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NASA systems engineering research consortium: Defining the path to elegance in systems

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Abstract

The NASA Systems Engineering Research Consortium was formed at the end of 2010 to study the approaches to producing elegant systems on a consistent basis. This has been a transformative study looking at the engineering and organizational basis of systems engineering. The consortium has engaged in a variety of research topics to determine the path to elegant systems. In the second year of the consortium, a systems engineering framework emerged which structured the approach to systems engineering and guided our research. This led in the third year to set of systems engineering postulates that the consortium is continuing to refine. The consortium has conducted several research projects that have contributed significantly to the understanding of systems engineering. The consortium has surveyed the application of the NASA 17 systems engineering processes, explored the physics and statistics of systems integration, and considered organizational aspects of systems engineering discipline integration. The systems integration methods have included system exergy analysis, Akaike Information Criteria (AIC), State Variable Analysis, Multidisciplinary Coupling Analysis (MCA), Multidisciplinary Design Optimization (MDO), System Cost Modelling, System Robustness, and Value Modelling. Organizational studies have included the variability of processes in change evaluations, margin management within the organization, information theory of board structures, social categorization of unintended consequences, and initial looks at applying cognitive science to systems engineering. Consortium members have also studied the bidirectional influence of policy and law with systems engineering.

Keywords: System Integration; Discipline Integration; Systems Engineering Processes ; System Exergy; Akaike Information Criteria; State Variable Analysis; Value Model; Cost Model; Information Theory;

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1. Introduction

In the after math of the Constellation Program cancellation, NASA was struggling with the direction and contribution of systems engineering to program success in general. As a result of one of these conversations the lead author met with former NASA Administrator and the Director of the University of Alabama, Huntsville Center for System Studies (CSS) on the topic of systems engineering in 2010. The conversation quickly settled on the need for systems engineering to focus on the product, or system, being developed and operated. The CSS Director was about to present his paper, "How do We Fix System Engineering"[1] which seemed to frame some of the questions we discussed. Coming out of a series of meetings on this, the lead author recommended the establishment of a research consortium to study engineering and organizational basis of systems engineering to the leadership at the Marshall Space Flight Center (MSFC). The consortium held its first kick off meeting in December 2010 with the emerging Space Launch System (SLS) as a complex system the consortium could study from pre-phase A through development completion at Design Certification Review (DCR). The consortium started with the 4 characteristics of an elegant system proposed in the paper: System Efficiency, System Effectiveness, System Robustness, and Minimizing Unintended Consequences.

The consortium was established with a broad research question to enable several subordinate research projects to address different aspects of system engineering. The primary research question can be stated as: "What are the fundamental engineering and organizational relationships of system engineering?"

The SLS has served as the study medium in which to investigate various aspects of systems engineering in system and organizational integration. Early studies explored various aspects of SLS including interviews of the Element Chief Engineers, evaluation of decisions through the task team and change request process, interviews of key discipline designers looking at how they interacted, system state variable modelling, and discussions on what constituted the integrating physics of a launch vehicle. Agent Based Modelling was also explored.[2] In addition, consortium research expanded beyond SLS and looked at applications of failure responses in electrical power grids, optimal system configurations, and failure categories.[3]

2. Systems engineering Framework

In the second year of the consortium, a systems engineering framework[4] was developed to capture the many facets that our research projects indicated as important. The systems engineering framework was the beginning of structuring an answer to our research question and consists of four elements: Understanding the Mission Context, System Integrating Physics, Organizational Structure and Information Flow, Policy and Law. These 4 elements are represented as the top row in Figure 1.

The first part of this framework, Understanding Mission Context, is well recognized in current systems engineering practice. This aspect involves understanding the mission (i.e., system application or uses), the mission environments, preferences of the stakeholders, and capturing the mission requirements.

The second part of the systems engineering framework is one half of the core of systems engineering: System Integrating Physics. This involves understanding what physical and/or logical relationships integrated the total system. This basis is believed to be the source of the system schedule, system cost, and system risks. The specific system integrating physics can have many different forms including exergy for thermodynamic systems (e.g., aircraft, electrical plants, helicopters, rockets, and ships); optical transfer function (i.e., image quality) for optical systems, logical relationships in purely software systems, and social/psychological relationships in purely social systems. Understanding these relationships provides the guidance needed to development and operate an elegant system.

The third part of the systems engineering framework represents the other half of the core of systems engineering: Organizational Structure and Information Flow. This aspect involves integrating the different disciplines that make up the system development and/or operations organization. The system engineer must recognize, engineer, and ensure complete and clear flow of information through the organizational structure. This structure includes not only the main line organization, but also matrix organization structure and decision board structure. Configuration Management and Data Management are key tools to aid in managing this information flow.

The fourth part of the systems engineering framework is the bidirectional influence of policy and law with the system. The system engineer must be cognizant of these effects on system decisions. Policies come in many forms from organizational and corporate to governmental (which may be local, state, or federal in the United States). The policies as well as governmental laws include labor, environmental, health, etc. The system engineer must account for compliance of these within the design decisions or account of the impact of failing to meet some aspect (e.g., system recall or cancellation, environmental lean-up costs, or economic impact costs).

Figure 1 shows the mapping of the consortium research tasks to the systems engineering framework (top rows) and the attributes of an elegant system (right most column).

Systems Engineering Framework						
System				**Organization**		
Understanding Mission: Understand and Define Mission Requirements	**Physics Relationships**			**Organization Structure & Relationships**	**Policy & Law**	
	System Performance: Understand the Driving Physics	System Cost/Schedule: Driving Physics defines the development/ operations cost and schedule	System Risk: Understanding of the Driving Physics defines the system uncertainties and sensitivities			System Attributes
System Value Model to capture Stakeholder Preferences	System Exergy, Optical Transfer Function, Structural Loads, Logic, etc.	Nanolauncher Cost Model, PBS	System Exergy, Optical Transfer Function, Structural Loads, Logic, etc.	Information Theory defines efficient decision making flows (boards) Decision Making process varies with decision	Appropriate application of constraints (not as solutions)	System Effectiveness
Understand and Define Mission Requirements	Goal Function Tree, System State Model, Engineering Statistics (AICc), Multidisciplinary Coupling Analysis		Goal Function Tree, System State Model, Engineering Statistics (AICc), Multidisciplinary Coupling Analysis	Biased Information Sharing, Mediated Learning		
	Mission and Derived Technical Requirements as basis for Verification System Value Model as the basis for Validation		Mission and Derived Technical Requirements as basis for Verification System Value Model as the basis for Validation	Cognitive Science Informs		
System Capability mapped to Mission Value	System Capability mapped to Mission Value	System Capability mapped to Mission Value	System Capability mapped to Mission Value	Robust Organization: Able to produce an elegant system with unstable inputs (e.g., Budget, Schedule, Mission Objectives)	Robust to Policy and Law: The degree to which System Value is insentive to changes	Robustness
System Exergy, Optical Transfer Function, Structural Loads, Logic, etc.	System Exergy, Optical Transfer Function, Structural Loads, Logic, etc.	Nanolauncher Cost Model, PBS System Value Model	System Exergy, Optical Transfer Function, Structural Loads, Logic, etc.	Information Theory defines efficient decision making flows (boards) Decision Making process varies with decision Cognitive Science Informs	Appropriate application of constraints (not as solutions) Best Balanced Solution vs. Perceived Solution	Efficiency
System Capability mapped to Mission Value	Goal Function Tree, System State Model, Engineering Statistics (AICc), Multidisciplinary Coupling Analysis	Nanolauncher Cost Model, PBS System Value Model	Unanticipated Consequences Categories	Unanticipated Consequences Categories must be managed	Appropriate application of constraints (not as solutions)	Unintended Consequence

Figure 1: System Engineering Framework Mapping of Research Projects

3. Systems engineering Postulates and Hypotheses

With a systems engineering framework established and guiding our research, members of the consortium began considering a more formal basis for systems engineering in response to our primary research question. We were challenged to look at postulates ("statements assumed to be true without proof"[5]), similar to the approach used by Ludwig Boltzman in explaining complex gas distribution relationships. A set of statements were formulated about systems engineering which the consortium leadership believed to be true. The draft systems engineering postulates were presented at the 2014 American Society of Engineering Management (ASEM) conference[4]. Feedback from this conference and discussion among the full consortium in two face to face meetings in 2015 have led to an update of the systems engineering postulates and designation of some as hypothesis ("unproved theory or supposition, tentatively accepted to provide a basis for further research"[6]). These postulates and hypothesis are briefly described in this section. A description/evidence/implications format is used. A description is provided for each postulate and hypotheses. Evidence of why we believe the postulate or hypothesis to be true is then provided followed by some implications of each. The implications address some of the application or research relevance for the postulate or hypothesis.

3.1. Systems engineering Postulates

Systems engineering is product specific.

Description: This is the first and foundational statement on systems engineering. Systems engineering is driven by the product (i.e., the system) and in particular the system's integrating physics, logic, and cognitive relationships that are foundational to the specific product or system being designed. Essential to this is the understanding of the mission or use of the product as formulated by the product goals.

Evidence: The ubiquitous tailoring of systems engineering approaches provides strong support for this postulate. Systems engineering cannot be generically approached but must be consistent with the system being developed or operated. Engineering processes always are specific to the system being designed. Our research surveying the "NASA 17 Systems Engineering Processes" provides support for this postulate indicating 72% of companies interviewed have systems engineering processes unique to their product. No standard process is followed by more than 7% of the respondents.[7]

Implications: This postulate states that any application of systems engineering should be organized based on consideration of the system being developed or operated. The systems engineering methods applied to a product will and should vary in emphasis and application based on the nature of that product, its environment, and its context.

The Systems engineering domain consists of subsystems and their interactions among themselves and with the system environment.

Description: From a physical, logical, and structural sense, a system is not a single mechanical, or electrical, or chemical entity; it encompasses a set of interacting subsystems. Systems engineering is concerned with combining multiple subsystems, of various physical and logical types, into a best balanced functional whole to accomplish the mission goals. This postulate addresses the system integration aspects of systems engineering. The discipline integration aspects are addressed by Postulate 3 below.

Evidence: The individual engineering disciplines deal with the development of their specific functions extremely well. When these functions are integrated with each other and with the environment, the inter-relationships drive the final system performance including emergent properties not evident from the individual system functions. Thus, the engineering of the individual functions is well addressed while the integration of the engineering functions is what makes these functions a system. The domain of systems engineering is the set of these relationships.

Implications: The systems engineer is focused on the interaction of these subsystems, not as a design engineer focused on the details, but as a well-versed integrator. These system interactions, including interactions with the system environment, can drive the design as strongly as the subsystem functions themselves and, when coupled, can potentially create unexpected system responses which must be predicted and managed.

The function of Systems engineering is to integrate engineering disciplines in an elegant manner.

Description: The systems engineering discipline is its own engineering discipline but it is not independent from other engineering and social disciplines Systems engineering seeks to integrate and incorporate the other engineering and social discipline in an elegant manner to produce an elegant system. This postulate addresses the discipline integration aspects of systems engineering. The system integration aspects are addressed by Postulate 2 above.

Evidence: Any complex system is developed and operated by multiple engineering and social science disciplines. These engineering and social disciplines work in an integrated fashion, formerly and informally, to produce these systems.

Implications: The systems engineering domain is focused on the interactions of the disciplines. The objective is a basic understanding of each discipline with a detailed understanding of their interactions. This incorporates various organizational integration aspects. The systems engineer must be cognizant of the organizational and sociological influences on the system development and operations. The systems engineer must also "engineer" these relationships.

Systems engineering influences and is influenced by organizational structure and culture.

Description: The focus of systems engineering is not isolated to the technical aspects of the system. The development process is driven by the system being developed which has a corresponding influence on the structure of the system's developmental and operational organizations. Similarly, the structure of the organization has an influence on the engineering of the system. These factors also impact the culture of the organization.

Evidence: Organizational mirroring provides examples where the organization maps to system functions. Our current research in" Biased Information Sharing" also shows that system margin is maintained by the organization and not always clearly identifiable in the system design.

Implications: The systems engineer must be cognizant of the culture, the organizational interactions, and their potential impact on the design of the system. The systems engineer must understand how information flows through the organization, is filtered and interpreted by the organization, and is captured by the system design or operational procedures. The systems engineer should work with project management and line management to address issues in organizational information flow and culture to improve the elegance of the system.

Systems engineering influences and is influenced by budget, schedule, policy, and law.

Description: Every project has overarching constraints that extend beyond the physical and environmental. Specifically, most (if not all) projects have a limited budget and schedule. In addition, all systems must conform to established organizational and government policy and laws. These policies and laws put additional constraints on budgets, schedules, and technical solutions.

Evidence: Every project has these constraints. Infinite budgets or schedule do not exist. Policy and law application pervade our systems.

Implications: Social choices drive the establishment of these constraints. Whether at the national or organizational level, choices are made to define budget limits, schedule limits, policies, and laws. Thus, social choice theory is linked to the physical and logical solutions through these constraints.

Systems engineering spans the entire system life-cycle.

Description: Systems engineering is not just a development phase activity but continues throughout system operation, decommissioning, and disposal. The organizational relationships and goals change as the system progresses through these phases but systems engineering continues to integrate the system functions and the system disciplines throughout all phases of the system life-cycle.

Evidence: Systems engineering during the development phases is well understood. During the operational phases, systems engineering is still essential as the system goes through maintenance upgrades, new application adaptations, obsolescence driven re-designs, etc. In addition, during decommissioning and disposal, systems engineering is essential to deal with the proper decoupling of the system and ensuring conformance with policy and laws affecting the disposal of the system.

Implications: As the system progresses through its life cycle, the need for systems engineering changes. A shift takes place from development to operations in terms of the scope of changes. The baseline system becomes the medium in which operational changes take place. The organization changes significantly as the system transitions from development to operations. Organizational relationships and needs are different. Culture can be very different. All of this affect the system and must be dealt with in systems engineering. Another organizational change and significant culture shift occurs during decommissioning and disposal.

Understanding of the system evolves as the system development or operation progresses.

Description: As the system progresses through development and operations, a deeper understanding is gained of the system as a whole. As the system progresses through development, more detailed decisions are needed and as understanding deepens these detailed decisions can be made. Understanding of the system could also regress, if organizational changes occur due to inactivity of an organizational element (loss of experience), retirement of key experienced individuals, or closure of suppliers.

Evidence: This deepening of understanding is seen in any system development. The technical assessment process shows this as systems progress from concept review to requirements review to design review to acceptance review. Similarly, lessons learned from the operations phase are abundant for any system. Commercial product upgrades, or new models, are driven by this deepening of understanding of the system as a whole.

Implications: Requirements are derived as the system design progresses. Thus, while mission requirements (i.e., part of understanding the mission context) are defined at the beginning of development, the system requirements cannot be established up front. They are a function of the design choices made and are understood progressively throughout the development phase. This also applies to cost and schedules, particularly for new systems where the development or operations result in unexpected changes. Similarly system models gain fidelity as the design progresses and the interaction between subsystem design maturity and system model maturity must be managed by the systems engineer.

3.2. Systems engineering Hypotheses

The hypotheses are statements that the consortium is debating and believe can be proven (or perhaps disproven) through research. These statements challenge some of the heuristic notions found in complexity theory and are set in a practical application context (with real boundaries and constraints) rather than in a theoretical infinite context.

If a solution exists for a specific context, then there exists at least one ideal Systems Engineering solution for that specific context.

Description: For a given system context that has a system solution, there exists an ideal (optimal or best balanced) design for the system to accomplish the mission. The context is defined by the budget, schedule, policy, law, and organizational culture.

Evidence: This hypothesis is stated to drive objective research into the question of an optimal system configuration (i.e, a best balanced system). Our research on exergy efficiency of a rocket indicates that an optimal system can be defined across multiple configurations. This is a result that has not previously been achievable in a quantifiable manner. In addition, the value model seems to offer the ability to define an objective function to optimize the system in a given context.

Implications: This hypothesis makes no statement about a global optimum. Rather, this hypothesis states there is a local optimum within the confines of the specific developmental and operational context. In the absence of the knowledge of a best balance, the system's development appears as a sociological balance of organizational preferences. If an optimal system can be defined, then this would create objective goal that would influence and guide the system development and operations for any organizational type.

System complexity is greater than or equal to the ideal system complexity necessary to fulfill all system outputs.

Description: In a given operational context, the minimum system complexity required to fulfill all of the system outputs is the optimal system complexity and the complexity of alternative system designs are equal to or greater than the ideal (i.e., optimal). Note that this is not a simpler is better hypothesis. Minimal complexity involves all aspects of the system. Being simple in only one context is not necessary the system with the minimal complexity. The minimal complexity solution involves a best balance of the system and may lead to some aspects being more complex than alternatives and other aspects being less complex. The minimal complexity is defined holistically and not based on a subset of system aspects. The definition of system complexity is a much-debated topic. Refer to Appendix B for a more detailed review of complexity.

Evidence: This is similar to the statement of Occam's razor. As Albert Einstein is reputed to have said, "everything should be made as simple as possible, but not simpler", which underlines a powerful truth of system modeling and systems engineering" (Einstein, n.d.).

Implications: This postulate asserts that less complexity is preferable for a given context. The system complexity necessary to complete all intended outcomes of the system must be realized or the system will not satisfy all of its operational needs.

Key Stakeholders preferences can be accurately represented mathematically.

Description: Understanding and mathematically representing the preferences of key stakeholders is essential in enabling systems engineers to make decisions that are consistent with the stake holder's preferences and to ensuring system goals are accomplished. This also provides a basis for the validation of the system performance. Such representations also provide a basis for why decisions were made at any point in the system development.

Evidence: Several approaches have represented preferences in mathematical form including Game Theory and Decision Theory.

Implications: A system value model should be constructible for a given system and stakeholders.

4. System Principles Documents

The consortium work is documented annually. The December 2014 edition was entitled, "Engineering Elegant Systems: Principles of Systems engineering".[8] This captured a complete picture of our work and how to apply the current set of results. The December 2015 edition will consist of two volumes. The consortium decided to separate the theory aspects from the practical application aspects to make the content of each more clear. The theoretical aspects are documented in, "Engineering Elegant Systems: Theory of Systems Engineering.".[9] The practical application of the theory is then presented in "Engineering Elegant Systems: The Practice of Systems Engineering."[10] These two documents capture the theoretical details along with key application findings of the consortium work.

5. Systems engineering Processes

The consortium started with a review of the NASA 17 Systems Engineering Processes based on a previous Marshall Space Flight Center engineering project survey[9]. The survey looked at each process focusing on the subordinate research question: "How do the systems engineering processes contribute to the success of a system development or prevention of the failure of the system development?" The consortium expanded the survey to include 130 engineers at 102 companies. This report indicated that 72% of the companies do not use one of the published systems engineering process standards and that no standard was employed by more than 7% of the companies as shown in Figure 2.**Error! Bookmark not defined.** This provided support to our first postulate. The survey was expanded again to all NASA centers and a statistical analysis was conducted on the survey results.[10,11,12] The results of the surveys indicated that processes are specific to the product being developed, particularly for commercial companies. The surveys also indicated that only 8 of the NASA 17 processes contributed to the success of the system or prevention of failure of the system.

In looking at the systems engineering processes, it is important to recognize that all engineering disciplines have processes to accomplish their designs and analysis. These disciplines, however, are focused on the engineering equations and solutions which achieve the goal(s) of the component being designed. Systems engineering processes are important and necessary to achieve a system design. But they are not sufficient. What then are the engineering equations that system engineers need to focus? Considering this question led us to the Systems Engineering Framework presented in Section 2 above. The engineering solutions are found by understanding the system integrating physics or logic.

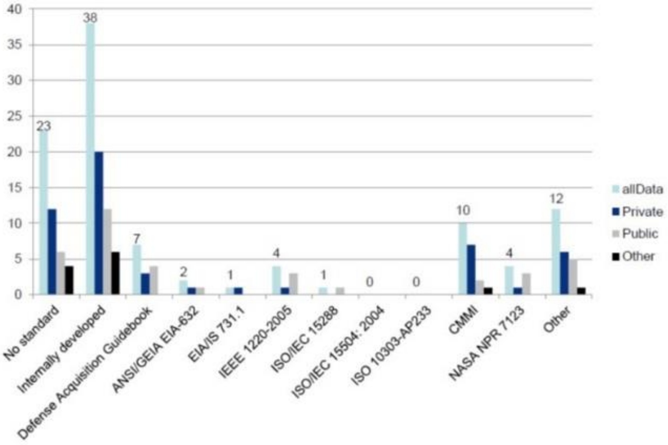

Figure 2: System Engineering Standards Use

6. System Integrating Physics

The consortium is researching several engineering approaches to integrate the system to answer the subordinate research question: "What are the physical/logical integrating relationships of a system?" The basic theory being investigated is that an integrating physics exists dependent on the function of the specific system (an implication of our first postulate). In the consortium research, this appears to take the form of an integrating engineering discipline (i.e., thermodynamics, structural mechanics, or optical physics). A given system will have this integrating (primary) discipline that ties together all engineering functions of the system. The research has found that the primary discipline provides the integration and that the other disciplines support or affect this aspect of the system. Thermodynamic systems abound in this context. Aircraft[13], electrical power, rockets, and ships are all examples of thermodynamic systems some of which are shown in Figure 3. Buildings, derricks, towers, are all examples of structural systems. Telescopes, interferometers, are examples of optical physics systems as illustrated in Figure 4. Note that in each of these systems, the specific application depends on the system itself with unique characteristics in the application. Ships are certainly different thermodynamic systems than aircraft or rockets. The other engineering disciplines support the primary discipline. Thus, rockets have an important structural component but this is not the system integrating component. Optical systems are certainly affected by thermodynamics and structural dynamics and these must be managed very carefully. The effects of these disciplines do not integrate the optical system, however, and their effect is measured in terms of their impact on image quality. There is some evidence that there are systems which have more than one integrating discipline. Spacecraft capsules, for example, which are control volumes in-space but treated as control masses during atmospheric re-entry. Of course, these are both thermodynamic relationships and research needs to look more closely at these types of examples.

This research also is beginning to provide insights into a more in depth research question on the mathematics of system engineering stated as: "What is the mathematical basis of system engineering?"

Several aspects have been evaluated in the consortium research. Thermodynamic system exergy as the integrating physics for a launch vehicle has been assessed. Information theoretic statistics have been applied in Akaike Information Criteria (AIC) to assess sensor optimization at a system level. A State Variable modelling approach is being matured which forms the basis of an integrated system model. Multidisciplinary Coupling Analysis (MCA) is a promising system analysis technique looking at coupling effects between system functions. And an investigation being conducted in the application of the integrating physics through the product breakdown structure (PBS) in system cost modelling. System robustness is also being investigated through a capability model mapped to various design reference missions (DRM). Finally, a system value model is seen as providing an integration of both the system integrating physics and the stakeholder preferences. Each of these research projects is briefly described in the following subsections.

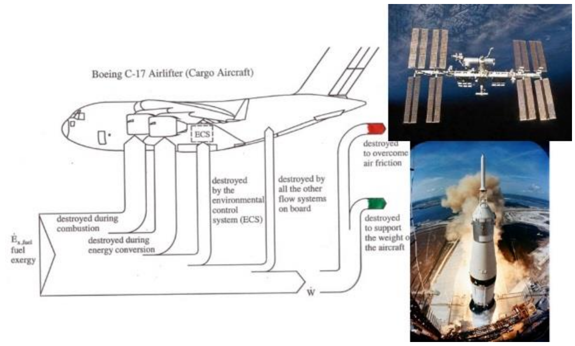

Figure 3: Thermodynamic Systems

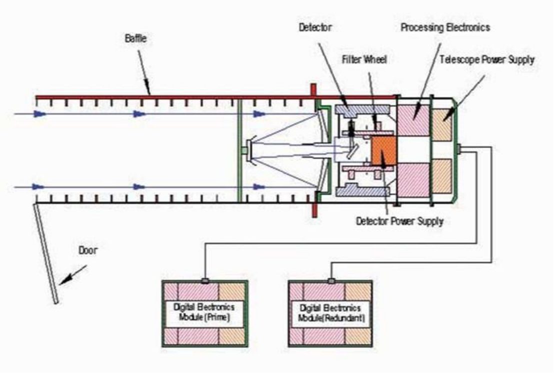

Figure 4: SWIFT Telescope- An Optical System

6.1. System Exergy

Rockets and launch vehicles are thermodynamic systems. These systems function by converting chemical energy stored in the propellants into thrust to provide the vehicle with kinetic and potential energy. As such the application of both the first and second laws of thermodynamics are essential to their function. Thus, thermodynamics form the system integrating physics for these vehicles.

The thermodynamic property which includes both energy (first law) and entropy (second law) is exergy. This has been developed for aircraft and hypersonic vehicles by the Air Force Research Laboratories,[14] and the consortium has added to the Air Force work developing the exergy balance relationship for launch vehicles. By calculating the exergy balance relationship, a thermodynamic efficiency for the system can be calculated. This efficiency accounts for variations in payload mass and orbital altitude, providing the ability to compare the efficiency of different launch vehicles.[15,16] Thus, the identification of the system integrating physics allows different system configurations to be compared objectively, providing a means to answer the question, "Which is the most efficient system configuration?"

This approach also applies to crewed spacecraft (i.e., modules and capsules). These systems are primarily large crew environment volumes, defined by the functioning of the environmental control and life support systems (ECLSS). Their structure, power, and thermal management functions are all defined and managed by the cabin environments. Consortium members are currently developing an exergy model for the International Space Station (ISS) ECLSS to demonstrate the integrating nature of system thermodynamic exergy for these spacecraft. In the case of capsules, the service module propulsion is a secondary function to the ECLSS.

Capsules sometimes also form a dual role and function as a control mass during re-entry. Thus, capsules have two functions: maintenance of the crew environment and re-entry. The re-entry functions are also managed by an exergy balance. Similarly, planetary landers are integrated by exergy where they have propulsion stages for descent and ascent and crew volumes for transporting the crew. The consortium is currently investigating these integrating relationships.

6.2. Information Theoretic System Statistics

Akaike Information Criteria (AIC) is a statistical method based on Kulback-Leibler (K-L) information distance.[17] This is a more general form of information entropy initially defined by Shannon.[18,19] This method is very powerful in comparing different statistical models and providing a relative information distance to the physical truth of the system. This is a scalar measure and provides some very powerful comparison tools. AIC can be corrected (AICc) to compare models with a relatively small dataset. The delta between the best (lowest value) and associated weightings allow models to also be integrated to produce a composite statistical measure for a system.[20]

These techniques provide the ability to define the sensor configuration which provides the most information for the data collected. This is an improvement over the use of Fisher Information approaches which gives a cumulative information curve indicating every sensor added provides additional information. AIC methods penalize models for adding parameters (i.e., sensors) that do not contribute strongly to reducing the information difference from the physical truth. AIC also penalizes models which do not have sufficient parameters to describe the system performance.[21]

These methods have been developed and demonstrated using a structural dynamics square plate model[22] shown in Figure 5[23]. Current work is expanding to do a full assessment of the SLS structural dynamics, supporting the definition of the best sensor suite to detect the structural frequencies of interest during flight (development flight instrumentation), prelaunch modal testing, and prelaunch dynamic interface rollout test.

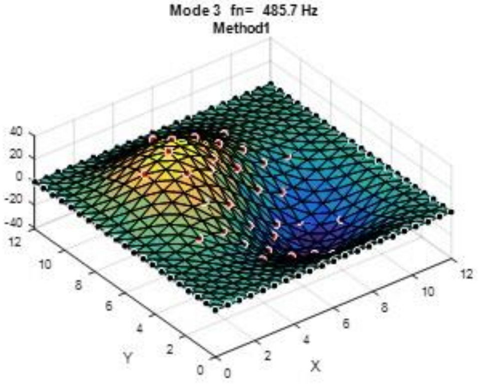

Figure 5: Sensor Mapping on Structural 2nd Mode Shape

6.3. System State Variable Modeling

System Integration has primarily been a natural language-based set of cross-checking and traceability processes. By contrast both System Analysis and System Integration are based on system models that use mathematics, physical laws, and logical reasoning. These system models are constructed from system and environment *state variables* to enable mathematical and logical representation of the system and the environment.

The use of natural language, important for system description, is not accurate for specific system integration and prone to communication error and terminology differences between engineering disciplines. System integration requires the use of system models based on math, physics, and logic which greatly aides in communication and enables a system representation which can represent all the disciplines necessary for the system functions and application. State variables are necessary to achieve these integrated system models, and enable mapping between multiple kinds of models about the system. These form the system state basis.

System state variables fully describe the system functions and interactions. Several approaches are being developed to construct these types of models. The Goal Function Tree has been employed by SLS to analyse failures in an integrated fashion. The Goal-Function Tree (GFT) is a top-down, formal, hierarchical representation of stakeholder intentions for the system. While in appearance it resembles a traditional functional decomposition, it is far more rigorous and advantageous due to its use of state variables and associated *constraints* as the output of functions. The constrained state variables are *goals*, which when translated into formal statements are requirements. A system concept of operations, when rigorously defined, specifies a sequence of desired or required events, each of which specifies a top-level goal for that portion of the sequence. A GFT can then be constructed to define all of the supporting goals and functions needed to achieve each goal or event defined in the concept of operations. The use of state variables ensures that the tree structure is physically and *logically valid*, which in turn means that the GFT can be employed for a variety of analytical uses. In the GFT paths any selected goal or function up the tree defines a scenario that can be used for testing. Because any failure that can threaten a top-level goal must threaten either that goal, or goals below it in the tree (if there is no redundancy), failure detection coverage can be assessed by placing detectors to identify failure to achieve goals along every path that can lead to a top-level goal. Taking the logical complement of the GFT creates the beginnings of the system fault tree, which in turn can be used for safety / hazard analysis or for *probabilistic risk assessment*. This form of the model provides a distinction between state variables that describe a specific element or subsystem function and those which govern the interactions between the subsystem and the environment, providing a view of the systems engineering domain as contained in Postulate 2.

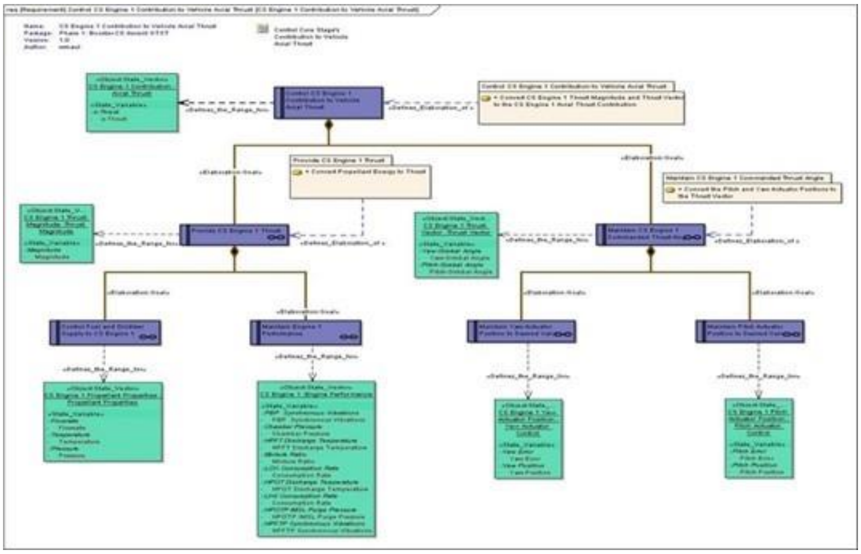

Figure 6: Goal Function Tree

This has led SLS to a system state transition model.[24,25] This model builds on the idea that systems are described by their state variables, a key element of our research. While, development of this model is not directly supported by our research, this as an important contribution to system modeling and should be used in most (if not all) systems engineering applications. The model is developed building on the consortium state variable research using software state machine approaches. The model is constructed representing all of the vehicle hardware and software states. Vehicle execution, state transitions, can then be modeled and the system evaluated across all subsystem functions for proper sequencing, and expected and unexpected interactions.

6.4. Multidisciplinary Coupling Analysis (MCA)

Typical systems engineering processes focus on hierarchical decomposition of design and development tasks. This provides a very linear structure of simple relationships but is quickly overwhelmed by system interactions in complex systems. System couplings provide the medium in which to understand the interactions of the system functions and the interaction of the system with the environment. There are many types of physical and logical couplings for a system. These couplings are not always obvious and can lead to emergent behaviour which can modify the system couplings (i.e., adding new or changing the response of known couplings). System analytical techniques which support the full set of system interactions include Multidisciplinary Design Optimization (MDO) and its application for Multidisciplinary Coupling Analysis (MCA).

MCA is a comprehensive system analysis tool looking at coupling aspects across the systems engineering domain (subsystems and the environment). Research is currently assessing Ares I thrust oscillation relationships. After the Constellation Program, a new method of analyzing the coupling of the solid rocket motor acoustics to the vehicle structural modes (clearly a system affect) was proposed, called Acoustic Structural Interaction (ASI)[26]. A complete model of these couplings is being developed to explain these interactions in the ASI construct.

6.5. System Cost Modeling

System cost models have not yielded very accurate results. Various approaches have been considered to address the inaccurate cost estimates generated by these cost models[27]. System cost, based on the physics and logic of the system, is being investigated for the Nanolauncher project (a nanosatellite launch vehicle). The primary component of the system cost is labor, not materials, and is based on the tasks necessary to achieve the physics or logic which defines the system functions. Thus, a product breakdown structure (PBS) which captures the architectural view of the system is being constructed. This project is seeking to show the relationship of the physics of the system to the major cost elements. It is also exploring the regulatory costs incurred on this project. This project may provide insight into both the cost basis of a system and the regulatory costs incurred on the system.

6.6. System Robustness

System robustness is a challenging topic to define and the consortium is addressing this as the subordinate research question: "What characteristics define a system as robust?" Robustness in the literature depends on the discipline defining robustness and has a variety of contexts including: robustness to environmental changes, robustness in use, and robustness to subsystem failures.[28] These are all plausible definitions, each representing aspects of system robustness. The consortium is investigating system robustness as a composite of these definitions: The ability to provide expected output with durability to input (including environment) variations, subsystem anomalies, and applications beyond the original intended use.

Early research looked at system variance and its relationship to system robustness. Variance was shown to not be a good measure of robustness. In fact, using system variance, could drive the system to be less robust rather than being more robust. That is, the system can become more brittle to changes, rather than more tolerant of changes.[29]

System robustness is also being investigated as system resilience or anti-fragility. These aspects have been considered by the consortium[30] and appear to be similar concepts. The consortium determined to retain the term robustness as originally defined in "How Do We Fix System Engineering?"[1]

To characterize system robustness, a system capability model of the SLS is being developed describing the key attributes of the system in its application environment. These capabilities are then being mapped to a broad set of design reference missions (DRM) to characterize how well the system performs in different uses as illustrated in Figure 7. There are several DRMs defined at the Langley Research Center (LaRC) that are of interest.[31,32] The capability model is expected to yield characteristics in terms of environmental and failure robustness. The DRM mapping will then characterize the use applications for the system. The results of this work will feed into the value model being constructed.

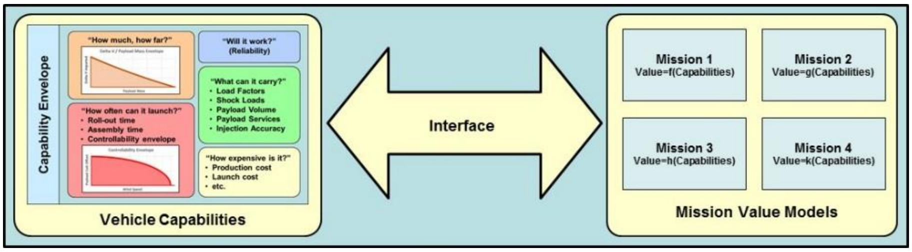

Figure 7: System Robustness Capability Mapping

6.7. System Value Model

A system value model is a model of the value of the system to various stakeholders. This brings in specific aspects of the design and relates them to the value the system provides.[33,34,35,36] A value model of the SLS is being constructed to integrate the physical and organizational aspects of the system in a single model.[37] This addresses the subordinate research question: “How are organizational preferences integrated with system physical/logical characteristics?” The value model will capture the stakeholder preferences (expectations) along with the system integrating physics and system robustness aspects. It is anticipated that this model will provide a mathematical representation for the value of the system to relevant stakeholders (e.g., flight crew, President of the United States, the United States Congress). Depending on the stakeholder, this model could vary in its relative value to the stakeholder. This comparison will be instructive and help to integrate these different values is of interest.

The system value can be tracked from initial stakeholder definition, through design, and finally to system validation. This provides a measure of the system capabilities, tied directly to the system design, which can guide decisions during system development. It is also expected that the system value model will provide a mathematical basis for system validation, clearly differentiating system validation from system verification.

7. Organizational Structure and Information Flow

The consortium is addressing the subordinate research question: “What are the organizational integrating relationships of a system?” Systems engineering is responsible for integrating the various disciplines within an organization to develop or operate a system. This aspect is equal with understanding the system integrating physics. If the system is understood, but the organization is not the system development may never be successfully completed. While, if the organization is understood but not the physics, the system will not work. Systems engineering must deal with both of these aspects in order achieve an elegant system.

The structure of the organization is a sociological function and brings in aspects not traditionally thought of as engineering. These aspects are essential because complex systems are developed by complex systems (organizations). The systems engineer must understand how the organization develops, communicates, and maintains information about the system. Information maintained within the organization is not always readily identified in the system design. Managing this is a crucial role of the system engineers. Discipline engineers are reservoirs of information which they generate and maintain. The systems engineer manages the channels between these reservoirs ensuring the right information is provided to the right discipline as needed. This brings in information theory as a key element in understanding information flow throughout the organization. This applies not only in the design process but also governs the decision making structure within the organization. Configuration Management and Data Management, from this viewpoint, are important tools for the systems engineer to manage the system information.

The consortium is studying various aspects of organizational influence on the system design. Early in SLS, interviews of the mid-level chief engineers and discipline lead engineers were conducted. Biased information sharing has been investigated within SLS looking at how margin is maintained and shared within the organization. Decision making processes have been assessed looking at the important factors in decision making through the SLS change process. An information theory model of a decision making board structure has been developed indicating important attributes in organizing decision board structures. The separation of the SLS Avionics and Software Control Board (ASCB) and the Chief Engineers Control Board (CECB) is being assessed for efficiency changes in the SLS decision making process. Finally, new research in cognitive science has started looking at mediated learning. This aspect is also bringing work from external efforts mapping cognitive science terms to engineering management terms. Finally, policy and law impacts on systems engineering are being monitored in a company performing large systems engineering projects. This is shedding considerable light on the impact of government oversight activities.

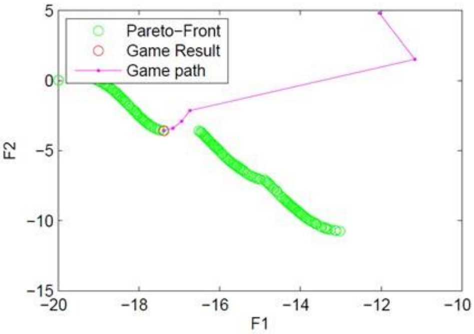

Figure 8: Biased Information Sharing Progressing Toward Pareto Front

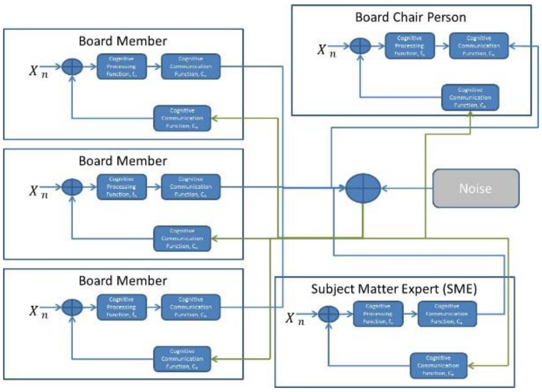

Figure 9: Information Theory Based Decision Board Model

7.1. Chief Engineer Interviews

To gain a perspective on the view of various systems engineering aspects and goals for the SLS, a series of interviews were conducted with the SLS Element Chief Engineers and the SLS Systems engineering and Integration (SE&I) Discipline Lead Engineers (DLE). These interviews provided insight into the organizational view of different aspects of the system including affordability, performance, and operations.[38]

7.2. Biased Information Sharing

Early in the SLS, a series of interviews with the senior design engineers within the organization were conducted. A key finding in these interviews is that design margin is maintained by the organization, and not in the design. This led to further study and the development of simulations to show how the margin is negotiated and shared, as illustrated in Figure 8. Several factors in the sharing of margin were identified.[39]

7.3. Decision Making Processes

SLS decision making processes were studied for three different changes. A survey was asked of the participants in both the decision task team process and in the change request evaluation process. It is interesting that all three changes had very different affects groups and all three were conducted very differently in the task team phase. Yet, participants in all three changes indicated high quality and proper decisions were made. All three decisions followed the same process during the CR portion of the evaluation. Thus, it appears, the importance of having a complete and knowledgeable set of reviewers appears to be most important, while the process employed could vary significantly.[40]

7.4. Information Theory of Decision Structures

Information theory has been applied to decision making structures, looking particularly at board structures as shown in Figure 9. The theory indicates that knowledgeable decisions makers (i.e., knowledgeable of all aspects of the subject) and board scope are significant factors. Delegated boards with large overlap in scope are shown to have high information uncertainty in decision making. This was seen in the NASA Constellation Program Ares I Project where multiple boards and working groups existed in a largely overlapping structure. This structure had difficulty making decision and could take months. SLS addressed this problem by establishing a single large board. Thus, all of the relevant expertise participates in the decisions and delegated boards do not have overlapping scopes. This is carefully managed in SLS to ensure consistency. This mode is supported by the model where scope overlap is minimized and decision uncertainty is much lower. The model includes a control theory based model of the cognitive decision process by the board members and future work will be to update this with a cognitive science definition of the functions in the relationship.

7.5. SLS Board Structure Efficiency

The SLS Chief Engineers Control Board (CECB) in the last year separated the avionics and software decisions to an Avionics and Software Control Board (ASCB) with the intent to improve overall efficiency. The change in decision efficiency is being studied, looking at software changes conducted by the CECB before the separation and software changes conducted by the ASCB after the separation. The overlap in board scope is also being characterized through the knowledge basis of the board members. This study will provide more light on the relationship of delegated boards and provide some quantitative data for the information theory model discussed in section 5.4.

7.6. Minimizing Unintended Consequences

The consortium's initial consideration of unintended consequences has a basis in sociology research. Social structure theory categorizes unintended consequences as[41]:

- Ignorance (limited knowledge of the problem)
- Historical Precedent (confirmation bias)
- Error (mistakes in calculations, working from habit)
- Short Sightedness (imperious immediacy of interest, focusing on near term and ignoring long term consequences)
- Cultural Values (cultural bias in what can and cannot happen)
- Self-Defeating Prophecy (by stating the hypothesis you induce a set of conditions that prevent the hypothesis outcome)

Incorporating updated research and applying these concepts in system engineering is future work for the consortium.

7.7. Mediated Learning

Cognitive science principles are being applied by investigation of mediated learning. This capability provides methods for understanding and teaching systems thinking. This is an important aspect in understanding how to teach this difficult subject to systems engineers.

An activity external to the consortium recently generated a mapping of engineering management terms with cognitive science terms. This information is being collected by the consortium to help in the understanding of the relationship between cognitive science and systems engineering.

7.8. Policy and Law Influences

Policy and law exert significant influence on systems engineering (postulate 5). A failure to properly understand the significance of policy and law can drive systems down unnecessary paths. Some policies are loose and can be adjusted with a good solution for the system. Other policies are rigid and cannot be changed, leading to strict constraints on the system solution. Failure to understand this can lead to unnecessary constraints or system failure when violating a strict policy. Understanding the subtleties of politics is extremely important. Overly, explicit political statements can also drive systems toward inefficient or unsatisfactory solutions. The general approach is to define a good system solution based on the mission, integrating physics efficiency, and system value. Then present this solution to the political interests for review. If there are sensitive points, these can be more clearly identified and the system design adjusted, and if not, the solution implementation can proceed with the needed support. These types of influences need to be understood by the systems engineer.

The influence that policy and law have on systems engineering decisions is being studied by the consortium. A company involved in large systems engineering projects is being studied over a period of six months. Systems engineers are asked to answer a brief set of questions twice a day (early morning and mid-afternoon) on the work they are doing and the perceived benefit of the work to the system. This should provide strong quantitative data on how policy and law, including government oversight, affect engineering activities on large system projects.

8. Summary

The NASA Systems Engineering Research Consortium is making progress in understanding the engineering and organizational basis for systems engineering. A systems engineering framework has been defined which has helped organize the research structure. A set of postulates and hypotheses have been put forward to challenge research and help establish an engineering basis for systems engineering. The consortium has seen some substantial contributions to systems engineering in the areas of system integrating physics and has several projects which are expected to have significant contributions to the discipline over the next two years. Organizational and Information Flow is an essential part of discipline integration by the system engineer. Several important findings have been identified in the course of our work and several significant contributions are expected in the next two years as well. The consortium work is planned to continue through the beginning of 2018. It is hoped that this work will lead to several fruitful avenues of research in advancing the discipline of systems engineering.

Acknowledgements

Special thanks is due to the co-investigator on this project, former NASA Administrator, Michael D. Griffin. From our first conversation Mike has provided challenging questions and thoughts. Much of our research has come from seemingly simple questions that Mike has asked and the characteristics of elegance he defined in his paper on systems engineering.

The SLS Chief Engineer, Garry Lyles, initially prompted the first discussion with Mike, and Garry has been a steadfast supporter of this research effort. Without his support and advocacy the consortium would not have been possible.

Thanks also to former NASA Chief Engineer, Mike Ryschkewitsch, current NASA Chief Engineer, Ralph Roe, and NASA Systems Engineering Technical Fellow, Jon Holladay. Their support to the consortium the past two years has been critical to our success and has allowed us to get to the point of providing significant contributions to the discipline of systems engineering.

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