Engineering Elegant Systems: Engineering at the System Level

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**Understanding Systems Engineering**
- Postulates
- Hypothesis
- Principles

**Systems Engineering Domain**
- System Integration
  - System State Variables
    - Goal Function Tree
    - State Analysis Model
  - System Value Model
  - System Integrating Physics
  - System Autonomy
  - Multidisciplinary Design Optimization (MDO)
  - Engineering Statistics
  - Methods of System Integration

- Discipline Integration
  - Sociological Concepts in Systems Engineering
  - Information Flow
  - System Dynamics

**Summary**
Understanding Systems Engineering
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.
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  • 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.
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◆ 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
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
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**
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
     \[ I(f, g) = \int f(x) \log(f(x)) \, dx - \int f(x) \log(g(x|\theta)) \, dx = 0 \]
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
Mathematical Basis of Systems Engineering: Mathematical Category Theory
Systems are comprised of 2 basic structures

- **Postulate 2:** The Systems Engineering domain consists of subsystems, their interactions among themselves, and their interactions with the system environment
- **Components**
- **Relationships among components**
  - Physical
  - Logical
- **Relationships with the environment**
  - Physical

Major Components of the NASA Space Launch System (SLS)
Rocket Physical and Logical Relationships

- Electrical Forces (e.g., lightning, static)
- Thermal Work (e.g., frictional heating, temperature differences)
- Aerodynamic Forces (e.g., Drag, Friction)
- Structural Loads & Vibration
- Thermal

Diagram:
- Multi Purpose Crew Vehicle (MPCV)
- MPCV Spacecraft Adapter
- Interim Cryogenic Propulsion Stage (iCPS)
- iCPS Engine
- Launch Vehicle Stage Adapter (LVSA)
- Core Stage
  - Propellant Tanks
  - Core Stage Engines
- Left Solid Rocket Booster (SRB)
  - Propellant Tanks
  - Pump
- Right Solid Rocket Booster (SRB)
  - Propellant Tanks
  - Pump

Mass Flow
A Mathematical Category consists of
- Objects (i.e., system components): a, b, c, …
- Arrows (i.e., system relationships between components and the environment): f, g, …

A Mathematical Category has properties
- Domain/Codomain
  - \( f: a \rightarrow b \) where \( a \) is the domain of \( f \) and \( b \) is the codomain of \( f \)
- Identify Relationship
  - \( \text{id}_a = 1_a: a \rightarrow a \)
- Associativity
  - \( f \circ (g \circ h) = (f \circ g) \circ h \)
- Composition
  - Composition can be performed by various mathematical operations (i.e., addition, subtraction, multiplication, division)
  - \( a \rightarrow b \rightarrow c = a \rightarrow c \)
Mathematical Category Types

✿ **Category Types**
- Category of Sets
- Category of Arrows (objects are implied)
- Category of Groups
- Category of Categories
- Universal Category
- Category of Small Categories
- Abelian Categories

✿ **Objects within a category can be**
- Objects (i.e., individual parts or components)
- Sets (i.e., sets of individual parts)
- Groups
- Smaller Categories (i.e., stages, subsystems, assemblies)

✿ **Directed Graphs**
- Directed graphs, when they meet the property conditions, are a form a mathematical category
Mathematical Category Transformations

**Functors**
- Mathematical morphisms between categories, \( F: A \to C \)
- Creates a mapping from one category to another
- Includes composition in the mapping

**Natural Transformations**
- Transformation is the same among all objects
- Is commutative
- If invertible, then is a ‘natural equivalence’ or ‘isomorphism’

**Isomorphism**
- If the relationships (arrows) are invertible between two objects, then the objects are isomorphic, \( a \cong b \)
  - \( a \to b \to a, f = g', g = f' \)
- Categories can be isomorphic, \( A \cong B \)
  - The objects can be different, but the relationships between the objects of the two categories are preserved
    - i.e., different copies of the same system are isomorphic
    - Or, two different designs of the same system type may be isomorphic (e.g., different automobile makes with similar models)
Co-cones/Co-limits

- **Co-cone**
  - A common codomain for Functors operating on Category C

- **Co-limit**
  - The limit of the Co-cone defining the conditions where all Functors and mappings to objects of the Category, C, are included

https://www.nasa.gov/content/goddard/nasa-engineer-set-to-complete-first-3-d-printed-space-cameras/
Systems Engineering Application

◆ Black Box
  • Since a Category may contain smaller Categories, then an engineering ‘black box’ is a Category treated as an object within a larger Category

◆ System Completeness
  • The mathematical structure of the system Category provides a mechanism to construct a completeness proof for a given system

◆ System Specification
  • The System objects and relationships form the basis of the system requirements
  • The Category must contain the correct and complete objects and relationships
    – Variations result in a system different than intended

◆ System Assembly
  • Co-cones and co-limits define the assembly operations needed to construct the system Category
  • The Functors map parts from the parts category(s) to the system category
    – The parts may map to sub-categories (i.e., assemblies and subsystems) within the system category
  • The limits define what must be included at each step of the assembly in order to be complete
Methods of System Integration

Goal: Techniques to Enable Integrated System Design and Assessments by the Systems Engineer
System State Variables

Goal: Utilize system state variables to understand the interactions of the system in relation to system goals and system execution
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
Booster – CS Ascent GFT
The state analysis model is split into two main components:
- Manager software model
- System Plant

Modeled using MATLAB Stateflow
- Allows the software model to look like the SysML Activity Diagrams
- Allows the System Plant to be modeled as State Machines
- Allows those two models to interact with each other within the MATLAB environment
  - Facilitates the ability to generate custom analysis tools

Reads in command sequence to execute model
State Analysis Model for SLS M&FM

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

Goal: Utilize system state variables to understand the interactions of the system in relation to system goals and system execution
A System Value Model is a mathematical representation of Stakeholders Preferences (Expectations) for the system
• The basic structure is straightforward
• 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?
**Mapping System Capability to Value**

<table>
<thead>
<tr>
<th>Mission A</th>
<th>Mission B</th>
<th>Mission C</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 20,000 m/s dV required</td>
<td>- 15,000 m/s dV required</td>
<td>- 32,000 m/s dV required</td>
</tr>
<tr>
<td>- Value = $50000 * m</td>
<td>- Value = $30000 * m</td>
<td>- Value = $80000 * m</td>
</tr>
<tr>
<td>- Demand = 25% of total</td>
<td>- Demand = 60% of total</td>
<td>- Demand = 15% of total</td>
</tr>
</tbody>
</table>

**“Will it work?” (Reliability)**
- Load Factors
- Shock Loads
- Payload Volume
- Payload Services
- Injection Accuracy

**“How much, how far?”**
- Delta-V / Payload Mass Envelope

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

**“How expensive is it?”**
- Production cost
- Launch cost
- etc.

**Missions Attempted**

**Missions Succeeded**

**Total Value Delivered by Launch Vehicle**

**Missions**
- Attempted
- Succeeded

**Mission demand**

**Payload avg. value delivered vs location**

**Average value/kg (in $1000s)**
- LEO
- GEO
- Luna
- NEO
- Mars
- Jupiter Saturn

<table>
<thead>
<tr>
<th>Location</th>
<th>LEO</th>
<th>GEO</th>
<th>Luna</th>
<th>NEO</th>
<th>Mars</th>
<th>Jupiter Saturn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. value/kg (in $1000s)</td>
<td>80</td>
<td>60</td>
<td>40</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Notes:**
- Alpha
- Beta
- Gamma
Launch Vehicle Value related to impact to national GDP

Rockets are thermodynamic systems, there thermo-economics can be applied

\[
\dot{C}_T = \sum_i c_{ei} \dot{\epsilon}_i + \sum_n \dot{Z}_n
\]

\[
c_{ei} = \frac{kg}{J/kg} \rightarrow \left(\frac{\text{propellant cost}}{\text{exergy}}\right) = \$/J
\]

\[
\dot{\epsilon}_i = \frac{kg}{yr} \left(\frac{J}{kg}\right) \rightarrow \left(\frac{\text{mass}}{\text{year}}\right) * \text{HHV} = \frac{J}{yr}.
\]

\[
\dot{Z}_n = L_R * \text{unit cost} + \frac{\text{manufacturing base cost}}{\text{yr}}
\]

Mission Reliability is an important value

\[
R_{\text{mission}} (R_m) = R_{\text{launch}} * A_O * R_{\text{flight}}
\]

Value to Satellite Industry can be used

<table>
<thead>
<tr>
<th>Δdiameter:</th>
<th>diameter:</th>
<th>Satellite Benefit (value of payload)</th>
<th>$ Value (Billions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4 Commercial Communications:</td>
<td>$45.69</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5 Optical Sensing:</td>
<td>$24.80</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>8 Interplanetary Missions:</td>
<td>$6.53</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>10 Astronomical Telescope:</td>
<td>$1.31</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Human Exploration:</th>
<th>(measured by using % of US GDP)</th>
<th>$ Value:</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Renown:</td>
<td>0.06</td>
<td>$1,116,000,000,000.00</td>
</tr>
<tr>
<td>Extended Science</td>
<td>0.1</td>
<td>$1,860,000,000,000.00</td>
</tr>
<tr>
<td>Technological Gains:</td>
<td>0.056</td>
<td>$1,041,600,000,000.00</td>
</tr>
<tr>
<td>Medical Advances:</td>
<td>0.1</td>
<td>$1,860,000,000,000.00</td>
</tr>
</tbody>
</table>
Launch Vehicle Value based on 3 factors (currently)

- **Value is not cost!!!! It includes cost.**
- **Industry Value**

**Mission Reliability (96%)**
- \[ V_2 = (R_m)(\text{Value of Satellite Benefit}) \]
- \[ V_L = (1 - R_m)(\text{Value of Satellite Benefit}) \]
  + Unit Cost + Satellite Cost

**Payload Accommodation**
- \[ V_3 = \Delta \text{diameter} \times \left(\frac{\Delta \text{value of payload}}{\text{meter}}\right) \]

<table>
<thead>
<tr>
<th>Launch Vehicle Value</th>
<th>Value</th>
<th>Benefit - Ct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value to Scientific Uses</td>
<td>=</td>
<td>$63,008,431,752.36</td>
</tr>
<tr>
<td>Value to Commercial Services</td>
<td>=</td>
<td>$20,584,576,252.36</td>
</tr>
<tr>
<td>Value to Resource Mining</td>
<td>=</td>
<td>($2,252,876,665.31)</td>
</tr>
<tr>
<td>Value to Human Exploration</td>
<td>=</td>
<td>$2,936,540,961,752.35</td>
</tr>
<tr>
<td>Total Value</td>
<td>=</td>
<td>$3,017,881,093,091.75</td>
</tr>
</tbody>
</table>

| V2 (Commercial Communication) | = | $43,859,739,840.00 |
| V2 (Optical Sensing) | = | $23,809,573,056.00 |
| V2 (Interplanetary) | = | $6,265,677,120.00  |
| V2 (Astronomical Telescope) | = | $1,253,135,424.00  |
| total V2               | = | $75,188,125,440.00 |

<table>
<thead>
<tr>
<th>Value Lost from Failed Mission</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>V(L) (Commercial Communication) =</td>
<td>$7,995,274,012.95</td>
</tr>
<tr>
<td>V(L) (Optical Sensing)</td>
<td>=</td>
</tr>
<tr>
<td>V(L) (Interplanetary)</td>
<td>=</td>
</tr>
<tr>
<td>V(L) (Astronomical Telescope)</td>
<td>=</td>
</tr>
<tr>
<td>total Value Lost</td>
<td>=</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Satellite Benefit (SB)</th>
<th>4 meters</th>
<th>5 meters</th>
<th>8 meters</th>
<th>10 meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial Communications:</td>
<td>$45.69</td>
<td>$45.69</td>
<td>$45.69</td>
<td>$45.69</td>
</tr>
<tr>
<td>Optical Sensing:</td>
<td>$12.40</td>
<td>$24.80</td>
<td>$24.80</td>
<td>$24.80</td>
</tr>
<tr>
<td>Interplanetary Missions:</td>
<td>$2.61</td>
<td>$5.87</td>
<td>$6.53</td>
<td>$6.53</td>
</tr>
<tr>
<td>Astronomical Telescope:</td>
<td>$0.00</td>
<td>$0.00</td>
<td>$0.13</td>
<td>$1.31</td>
</tr>
<tr>
<td>Total:</td>
<td>$60.70</td>
<td>$76.36</td>
<td>$77.15</td>
<td>$78.32</td>
</tr>
</tbody>
</table>

Launch Vehicle Value

<table>
<thead>
<tr>
<th>Revenue Value (V1)</th>
<th>$3,017,881,093,091.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission Reliability Value (V2)</td>
<td>$66,294,779,977.80</td>
</tr>
<tr>
<td>Payload Size Value (10m Fairing) (V3)</td>
<td>$78,320,964,000.00</td>
</tr>
</tbody>
</table>
System Physics and System Integrating Physics

Goal: Utilize the key system physics to produce an elegant system design
System Integrating Physics

◆ **Consortium is researching the significance of identifying and using the System Integrating Physics for Systems Engineering**
  • First Postulate: Systems Engineering is Product Specific.
    • States that the Systems are different, and therefore, the Integrating Physics for the various Systems is different

◆ **Launch Vehicles**
  • Thermodynamic System

◆ **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 in EDL

◆ **Other Thermodynamic Systems**
  • Fluid Systems
  • Electrical Systems
  • Power Plants
  • Automobiles
  • Aircraft
  • Ships

◆ **Not all systems are integrated by their Thermodynamics**
  • Optical Systems
    • Logical Systems
      • Data Systems
      • Communication Systems
  • Biological Systems

◆ **System Integrating Physics provides the engineering basis for the System Model**
Launch Vehicle System Exergy Efficiency

\[ \Delta m_{\text{prop}} \sum_{\text{stage}} (h_{\text{prop}} + \frac{v_e^2}{2}) - X_{\text{des}} = \left( M_{\text{vehicle, final}} \frac{v_{\text{vehicle, final}}^2}{2} - M_{\text{vehicle, initial}} \frac{v_{\text{vehicle, initial}}^2}{2} \right) + \left( \frac{GM_{\text{M, vehicle, initial}}}{r_{\text{altitude, initial}}} - \frac{GM_{\text{M, vehicle, final}}}{r_{\text{altitude, final}}} \right) \]
\[ \Delta m_{\text{propellant,engine}} \left( h_{\text{prop,engine}} + \frac{v_{e,\text{engine}}^2}{2} \right) + \]

\[ \Delta m_{\text{propellant,thruster}} \left( h_{\text{prop,thruster}} + \frac{v_{e,\text{thruster}}^2}{2} \right) + \sum_t (\sigma A e (T_{\text{radiator}}^- - T_{\text{radiator}}^+)) \]
Crew Module Exergy Balance: ISS ECLSS

\[ \Delta X_{ECLSS} = \sum_{\text{process}} m_{\text{fluid}} \left( (h_{\text{final}} - h_{\text{cabin}}) - T_{\text{cabin}} (s_{\text{final}} - s_{\text{cabin}}) + \left( \frac{v_{\text{final}}^2}{2} \right) \right) - \]

\[ \sum_{\text{process}} m_{\text{fluid}} \left( (h_{\text{initial}} - h_{\text{cabin}}) - T_{\text{cabin}} (s_{\text{initial}} - s_{\text{cabin}}) + \left( \frac{v_{\text{initial}}^2}{2} \right) \right) = \sum \left( 1 - \frac{T_{\text{cabin}}}{T_{\text{crew}}} \right) Q_{\text{crew}} - \]

\[ \sum \left( \frac{T_{\text{cabin}} - T_{\text{coolant}}}{T_{\text{coolant}}} \right) Q_{TMS} + \sum W_{\text{EPS}} - P_{\text{cabin}} (V_{\text{final}} - V_{\text{initial}}) + m_{\text{in}} \left[ \sum (h_{\text{in}} - \right] \]

\[ \Delta X_{ECLSS} = \Delta X_{\text{ACS}} + \Delta X_{\text{AR}} + \Delta X_{\text{THC}} + \Delta X_{\text{WRM}} + \Delta X_{\text{WM}} \]

- Incorporate chemical process product and reactant enthalpy and entropy terms

- Calculate Efficiency
System Autonomy

Goal: Establish system interfaces to provide autonomy algorithms with system information necessary and sufficient to manage system
Spacecraft and Surface System Autonomy is the enabling capability for Human Exploration beyond Lunar Sortie Missions
  • Autonomy is necessary for complex system operations
  • Timely response to unplanned or unscheduled events

Propulsion, Structure, Thermal Conditioning, ECLSS, Electrical Power, Avionics, RCS, Communication are all understood sufficiently to allow engineered solutions to be reliably produced
  • Challenges do exist in terms of Space Environmental Effects, efficiency, compact size
    – Radiation Hardened computer processors needed
  • Physics and demonstrated solutions are available from which to engineer a vehicle

Operations are sufficiently understood for terrestrial based execution, not on-board execution
  • Manual operations provide a rich knowledge base of planning and execution processes
  • Manual operations have a generic template (derived from Apollo/Saturn) applied uniquely to each spacecraft
  • Terrestrial based manual operations will not support operations beyond 5 light minutes from Earth

Autonomous Operations are essential to Human Exploration of the Solar System
Subsystem Management Functions for System Control

- Performance
- Monitoring
- Diagnostics
- Prognostics
- Control
- Subsystem
Autonomy System Stack

3 Levels
- Mission Execution and Planning
- Vehicle Management
  - Subsystem Integration Based
  - Physics form basis of subsystem interactions
    - Form basis of normal or failed states
- Subsystem Level
  - Physics based

Mission Objectives & Constraint Data
Mission Planning
Mission Execution
Vehicle ISHM
Vehicle Control
System Control
System

Control Logic
Actuation

Prognostics
Diagnostics
Detection
System Design and Optimization

Goal: Apply system design and optimization tools to understand and engineer system interactions
Multidisciplinary Design Optimization

Engineering Statistics

Goal: Utilize statistical methods to understand system uncertainties and sensitivities

Systems Engineering makes use of Frequentist Approaches, Bayesian Approaches, Information Theoretic Approaches as appropriate
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
Flat Plate FEA Analysis and Akaike Information Criterion (AIC)

Results
- Sources of AICc:
  - Bias: $\propto$ mean square error (MSE)
  - Total Corrections: "penalties" for over-fitting

\[ AICc = N \log(MSE) + 2K + \frac{2K(K+1)}{N-K-1} \]

MWEI ‘Best’ is worst bias and $AICc_{Local}$

AICc and its Sources

Left 1: Bias
Right 1: $2K$
Left 2: AIC
Right 2: 2nd Order
Left 3: AICc
Right 3: Corrections

Bias Correction
Small Sample Correction
Total Corrections

Model Type
Left Axes:
Right Axes:
Verification Process
Method 1: ‘Intelligent’ Guess

- **Final Solution:**

  Overlaid on Peaks

  ![Diagram showing points and labels]

  **Note:**
  - 2 initial guesses ‘removed’ (red)
  - NEW points added (blue)
  - MOST initial guesses ‘survive’ (green)
Sensor Location

- Sensor Placement is determined by locations of highest residual error
  - Indicates lowest level of information about the system

- System model allows determination of highest residual error location
  - Must properly model physics of the system to be measured and associated interactions
  - Placing the first sensor here changes the information available and biases all other locations
  - Provides keystone for locating sensors appropriately

- Provides an objective method to determine proper sensor measurement locations
Methods of System Integration

Goal: System Design and Analysis
System Models Contain an Understanding of the System

- 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

Discipline Physics Models

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

Engineering Statistics

System Integrated Physics Model (System Exergy)

Goal Function Tree (GFT)

System Functions & State Variables

Goals

System State Transition Model

Value Model

Multidisciplinary Design Optimization (MDO)
System Design and Integration

Mission Requirements
(i.e., Level 1 Requirements, Needs, Goals, and Objectives (NGOs))

System Concept
of Operations

Goal Function Tree (GFT)

System Value Model

System Capability Model

System Integrating Physics Model

System Design and Analysis Models

Uncertainties, Sensitivities

MDO/MCA

Uncertainties, Sensitivities

MDO/MCA

System State Transition Model

Engineering
Statistics

Design Information

Concept/Architecture
Selection

Preliminary
Design

Critical
Design

Verification and
Validation

Operations and
Production
Methods of Engineering Discipline Integration

Goal: Understand How Organizational Structures influence Design and Operations Success of Complex Systems
Sociological Concepts in Systems Engineering

- Specification of Ignorance is important in the advancement of the understanding of the system
- Consistent use of Terminology is important for Communication within the Organization
- Opportunity Structures
  - Provide opportunity to mature ideas
    - Task teams, working groups, communities of practice, etc.
- Socially Expected Durations will exist about the project
- Both Manifest and Latent Social Functions exist in the organization
- Social Role Sets
  - Individuals have a set of roles for their position
- Cultural Subsets will form
  - i.e., disciplines can be a subset within the organization
  - Insider and Outsider attitudes can form
    - Be Aware of the Self-Fulfilling Prophecy, Social Polarization
- Reconsiderations Process (i.e., Reclama Process)
  - Provides ability to manage social ambivalence
  - Must be able to recognize social beliefs that may be contributing to the disagreement
  - Helps to avoid putting people in to social dysfunction or complete social anomie
    - Conformity
    - Innovation
    - Ritualism
    - Retreatism
    - Rebellion
Information Flow through a program/project/activity is defined by Information Theory

- Organizational communication paths
- Board Structure

Decision Making follows the First Postulate

- Decision Process is specific to the decision being made

- Tracked 3 SLS CRs, with 3 separate task team processes, all had equally rated effectiveness

Margin is maintained by the Organization, not in the margin management tables

- Biased Information Sharing
- Margin Management is focused on Managing the Disciplines (informed by the System Integrating Physics)

SLS Organizational Structure was defined by the LSE as a recommendation to the Chief Engineer and the Program Manager
Information Theory Model
• Information Theory can be used to understand decision making structures and information flow

\[ \bar{I} = H = - \sum p_n \log p_n \]

Practitioner’s Guidance
• Understand and define the scope of each needed decision body

• Ensure that each decision body has all affected or contributing disciplines represented, including understanding of the types and magnitudes of uncertainties affecting decisions within that decision body's scope, but no more

\[ -H(p_1, p_2, \ldots, p_n, q_1, q_2, \ldots q_m) \geq H(p_1, p_2, \ldots, p_n) \]

• Minimize the number of decision bodies based on scope. The efficiency of the structure decreases with distributed and overlapping scopes.

\[ -H(S, D, X, Y, Z) \leq H(S) + H(D) + H(X) + H(Y) + H(Z) \]
Interviewed 12 Marshall engineers/designers (w/J. Shelton)
• Understand strategies used to integrate subsystems with each other

Common strategy across subsystems – margins
• Keep some percentage of a parameter in “back pocket” as hedge for future negotiations
• Biased Information Sharing
• (Here, “margins” different from “safety margin”)

How does maintaining a margin affect optimality of the final design?
• Model as simple 2 Player System with 3 design parameters
• 15 problem test suite
Simulation Results

No margin: $m = 1$

Static margin, $m = 1.3$

Descending margin, $m = 1.3 - 0.1i$ until $m = 1$

- No margin condition reaches optimality quickest
- Descending margin still reaches optimal, but requires more iterations
- Margins are an issue
  - Interviews highlight real-world consequences
  - Simulations quantify extent of the problem
  - Still possible to achieve optimal design with descending margin, but takes additional time to achieve
Discipline Integration Models

- **Organizational Structure & Mapping**
- **System Functions**
- **Goal Function Tree (GFT)**
- **Value Model**
- **Organizational Values**
- **Goals**
- **Value Attributes**

**Allow systems engineers to:**
- Understand information flow through the development and/or operations organization
- Integrate discipline information into a system level design
- Analyze information flow, gaps, and blind spots at the System level

**Tools:**
- MagicDraw Enterprise (SysML)
- Matlab
- Matlab StateFlow
- JAVA
- Anylogic
- Extend

**Models:**
- Agent Based Model (ABM)
- System Dynamics Model
- Discrete Event Simulation
System Dynamics

Goal: Understand how information about the system flows through the organization and into the design and operations
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

For Each Probabilistic Case

Delivered Cargo → Returnable Cargo → Vehicle Loading

Distributed Cargo

On-Orbit Parameters
- Desired Recoverable Fraction
- Cargo On-Orbit Period

Vehicle Reliability

Nominal Flight Schedules
- Flight Rates
- Lockout Restrictions

Vehicle Descriptions
- Upmass/Downmass Capacity
- Press & Unpress Carrier Limits
- Altitude Adjustment

Crew Time Requirements

Cargo Uormass Requirements

Quiescent Periods

Expected Cargo

Probabilistic Cases

On-Orbit Parameters
- Desired Recoverable Fraction
- Cargo On-Orbit Period

Loading Factors
- Carrier Arrangements
- Average Tare Factors

Maritime Cargos

Cargos in Queue

Vehicle Loading

Return Cargo

Vehicle Loading

Non-Queuing Cargo

Loading Factors
- Carrier Arrangements
- Average Tare Factors

Expected Cargo

Probability of Exceeding Fraction of Required Upmass

For Each Probabilistic Case

Nominal Flight Schedules
- Flight Rates
- Lockout Restrictions

Vehicle Descriptions
- Upmass/Downmass Capacity
- Press & Unpress Carrier Limits
- Altitude Adjustment

Crew Time Requirements

Cargo Upmass Requirements

Expected Values

Expected Cargo

Probability of Exceeding Fraction of Required Upmass

STS - ISS Transportation / Operation Analysis
Policy and Law Assessments

Goal: Understand How Policy and Law Constrain the Design and Operations of a System and How the System Engineer Should Interpret These Constraints
Impact of Government Oversight Time Allocation Study

- Motivation: Industry and government leaders agree that government oversight leads to cost growth, but there is less agreement on how much and through what mechanisms.

- Research Plan:
  - Build an empirical basis for measuring the extent and nature of the impact of oversight
  - Non-invasive “Time Allocation Study:” Statistically valid aggregated observations of how engineers actually spend their time throughout a product’s life cycle.
    - Part One: Collect time-recall diaries to develop a composite list of activities performed
    - Part Two: Survey Population over several months at random times per day to accurately observe amount of time spent on activities

- Data collection is complete and analysis is in process
  - Most non-value added oversight is internal company driven
  - Government generated insight/oversight is a small % of work done (< 10%)
Percentage of total time spent on each oversight category

Brainard, S. M., Zsajnfarber, Z., “Understanding the burden of government oversight on engineering work: adding empirical data to the debate”, submitted to Space Policy
System Engineering Supporting Activities

Process Application and Execution for the Specific System
 Processes


- SEMP is essential to capture appropriate application of processes to the specific system

  - Process application is specific to the system being developed
    - Tailoring is not a special exception, it is the norm
System Engineering Standards in Practice
### Original NASA Study and New Study Commercial Focused Projects

| Correlation of 0.4 or greater noted Project Success and System Engineering Processes |
|---|---|---|---|---|---|---|---|---|---|---|
| Original Study Correlations |  |
| Agriculture | Aerospace | Defense and security | Transportation | Communications | Electronics | Energy | Infrastructure |

| Technical success relative to initial req. | .4 | .4 | .4 | .4 | .4 | .4 | .4 | .4 | .4 | .4 |
| Technical success relative to similar projects | .6 | .6 | .6 | .6 | .6 | .6 | .6 | .6 | .6 | .6 |
| On schedule relative to original project plan | .4 | .4 | .4 | .4 | .4 | .4 | .4 | .4 | .4 | .4 |
| On schedule relative to similar projects |  |
| On budget relative to original project plan | .5 | .5 | .5 | .5 | .5 | .5 | .5 | .5 | .5 | .5 |
| On budget relative to similar projects |  |
| Satisfaction with project management process | .5 | .5 | .5 | .5 | .5 | .5 | .5 | .5 | .5 | .5 |
| Overall project success (organization view) |  |
| Overall project success (stakeholder view) | .4 | .4 | .4 | .4 | .4 | .4 | .4 | .4 | .4 | .4 |

**Processes with > 3 Correlations ≥ .4**

**Processes with < 3 Correlations ≥ .4**

Original Study Correlations
### ORIGINAL NASA STUDY AND NEW STUDY GOVERNMENT FOCUSED PROJECTS: CHECK

Correlation of 0.4 or greater noted Project Success and System Engineering Processes

<table>
<thead>
<tr>
<th>Processes with &gt; 3 Correlations ≥ .4</th>
<th>Processes with &lt; 3 Correlations ≥ .4</th>
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<tbody>
<tr>
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<tr>
<td>Technical success relative to similar projects</td>
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<tr>
<td>Overall project success (stakeholder view)</td>
<td>.6 .4 .4 .5 .4</td>
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</tbody>
</table>

Original Study Correlations
Summary

- Discussed approach to Engineering an Elegant System

- **Systems Engineering Framework and Principles**
  - System Integration
  - Engineering Discipline Integration

- **Several methods and tools are available for conducting integrated system design and analysis**
  - System Integration
    - System State Variables
      - Goal Function Tree
      - State Analysis Model
    - System Value Model
    - System Integrating Physics
    - System Autonomy
    - Multidisciplinary Design Optimization (MDO)
    - Engineering Statistics
  - Discipline Integration
    - Sociological Concepts in Systems Engineering
    - Information Flow
    - Systems Thinking (Cognitive Science)
    - Policy and Law
    - System Dynamics Modeling

- **Systems Engineering Approach defined in two documents**

- Send requests for documents to: michael.d.Watson@nasa.gov