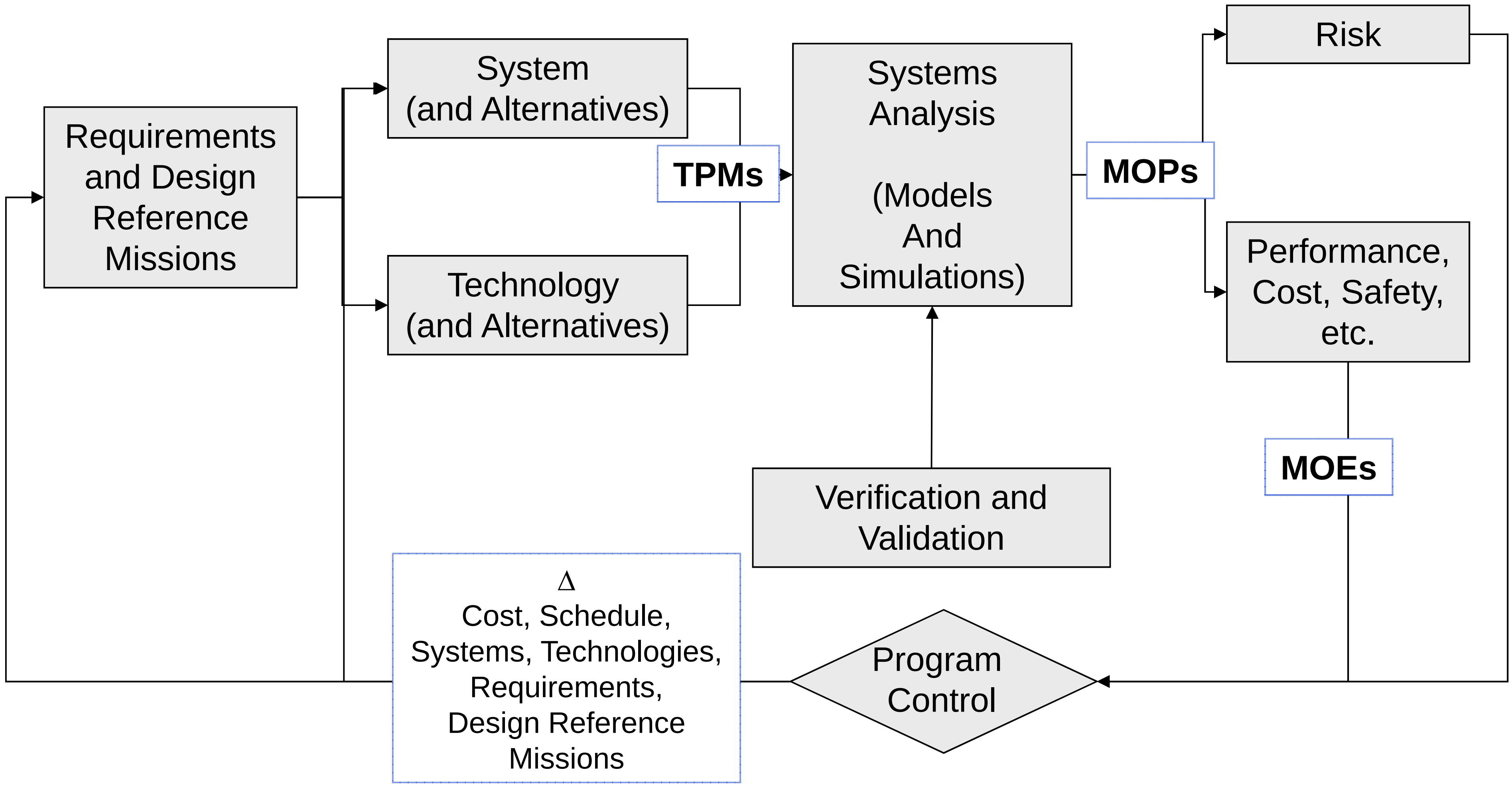
- Metrics are measurements collected for the purpose of determining project progress and overall condition by observing the change of the measured quantity over time. Management of technical activities requires use of three basic types of metrics:

  - **Measure of Effectiveness (MOE):** The metrics by which an acquirer will measure satisfaction with products produced by a technical effort.

  - **Measure of Performance (MOP):** An engineering performance measure that provides design requirements that are necessary to satisfy an MOE. There are typically several MOPs for each MOE.

  - **Technical Performance Measure (TPM):** Key indicators of system performance, TPMs are critical MOPs which, if not met, put the project at cost, schedule, or performance risk.

Systems Analysis Cycle



Technical Metrics – DAU Example

- Product metrics are those that track key attributes of the design to observe progress toward meeting customer requirements. Product metrics reflect three basic types of requirements: operational performance, life-cycle suitability, and affordability. The key set of systems engineering metrics are the Technical Performance Measurements (TPM.) TPMs are product metrics that track design progress toward meeting customer performance requirements. They are closely associated with the system engineering process because they directly support traceability of operational needs to the design effort. TPMs are derived from Measures of Performance (MOPs) which reflect system requirements. MOPs are derived from Measures of Effectiveness (MOEs) which reflect operational performance or stakeholder requirements.

- **MOE**: The vehicle must be able to drive fully loaded from Washington, DC, to Tampa on one tank of fuel.

- **MOPs**: Vehicle range must be equal to or greater than 1,000 miles. Vehicle must be able to carry six passengers and 300 pounds of cargo. The vehicle must meet DOT requirements for driving on interstate and secondary highways.

- **TPMs**: Fuel consumption, vehicle weight, tank size, power train friction, etc.

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Mars Mission Example FOMs & Metrics

CATEGORY	FOM	STD. METRIC
Safety/Risk	LOC / LOM	Risk Assessment
	Crew Health	Rad. Exposure
	Programmatic Risk	High Sensitivity of Gear Ratio = More risk
	Tech Dev Risk	R&D Degree of Difficulty
Performance	Trip Time Reduction	Add 1 Launch & Reduce Trip Time
Affordability	Development Cost	DDTE $
	Recurring Cost	Recurring $
	Marginal Cost	Marginal $
	Launch Cost	Launch $
Schedule	Tech. Dev.	Time to TRL 6
	Cargo IOC/TMI	Integrated Cargo Stack Deployment Time
Extensibility/ROI	Science Return	Crew Time @ Dest.
	Mission Capture	% Portfolio Captured
		% Portfolio Enhanced
	Commercial Opportunity	Commercial crew/cargo/prop resupply potential?
		Mission element commercial application?
	Int'l Partner Potential	Opportunities for Int'l Partnerships

Requires detailed risk assessment

Requires extensive trajectory analysis

Requires detailed cost analysis

- **Labor / Time Intensive Evaluations Required to Quantify Many Standard Metrics**
- **We can use pseudo-metrics that:**
  - Can be supported by current level of analysis
  - We know, through experience, correlate well to the standard metrics

Mars Mission Example FOMs & Psuedo-Metrics

CATEGORY	FOM	STD. METRIC	PSEUDO-METRIC	GOAL
Safety/Risk	LOC	Risk Assessment	Crew Critical Docking (& # burns?)	Min
	LOM	Risk Assessment	Non-Crew Critical Docking (& # burns?)	Min
			Total Hardware Duration (active & dormant)	Min
	Crew Health	Radiation Exposure	Time of Flight (deep space vs. planetary body)	Min
			Solar Proximity	>1 AU
	Programmatic Risk	High Sensitivity of Gear Ratio = More Risk		Min
	Tech. Dev. Risk	R&D Degree of Difficulty		Min
Performance	Trip Time Reduction	Add 1 Launch & Reduce Trip Time		Max
Affordability	Development Cost	DDTE $	# of Technologies Below TRL 6 @ PDR	Min
	Recurring Cost	Recurring $	Total Program Duration	Min
			Total # of Elements	Min
	Marginal Cost	Marginal $	# of Unique Elements	Min
	Launch Cost	Launch $	# of Launches	Min
Schedule	Tech. Dev.	Time to TRL 6		Min
	Cargo IOC/TMI	Integrated Cargo Stack Deployment Time		Min
Extensibility/ROI	Science Return	Crew Time @ Destination		Max
	Mission Capture	% Portfolio Captured		Max
		% Portfolio Enhanced		Max
	Commercial Opportunity	Commercial crew/cargo/prop resupply potential?		Yes
		Mission element commercial application?		Yes
	Int'l Partner Potential	Opportunities for Int'l Partnerships		Yes

Example – 2GRLV Product Metrics

- MOEs
  - $/lb to Low Earth Orbit
  - Safety
- MOPs
  - Probability of Loss of Crew
  - Probability of Loss of Vehicle
  - Probability of Loss of Payload
  - Probability of Loss of Mission
  - Total Annual Operational Cost
  - Acquisition Cost
  - Operability
  - Design Risk

Example -- 2GRLV Product Metrics (con't)

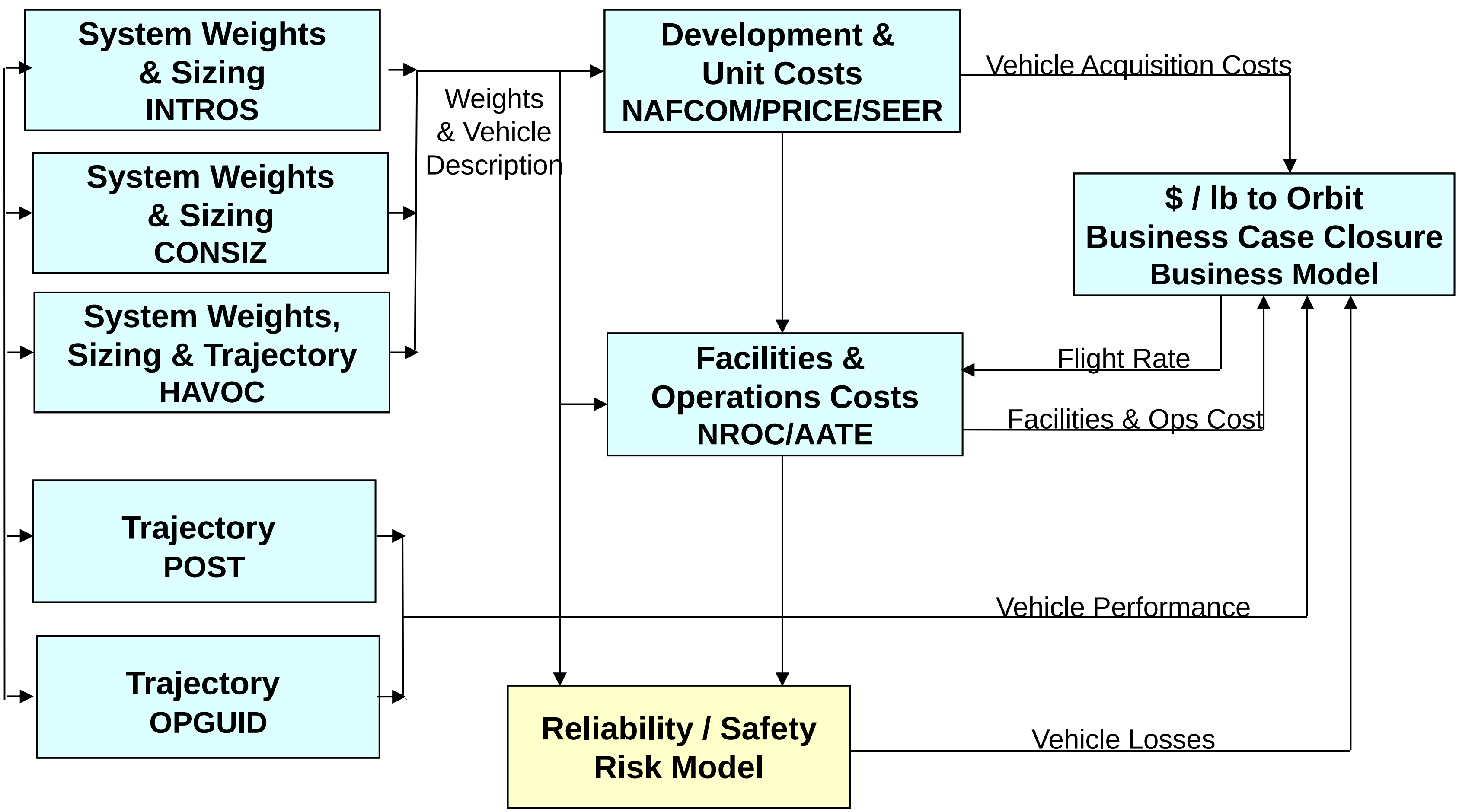
- TPMs
  - Development Cost
  - Production Cost
  - Turn-around Time
  - Dispatch Time
  - Integration Time
  - Maintenance Time
  - etc.

Acquisition Cost

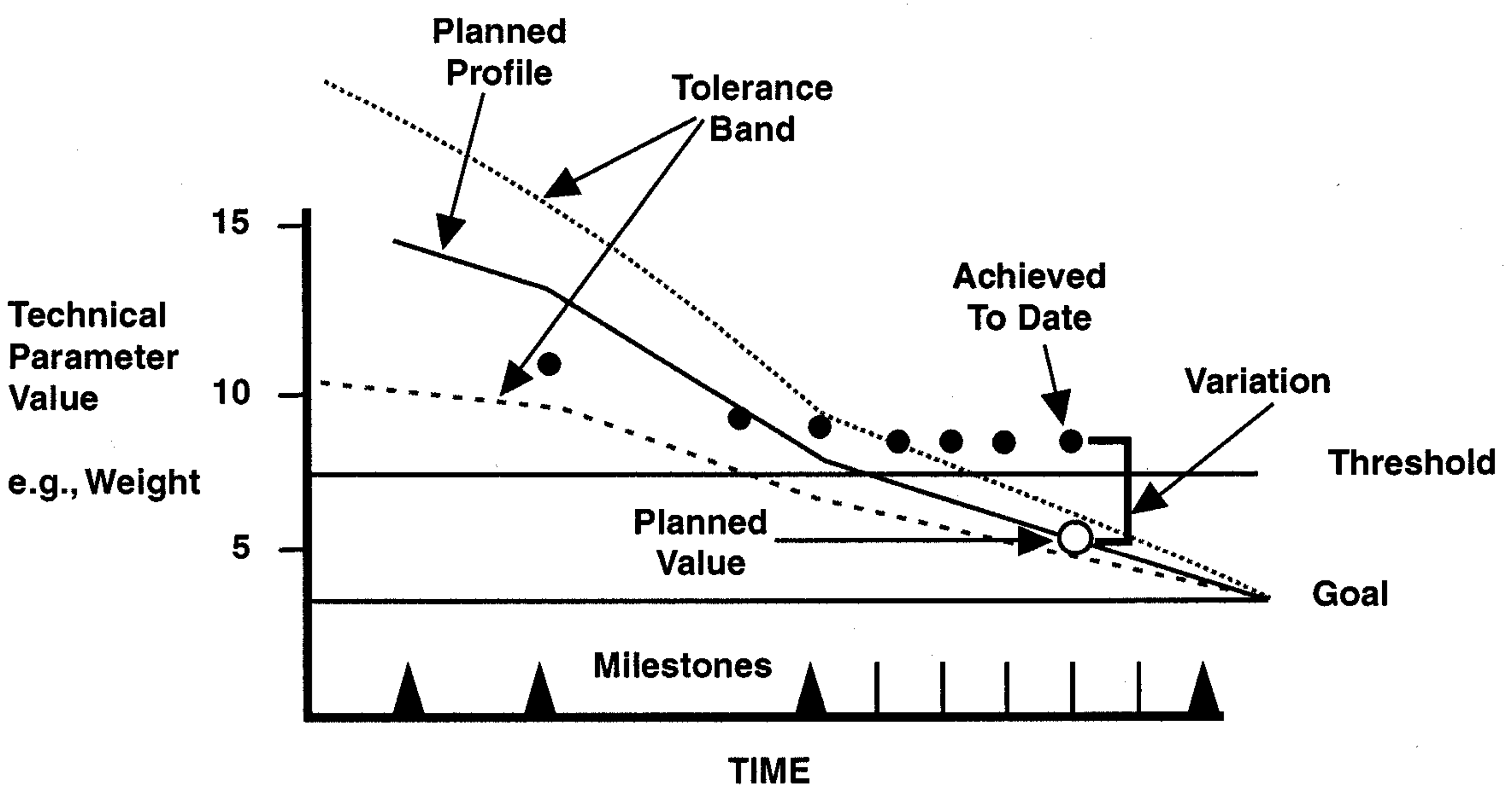
Operability

Example -- 2GRLV Systems Analysis

Performance Models   Cost & Operations Models   Economic Model



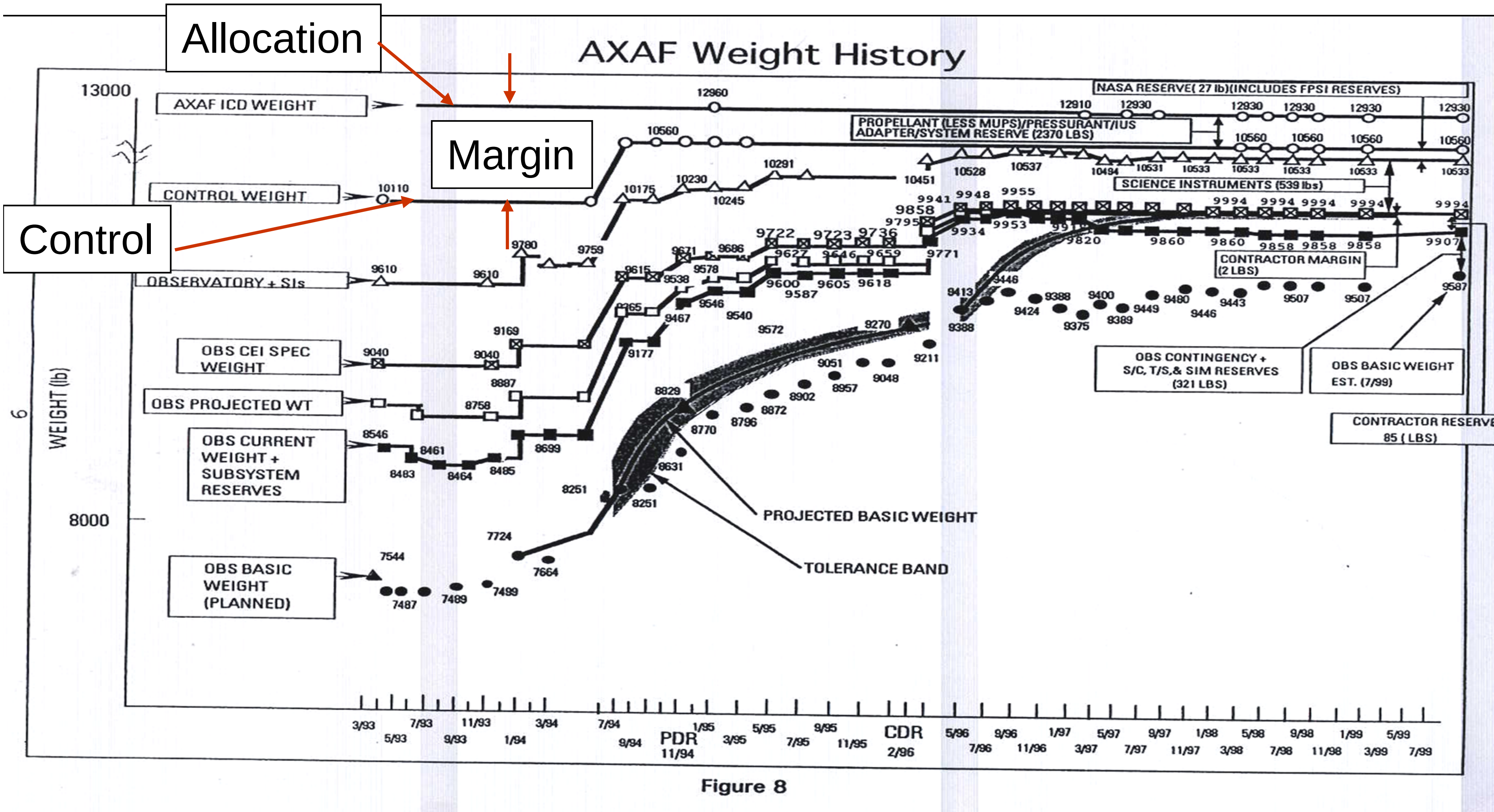
Technical Performance Measurement – The Concept



Ref. SE Fundamentals

Example – Chandra Weight History

(estimates) (estimates & actuals) (actuals)



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Case Study

TPM Application
HDD Development/Qualification

R Allan Ray

2/8/01

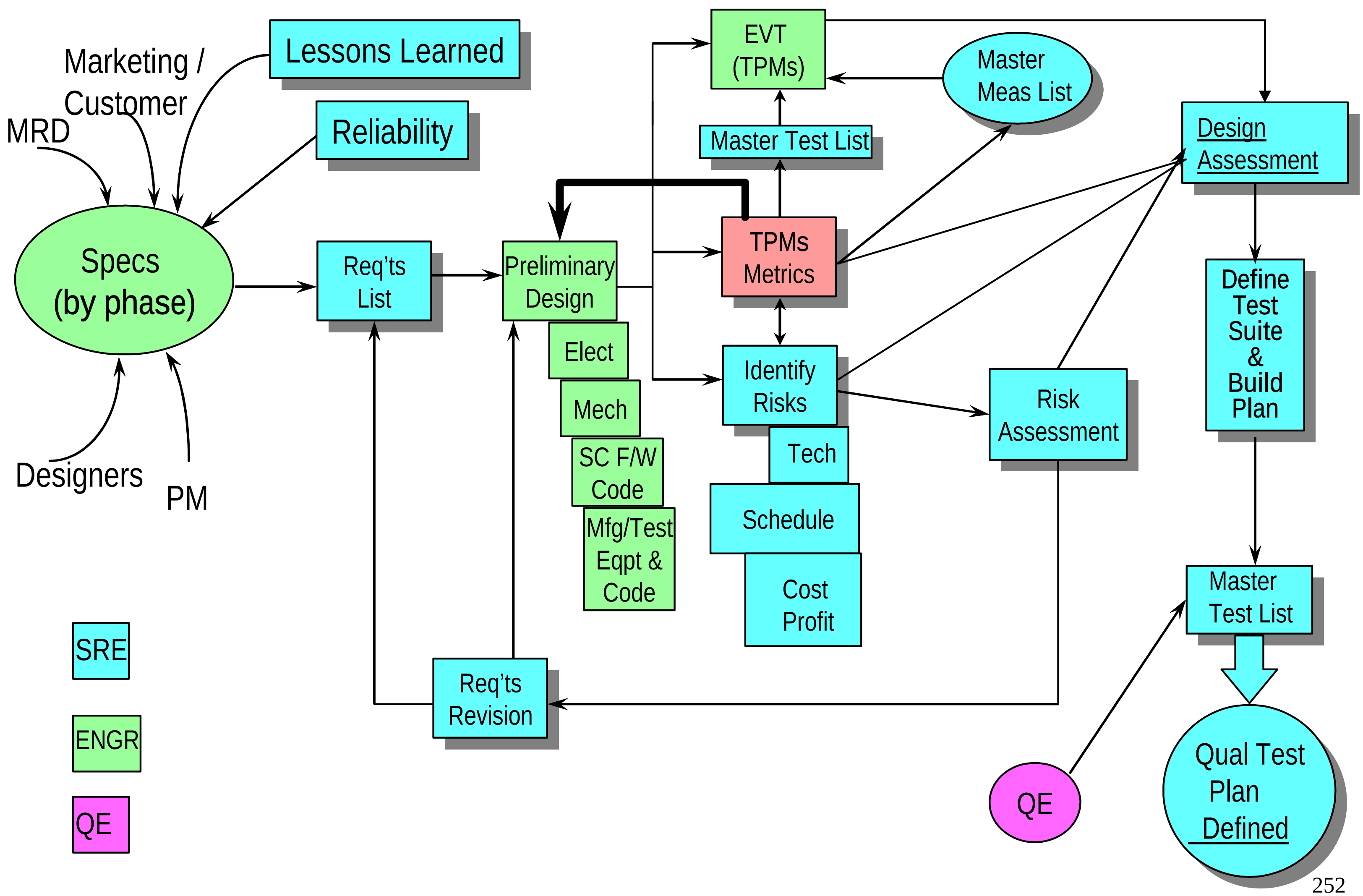
Application of Systems Engineering Tools

- Flexibility is a key feature of the Systems Engineering (SE) discipline.
- Processes, organizational constructs and tools that constitute SE can be effectively and profitably tailored and applied in many areas.
- Demonstrating ROI requires several years for most government projects leading to (business) management skepticism and reluctance to implement the discipline.
- This presentation describes the successful implementation of one SE tool and organizational concept in the Information Technology industry.
- ROI was demonstrated/documented in 9 months.

Hard Disk Drive Industry

- Market Segments--Personal and Enterprise
- Enterprise Products--Workstations, Servers, Storage Area Networks,RAIDs, Network Attached Storage, Set-top Appliances("Smart VCRs")
- Customer Set-- EMC, Sun, SGI, IBM, HP, Dell, Compaq, Gateway
- Major Players/Competitors--Seagate, Maxtor, IBM, Fujitsu
- Market Survival--TTM, Price, Responsiveness
- Drive Info
  - 9G-180G available, 500G in development
  - 7200 - 15000 rpm available, 20000 rpm in development
  - 4 - 10 msec seek times
  - 100% Duty Cycle, 24/7
  - Industry "sweet spot" 18 & 36G
  - Design--US Manufacture—Asia
  - 5 year Warranty, Typical 3 year use in OEMs

HDD Development - to - Qualification Process



Technical Performance Measurement (TPM)

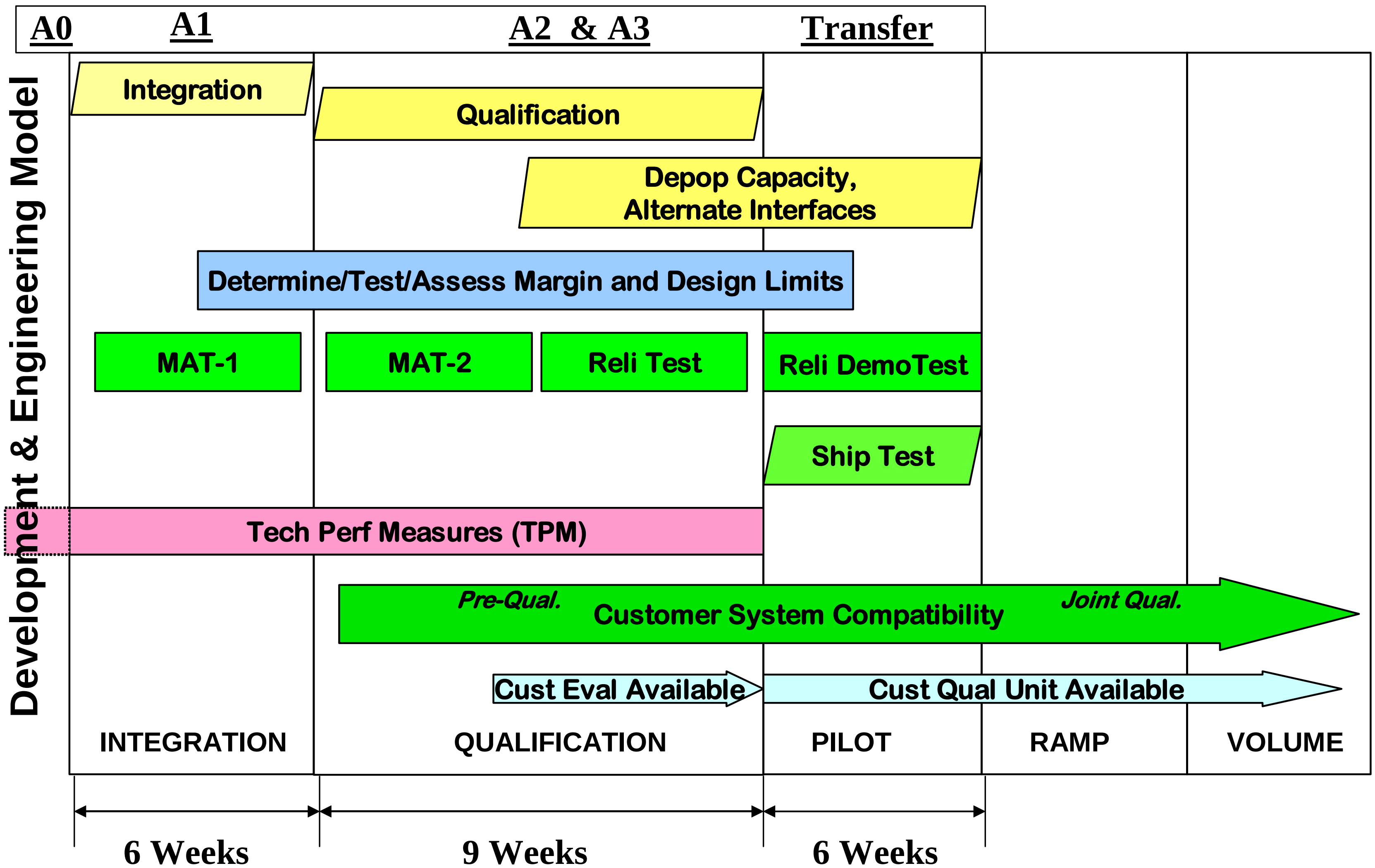
- What
  - A closed-loop process for continuing analysis, test and demonstration of the degree of maturity of selected drive technical parameters.

- Objective
  - Provide a set of measurements that characterize drive performance and “health” at any stage of design or development.

TPM Application -- HDD

- WHY?
  - *Assess compliance* with drive specifications and customer expectations
  - Assess drive design/development maturity
  - Assess and mitigate *technical risks*
  - Provide drive characteristics to Product Assurance Lab for test equipment set-up
  - Provide reliability requirements to design groups
  - Reduce technical problems encountered in reliability demonstration test
  - *Provide data for design assessment, readiness reviews, decisions*
  - Support shortened cycle times
  - Reduce development costs
  - Management visibility of drive program health

Test Phases


A0
A1
A2 & A3
Transfer
Development & Engineering Model
Integration
Qualification
Depop Capacity, Alternate Interfaces
Determine/Test/Assess Margin and Design Limits
MAT-1
MAT-2
Reli Test
Reli DemoTest
Ship Test
Tech Perf Measures (TPM)
Pre-Qual.
Customer System Compatibility
Joint Qual.
Cust Eval Available
Cust Qual Unit Available
INTEGRATION
QUALIFICATION
PILOT
RAMP
VOLUME
6 Weeks
9 Weeks
6 Weeks

TPM Application -- HDD

- Approach
  - Select parameters that are performance based, measurable indicators of drive maturity related to customer requirements, design requirements, reliability and producability.
  - Measure selected parameters of drive operation against specs and expectations from Design Phase (A0) through Qualification (A3).
  - Leverage tests scheduled and conducted by design engineering and manufacturing.
  - Product Assurance (PA) Engineers and Core Team specify required measurement data.
  - Characterize and document drive configuration & performance at each phase entry and at any *deviation* from planned profile.

TPM Application -- HDD

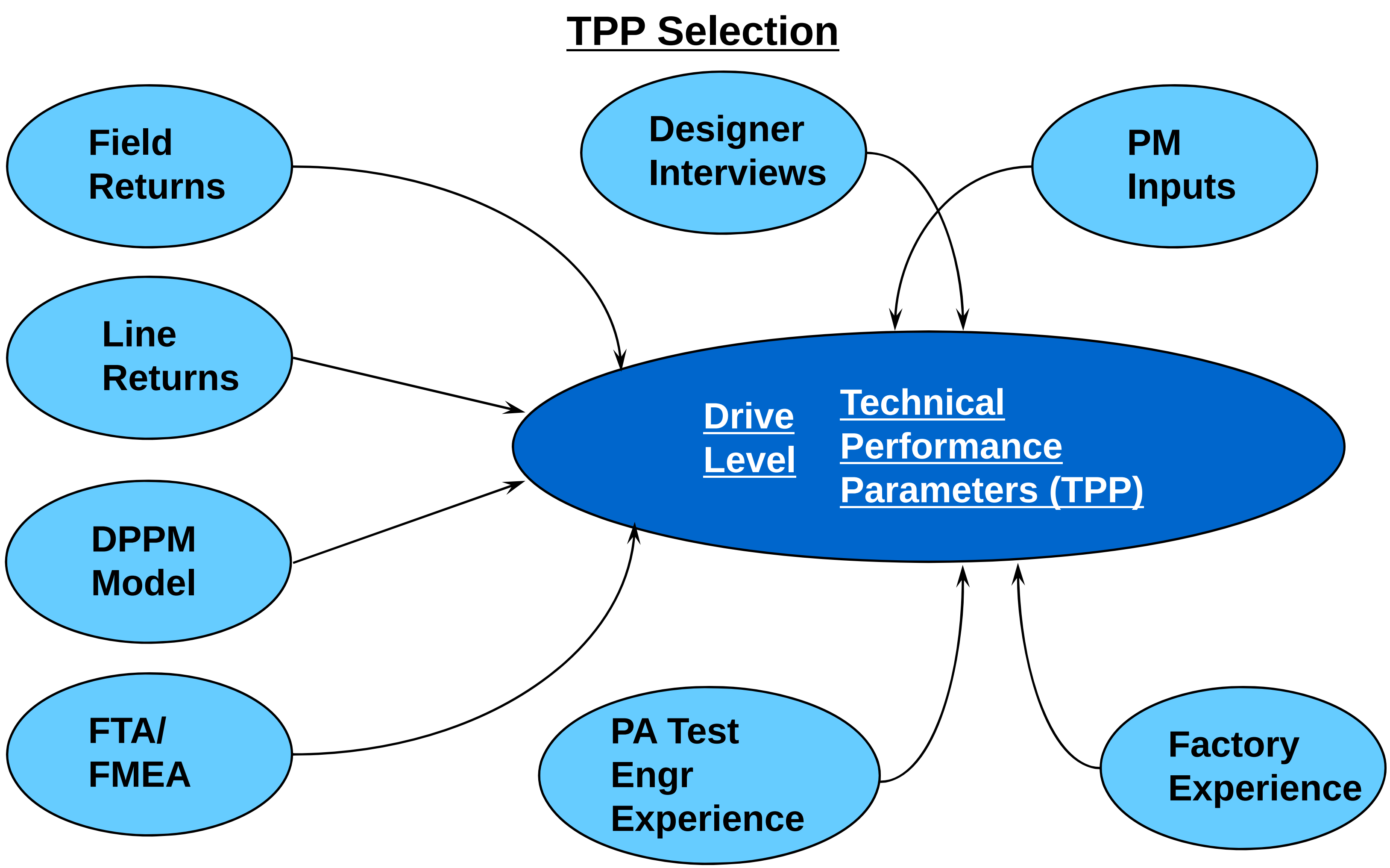
- PA Test Engineer collects and analyzes measurement data in 2 phases:

- Phase 1: A0 / Engineering Models
  - Data compared against design requirements and designer expectations.
  - *Focus is on Robustness and Design Convergence*.
  - Deliverables: Feedback to Designer, PA Lab and Core Team regarding design "system" *sensitivity* to parametric changes as they occur.
  - Report to Core Team at Phase A1 entry -- 8 days prior to entry date.

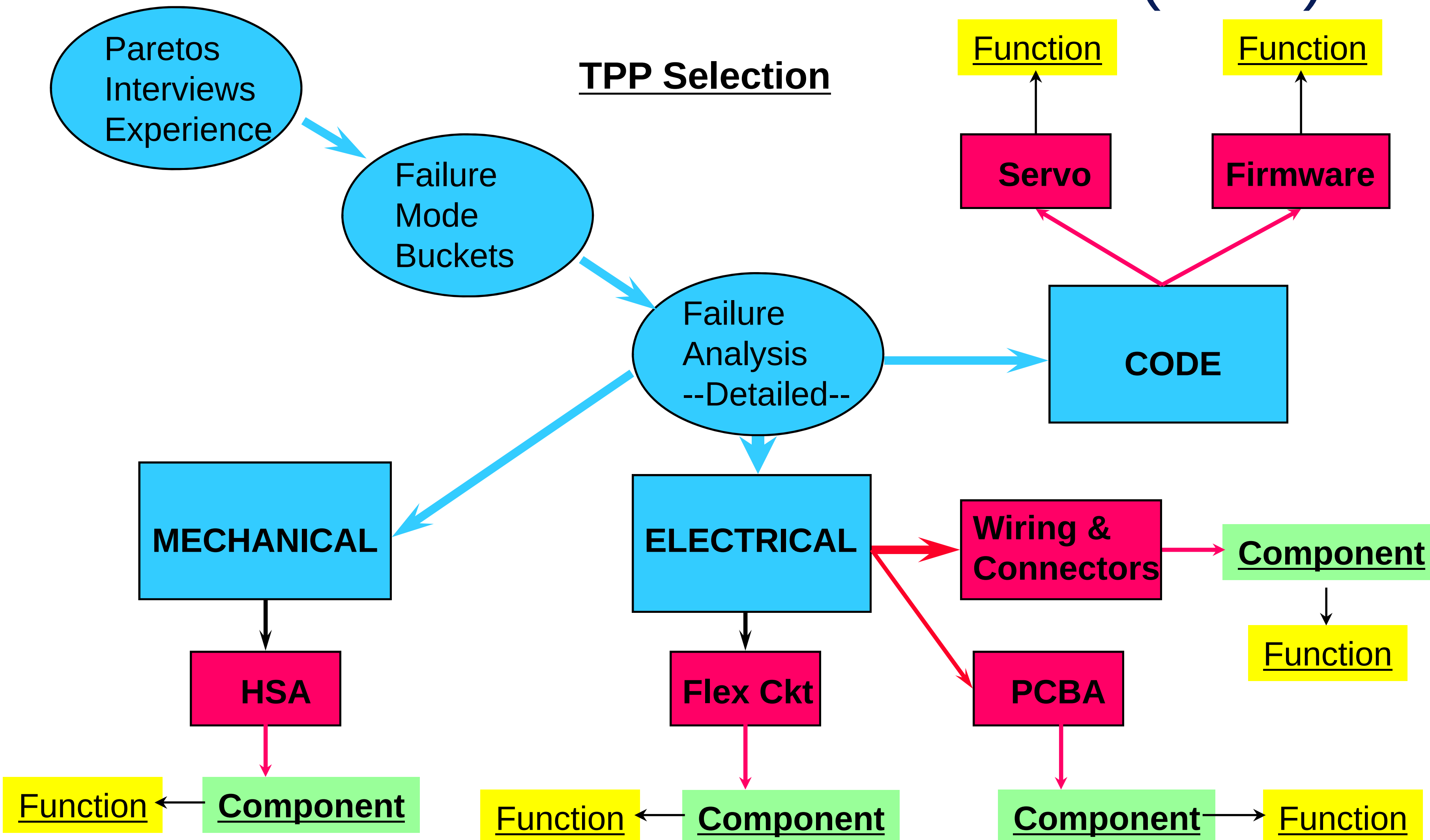
TPM Application – HDD (con't.)

- Phase 2: Qualification Phases A1, A2, A3
  - Parameters measured as drive performance is refined, final adjustments made to head / media combos, code changes implemented.
  - *Focus is on Drive Maturity*.
  - Deliverables: Maturity assessments and analysis feedback to Core Team and PA Test Team as changes are implemented.
  - Maturity Assessment to Core Team at each Phase entry -- 8 days prior to entry date.

Technical Performance Measures (TPM)



Technical Performance Measures (TPM)



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Technical Performance Measures (TPM)

TPM	TPP
•Acoustics	Motor Parameters Servo Code (Seek Time) Basecasting Seals PCBA
•Operations/second	Read Settle Time Write Settle Time WUS RUS Seek Times Head Switch Time Channel Speed Soft Error rate Bit Error Rate

Technical Performance Measures (TPM)

TPM	**TPM**
•**Non-Op Shock**	**Base / Cover** **Heads / Media** **Motor** **Suspension** **Code**
•**Current Consumption**	**PCBA** **Coil** **Motor** **Disk Size** **Number of Interfaces** **Features (power saver)** **Spin-up time** **Seek Time** **Read / write Time**

SE Tools/Methods

- Failure Mode, Effect & Analysis (FMEA)
  - Owned by PA Test Engr
  - Tailor the process to quickly identify critical problems
  - Account for failures in previous programs (development, factory, field)
  - Performed during pre-A0 and maintained/updated throughout development

- Fault Tree Analysis (FTA)
  - Created for each program
  - Perform at pre-A0. Detailed--use to select the FMEA areas
  - Determine which areas require FMEA
  - Use data to create and maintain "watch list"

TPM Application -- HDD

- Parameter Characteristics
  - Significant determinants of total drive performance
  - A direct measure of value determined from test
  - May represent areas of risk that require visibility
  - Time-phase values can be predicted for each parameter and substantiated during design, development, test
  - Select enough parameters to sufficiently describe drive health
    - Too many – may focus on non-essentials
    - Too few – may miss important indicators
    - 5 to 10 as a rule

TPM Application -- HDD

- Implementation
  - Deploy through the Quality & Design Engr Core Team Reps to Functional Depts
  - Initiate on next generation product as Pathfinder
  - Refine procedures and measurements
  - DRs are those documented in the Phase 0 deliverables and Qual Phase Entry requirements
  - Documented as part of the Product Quality Plan
  - PA Test Engr will supply measurements reqt's and coordinate with DE Core Team Rep to determine test schedule detail
  - PA Test Engr & Core Team work together to obtain data
  - Collect cost-to-manufacture data at transfer for ROI comparison

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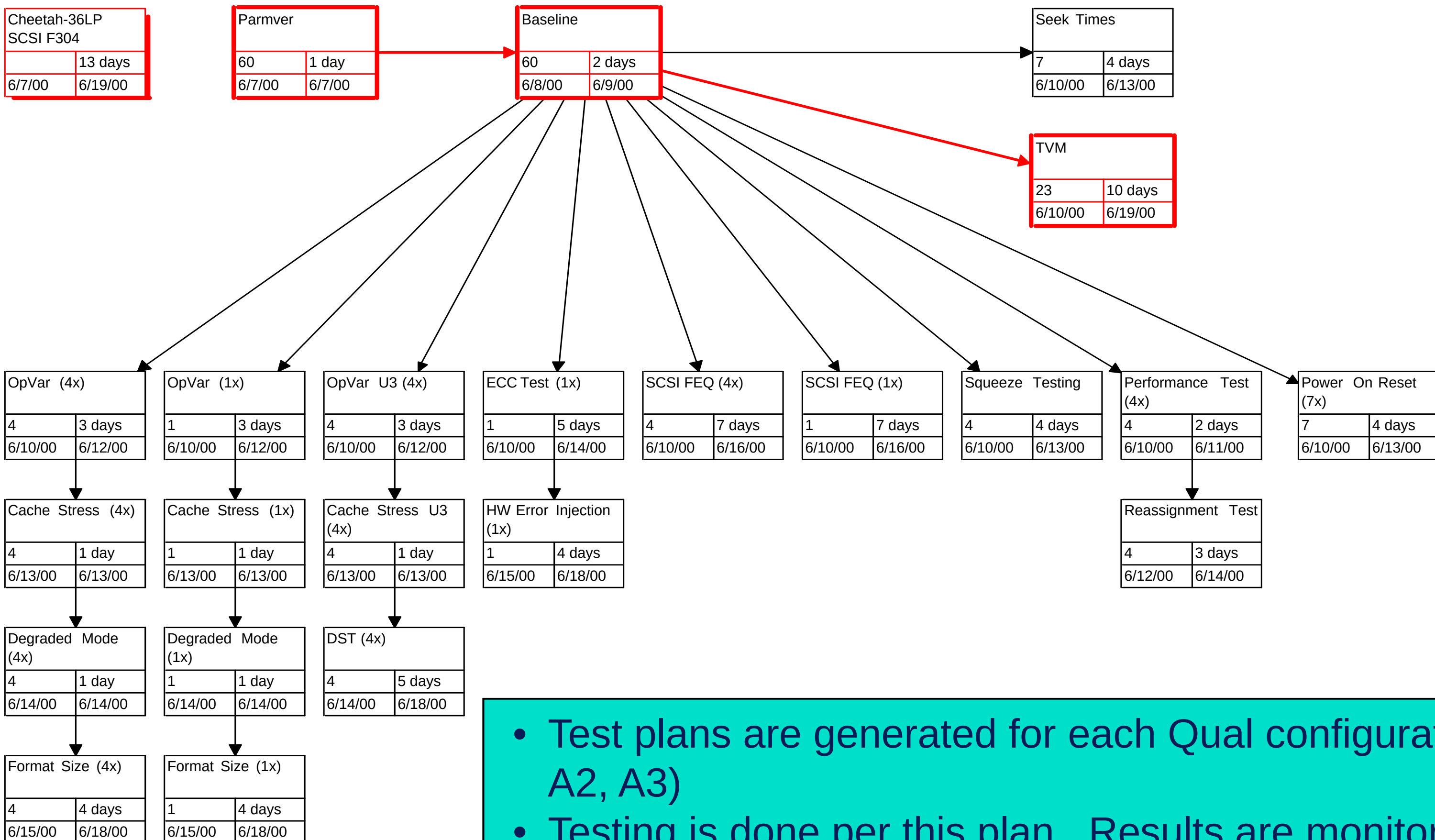
TPM Application -- HDD

Technical Performance Measure Process Example Data Sheet

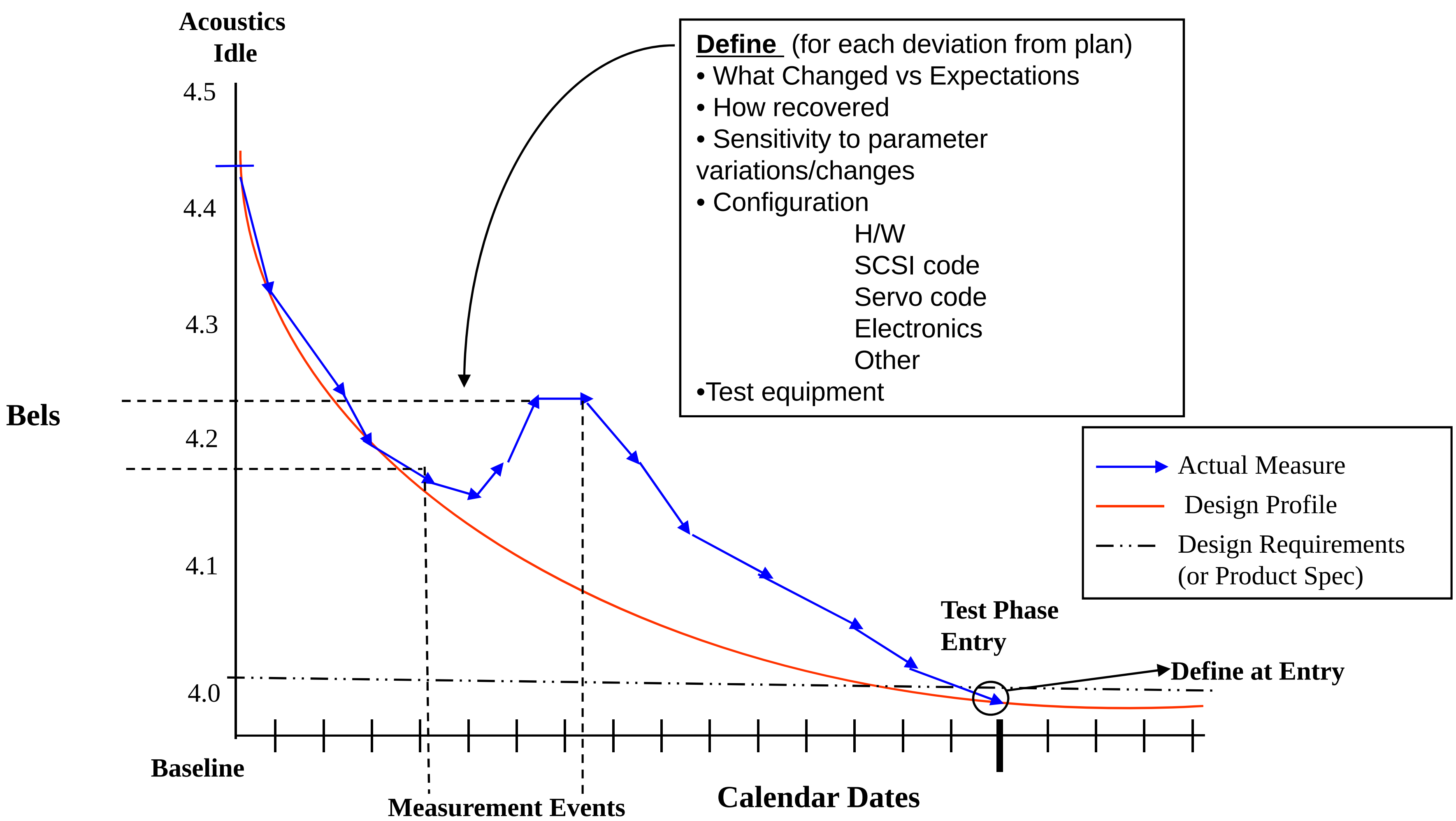
Drive Characteristic	Data Supplier	Units	Begin Reporting	Stat	MAT 0.0 5/1/99	GEN 1.0 7/1/99	GEN 2.0 11/1/99	CTU 1/1/00
Acoustics (Idle)	Dev. Engr	bels	MAT 0.0	Min	5	3	3	0
		bels	MAT 0.0	Avg	6	4	4.5	3.8
		bels	MAT 0.0	Max	7	5	6	3.8
Off Track Capability (OTC as % of Track Pitch, Per Head)	MFG Engr	%	MAT 0.0	-3sig				11
		%	MAT 0.0	Avg				11
		%	MAT 0.0	+3sig				50
Stiction (1 day/1 day)	HDIG	grams/hd (avg)	MAT 0.0	Min				0
		grams/hd (avg)	MAT 0.0	Avg				7
		grams/hd (avg)	MAT 0.0	Max				7
Contact Start-Stops (Ambient, % Failure-Rate at 10K CSS)	HDIG	%	MAT 0.0	Min				0
		%	MAT 0.0	Avg				5
		%	MAT 0.0	Max				5
Non-Repeatable Run-Out (NRRO as a % of Track Pitch, Per Head)	MFG Engr	%	MAT 0.0	-3sig				0
		%	MAT 0.0	Avg				9
		%	MAT 0.0	+3sig				9
Rotational Vibration (Unrecovered Write Fault Threshold)	Prod. Assur.	Rad/s^2	Gen 1.0	Min				37
		Rad/s^2	GEN 1.0	Avg				37
		Rad/s^2	GEN 1.0	Max				100
Seek Time (Average Track Write)	MFG Engr	msec	GEN 1.0	-3sig				0
		msec	GEN 1.0	Avg				4.2
		msec	GEN 1.0	+3sig				4.2
Seek Time (Average Track Read)	MFG Engr	msec	GEN 1.0	-3sig				0
		msec	GEN 1.0	Avg				3.8
		msec	GEN 1.0	+3sig				3.8
Random Write, 16 tags, 2KB across drive	Sys Integration	IOPS	GEN 1.0	Min				130
		IOPS	GEN 1.0	Avg				130
		IOPS	GEN 1.0	Max				200
Random Read, 16 tags, 2KB across drive	Sys Integration	IOPS	GEN 1.0	Min				140
		IOPS	GEN 1.0	Avg				140
		IOPS	GEN 1.0	Max				200
Raw Read Error-Rate	Prod. Assur.	Errors/bits	GEN 1.0	Min				0
		Errors/bits	GEN 1.0	Avg				1.00E-07
		Errors/bits	GEN 1.0	Max				1.00E-07
Pack Write Time	MFG Engr	minutes	GEN 1.0	-3sig				0
		minutes	GEN 1.0	Avg				30
		minutes	GEN 1.0	+3sig				30
% Drives with Unrecoverable Errors in MGT	Prod. Assur.	%	GEN 1.0	Min				0
		%	GEN 1.0	Avg				5
		%	GEN 1.0	Max				5

Qualification Testing Overview



- Test plans are generated for each Qual configuration (e.g. A1, A2, A3)
- Testing is done per this plan. Results are monitored by the test engineers & the Core Team

TPM Application -- Example



Define (for each deviation from plan)
- What Changed vs Expectations
- How recovered
- Sensitivity to parameter variations/changes
- Configuration
  - H/W
  - SCSI code
  - Servo code
  - Electronics
  - Other
- Test equipment

Key Points

- A carefully structured metrics hierarchy forms the basis for organizational learning in the system development.

- Products of a system of technical metrics include
  - More optimal system solution within a given programmatic context.
  - A knowledge basis (e.g. parametric models) that can be applied to other system developments.

References

- *IEEE Standard for Application and Management of the Systems Engineering Process*, IEEE Std 1220-2005, September 2005.
- *Systems Engineering Fundamentals*, Supplementary Text Prepared by the Defense Acquisition University Press, Fort Belvoir, VA 22060-5565, January 2001.

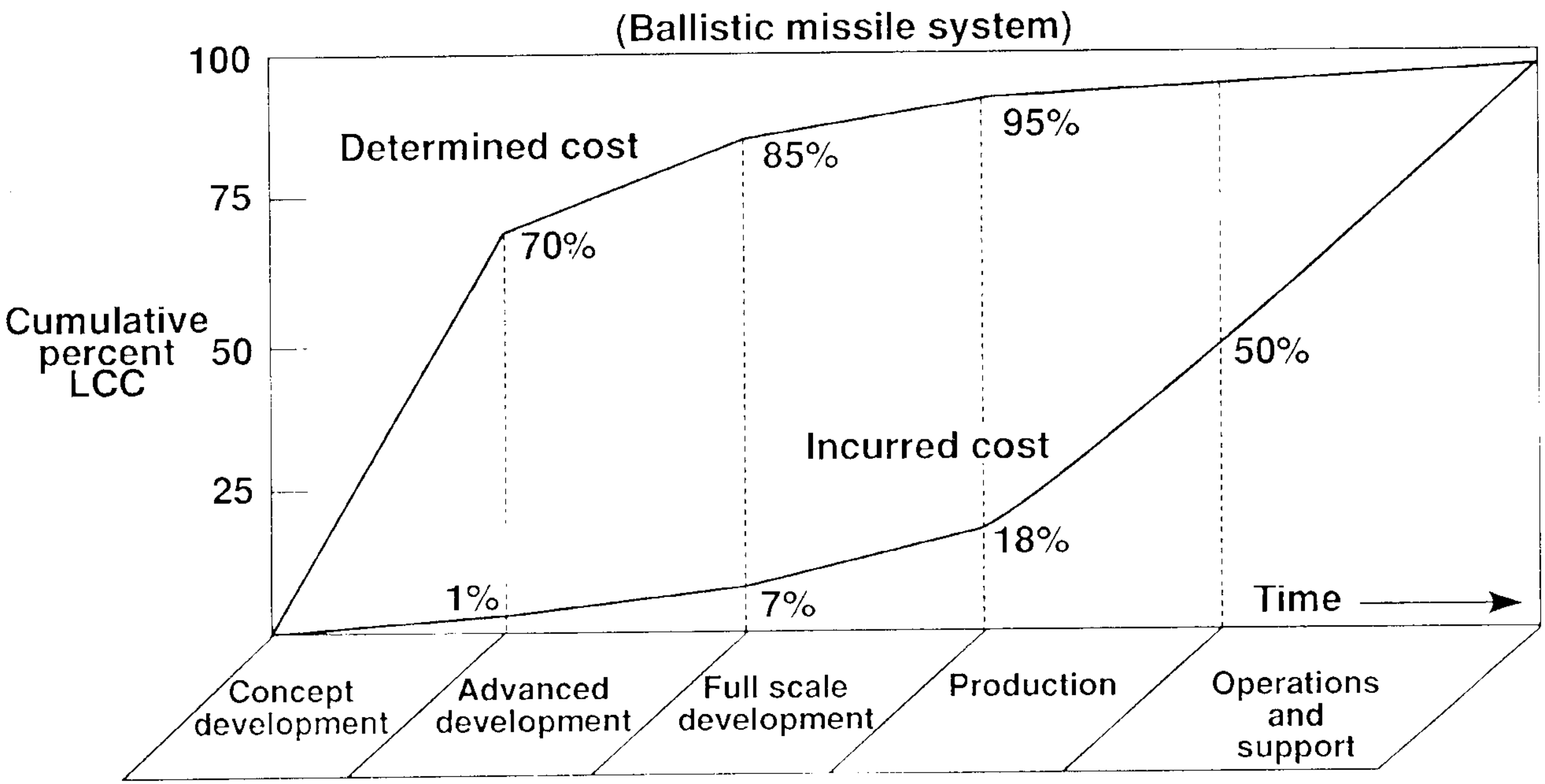
Lesson 12:
Margin Modeling

Objectives

- Reference to IEEE-1220 processes
  - 6.7.5.1 Select Methodology and Success Criteria
  - 6.7.6.2 Analyze System and Cost-Effectiveness
  - 6.7.10 Design Effectiveness Assessment

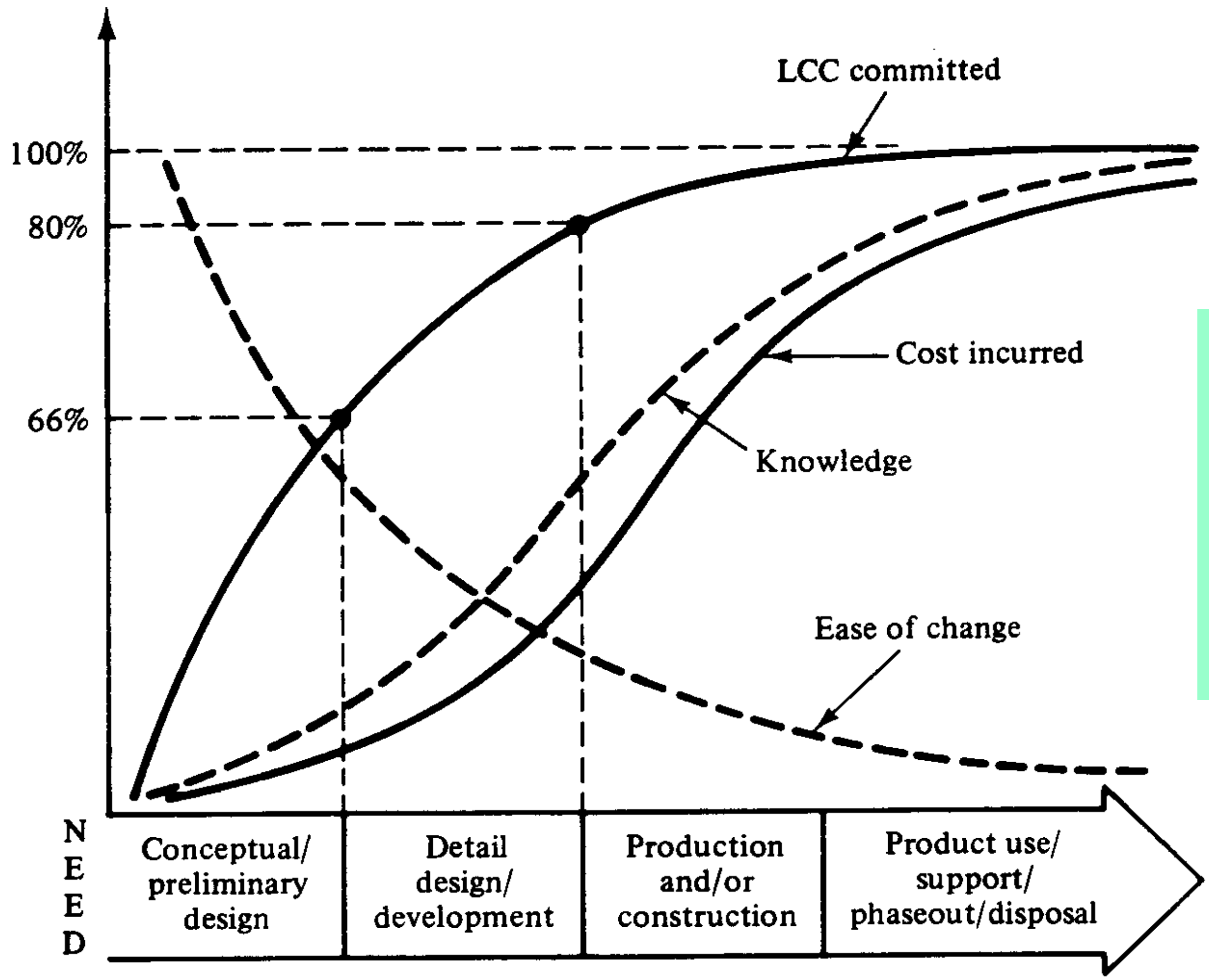
- Describe & illustrate a model-based approach to estimate technical performance metrics to assess system effectiveness.

Life Cycle Cost Gets Locked In Early



Source: Boeing Company

The Knowledge Curve



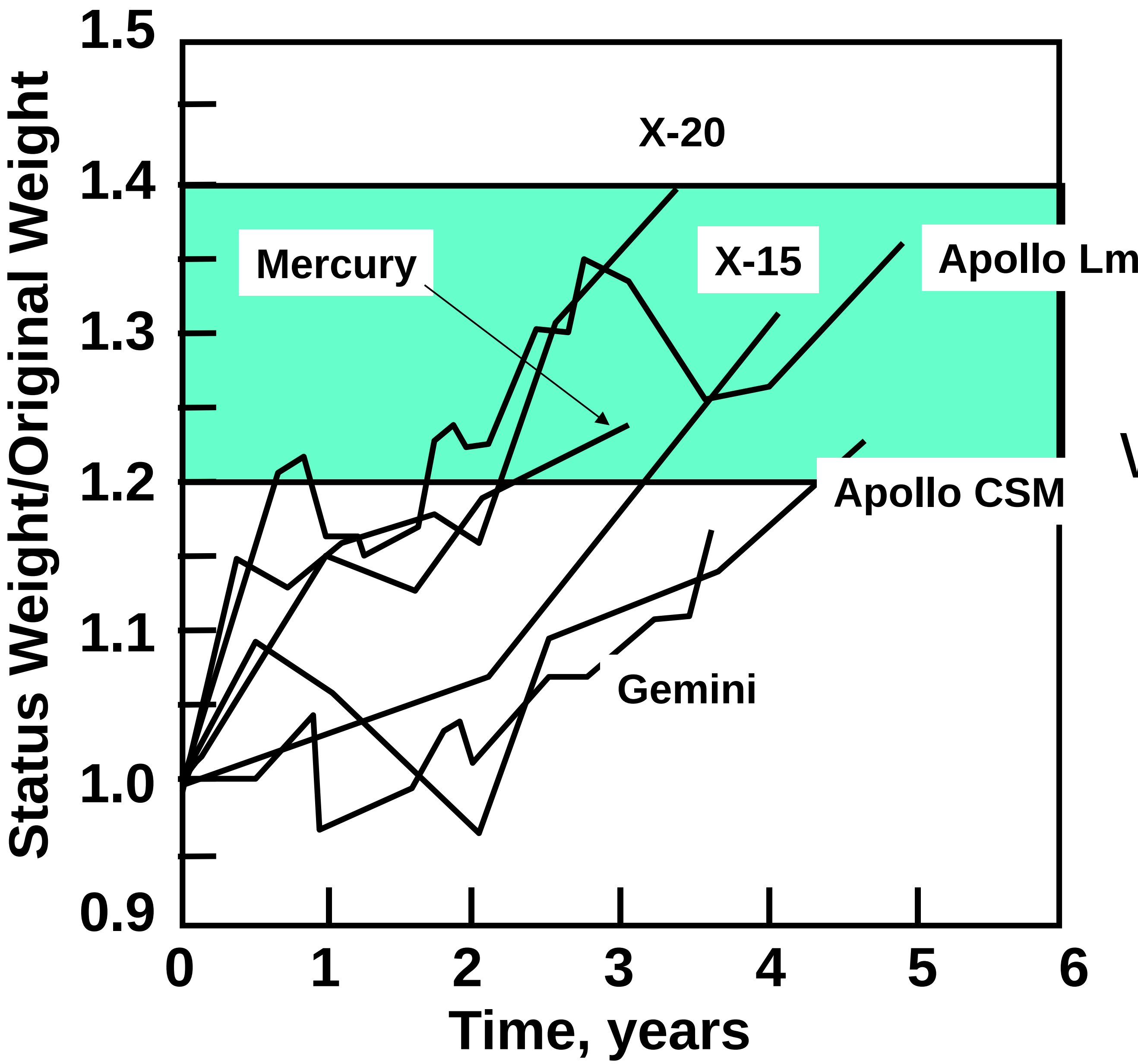
Improved systems analysis can accelerate the knowledge curve, leading to better decisions earlier.

Types of Design Margins

- Weight
  - Development weight increment
  - Growth in system capability
- Structural Design Margins
  - Load criteria
  - Safety factors
  - Life
- Design Configuration Margins
  - Equipment density
  - Interconnection provisions
  - Equipment mounting
  - Equipment Access

Weight Margin

- Recognize growth - inevitable
  - Planned – future systems
  - Unplanned – surprises
- Establish realistic weight definition/allotment
  - Growth
  - Development
  - Contingency
  - Uncertainty
- Utilize weight as a controlling factor
  - Program margin of success
  - Cost reduction



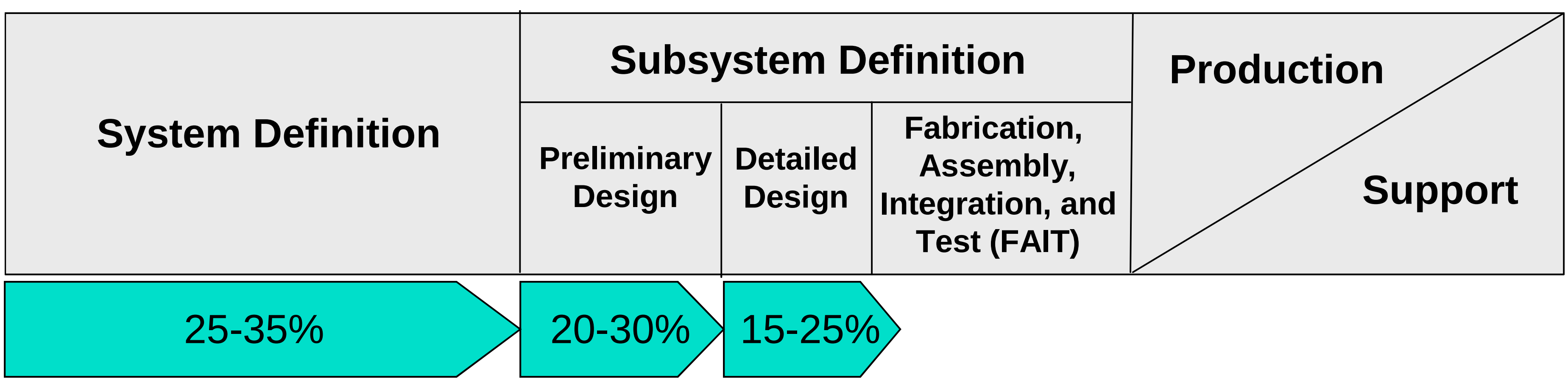
Spacecraft Weight Growth History

Weight Allotment Convention Definition

- Analyze past history of other vehicles
- Define allotment
  - Structure
  - Systems
- Define weight statement
  - Target
  - Nominal
  - Maximum

NASA Design Margins for Spacecraft

- Pre-Phase A -- 25-35%
- Phase A -- 25-35%
- Phase B -- 20-30%
- Phase C -- 15-25%



Technical Resource Management

Allocation

(estimates) (estimates & actuals) (actuals)

Margin

Control

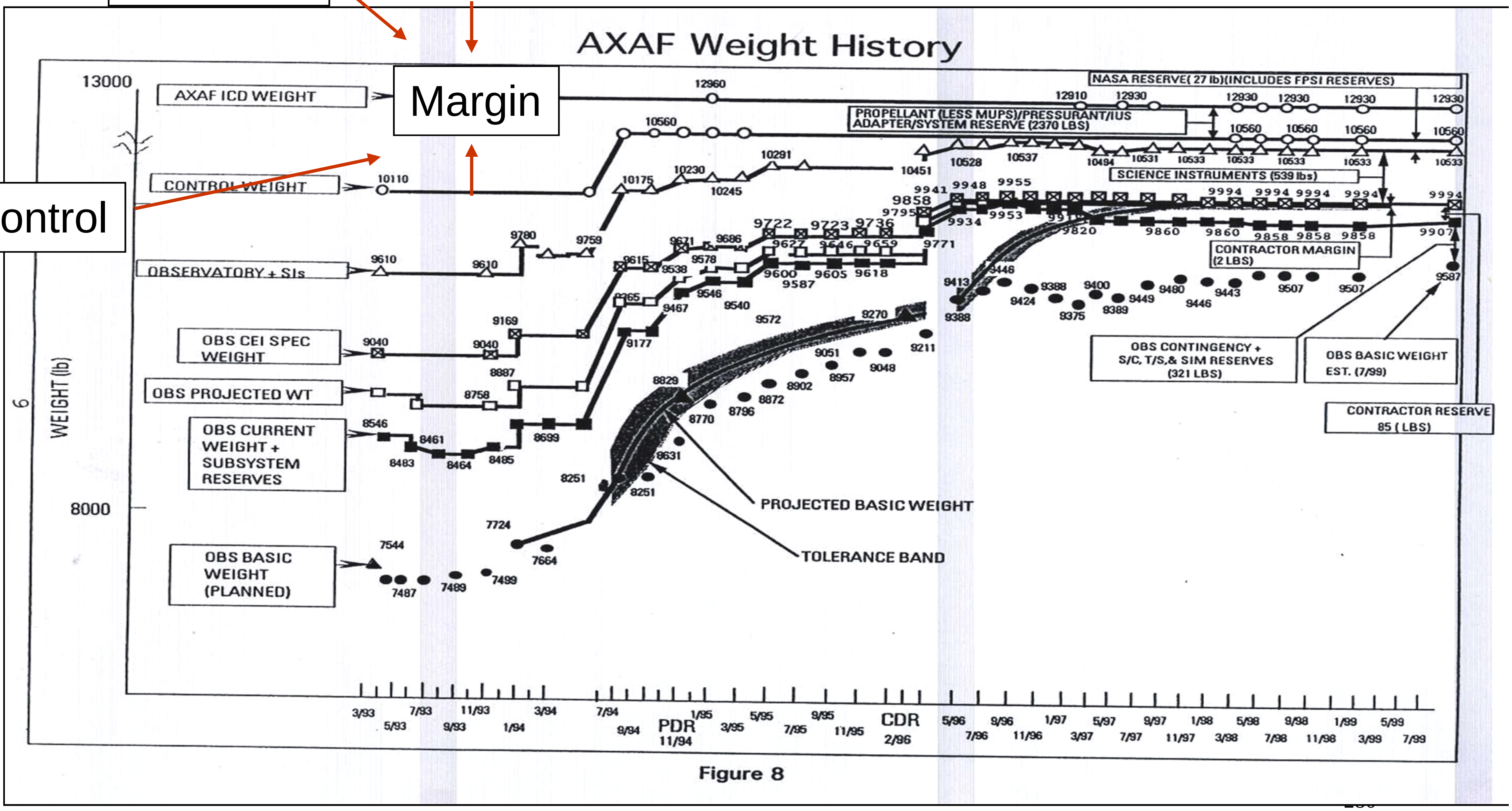
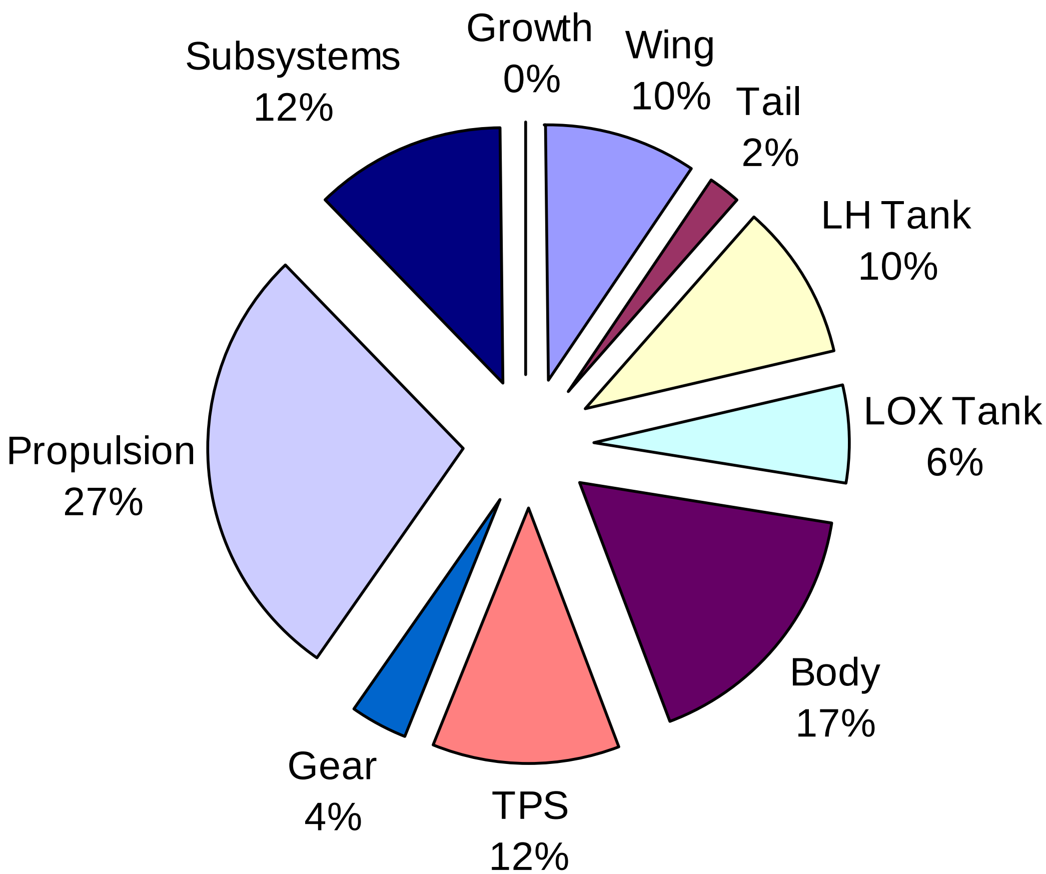


Figure 8

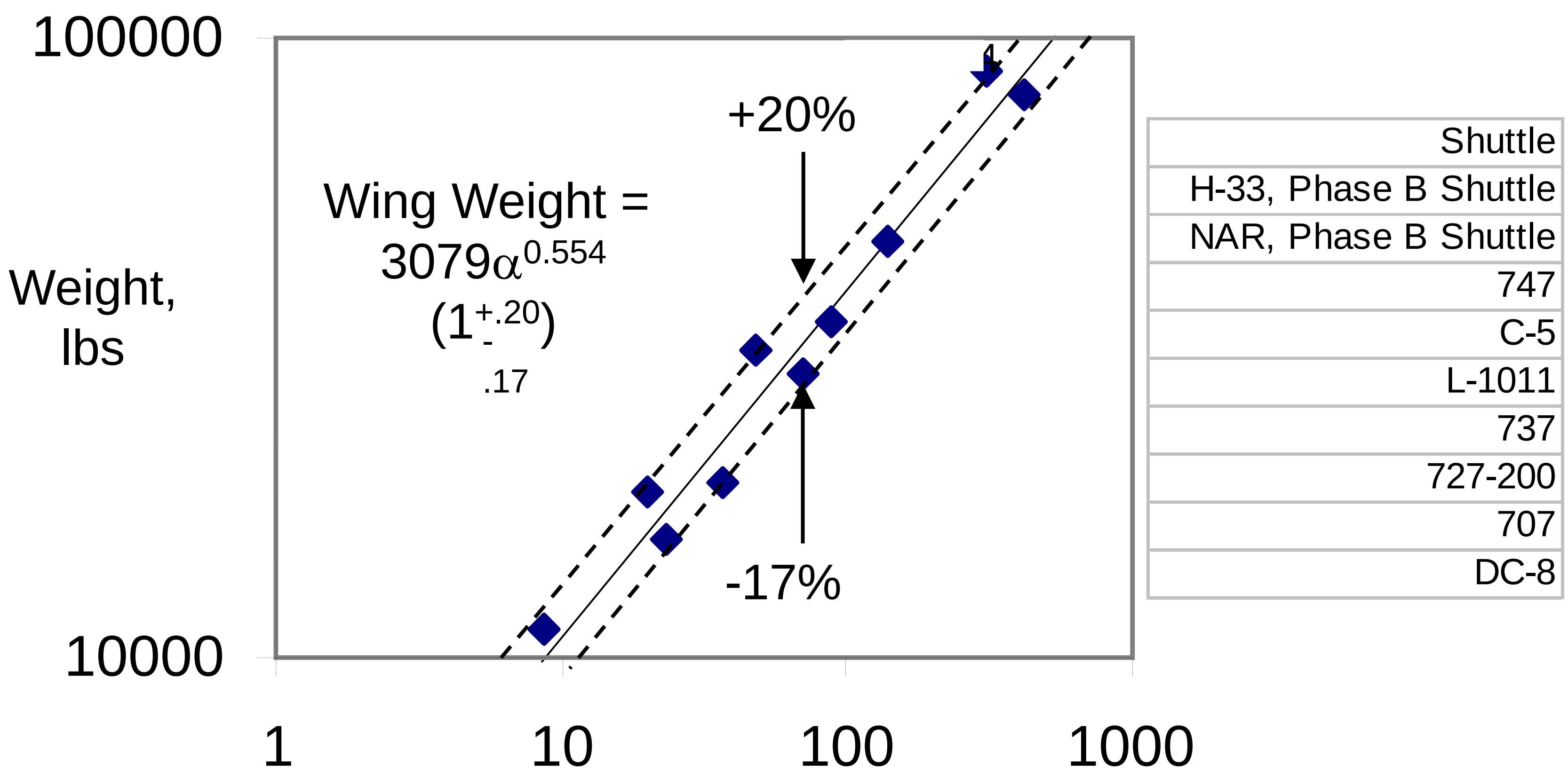
Space Shuttle Weight Growth Phase C/D (1972-1983)

Wing	0.27
Tail	0.14
LH Tank	0.13
LOX Tank	0.13
Body	0.03
Gear	0.06
TPS	0.01
Propulsion	0.12
Subsystems	0.50
Isp, sec	-2.5

Single-Stage-to-Orbit Weight Distribution



Historical Weight Estimating Relationship (Wing)

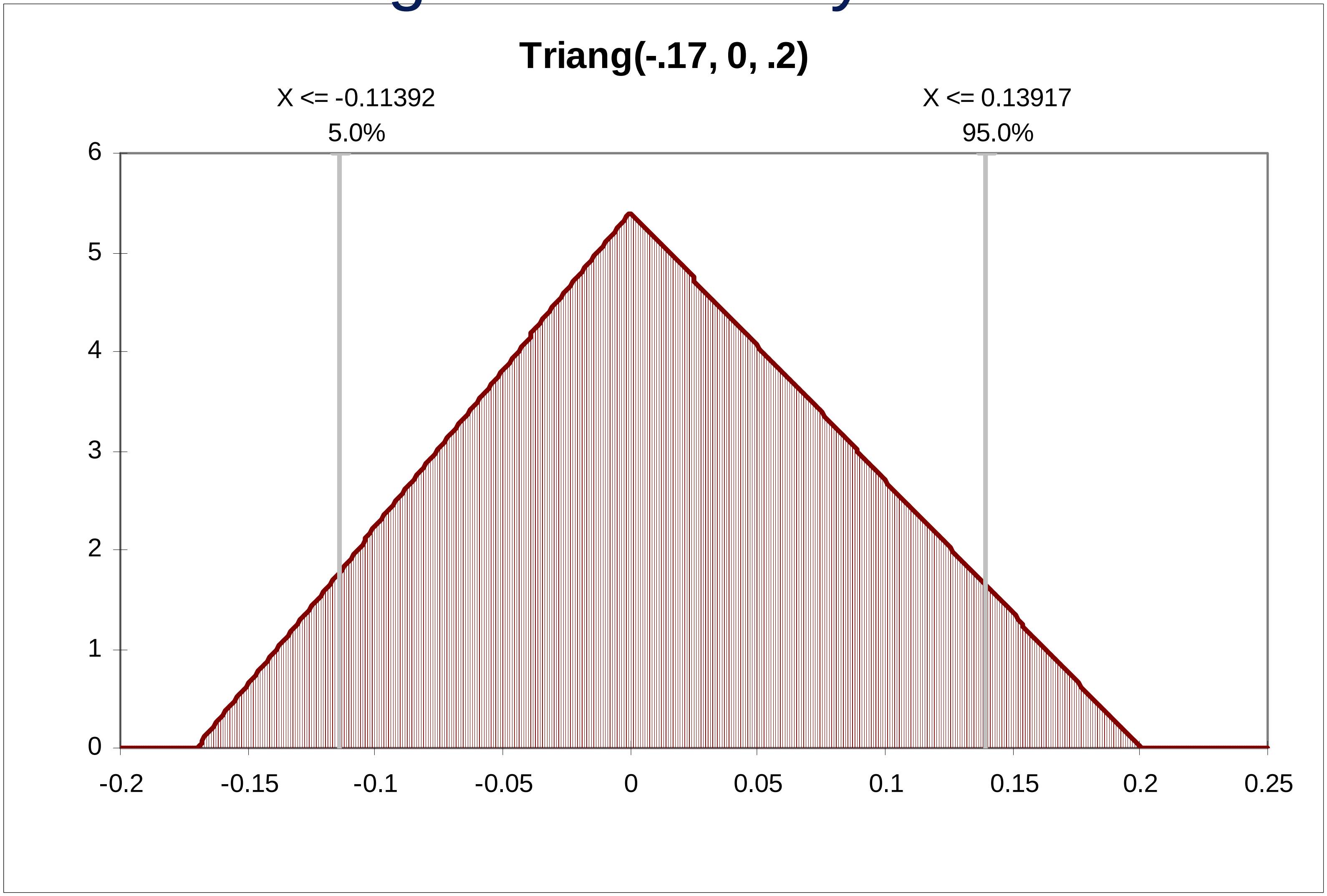


$$\alpha = \left(\frac{\text{Design Weight*Maneuver Load*Safety Factor*Structural Span}}{\text{Root Chord}} \right)$$

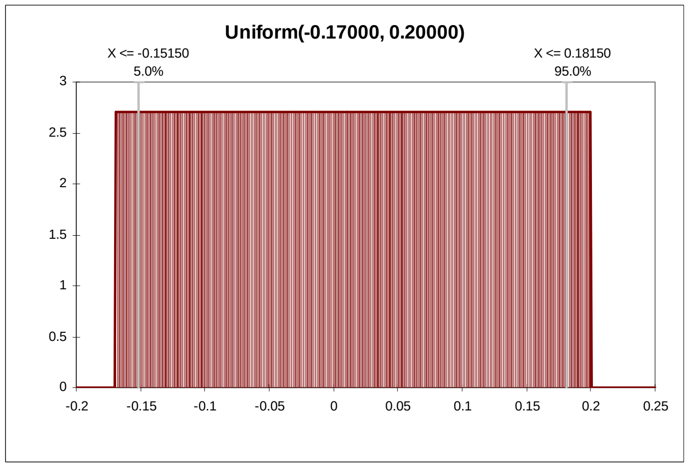
Conceptual Weight Estimation Uncertainties

Historical Weight Estimation Relationship Errors	Wing	-0.17	0.20
	Tail	-0.70	1.06
	LH Tank	-0.18	0.41
	LOX Tank	-0.51	0.49
	Body	-0.36	0.64
	Gear	-0.15	0.21
Selected Errors	TPS	-0.30	0.30
	Propulsion	-0.30	0.30
	Subsystems	-0.30	0.30

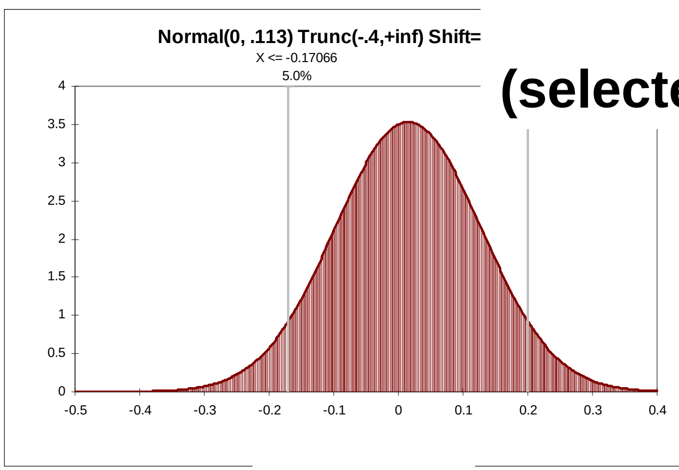
Weight Uncertainty Model



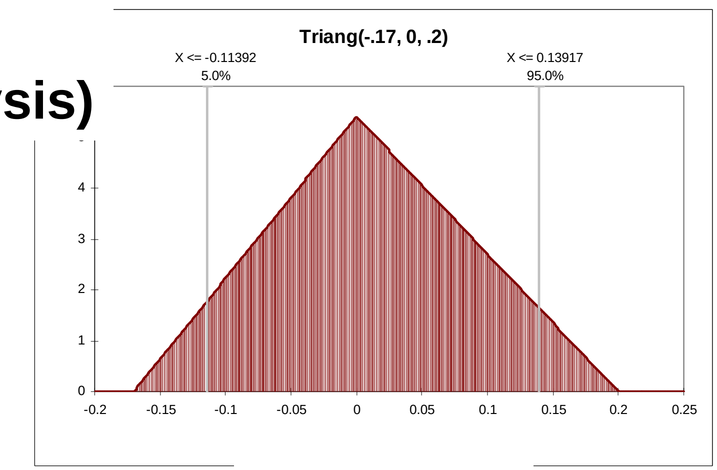
Examples of Probabilistic Uncertainty Models



Uniform (selected for analysis)



Normal



Triangular

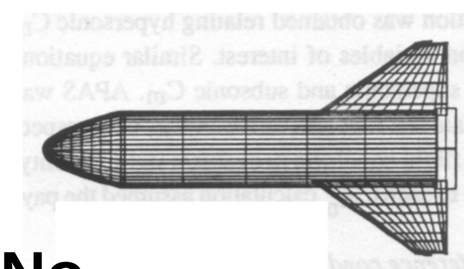
Monte Carlo Simulation

Apply Uncertainty

Wing Weight = $3079\alpha^{0.554}(1+\delta)$

.
.
.

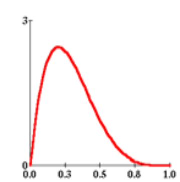
Conduct Experiment

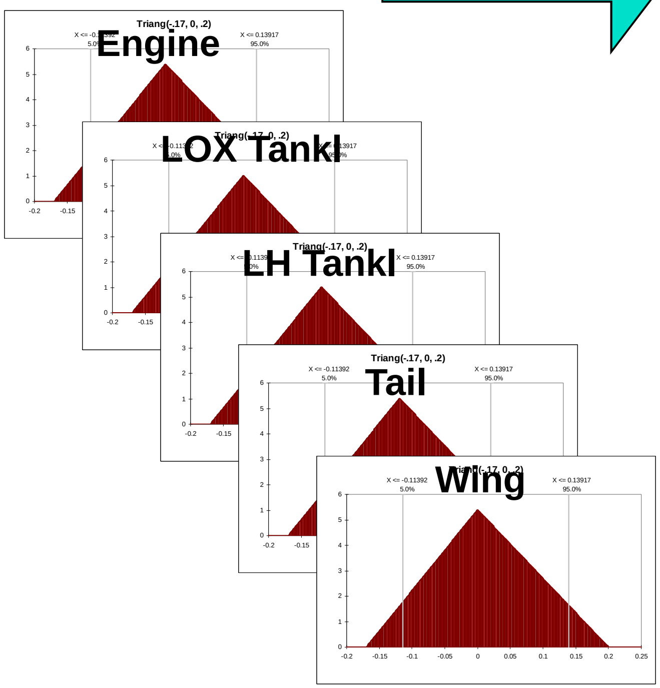


No

N iterations?

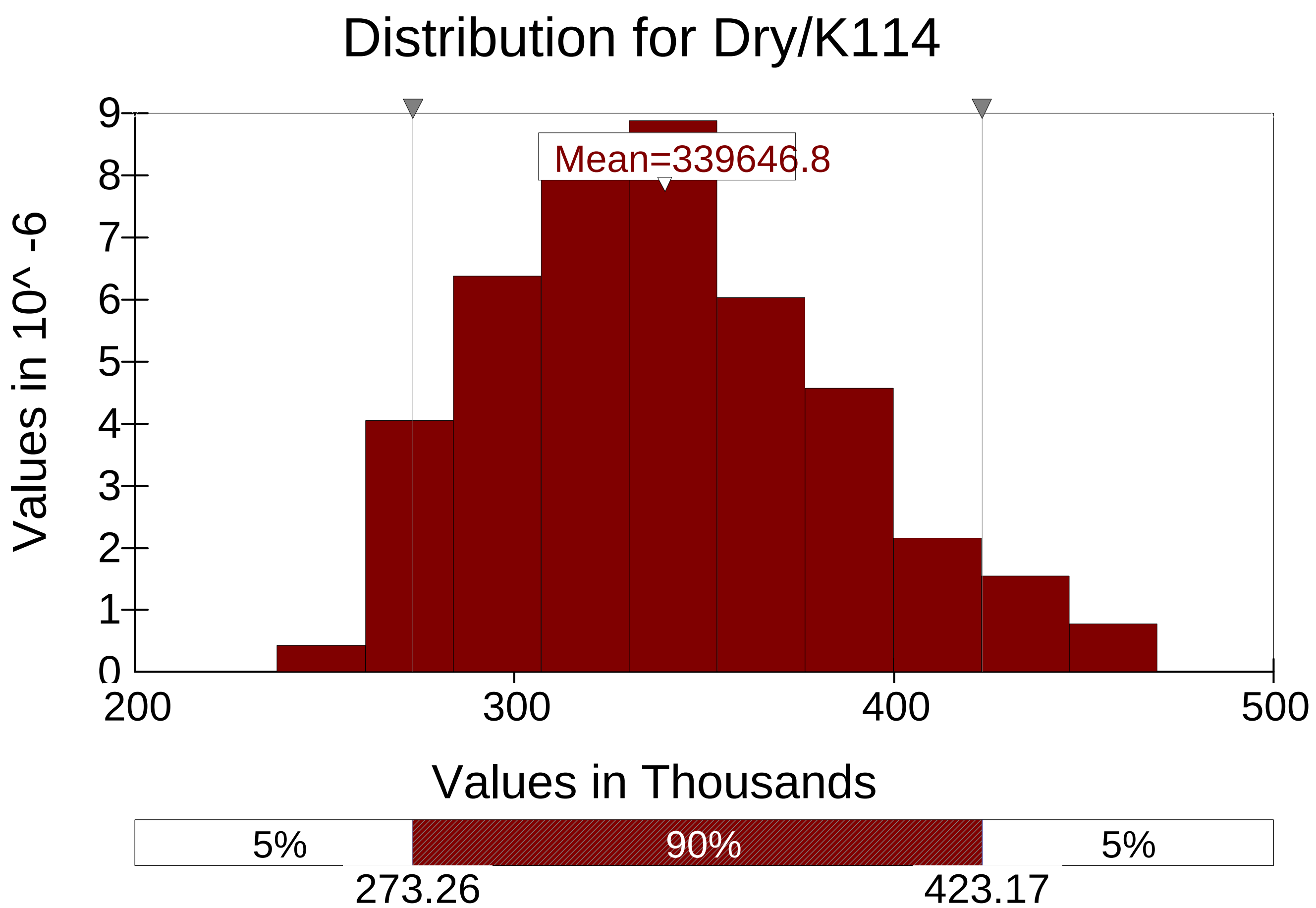
Output Distribution





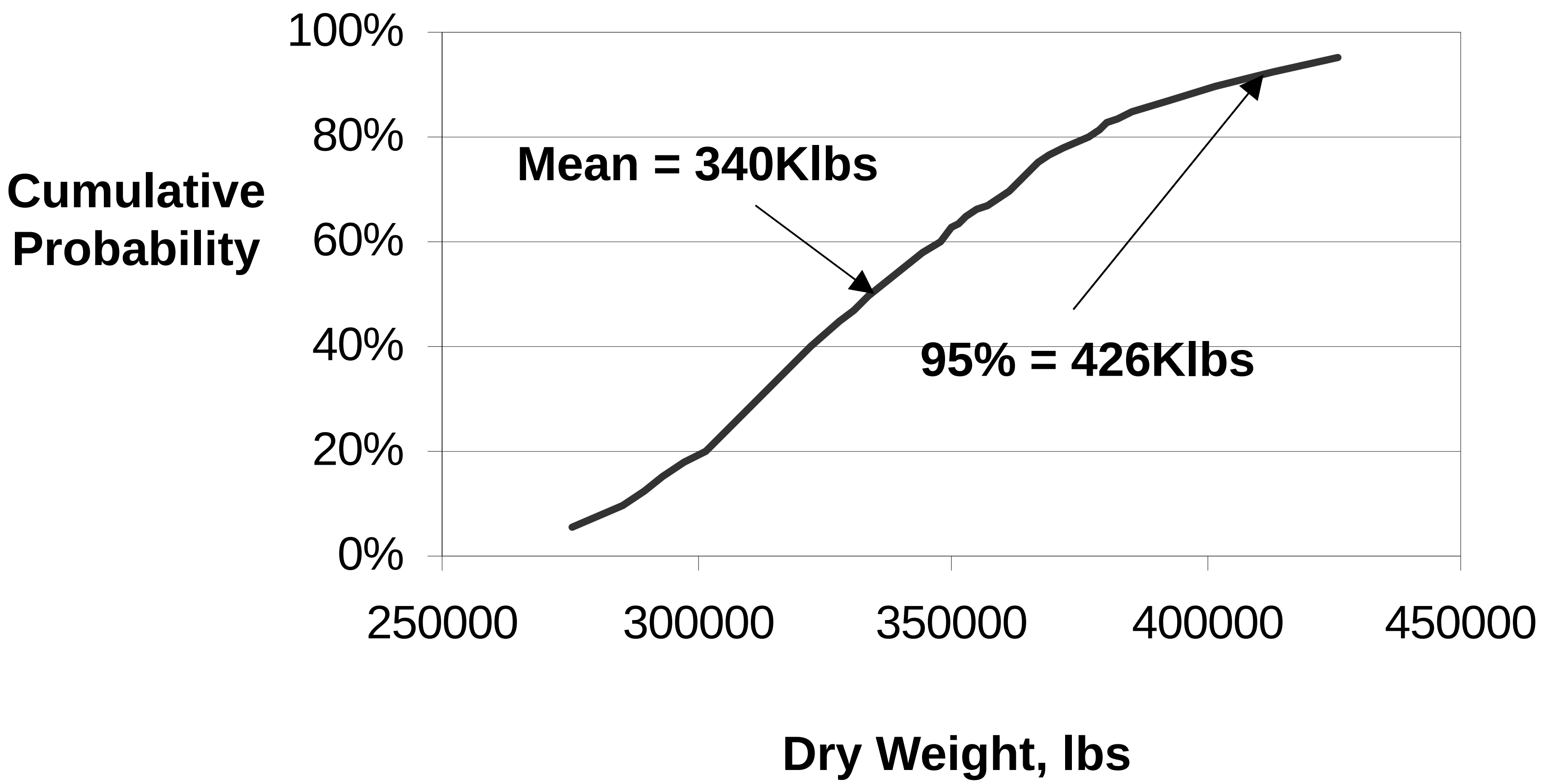
Randomly Pick Weight Uncertainty

Weight Probability Distribution



Dry Weight = 339Klbs ± 25% with 90% Confidence

Weight Uncertainty Impacts



Weight Uncertainty Impacts

SSTO

Cum. Probability	Dry Weight, lbs	ΔDry Weight / Mean Dry Wt.	ΔDry Weight / Payload
Mean	339,884	0.00	0.0
60%	348,204	0.02	0.3
70%	361,014	0.06	0.8
80%	376,621	0.11	1.5
90%	401,815	0.18	2.5
95%	426,189	0.25	3.5

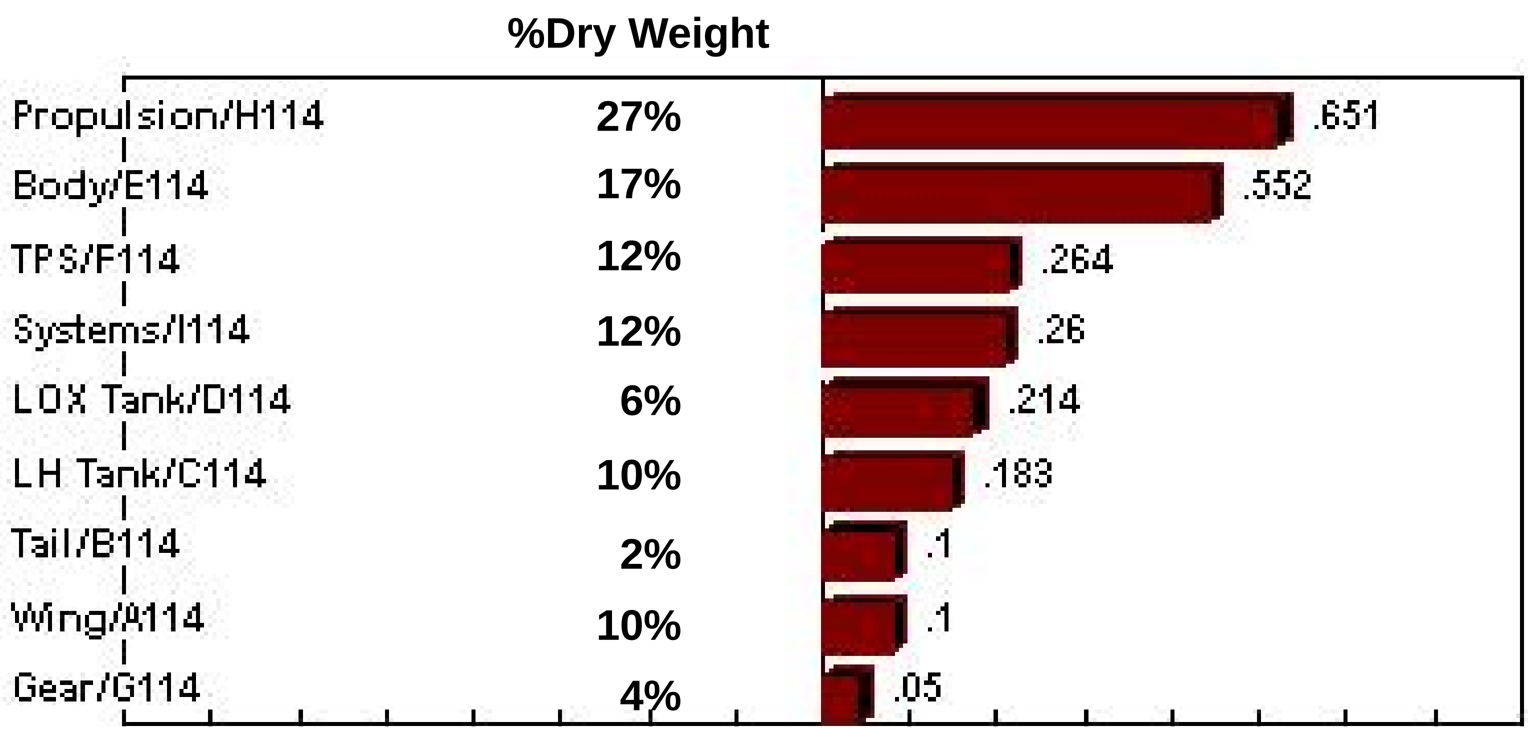
SSTO

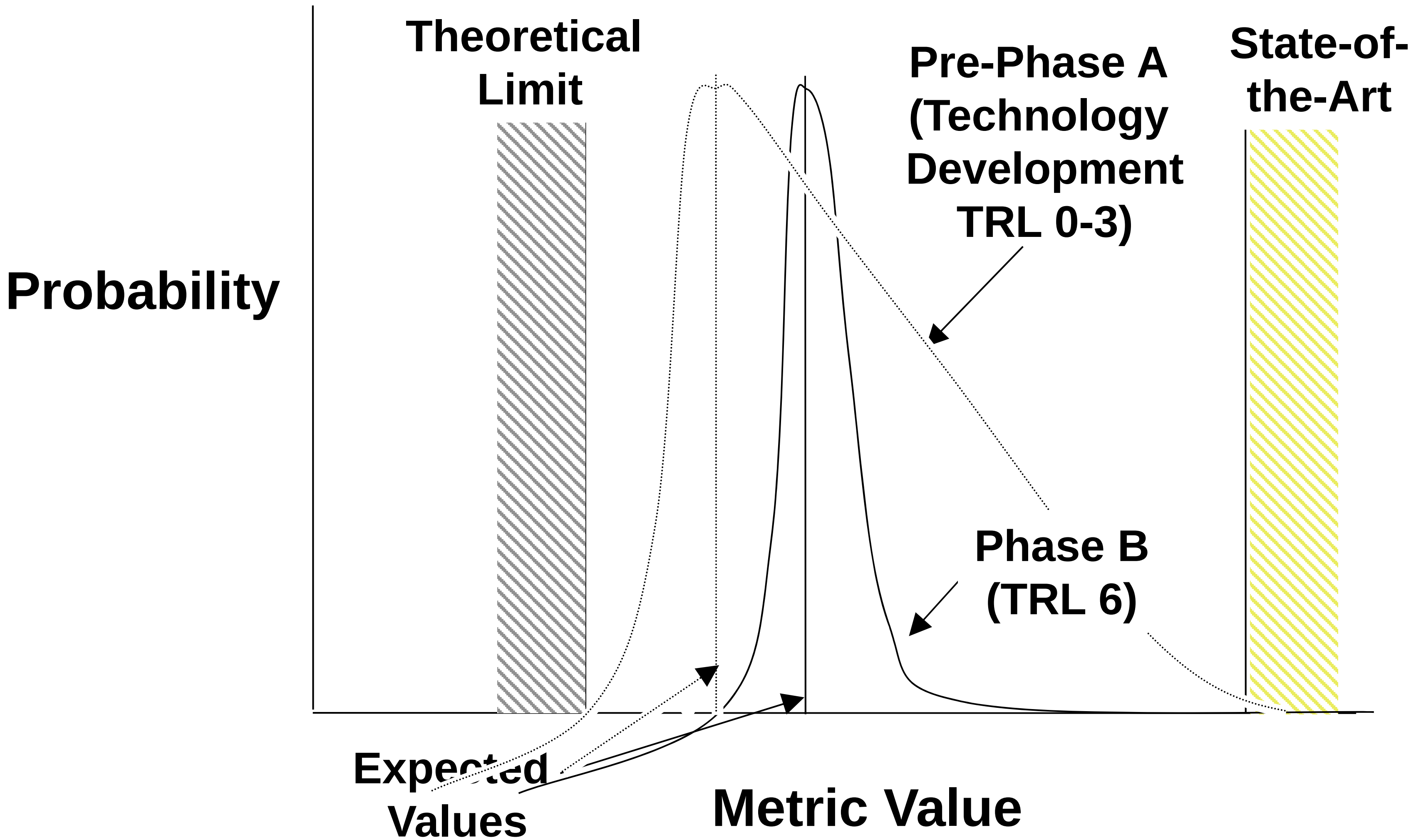
Isp = ± 5%
Drag = ± 15%
Volume = ± 5%

Cum. Probability	Dry Weight, lbs	ΔDry Weight / Mean Dry Wt.	ΔDry Weight / Payload
Mean	349,035	0.00	0.0
60%	355,326	0.02	0.3
70%	371,730	0.07	0.9
80%	392,926	0.13	1.8
90%	430,897	0.23	3.3
95%	456,781	0.31	4.3

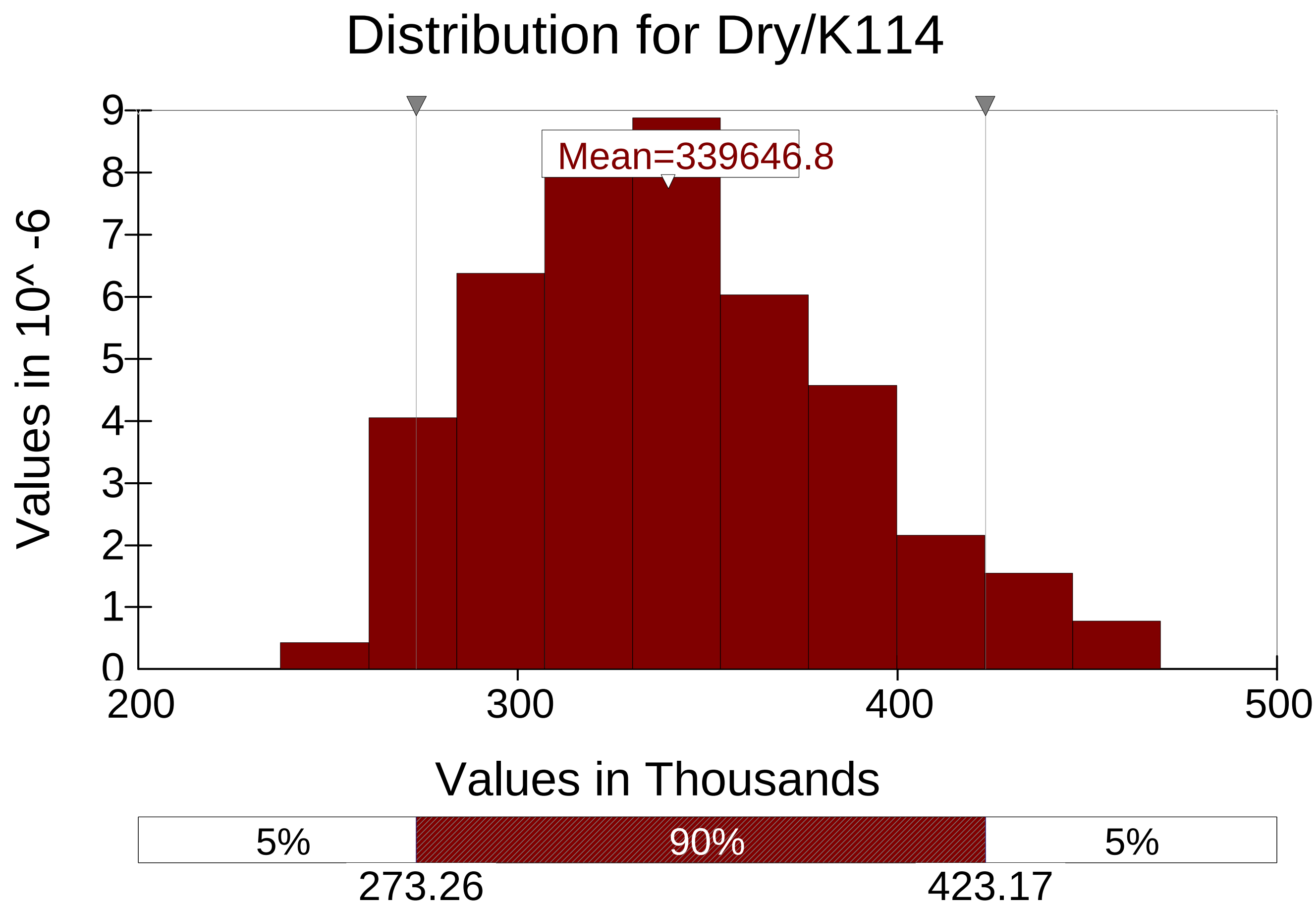
Payload = 25,000 lbs

Ranking of Weight Uncertainty Impacts




Theoretical Limit
Pre-Phase A (Technology Development TRL 0-3)
State-of-the-Art
Probability
Phase B (TRL 6)
Expected Values
Metric Value

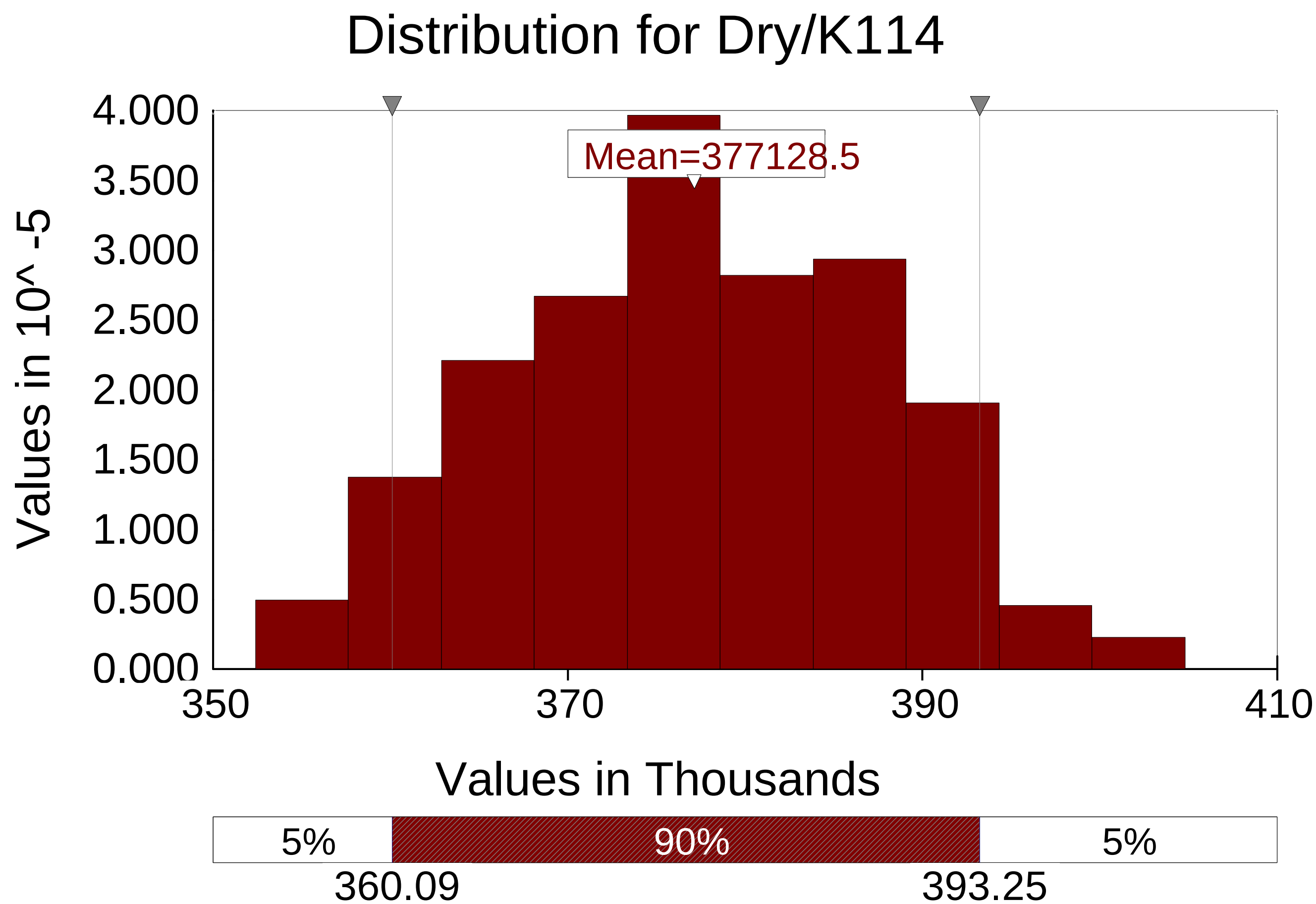
Estimates without Technology Investment



Dry Weight = 339Klbs ± 25% with 90% Confidence

Beginning a system development program without a solid technology base is extremely risky!!!

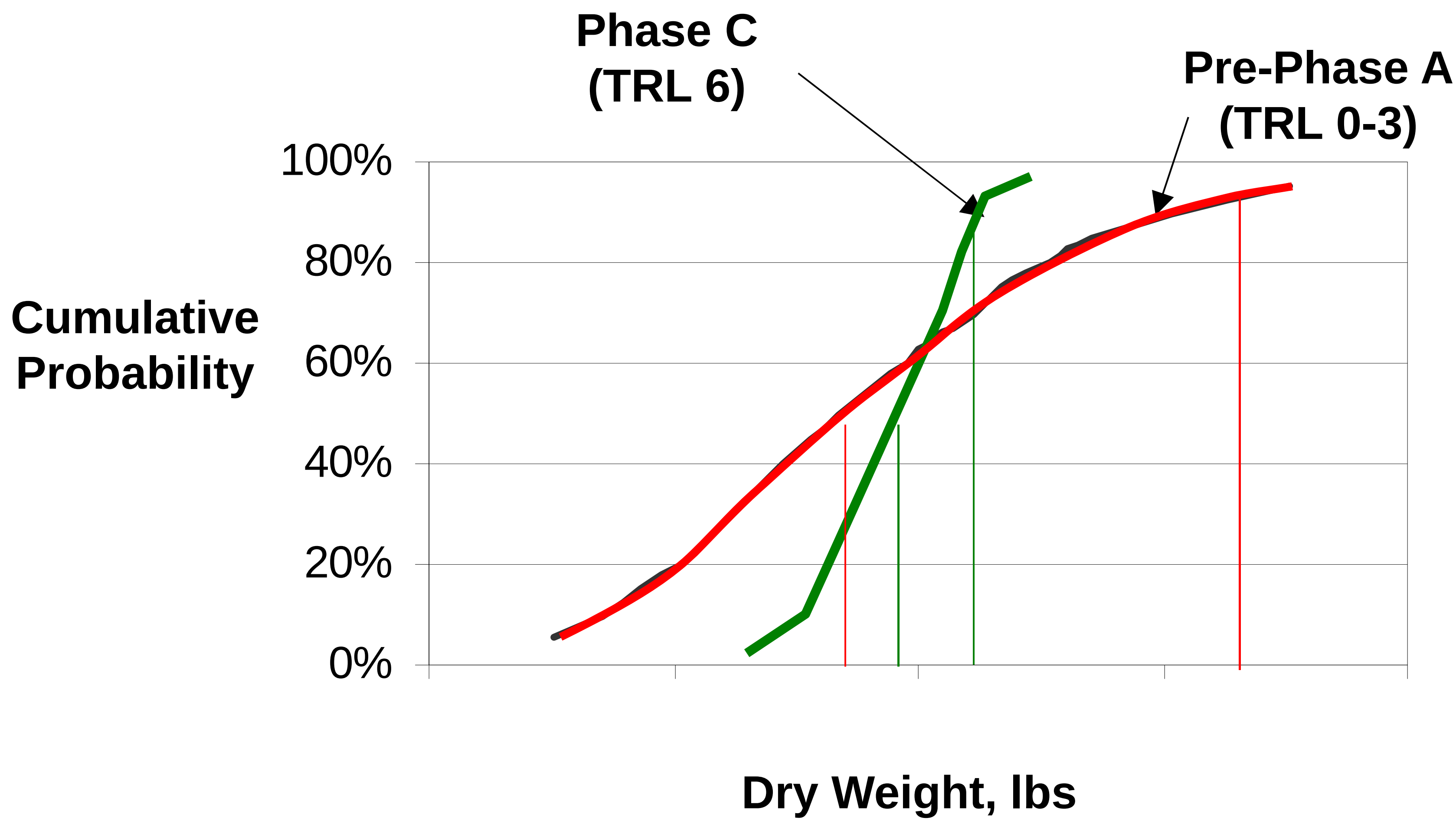
Estimates with Technology Investments



Dry Weight = 377Klbs ± 5% with 90% Confidence

Technology Program should be structured to reduce uncertainties to an acceptable level for a given confidence

Benefit of Strategic Technology Investment



Key Points

- Systems analysis adds value through reducing uncertainty.

- Margin management strategies allow for optimal systems design
  – Inadequate margins lead to excessive technical changes to meet requirements, schedule slips, and budget overruns.
  – Excessive margins lead to poorly performing systems that inefficiently use resources and are too expensive for the performance they provide.

References

- *Estimating and Budgeting Weight and Power Contingencies for Spacecraft Systems,* ANSI/AIAA G-020-1992.

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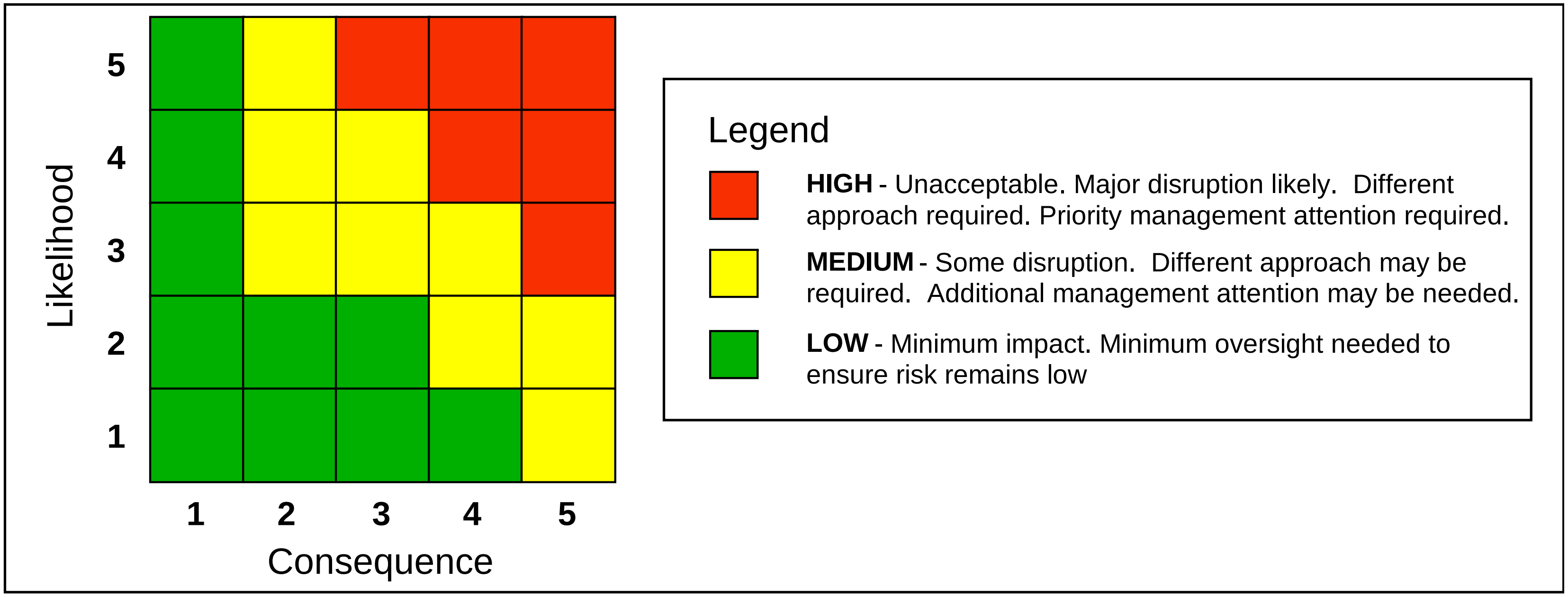
Lesson 13: Risk Analysis

Objectives

- Reference to IEEE-1220 processes
  - 6.7.4 Identify Risk Factors
  - 6.7.6.4 Quantify Risk Factors
  - 6.7.7 Select Risk Handling Options

- Illustrate risk analysis method using a technology risk analysis application.
  - This analysis primarily addresses risk identification, and to a lesser extent risk quantification.

Risk Classification



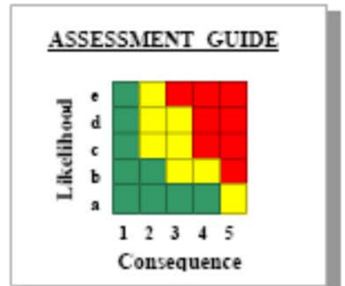
Risk classification involves understanding both the likelihood of an event and its associated consequences.

Sample Definitions of Likelihood & Consequence

CVN 77 Program Risk Assessment

What is the Likelihood the Risk Will Happen?		
Level	Chance of Occurrence	Your Approach and Processes
A	Not Likely: 10% chance	...Will effectively avoid this risk based on standard practices
B	Low Likelihood: 25 chance	...Have usually avoided this type of risk with minimal oversight in similar cases
C	Moderate: 50% chance	...May avoid this risk, but workarounds will be required
D	Highly Likely: 75 % chance	...Cannot avoid this risk with standard practices, but a different approach may work
E	Near Certainty: 90% chance	...Cannot avoid this risk with standard practices, probably not able to mitigate

Given the risk is realized, what would be the magnitude of the impact?			
Level	Technical Performance	Schedule Impact	Cost $ (millions)
1 Negligible	Small performance shortfall in specific technical area; overall system performance unaffected	Minimal schedule slip but able to meet need dates w/o add'l resources. Critical path unaffected	Cost increase <1
2 Marginal	Minor performance shortfall in specific technical area; overall system performance below goal but w/in acceptable limits	Additional resources required to meet need dates. Critical path unaffected	Cost increase 1-6
3 Moderate	Moderate performance shortfall in specific technical area; overall system performance below goal & possibly below acceptable limits	Minor schedule slip; will miss need date. Critical path unaffected	Cost increase 6-20
4 Critical	Overall system performance below acceptable limits	Major schedule slip. Program critical path affected (<1 month)	Cost increase 21-50
5 Catastrophic	Overall system performance unacceptable to the degree that the ship is undeliverable	Major schedule slip Program critical path affected (>1 month)	Cost increase >50



HIGH – Major program disruption, immediate priority management action required.

MODERATE – Moderate disruption, possible management action required

LOW – Minimum impact

Questions about Risk Management?

Call Systems Engineering - Risk Management, Dept E47

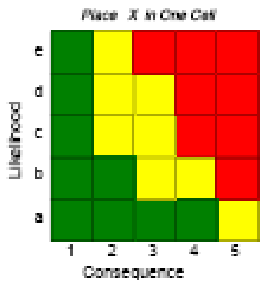
Steve Waddell, NNS 757- 688-3760

Risk Information & Mitigation Planning

Figure 2.1-1 Risk Information Sheet (RIS)

CVN 77 Risk Information Sheet

RIS # ________ WBS: ________________ IPT: ____________________________________ M/D/Y __/__/__
Risk Title: ______________________________ Risk Lead: ______________________________

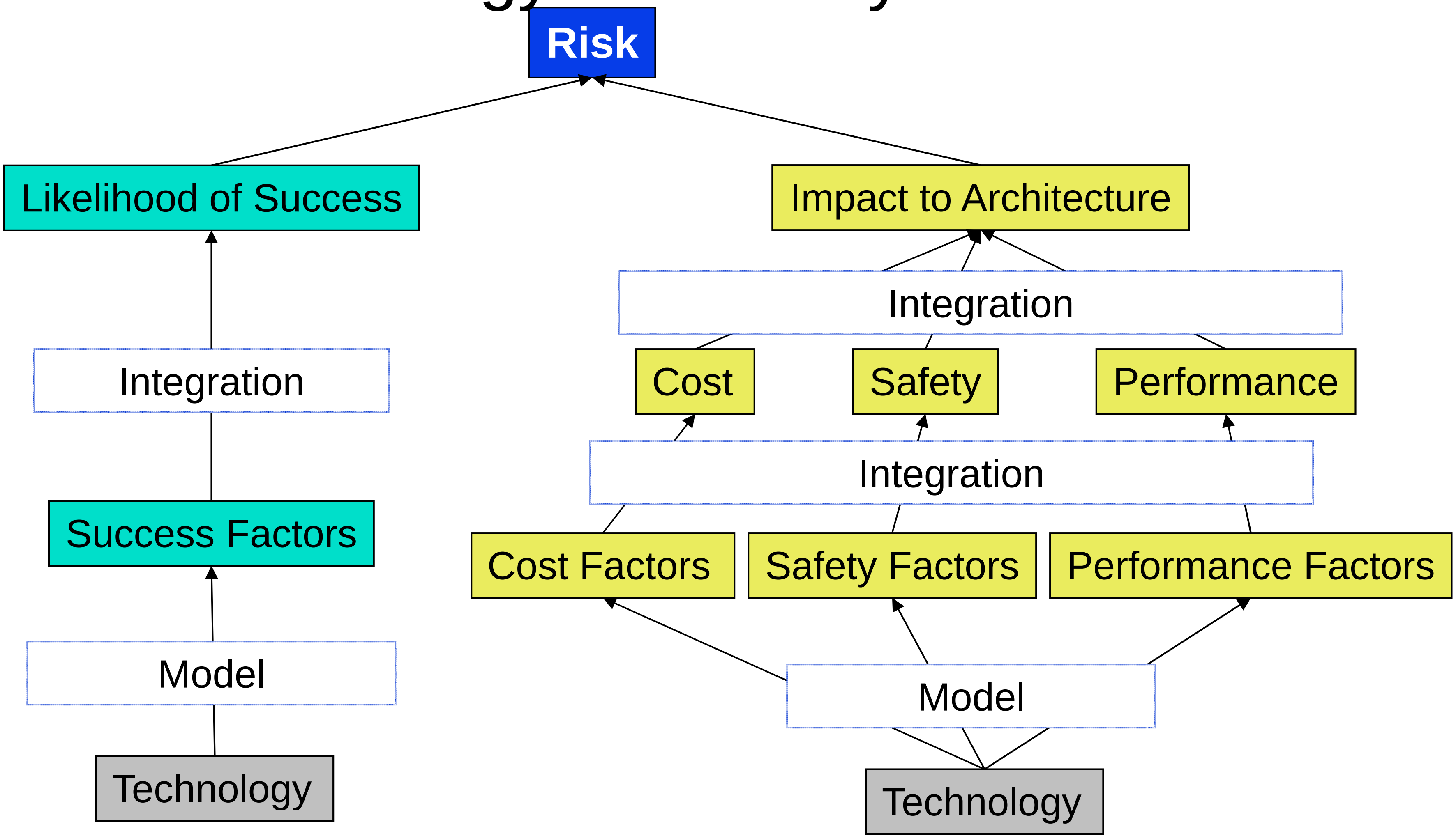
Risk Type *(Check one)*		
☐ Technical ☐ Schedule ☐ Cost	**Description of Risk Condition:** **Consequence if Realized:** **Context** *(what, how, why & where of risk conditions):*	

Risk Mitigation Plan *(Implementation plan may be provided as an attachment)*

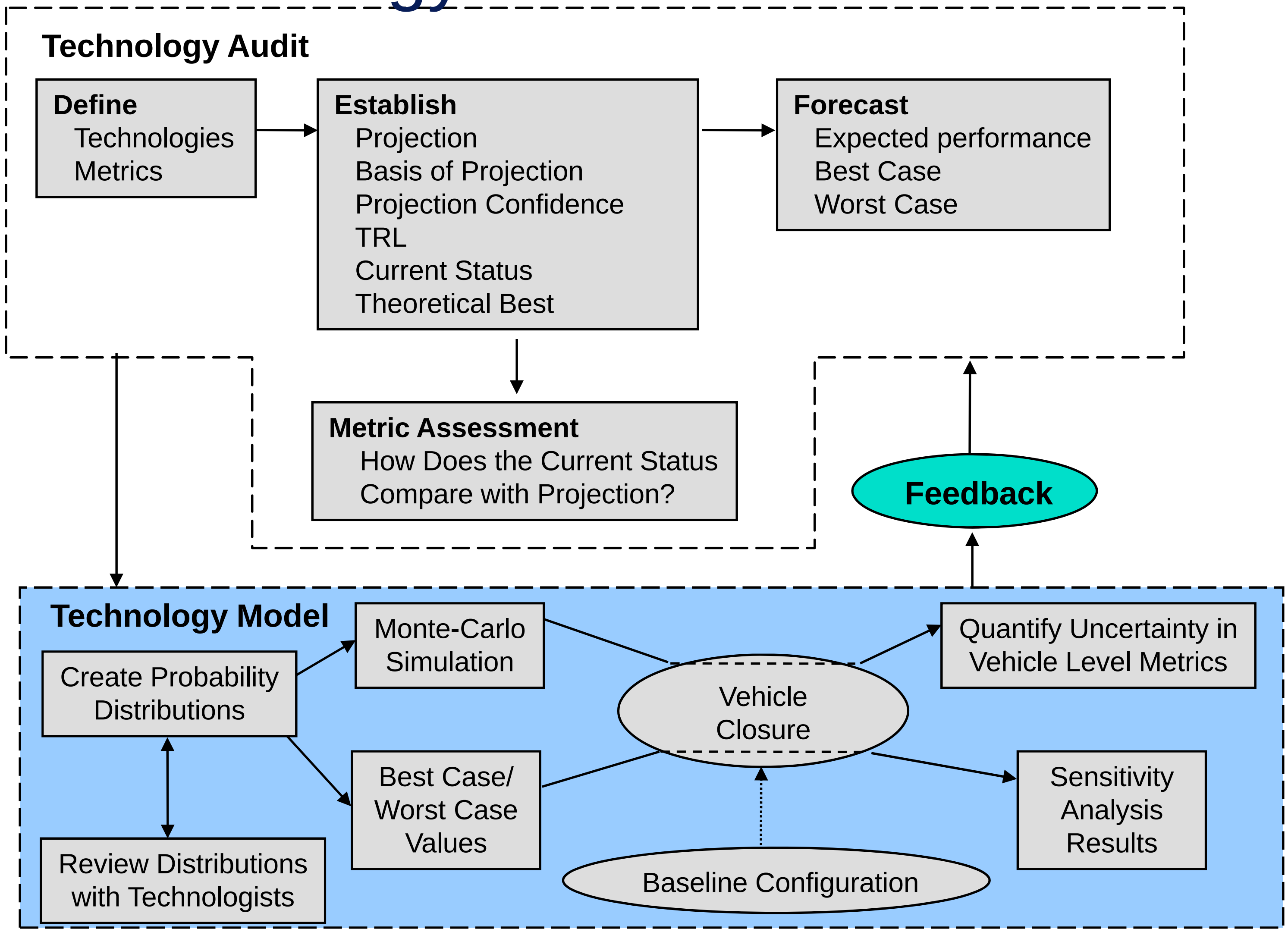
Action / Event	Date		Success Criteria	Risk Level if Successful	Comments
	Start	Finish			

Send completed worksheets to Dept E47, Systems Engineering - Risk Management, Bldg 902 or to waddell_js@nns.com.

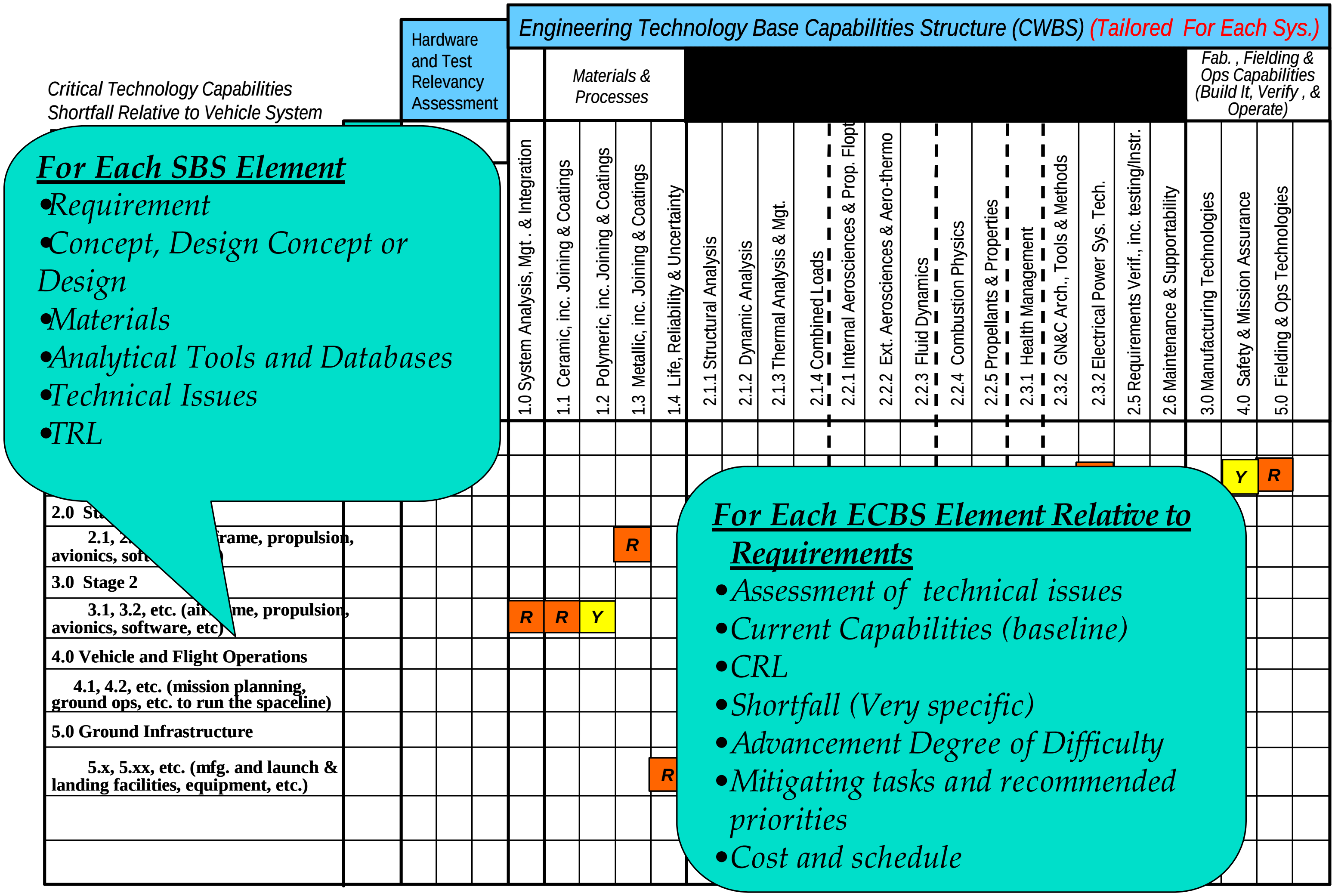
Technology Risk Analysis Model



Technology Audit & Assessment



Technology Audit Process



Will the technology mature to meet the performance expectation on schedule & within budget?

January 2003

Capability Readiness

- Capability Readiness Level (CRL) addresses readiness of the basic programmatic/engineering/infrastructure capability to support the design, fabrication, verification and operation the systems needed to satisfy customer driven/derived requirements. CRL indicates the uncertainty associated with the engineering capability needed to analyze and predict the performance and operations of the hardware/software. Applies to the micro-technologies.

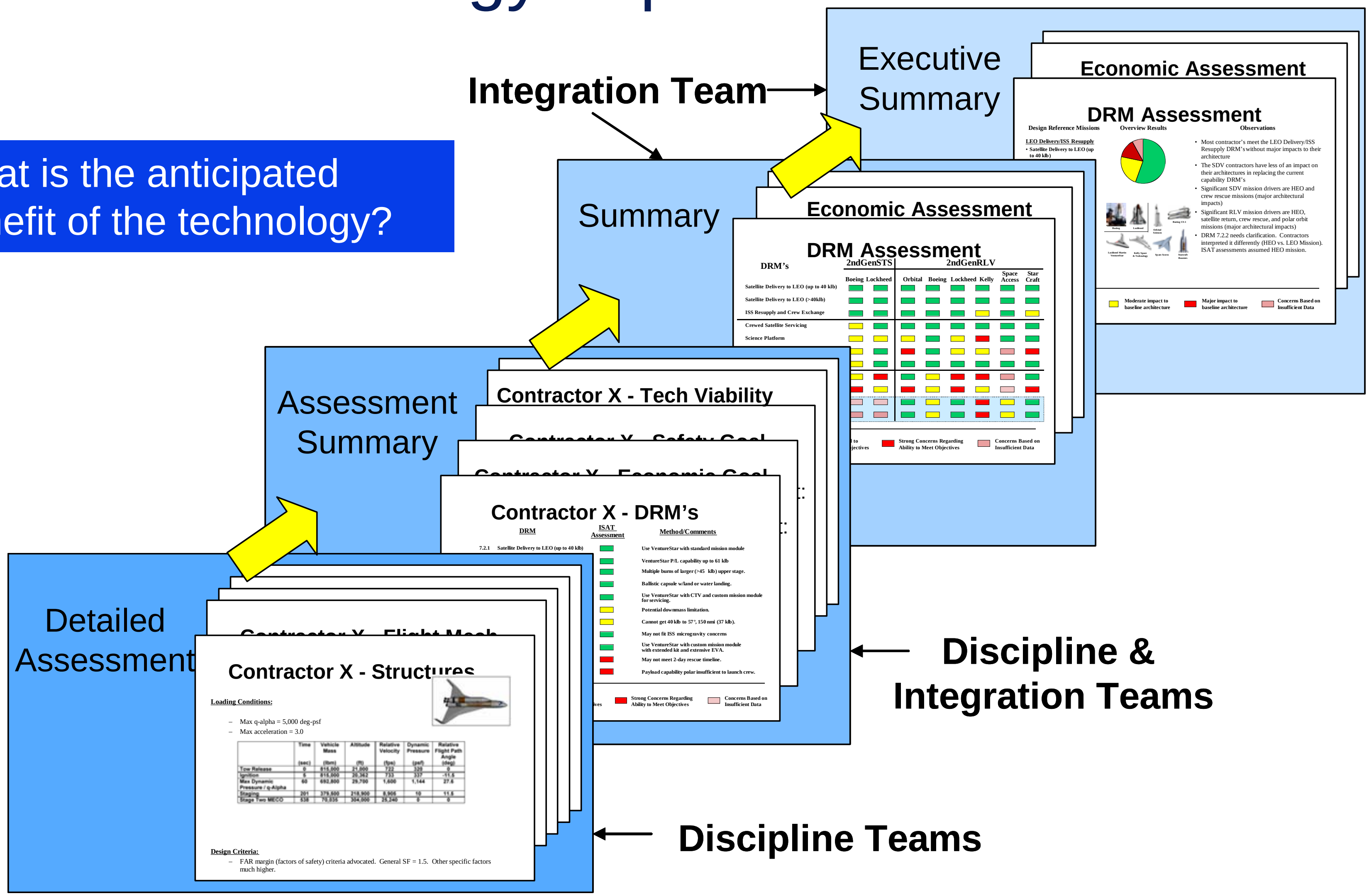
- Capability shortfall (or shortfall) is the gap between the current capability of the enabling engineering/infrastructure and the capability needed to meet the SBS requirements of a particular SBS element. These are the uncertainties that constitute the risks.

Materials & and Process Capability Readiness Level (CRL) (Example)

Materials Readiness Level (MRL)		Process Readiness Level (PRL)
Material routinely available and used in components	CRL 6	Process applied to object has produced defect free components; process parameter ranges identified
Material applied to shapes of the size and type of objective component with verified properties	CRL 5	Process has been applied to shapes of the size and type of the objective component
Material applied to objective shape with verified properties	CRL 4	Process has been modified to apply to objective shape
Material data properties verified	CRL 3	Process produces desired physical and mechanical properties
Material within family identified	CRL 2	Process has been applied to simple test coupons
Material family/families identified	CRL 1	General classes of possible processes identified

Technology Impact Assessment

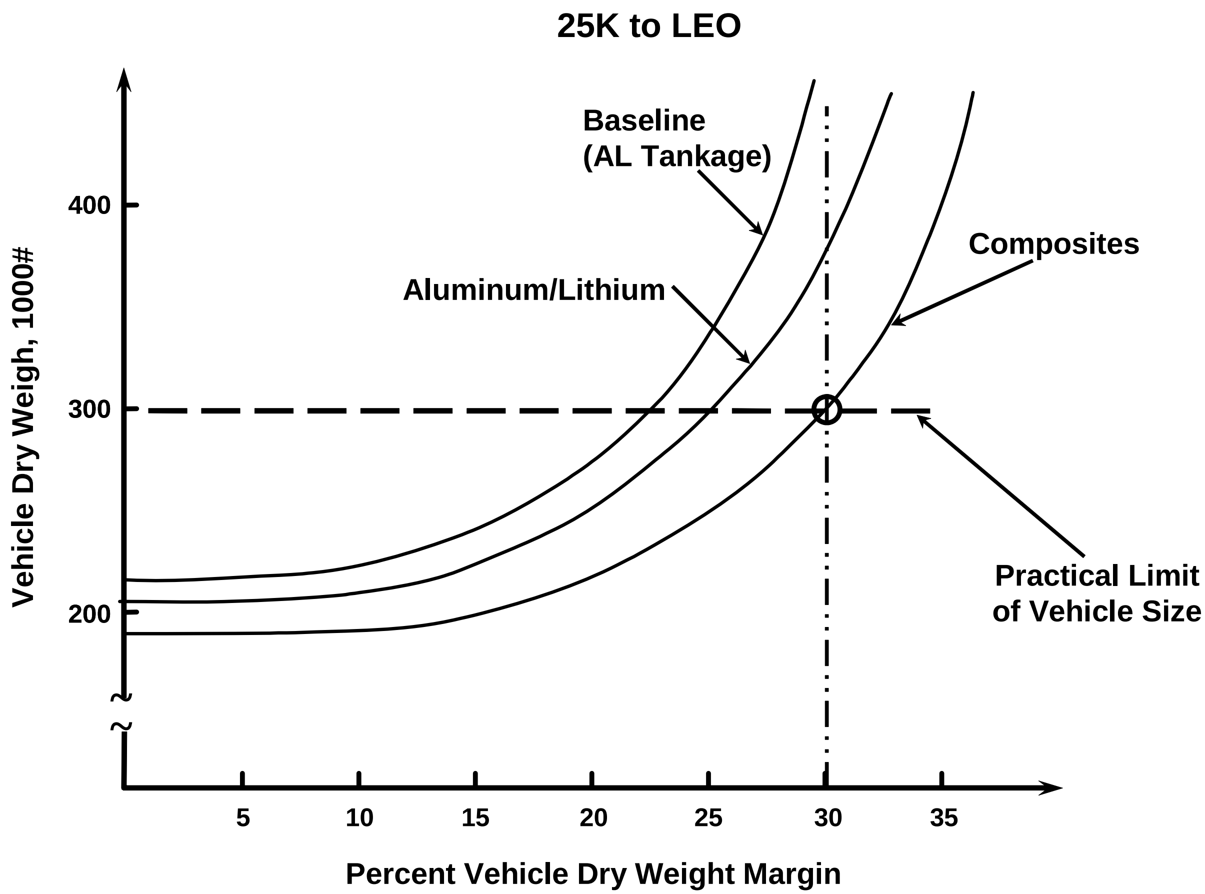
What is the anticipated benefit of the technology?



Technology Risk Analysis Example

Metrics

SSTO Metric Example: Impact of Technologies - ϕA



Risk Analysis

- The use of composites for tankage significantly increases Vehicle dry weight margin above that of more conventional materials.

- But, composite application in cryogenic tankage are novel, and unforeseen problems could significantly increase cost & slip schedules.

Key Points

- Systems analysis can not only be used in risk analysis, but also in risk identification.
- Using methods analogous to trade studies, systems analysis can provide decision support for risk handling options.

References

- *Risk Management Procedural Requirements,* NPR 8000.4, March 2005.
- *CVN 77 Risk Management Plan* (draft), Newport News Shipbuilding, 1999.