Model Integration Approaches for System Design and Analysis

10 September 2019

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Space Launch System

Outline

- **System Modeling Types**
- **System Relational Modeling (i.e., MBSE)**
- **System Integrating Physics**
- **System Value Models**
- **System Stave Variable Modeling**
  - Goal Function Tree (GFT)
  - State Analysis Model (SAM)
- **System Statistical Modeling**
- **System Dynamics Modeling**
- **Summary**

System Models

- **System Models are important to gain understanding of the System**
  - Systems Engineering Principle 4(a): Systems engineering obtains an understanding of the system

- **System Models convey information at the system level**
  - Complementary to discipline based engineering models
  - Integrate system functions and relationships within the system context
    - Systems Engineering Principle 3(i): Systems engineering seeks a best balance of functions and interactions within the system budget, schedule, technical, and other expectations and constraints.
  - Provide a technical systems basis for system operations and maintenance functions, approaches, and procedures
  - Provide a relationship of the system capabilities to the stakeholder expectations

System Model Types

- **System Modeling is based on a set of system models rather than a single system model**
- **System Modeling Types**
  - Relational (i.e., MBSE)
  - Physics-Based
  - State Variable
  - System Value
  - Statistical
  - System Dynamics

System Relational Models

System Relational Models

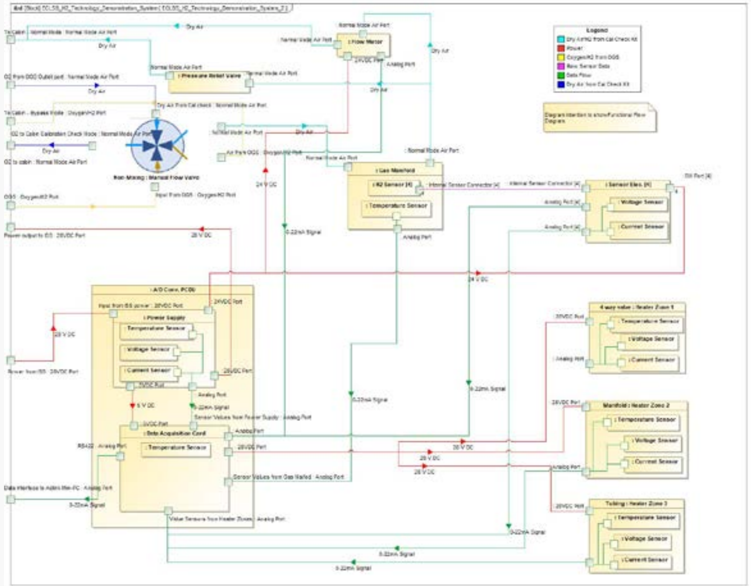
- **System Relational Models focus on the relationships between system components, system process flows, and requirements**
  - Model Based Systems Engineering (MBSE) typically refers to SysML based models

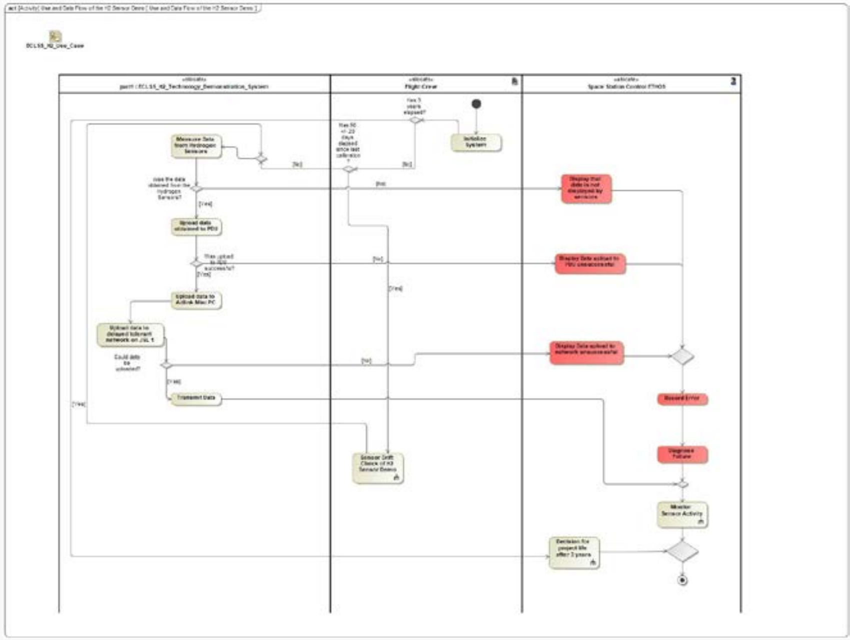
  - Several vendors provide these tools
    - Cameo Systems Modeler/Magic Draw
    - Innoslate (Lifecycle Modeling Language (LML))
    - Enterprise Architect
    - Rationale Rhapsody
    - Visual Paradigm
    - Modelio SysML Architect
    - Eclipse Papyrus

  - Other tools provide better capabilities in some aspects
    - Requirements Management
      - Cradle
      - Doors
      - CORE
    - Visualization
      - Visio
      - Tom Sawyer

System Relational Models

- **System Relational Models Support**
  - System Block Diagrams and Internal Block Diagrams define relationships between components/assemblies/subsystems of the system
  - Provides Requirements traceability including verification support
  - Provides Activity Diagrams, State Machine Diagrams to illustrate Use Cases and Process Flows
    - Use Cases can provide a structure to feed into an initial Discrete Event Simulation (DES) model to support statistical process flow analysis





System Integrating Physics

System Integrating Physics

- **Physics provides some help with capture of the system physics relationships to develop a physics based model.**

- **These Integration relationships exist in physics but are not often used in engineering design**

- **These physics based integration relationships are driven by the system type**
  - Thermodynamic Systems
    - Aircraft
      - Propeller Driven
      - Jet Aircraft
      - Electric
      - Rotorcraft/VTOL
      - Gliders
    - Automobiles
    - Electrical Systems
    - Fluid Systems
    - Launch Vehicles and Spacecraft
      - Robotic
        - Integrated through the bus which is a thermodynamic system

          Each Instrument may have a different integrating physics but integrates with the bus thermodynamically

      - Crew Modules
        - Integrated by the habitable volume (i.e., ECLSS)

          A thermodynamic system

      - Entry, Descent, and Landing (EDL)
        - Integrated by thermodynamics as spacecraft energy is reduced (i.e., destroyed) in EDL
    - Power Plants
    - Ships

  - Optical Systems
  - Logical Systems
    - Data Systems
    - Communication Systems
  - Structural Systems
  - Biological Systems

- **System Integrating Physics provides the engineering basis for the System Model**

Thermodynamics Has Balance Relationships

Energy Balance (First Law of Thermodynamics)

- $E_{\mathrm{in}} - E_{\mathrm{out}} = E_{sys2} - E_{sys1}$,
- $Q - W = m(u_2 - u_1) + \frac{1}{2}m(v_2^2 - v_1^2) + mg(z_2 - z_1)$ for a control volume

Entropy Balance (Second Law of Thermodynamics)

- $S_{\mathrm{in}} - S_{\mathrm{out}} + S_{gen} = (S_{sys2} - S_{sys1})$, where $S_{gen} \geq 0$

Exergy Balance (Integration of First and Second Laws)

- $X_{\mathrm{in}} - X_{\mathrm{out}} + X_{\mathrm{des}} = (X_{sys2} - X_{sys1})$, where $X_{\mathrm{des}} = T_0 S_{gen} \geq 0$ (T_0 in Kelvin)
- $\sum(1 - \frac{T_0}{T_k})Q_k - [W - P_0(Vol_2 - Vol_1)] + X_{\mathrm{des}} = m\left[(h_2 - h_1) + T_0\left(S_{sys2} - S_{sys1}\right) + \frac{1}{2}(v_2^2 - v_1^2) + g(z_2 - z_1)\right]$ for a control volume

All relationships maintain mass balance

- $m_{\mathrm{in}} - m_{\mathrm{out}} = m_2 - m_1$

Exergy Balance Relationship

- **Exergy Balance for a rocket balances the exergy expended (fluid flow out of the nozzle) with the change in the vehicles kinetic and potential energy**
  - Mass balance is maintained
  - Rockets are control volumes, not control masses
    - Each stage is a constant control volume
    - The vehicle is the integration (addition) of separate control volumes
    - Staging results in the dropping of a control volume (mass drop) but not a change in the individual stage control volumes
    - Entropy and Enthalpy of propellant products assumed negligible (are for LOX, LH2)

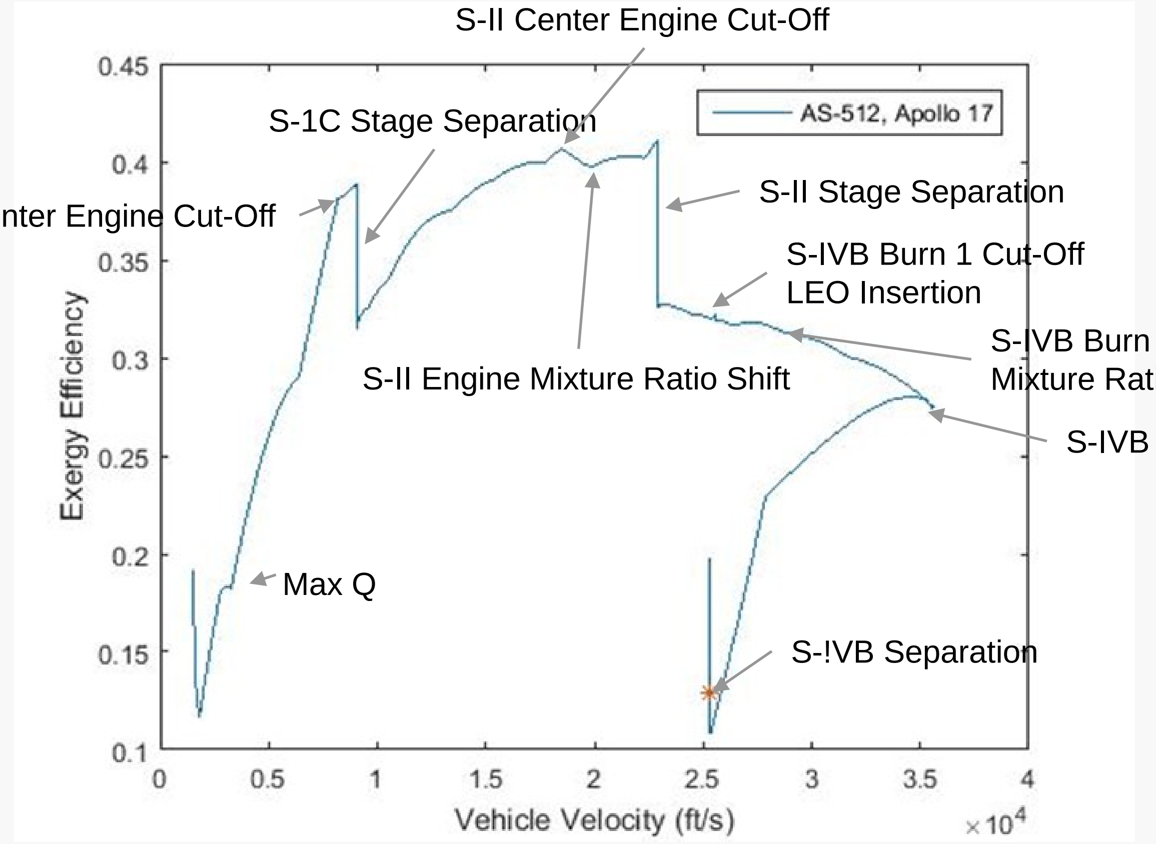
- $\Delta m_{prop} \sum_{stage}\left(h_{prop} + \frac{V_e^2}{2} + \frac{GM_E}{r_{altitude,initial}}\right) - X_{des} = \left(M_{vehicle,final}\frac{V_{vehicle,final}^2}{2} - M_{vehicle,initial}\frac{V_{vehicle,initial}^2}{2}\right) + \left(\frac{GM_E M_{vehicle,initial}}{r_{altitude,initial}} - \frac{GM_E M_{vehicle,final}}{r_{altitude,final}}\right)$
  - Represents energy expended in gaining velocity and altitude
  - Rocket equation can be derived from the exergy balance for a rocket
  - Orbital mechanics energy balance is also maintained in the exergy balance equation for a rocket

- $\eta_{exergy} = \frac{X_{recovered}}{X_{expended}} = \frac{X_{final}-X_{initial}}{X_{expended}} = 1 - \frac{X_{des}}{X_{expended}} = 1 - \frac{X_{des}}{\Delta mprop\left(H_{prop}+\frac{V_e^2}{2}\right)}$; Launch Vehicle, Planetary Departure (Accelerating)

- $\eta_{exergy} = \frac{-X_{recovered}}{X_{expended}} = \frac{X_{initial}-X_{final}}{X_{expended}} = 1 - \frac{X_{des}}{\Delta mprop\left(H_{prop}+\frac{V_e^2}{2}\right)}$; Lander, Planetary Arrival (Braking)

Launch Vehicle System Exergy Efficiency

$$\Delta m_{prop}\sum_{stage}\left(h_{prop}+\frac{V_e^2}{2}\right)-X_{des}=\left(M_{vehicle,final}\frac{V^2_{vehicle,final}}{2}-M_{vehicle,initial}\frac{V^2_{vehicle,initial}}{2}\right)+\left(\frac{GM_EM_{vehicle,initial}}{r_{altitude,initial}}-\frac{GM_EM_{vehicle,final}}{r_{altitude,final}}\right).$$



S-II Center Engine Cut-Off

S-1C Stage Separation

S-II Stage Separation

S-1C Center Engine Cut-Off

S-IVB Burn 1 Cut-Off
LEO Insertion

S-IVB Burn 2 Engine
Mixture Ratio Shift

S-II Engine Mixture Ratio Shift

S-IVB Burn 2 Cut-Off

Max Q

S-!VB Separation

Un-crewed Spacecraft Exergy Balance and Optical Transfer Function

Spacecraft Exergy Balance

$$\Delta \boldsymbol{m}_{\boldsymbol{propellant,engine}}\left(\boldsymbol{h}_{\boldsymbol{prop,engine}}+\frac{\boldsymbol{V}_{\boldsymbol{e,engine}}^{2}}{\mathbf{2}}\right)$$

$$+\Delta \boldsymbol{m}_{\boldsymbol{propellant,thruster}}\left(\boldsymbol{h}_{\boldsymbol{prop,thruster}}+\frac{\boldsymbol{V}_{\boldsymbol{e,thruster}}^{2}}{\mathbf{2}}\right)$$

$$+\sum_{t}\left(\sigma Ae\left(T_{radiator}^{4}-T_{space}^{4}\right)+\boldsymbol{V}_{\boldsymbol{bus}}\boldsymbol{I}_{\boldsymbol{bus}}\cos\left(\theta\right)\right)\boldsymbol{\Delta t}-\boldsymbol{X}_{\boldsymbol{des}}$$

$$=\left(\boldsymbol{M}_{\boldsymbol{vehicle,final}}\left(\frac{I_{c,final}\,\omega_{vehicle,final}^{2}}{\mathbf{2}}+\frac{\boldsymbol{V}_{\boldsymbol{vehicle,final}}^{2}}{\mathbf{2}}\right)\right.$$

$$\left.-\boldsymbol{M}_{\boldsymbol{vehicle,initial}}\left(\frac{I_{c,initial}\,\omega_{vehicle,initial}^{2}}{\mathbf{2}}+\frac{\boldsymbol{V}_{\boldsymbol{vehicle,initial}}^{2}}{\mathbf{2}}\right)\right)$$

$$+\left(\frac{\boldsymbol{GxM}_{\boldsymbol{E}}\boldsymbol{M}_{\boldsymbol{vehicle,initial}}}{\boldsymbol{r}_{\boldsymbol{altitude,initial}}}-\frac{\boldsymbol{GxM}_{\boldsymbol{E}}\boldsymbol{M}_{\boldsymbol{vehicle,final}}}{\boldsymbol{r}_{\boldsymbol{altitude,final}}}\right)$$

$$+\left(\sum\left(1-\frac{T_{fluid}}{T_{instrument}}\right)Q_{instrument}+\sum_{battery}P_{electric,stored}\right.$$

$$\left.+\sum_{instruments}P_{electric,used}\right)\boldsymbol{\Delta t}$$

Optical Transfer Function

$$\iint_{-\infty}^{\infty}\psi_{\mathrm{obj}}\mathrm{s_{f}dxdy}$$

$$=\iint_{-\infty}^{\infty}\psi_{obj}(x_{0}+\boldsymbol{\epsilon}x,y_{0}+\boldsymbol{\epsilon}y)\mathrm{e}^{\mathrm{j}\left(\frac{\mathrm{k_{0}}}{2\mathrm{f_{1}}}\right)(\mathrm{x^{2}+y^{2}})}\mathrm{circ}\left(\frac{\mathrm{x+\Delta x+\delta x}}{R},\frac{\mathrm{y+\Delta y+\delta y}}{R}\right)\mathrm{dxdy}$$

Where

$$\epsilon x=1.22\lambda_{0}\left(\frac{f_{1}}{d_{0}+\epsilon z+\omega_{y}\Delta t}\right)+v_{x}\Delta t+\omega_{y}\Delta t$$

$$\epsilon y=1.22\lambda_{0}\left(\frac{f_{1}}{d_{0}+\epsilon z+\omega_{x}\Delta t}\right)+v_{y}\Delta t+\omega_{x}\Delta t$$

$$f_{1}=-\frac{R}{2}=-\frac{\sqrt{(x+\Delta x+\delta x)^{2}+(y+\Delta y+\delta y)^{2}+(z+\Delta z+\delta z)^{2}}}{2}$$

$\Delta x=\alpha x\Delta T$

$\Delta y=\alpha y\Delta T$

$C^{2}>\boldsymbol{4Mk}$ Over Damped

$$\delta x=c_{1}e^{-\left(\frac{C}{2M}-\frac{1}{2M}\sqrt{C^{2}-4Mk}\right)t}+c_{2}e^{-\left(\frac{C}{2M}+\frac{1}{2M}\sqrt{C^{2}-4Mk}\right)t}$$

$C^{2}=\boldsymbol{4Mk}$ Critically Damped

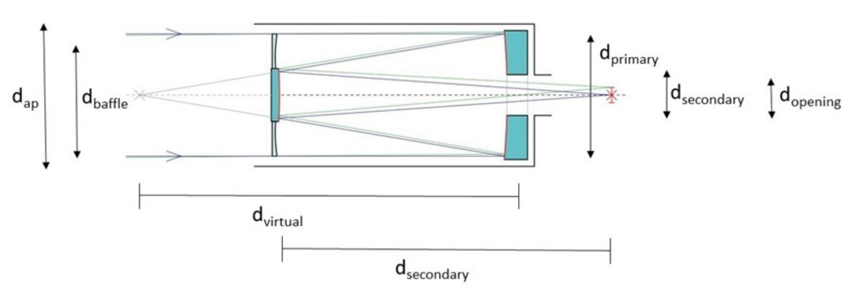
$$\delta x=(c_{1}+c_{2})e^{-\left(\frac{C}{2M}\right)t}$$

$C^{2}<\boldsymbol{4Mk}$ Under Damped

$$\delta x=c_{3}e^{-\left(\frac{C}{2M}\right)t}cos\left(\sqrt{4Mk-C^{2}}t-\varphi\right)$$

$$\tan(\varphi)=\frac{x'(0)}{x(0)\sqrt{\frac{k}{M}}}$$

$$c_{3}{}^{2}=\sqrt{x(0)^{2}+\frac{M}{k}x'(0)^{2}}$$



System State Variables

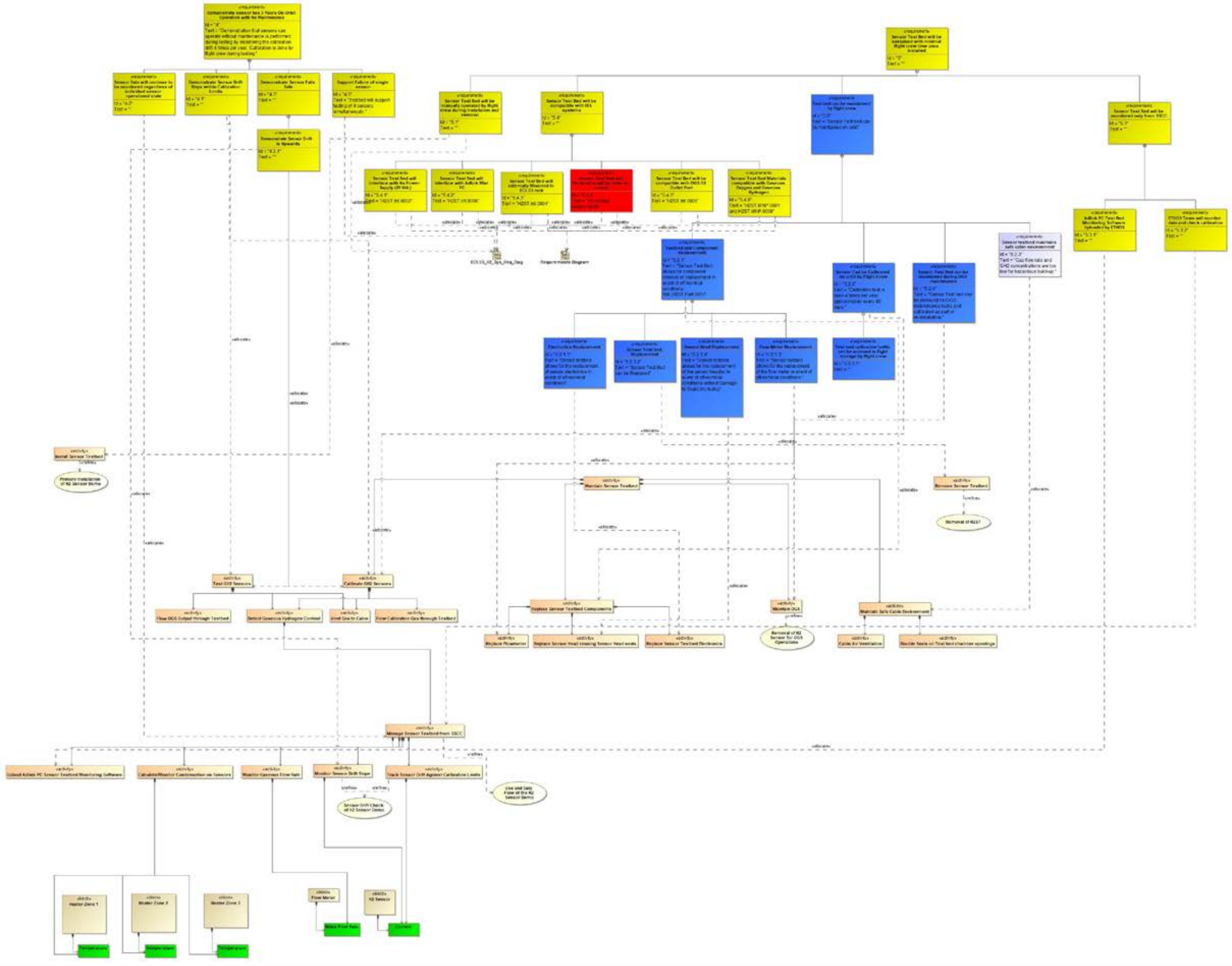
System State Models

- **System Stage Models represent the system as a whole in terms of the hardware and software states that the system transitions through during operation**

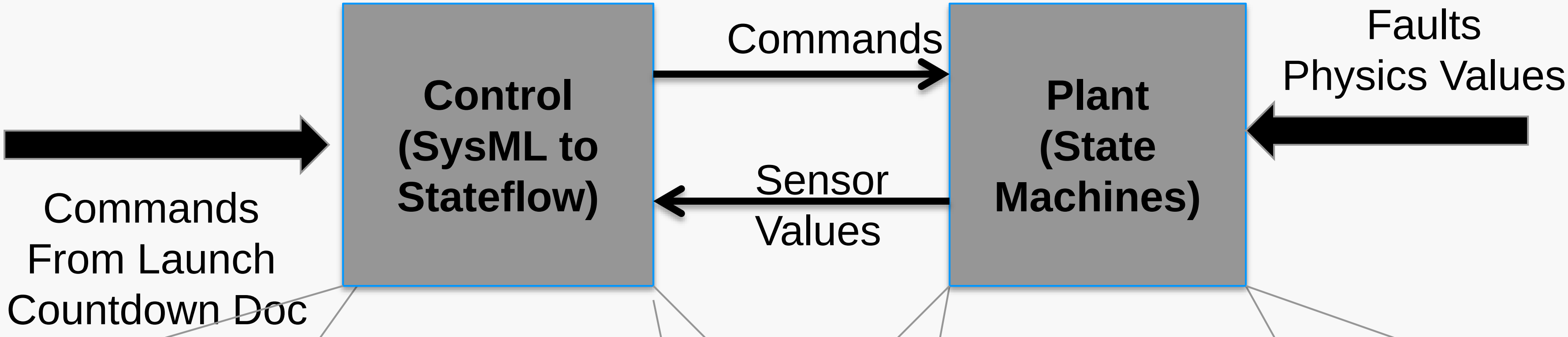
- **Goal Function Tree (GFT) Model**
  - “Middle Out” model of the system based on the system State Variables
  - Shows relationship between system state functions (hardware and software) and system goals
  - Does not contain system physical or logical relationships and is not executable

- **System State Machine Model**
  - Models the integrated State Transitions of the system as a whole (i.e., hardware states and software states)
  - Confirms system functions as expected
    - Checks for system hazardous, system anomalies, inconsistent state progression, missing states, improper state paths (e.g., short circuits in hardware and/or software design)
    - Confirms that the system states progress as stated in the system design
  - Executable model of system

Hydrogen Sensor Goal Function Tree



State Analysis Model for SLS M&FM



Control (SysML to Stateflow)

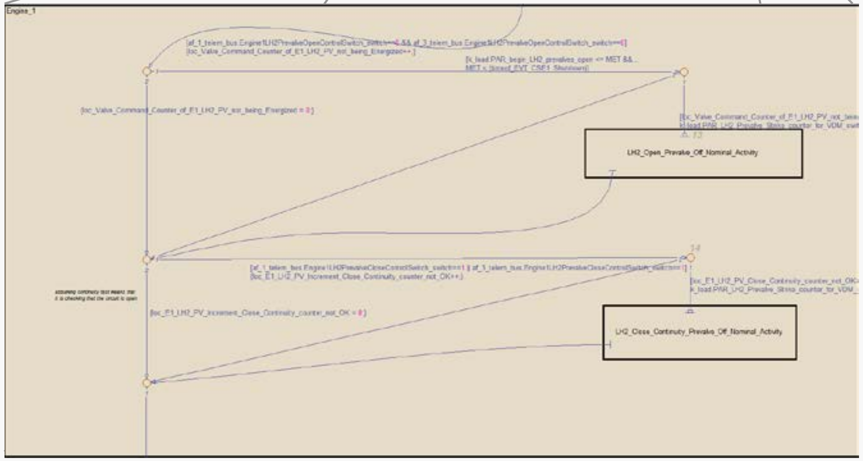
Plant (State Machines)

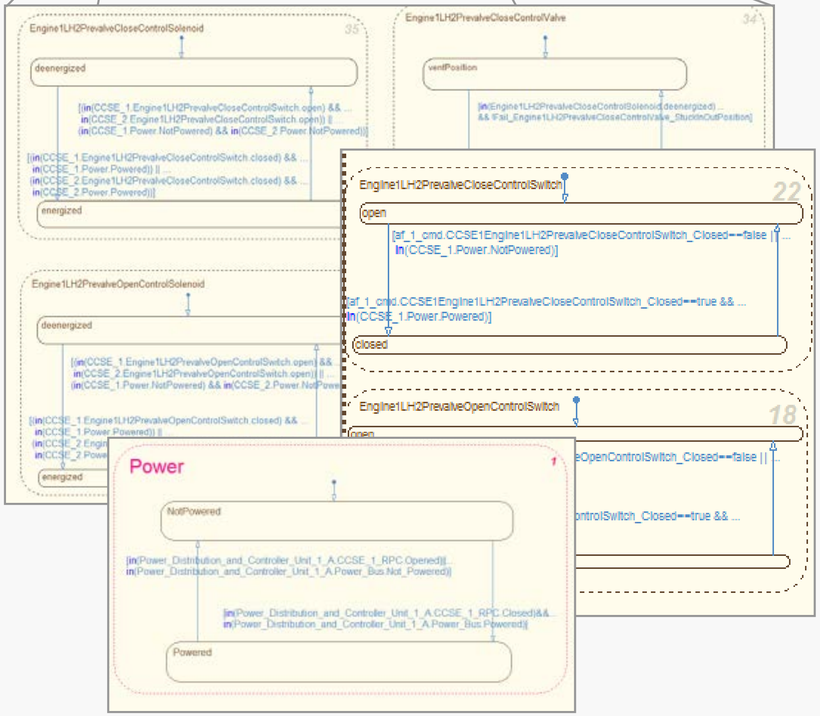
Commands

Sensor Values

Faults
Physics Values

Commands
From Launch
Countdown Doc



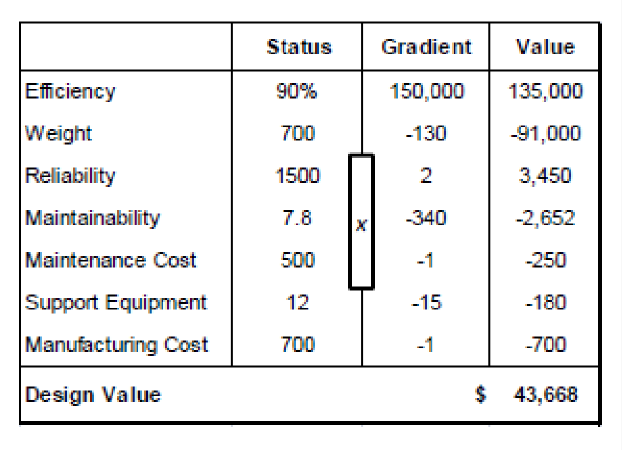


- 14% of R12 modeled
- Over 7,200 Transitions in the Vehicle and Software
- Over 3,500 States in the Vehicle

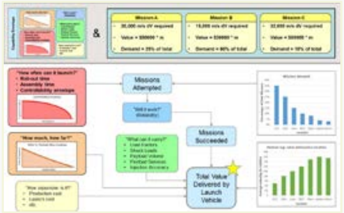
System Value

System Value Model

- **A System Value Model is a mathematical representation of Stakeholders Preferences (Expectations) for the system**
  - The basic structure is straight forward
  - The sociology/psychology of representing the Preferences can be a challenge
- **The System Value Model is the Basis of System Validation!!!**
  - The Requirements and Design Models form the basis of System Verification
  - The System Value Model forms the basis of System Validation
- **Constructing an SLS Value Model to compare to System Validation results**
  - Can expand to Integrated Stack with input from MPCV and GSDO
- **System Value model also provides basis for a measure of System Robustness**
  - How many mission types are supported by the system?



	Status	Gradient	Value
Efficiency	90%	150,000	135,000
Weight	700	-130	-91,000
Reliability	1500	2	3,450
Maintainability	7.8	-340	-2,652
Maintenance Cost	500	-1	-250
Support Equipment	12	-15	-180
Manufacturing Cost	700	-1	-700
Design Value		$	43,668

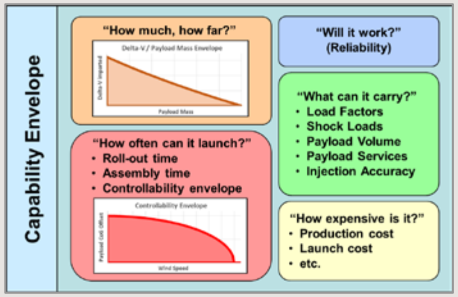


$$\pi = f_{aircraft}\; x_1, x_2, \dots, x_n$$

$$v_e = \sum_{j=1}^{m}\left(\sum_{i=1}^{n}\frac{\partial \pi}{\partial x_i}\cdot\frac{\partial x_i}{\partial y_j}y_j\right)$$

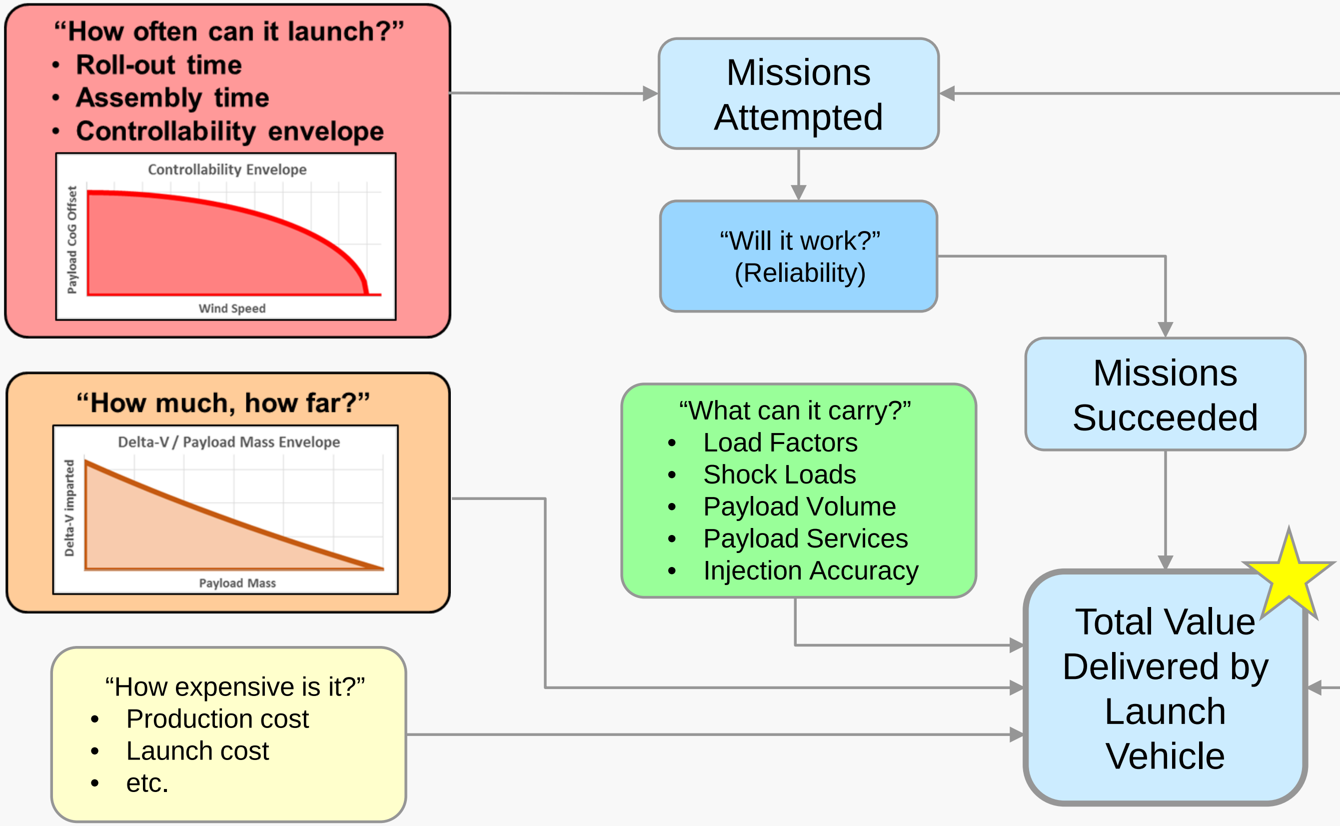
$$v_t = \sum_{k=1}^{p}\left(\sum_{j=1}^{m}\frac{\partial v_e}{\partial y_j}\cdot\frac{\partial y_j}{\partial z_k}z_k\right)$$

Mapping System Capability to Value



&

Mission A	Mission B	Mission C
20,000 m/s dV required	15,000 m/s dV required	32,000 m/s dV required
Value = $50000 * m	Value = $30000 * m	Value = $80000 * m
Demand = 25% of total	Demand = 60% of total	Demand = 15% of total



"How often can it launch?"
- **Roll-out time**
- **Assembly time**
- **Controllability envelope**

"How much, how far?"

"How expensive is it?"
- Production cost
- Launch cost
- etc.

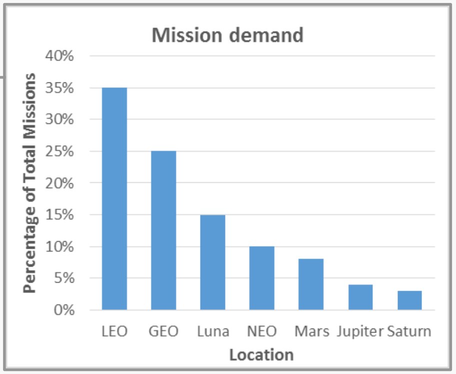
Missions Attempted

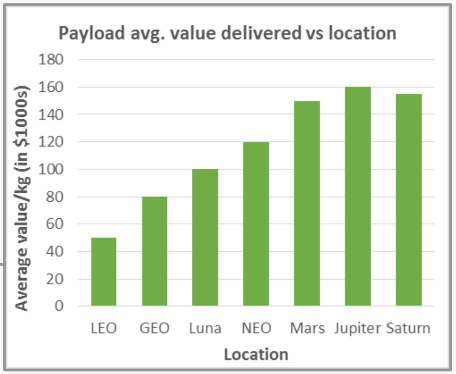
"Will it work?"
(Reliability)

"What can it carry?"
- Load Factors
- Shock Loads
- Payload Volume
- Payload Services
- Injection Accuracy

Missions Succeeded

Total Value Delivered by Launch Vehicle





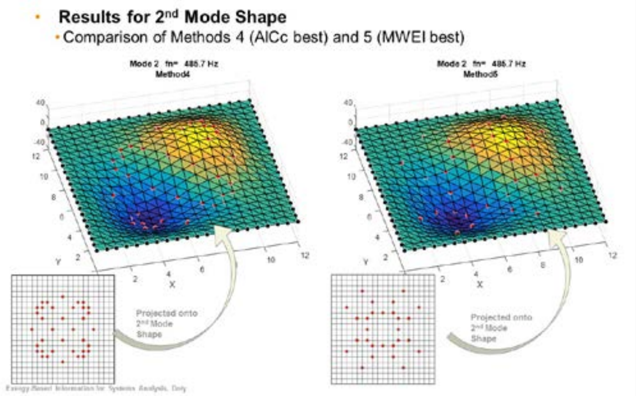
Engineering Statistics

Optimal Sensor Information Configuration

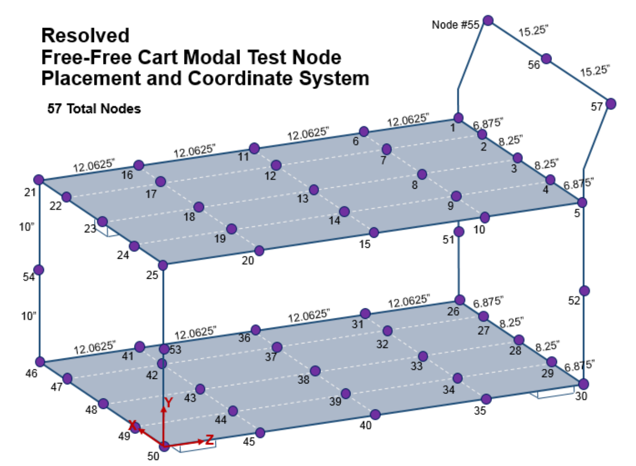
- **Applying Akaike Information Criteria (AIC) corrected (AICc) to assess sensor coverage for a system**

$$AICc(F) = -2\left(I^{KL}(F|G)\right) + 2K + \frac{2K(K+1)}{n-K-1}$$

- **Two Views of Information Content**
  - AIC Information
    - Information is viewed as the number of meaningful parameters
      - Parameters with sufficient measurements to be reasonable estimates
  - Fisher Information Matrix
    - Defines information as the matrix of partial second derivatives
      - Information is the amount of parameters with non zero values (so provides an indication of structure)
      - This value converges to a maximum as the number of parameters goes to infinity
      - Does not contain an optimum, always increases with added parameters
- **AIC/AICc has an adjustment factor to penalize sensor arrangements where: number of sensors < 3x(number of measurements)**
- **Provides an optimization tool for use with System Models**



- **Results for 2nd Mode Shape**
  - Comparison of Methods 4 (AICc best) and 5 (MWEI best)



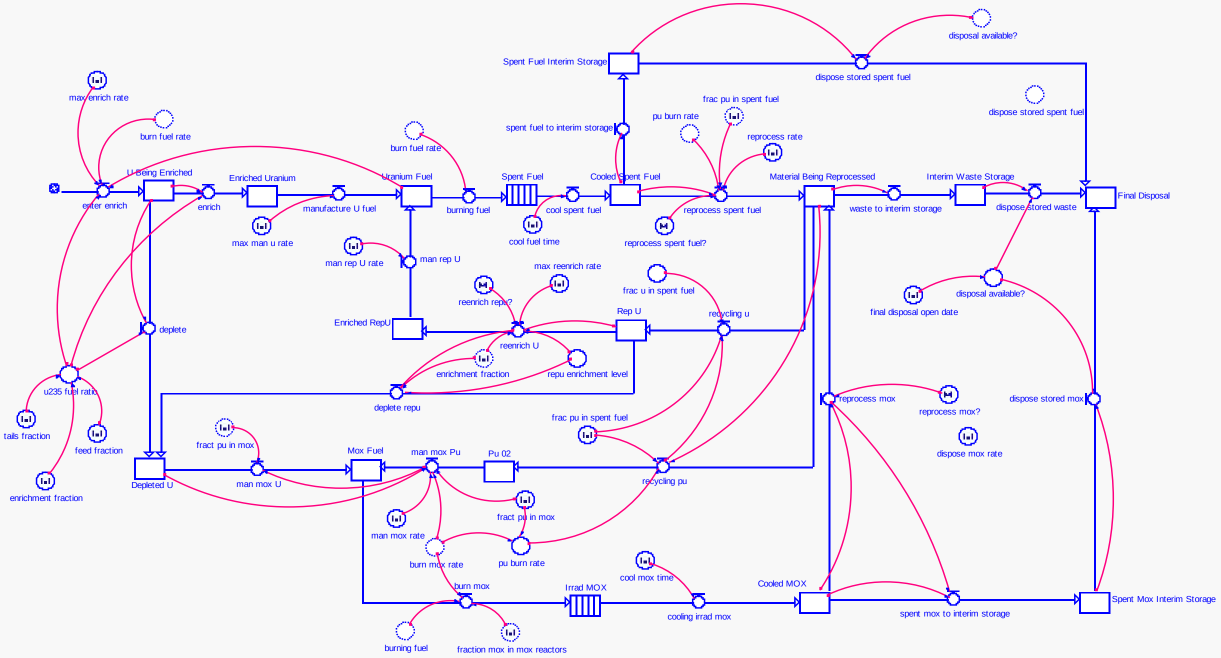
Resolved Free-Free Cart Modal Test Node Placement and Coordinate System

57 Total Nodes

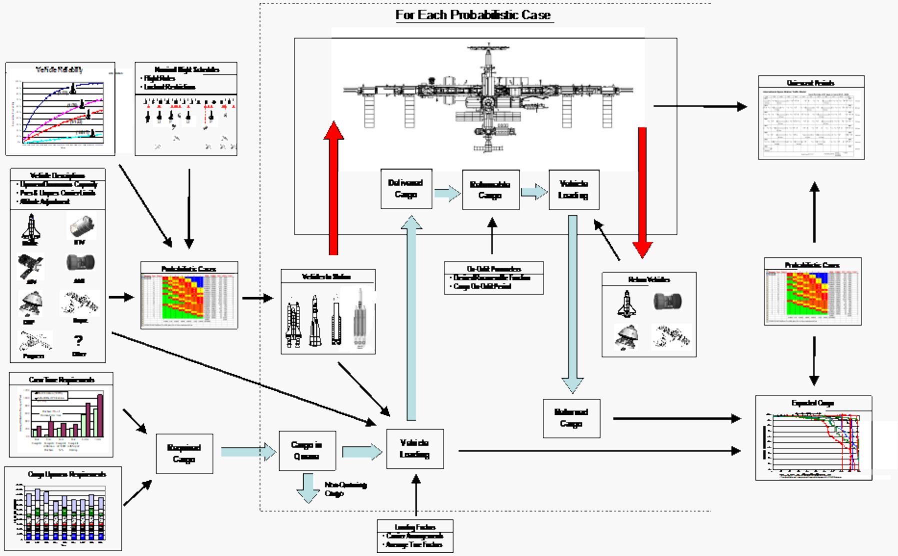
System Dynamics

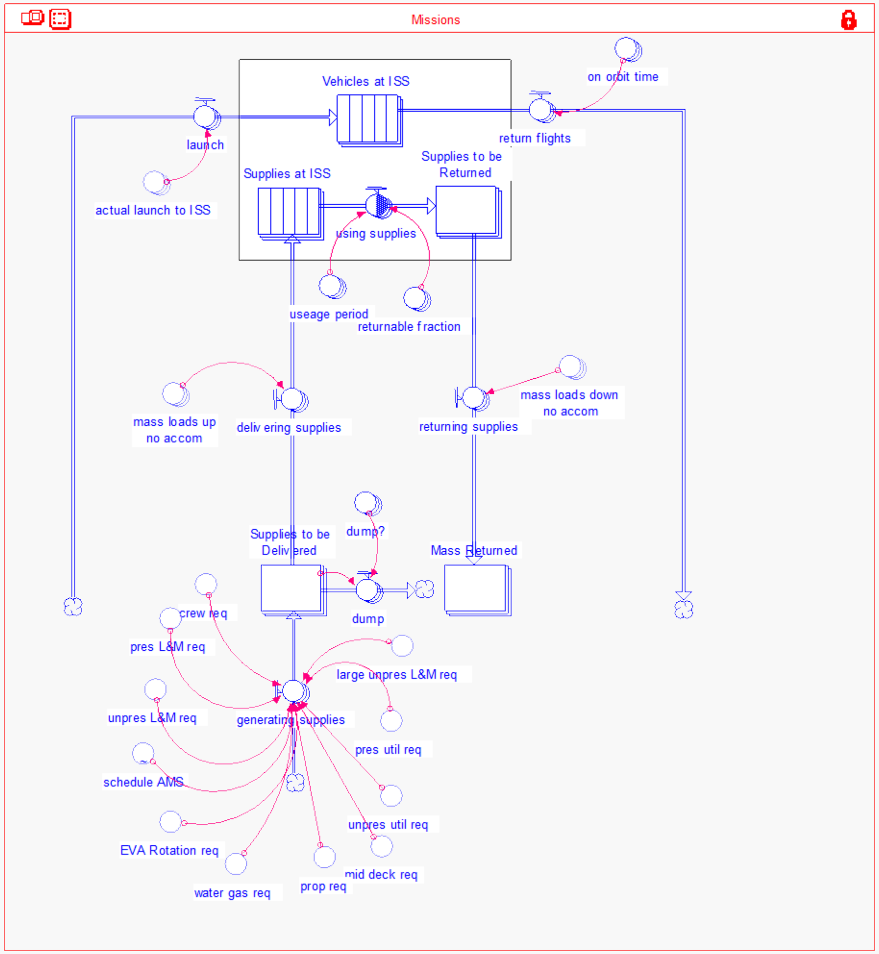
Tools and Methodologies

- Tools and techniques have been developed using the System Dynamics methodology that make it possible to efficiently decompose complex systems and to quickly set-up and test models of system operation.
- Tools promote understanding through visual diagramming and modeling.



STS-ISS Transportation / Operation Analysis





Summary

Design Analysis Cycle (DAC)

- **Understanding the systems integrating relationships provides an important advancement in the practice of systems engineering and contribution to the engineering of the system**
  - Provides a complete understanding of the system functions and interactions
    - Basis to define system GR&A in a way to have a closed set to begin design work
    - Basis of system closure criteria
    - Basis for identifying adjustments to the system function design solutions
    - Basis for determining optimal system performance
- **Provides a method to quickly compare system configurations and identify best balance result, reducing time necessary for DACs**
- **Provides a method to more completely test software algorithms, reducing amount of real-time software testing**
- **Analysis complements detailed design work done by the Engineering Disciplines**
  - System Exergy is an integrating relationship
    - Depends on results from each Engineering Discipline
  - A positive for systems engineers in conducting system level design
  - More difficulty to use (depends on results from each Engineering Discipline) for specific components of subsystems

Summary

- **System Modeling is composed of several different model types to gain a complete understanding of the system**
  - System Relational Modeling (i.e., MBSE)
  - System Integrating Physics
  - System Value Models
  - System Stave Variable Modeling
    - Goal Function Tree (GFT)
    - State Analysis Model (SAM)
  - System Statistical Modeling
  - System Dynamics Modeling

- **These System Models provide the basic understanding of the system leading to:**
  - Reduced development analysis cycle time
  - Reduced system software testing time
  - Better correlation of system capabilities with stakeholder expectations

- **The results of the research conducted by all Consortium members is available on the NASA Portal**
  - https://www.nasa.gov/consortium

  - “Engineering Elegant Systems: Theory of Systems Engineering”
    - NASA Technical Publication in work (Due out in October 2019)

  - “Engineering Elegant Systems: The Practice of Systems Engineering”
    - NASA Technical Publication in work (Due out in November 2019)

Backup

Motivation

- **System Engineering of Complex Systems is not well understood**

- **System Engineering of Complex Systems is Challenging**
  - System Engineering can produce elegant solutions in some instances
  - System Engineering can produce embarrassing failures in some instances
  - Within NASA, System Engineering does is frequently unable to maintain complex system designs within budget, schedule, and performance constraints

- **"How do we Fix System Engineering?"**
  - Michael D. Griffin, 61st International Astronautical Congress, Prague, Czech Republic, September 27-October 1, 2010
  - Successful practice in System Engineering is frequently based on the ability of the lead system engineer, rather than on the approach of system engineering in general
  - The rules and properties that govern complex systems are not well defined in order to define system elegance

- **4 characteristics of system elegance proposed as:**
  - System Effectiveness
  - System Efficiency
  - System Robustness
  - Minimizing Unintended Consequences

Consortium

◆ **Research Process**

- Multi-disciplinary research group that spans systems engineering areas
- Selected researchers who are product rather than process focused

◆ **List of Consortium Members**

- Michael D. Griffin, Ph.D.
- Air Force Research Laboratory – Wright Patterson, Multidisciplinary Science and Technology Center: Jose A. Camberos, Ph.D., Kirk L. Yerkes, Ph.D.
- Doty Consulting Services: John Doty, Ph.D.
- George Washington University: Zoe Szajnfarber, Ph.D.
- Iowa State University: Christina L. Bloebaum, Ph.D., Michael C. Dorneich, Ph.D.
- Missouri University of Science & Technology: David Riggins, Ph.D.
- NASA Langley Research Center: Peter A. Parker, Ph.D.
- Texas A&M University: Richard Malak, Ph.D.
- Tri-Vector Corporation: Joey Shelton, Ph.D., Robert S. Ryan, Kenny Mitchell
- The University of Alabama in Huntsville: Phillip A. Farrington, Ph.D., Dawn R. Utley, Ph.D., Laird Burns, Ph.D., Paul Collopy, Ph.D., Bryan Mesmer, Ph.D., P. J. Benfield, Ph.D., Wes Colley, Ph.D., George Nelson, Ph.D.
- The University of Colorado – Colorado Springs: Stephen B. Johnson, Ph.D.
- The University of Michigan: Panos Y. Papalambros, Ph.D.
- The University of Texas, Arlington: Paul Componation, Ph.D.
- The University of Bergen: Erika Palmer

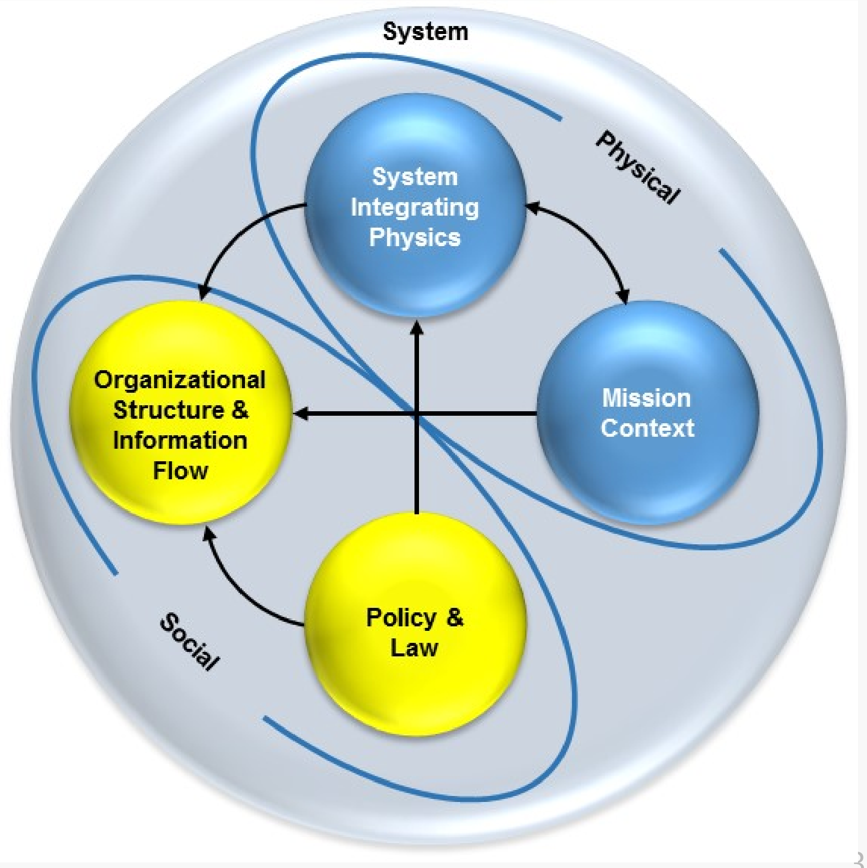
◆ **Previous Consortium Members**

- Massachusetts Institute of Technology: Maria C. Yang, Ph.D.
- Stevens Institute of Technology – Dinesh Verma
- Spaceworks – John Olds (Cost Modeling Statistics)
- Alabama A&M – Emeka Dunu (Supply Chain Management)
- George Mason – John Gero (Agent Based Modeling)
- Oregon State – Irem Tumer (Electrical Power Grid Robustness)
- Arkansas – David Jensen (Failure Categorization)

~50 graduate students and 15 undergraduate students supported to date

Understanding Systems Engineering

- **Definition – System Engineering is the engineering discipline which integrates the system functions, system environment, and the engineering disciplines necessary to produce and/or operate an elegant system.**
  - Elegant System - A system that is robust in application, fully meeting specified and adumbrated intent, is well structured, and is graceful in operation.



- **Primary Focus**
  - System Design and Integration
    - Identify system couplings and interactions
    - Identify system uncertainties and sensitivities
    - Identify emergent properties
    - Manage the effectiveness of the system
  - Engineering Discipline Integration
    - Manage flow of information for system development and/or operations
    - Maintain system activities within budget and schedule

- **Supporting Activities**
  - Process application and execution
    - Processes organize the engineering

Systems Engineering Postulates

System Integration (physical/logical system)
Discipline Integration (social system)
Both System and Discipline Integration

- **Postulate 1: Systems engineering is system specific and context dependent in application**
- **Postulate 2: The Systems Engineering domain consists of subsystems, their interactions among themselves, and their interactions with the system environment**
- **Postulate 3: The function of Systems Engineering is to integrate engineering disciplines in an elegant manner**
- **Postulate 4: Systems engineering influences and is influenced by organizational structure and culture**
- **Postulate 5: Systems engineering influences and is influenced by budget, schedule, policy, and law**
- **Postulate 6: Systems engineering spans the entire system life-cycle**
- **Postulate 7: Understanding of the system evolves as the system development or operation progresses**
- **Postulate 7 Corollary: Understanding of the system degrades during operations if system understanding is not maintained.**

Systems Engineering Principles

- **Principle 1: Systems engineering integrates the system and the disciplines considering the budget and schedule constraints**

- **Principle 2: Complex Systems build Complex Systems**

- **Principle 3: A focus of systems engineering during the development phase is a progressively deeper understanding of the interactions, sensitivities, and behaviors of the system, stakeholder needs, and its operational environment**
  - Sub-Principle 3(a): Mission context is defined based on understanding of the stakeholder needs and constraints
  - Sub-Principle 3(b): Requirements and models reflect the understanding of the system
  - Sub-Principle 3(c): Requirements are specific, agreed to preferences by the developing organization
  - Sub-Principle 3(d): Requirements and design are progressively elaborated as the development progresses
  - Sub-Principle 3(e): Hierarchical structures are not sufficient to fully model system interactions and couplings
  - Sub-Principle 3(f): A Product Breakdown Structure (PBS) provides a structure to integrate cost and schedule with system functions
  - Sub-Principle 3(g): As the system progresses through development, a deeper understanding of the organizational relationships needed to develop the system are gained.
  - Sub-Principle 3(h): Systems engineering achieves an understanding of the system’s value to the system stakeholders
  - Sub-Principle 3(i): Systems engineering seeks a best balance of functions and interactions within the system budget, schedule, technical, and other expectations and constraints.

Systems Engineering Principles

- **Principle 4: Systems engineering has a critical role through the entire system life-cycle**
  - Sub-Principle 4(a): Systems engineering obtains an understanding of the system
  - Sub-Principle 4(b): Systems engineering defines the mission context (system application)
  - Sub-Principle 4(c): Systems engineering models the system
  - Sub-Principle 4(d): Systems engineering designs and analyzes the system
  - Sub-Principle 4(e): Systems engineering tests the system
  - Sub-Principle 4(f): Systems engineering has an essential role in the assembly and manufacturing of the system
  - Sub-Principle 4(g): Systems engineering has an essential role during operations, maintenance, and decommissioning
- **Principle 5: Systems engineering is based on a middle range set of theories**
  - Sub-Principle 5(a): Systems engineering has a physical/logical basis specific to the system
  - Sub-Principle 5(b): Systems engineering has a mathematical basis
  - Sub-Principle 5(c): Systems engineering has a sociological basis specific to the organization(s)
- **Principle 6: Systems engineering maps and manages the discipline interactions within the organization**
- **Principle 7: Decision quality depends on system knowledge present in the decision-making process**
- **Principle 8: Both Policy and Law must be properly understood to not overly constrain or under constrain the system implementation**

Systems Engineering Principles

- **Principle 9: Systems engineering decisions are made under uncertainty accounting for risk**
- **Principle 10: Verification is a demonstrated understanding of all the system functions and interactions in the operational environment**
- **Principle 11: Validation is a demonstrated understanding of the system's value to the system stakeholders**
- **Principle 12: Systems engineering solutions are constrained based on the decision timeframe for the system need**
- **Principle 13: Stakeholder expectations change with advancement in technology and understanding of system application.**
- **Principle 14: The real physical system is the perfect model of the system**
  - Kullback-Liebler Information shows the actual system is the ideal information representation of the system
    - $I(f,g) = \int f(x)\log(f(x))\,dx - \int f(x)\log(g(x|\theta))\,dx = 0$

System Engineering Hypotheses

- **Hypothesis 1: If a solution exists for a specific context, then there exists at least one ideal Systems Engineering solution for that specific context**
  - Hamilton's Principle shows this for a physical system
    - $\int_{t_1}^{t_2}(\delta T - \delta V + \delta W)dt = 0$

- **Hypothesis 2: System complexity is greater than or equal to the ideal system complexity necessary to fulfill all system outputs**

- **Hypothesis 3: Key Stakeholders preferences can be accurately represented mathematically**

System Integrating Physics

- **Consortium identified the significance of understanding and using the System Integrating Physics for Systems Engineering**
  - First Postulate: Systems engineering is system specific and context dependent.
    - Systems are different, and therefore, the integrating physics for the various systems is different

  - Second Postulate: The Systems Engineering domain consists of subsystems, their interactions among themselves, and their interactions with the system environment
    - System interactions among properly defined system functions and with the environment are the basis of systems engineering

  - Sub-Principle 3(i): Systems engineering seeks a best balance of functions and interactions within the system budget, schedule, technical, and other expectations and constraints.

  - Sub-Principle (5a): Systems engineering has a physical/logical basis specific to the system
    - The physics of the specific systems defines the integration relationships

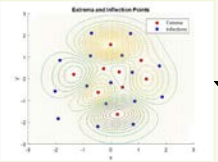
  - Principle 7: Decision quality depends on system knowledge present in the decision-making process
    - Understanding of system interactions must be included

  - Principle 12: Systems engineering solutions are constrained based on the decision timeframe for the system need
    - Understanding the system interactions shortens the development time and opens design space more for a given timeframe

Methods of System Integration

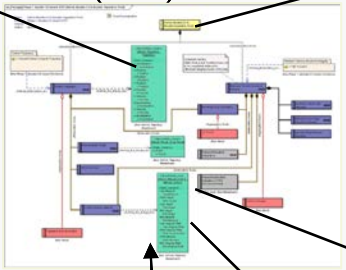
Goal: System Design and Analysis

System Models Contain an Understanding of the System


Engineering Statistics

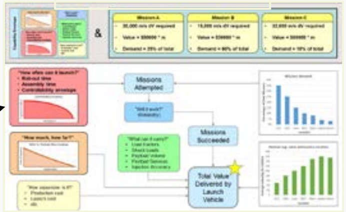
State Variables

Goal Function Tree (GFT)



Goals

Value Model



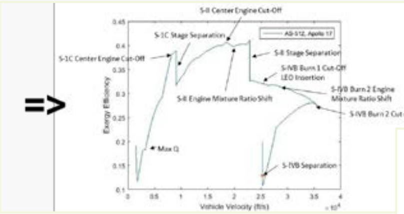
System Functions & State Variables


System State Transition Model

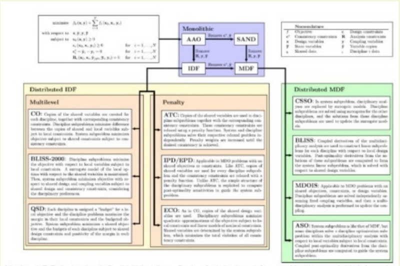
System Functions & State Variables

Discipline Physics Models

=>



System Integrated Physics Model (System Exergy)



Martins, J. R R. A., Lambe, A. B., "Multidisciplinary Design Optimization: A Survey of Architectures", AIAA Journal, Vol. 51,No. 9, September 2013, pp 2049 – 2075

Multidisciplinary Design Optimization (MDO)

- Allow systems engineers to:
  - Define system functions based on the system state variables
  - Understand stakeholders expectations on system value (i.e., capabilities)
  - Integrate discipline engineering models into a system level physics based model (e.g., system exergy)
  - Design and Analyze system responses and behaviors at the System level

- MagicDraw Enterprise (SysML)
- Matlab
- Matlab StateFlow
- Microsoft Excell

System Design and Integration