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BUILDING A PATH TO ELEGANT DESIGN

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Abstract

In 2010 at the International Aeronautical Congress, former NASA Administraor, Dr. Michael Griffin presented a paper entitled "How do we Fix Systems Engineering?" In that paper Dr. Griffin introduced the properties of Elegant Design. The four properties of an Elegant Design are that it is effective (i.e., it works), it is robust, it is efficient, and that it minimizes unintended consequences. In 2011 the NASA Marshall Space Flight Center (MSFC) initiated a research initiative with the University of Alabama in Huntsville to lead a consortium of universities to expand on these ideas and develop a research framework to develop basic principles of systems engineering that could be applied to the design and development of future launch vehicles and space missions. This paper will review the research framework that has been developed for this program. It will also review a set of draft postulates formulated by the researchers to provide a context for understanding the boundaries and influences of Systems Engineering.

Keywords

Systems Engineering, Elegant Design.

Introduction

The increasing complexity of modern aerospace, defense, automotive, and communication systems has resulted in an increased focus on systems engineering and the theoretical design of complex systems. With the sponsorship of NASA's Marshall Space Flight Center specifically, the NASA Space Launch System (SLS) program office and the NASA Chief Engineers Office, a consortium of universities has been established and led by a team of researchers from the University of Alabama in Huntsville (UAH). The objective of the consortium is to conduct research that will advance the theory and practice of systems engineering. Early in the development of the consortium's research agenda it was observed that there has been an increasing emphasis on studying the processes within systems engineering. A review of the 1995 and 2007 NASA Systems Engineering Handbooks (Huesner 2013) supported this observation. That study found that the 1995 handbook maintained a product focus (i.e., focused on the system being designed), while the 2007 handbook took a decidedly process-oriented focus, meaning it was more a recipe of how to conduct the elements of systems engineering itself. While understanding the process is an important component of successful design. the consortium's focus is on better understanding the fundmental science of complex system development. While good processes are essential to successful system development, there ought to be a solid scientific foundation that links development activities to producing an elegant product. Our research team set out to find that foundation and the linkages that leads to successful systems products. Current members of the consortium include: UAH, George Washington University, Iowa State University, MIT, Texas A&M, The University of Colorado, Colorado Springs, The University of Dayton, The Missouri University of Science and Technology, and Schaefer Corporation. Past members include: Spaceworks, The University of Arkansas, George Mason University, and Oregon State University. Stevens Institute of Technology has also participated with the consortium in the past and is currently a collaborating institution.

Elegant Design

A foundational concept in this initiative is Elegant Design. At the 2010 International Astronautical Congress in Prague, Griffin (2010) presented a seminal paper which addressed how to improve systems engineering. In that paper he indicated that "systems engineering as it is taught and practiced is fundamentally concerned with identifying the separable elements or blocks of a proposed design, characterizing the intended relationships between and among those elements, and verifying that the actual configuration is fabricated and operated as intended in its environment." He also argued that systems engineering "is *not* fundamentally about "process" [but that it] is about something more." That something more can be explained as "systems engineering is concerned with context over structure, with interactions over elements, with the whole over the sum of the parts." As a result, he proposed and developed the concept of elegant design. The four attributes of elegant design as defined by Griffin are: effectiveness, robustness, efficiency, and the minimization of unintended consequences. Effectiveness is concerned with whether the system operates as it was intended to operate. Robustness focuses on how well the system avoids performance that "radically departs from expected behavior" as a result of small perturbations in the system conditions. Efficiency is realized when the system "produces the desired result from what is thought to be a lesser expenditure of resources than competing alternatives." And fourth attribute is that the system "accomplishes its intended purposes while minimizing the unintended actions, side effects, and consequences."

Research Framework

In the initial year of the consortium. research projects were initiated that addressed aspects of elegant design laid a foundation for the development of a research framework. In the consortium's second year, the research team at UAH extended the research framework to identify the linkages between the research tasks and the attributes of elegant design. The research team identified four overarching systems engineering focus areas: 1) understanding the mission, 2) physics relationships, 3) organization structure and relationships, and 4) policy and regulatory requirements. The design of any systems begin with a clear understanding of the mission that the system is being designed to accomplish. In the view of the authors, physics relationships are (or at least should be) the driving force in determing the system design. We would also assert that the physics relationships are based on three subareas: 1) performance (i.e., what is the desired performance of the system), 2) cost/schedule (i.e., what will the system cost and how soon will be ready for use?), and 3) product risk (i.e., what are the chances that the system will not operate properly or the mission will fail?). Based on these focus areas (and their associated subareas) the research team created a matrix with the attributes of elegant design as the rows and the systems engineering focus areas (and their associated subareas) as columns. The matrix was populated by taking each of the consortium research tasks and identifying the appropriate attribute of elegant design and system engineering focus area with which they were aligned. Primary (in bold font) and secondary alignments were identified for each of the research tasks, since many of the tasks aligned with more than one attribute or focus area. The current version of the Research Framework (Exhibit 1), is shown on the next page. The Research Framework identifies the primary systems engineering focus area that corresponds to each of the four elegant design attributes (as indicated by the light gray cells). For instance, the systems engineering focus area that maps to system effectiveness is performance. This is appropriate given that the state of performance would yield a correspondingly effective or ineffective system. Likewise unintended consequences would increase the risk of system failure and must be part of the decision process in any system design.

Review of Supporting Research Projects

This section will briefly review some of the key research tasks undertaken over the last two (2) years by consortium members. While several studies/projects were initiated during the first two years of the consortium. Those that are presented in this section were the ones that garnered the greatest interest from the MSFC engineering community and the SLS program office..

Understanding the Mission/System Effectivenes

Chief Engineer Interviews (CEI) (Burns 2013). The CEI study focused on insights from experienced Chief and Senior Engineers at NASA MSFC regarding attributes of elegant design in systems engineering, including achieving design intent, robustness, efficiency and minimization of unintended consequences (Griffin, 2010). The study included personal interviews to identify areas of agreement, areas of differences, and areas for potential improvement.

Exhibit 1 – Research Framework

Systems Engineering Focus Areas						
Understanding Mission	Physics Relationships			Organization Structure & Relationships	Policy & Regulatory Requirements	
	Performance	Cost/Schedule	Product Risk	Organization		Product Attributes
Chief Engineer Interviews (Burns/UAH) Program/Engineering Decision Making (Utley/UAH) Interdisciplinary Design Model (Johnson/UCCS) SE Processes Evaluation (Componation/ISU)	**Interdisciplinary Design Model (Johnson/UCCS)** **Information Content of Exergy-Based Systems and Applications to Systems Engineering (Doty/Univ. of Dayton)** Design representation and margin management (Yang/MIT)	**Supply Chain Schedule Risk: Theoretical Framework (Burns/UAH)** SE Processes Evaluation (Componation/ISU)	SE Processes Evaluation (Componation/ISU)	**SE Processes Evaluation (Componation/ISU)** **Program/Engineering Decision Making (Utley/UAH)** **Design representation and margin management (Yang/MIT)**	Interplay between policy considerations and space systems design & development (Szajnfarber)	**System Effectiveness**
	Affordable Decisions and Cost Implications (Colley/UAH)	Affordable Decisions and Cost Implications (Colley/UAH)				**Efficiency**
Design Robust Engineered Systems (Malak/Texas A&M)	**Model Robustness versus Performance (Tumer/Oregon St)** **Interdisciplinary Design Model (Johnson/UCCS)**				Failure Event Classification Techniques (Jensen/UARK)	**Robustness**
Conceptual Blind Spots Lead to Errors (Gero/GMU)	**Failure Event Classification Techniques (Jensen/UARK)** **Interdisciplinary Design Model (Johnson/UCCS)** Model Robustness versus Performance (Tumer/Oregon St)		Conceptual Blind Spots Lead to Errors (Gero/GMU) Failure Event Classification Techniques (Jensen/UARK)	Conceptual Blind Spots Lead to Errors (Gero/GMU)	**Interplay between policy considerations and space systems design & development (Szajnfarber)**	**Unintended Consequence**

Bold - Primary Research Area

The CEI questions on achieving design intent went beyond the traditional systems engineering approach of using a process based approach to design, design reviews, and V&V (NASA, 2007) by also investigating a balance between a process and a product approach.

Participants noted that robustness continues to be challenging to define and measure. As noted, Griffin views it as a property of a system in which minor changes in input, design or environmental parameters produce correspondingly minor changes in system output. However, some definitions offered have focused on robustness within this original design intent, while others have defined it as the property of extending mission capability through evolving designs and adaptability to other missions. The engineers valued properly validated analytical models, yet there were consistent concerns about whether increasing the use of analytical models was outpacing the maturity and validity of some of the models. And while the technology roadmap has demonstrated in the past that early investments in technologies and processes yield significant returns in future launch designs regarding increased robustness and reductions in future time requirements and system costs, several participants considered these investments to be opportunistic and without a long term strategic focus.

Physics Relationships – Performance/System Effectiveness Interdisciplinary Design Model (Johnson, 2013). The objective of this task was to improve the quality and reduce the cost of current process-based, document-based systems engineering by replacing major parts of it with a disciplinary-structured, product-based, model-based approach. The motivation of this effort was that many current systems engineering practices are being scaled back or eliminated because they are deemed too expensive in relation to the value added, despite the fact that many system failures result from inadequate application of systems engineering practices. Current methods are inadequate to achieve future aerospace system development goals due to high failure rates and high development and operations costs of typical acquisition programs. The core strategy of this project has been, and continues to be to develop a suite of rigorous, state-based models that collectively will reproduce, but with higher quality and lower cost, many of the major products of traditional systems engineering. It is expected that new, useful products that tie systems engineering products to operational products will also be identified. Under this project prototype models were, and are being developed. using Systems Modeling Language (SysML) both to develop the model-based methodology, but also to test SysML’s capabilities to represent and facilitate these models. Also, procedures for using these models to reproduce typical aerospace systems engineering documents (such as Interface Control Documents, requirements, requirements traceability to each other, and to verificiation and validation) and analyses, but with higher quality (fewer errors and more comprehensive coverage) and at lower cost. To date, this project has developed several simple disciplinary design models and a Goal-Function Tree in SysML, of a “generic launch vehcile”, each including state variables. The project has identified new required representations and processes to extract information from these representations to reproduce ICD content”

Informal Representation and Team Decision-making in Complex Engineering Systems (Yang, 2012). This project interviewed designers and engineers at various organizations, including MSFC, and sought to formulate a framework for informal design representation in complex systems. The motivation grew from the fact that the design of large-scale engineering systems involves dynamic, complex interactions among a myriad of stakeholders, and that understanding these interactions might enable better strategies for designing. It was clear that those interactions among stakeholders are powerful, but difficult to model. Large-scale engineering systems require design teams to balance complex sets of considerations using a wide range of design and decision-making skills. Formal approaches such as Game Theory and Multidisciplinary Design Optimization (MDO) for optimizing complex systems offer effective strategies for arriving at optimal solutions in situations where system integration and design optimization are well-formulated and scoped. However, an analysis of interviews with subsystem designers and system-level integrators in the aerospace industry suggests that real-world practice may not fit these existing, formal models well. The interviews showed design teams operated in a hybrid Game Theoretic, Multi-Disciplinary Optimization structure depending on the level of disagreement between the two subsystems. Participants also reported that, in contrast to the “rational” actors of formal models, subsystem designers acted in a “conservative” manner, reporting parameters with large additional margins during the design process as a hedge against future need (Austin-Breneman et al., 2014).

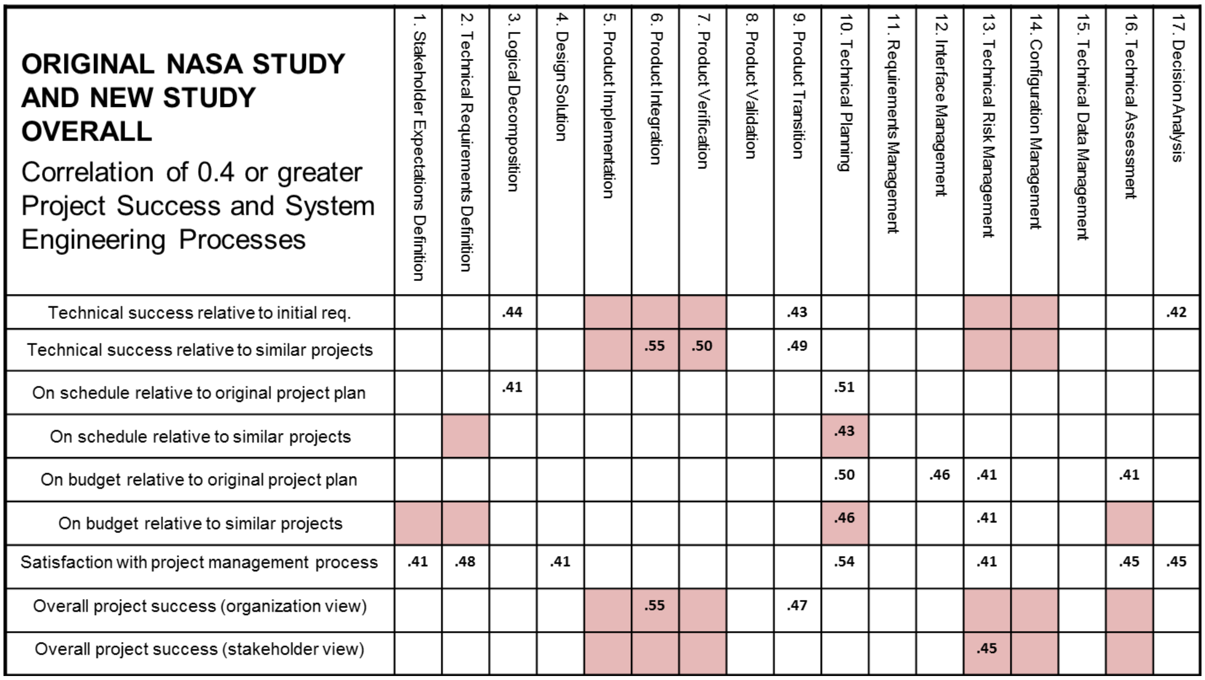
These interviews also provided a view into the types of informal representations that are used in the aerospace industry, from simple hand sketches to large scale physical prototypes. The role of these representations ranges from a tool to help the designer think through a problem to a way to garner support from various design stakeholders. The analysis demonstrated that design representation was driven by the intended audience, not necessarily functionality. These findings may influence future directions for improving formal approaches to complex system design.

Organization and Structure/System Effectiveness

SE Process Evaluation (Componation, 2013. The objective of this study was to collect data on system engineering processes and project effectiveness in commercial and government research and development projects. This is an expansion of an earlier study that focused on MSFC. This year the survey focused on other organizations (both government and commercial). The goal was to determine the differences and similarities between commercial and government use of systems engineering processes in research and development projects. A secondary goal was to provide project and engineering managers with guidance on how to prioritize expenditures for system engineering to better-fit specific technical and programmatic risks so they can better manage scare research and development resources.

In the original NASA study, some correlations (shaded blocks in Exhibit 2) between the systems engineering processes of product implementation, project integration, and product verification and technical success metrics were found. These are all processes that are typically found later in the product development life cycle. In this new study correlations (correlation numbers in Exhibit 2) were found to have different focus areas, a notable increase in correlations between 3. Logical Decomposition, 9. Product Transition, and 13. Technical Risk Management with the project success metrics.

Exhibit 2: Systems Engineering and Project Success in Government and Commercial Organizations



ORIGINAL NASA STUDY AND NEW STUDY OVERALL Correlation of 0.4 or greater Project Success and System Engineering Processes	1. Stakeholder Expectations Definition	2. Technical Requirements Definition	3. Logical Decomposition	4. Design Solution	5. Product Implementation	6. Product Integration	7. Product Verification	8. Product Validation	9. Product Transition	10. Technical Planning	11. Requirements Management	12. Interface Management	13. Technical Risk Management	14. Configuration Management	15. Technical Data Management	16. Technical Assessment	17. Decision Analysis
Technical success relative to initial req.			.44		▨	▨	▨		.43				▨	▨			.42
Technical success relative to similar projects					▨	▨ .55	▨ .50		.49				▨	▨			
On schedule relative to original project plan			.41							.51							
On schedule relative to similar projects		▨								▨ .43							
On budget relative to original project plan										.50		.46	.41			.41	
On budget relative to similar projects	▨	▨								▨ .46			.41			▨	
Satisfaction with project management process	.41	.48		.41						.54			.41			.45	.45
Overall project success (organization view)					▨	▨ .55	▨		.47				▨	▨		▨	
Overall project success (stakeholder view)					▨	▨	▨						▨ .45	▨		▨	

Of note was the limited number of correlations that were found in common in the two studies. Only five correlations of 0.4 or higher were found in both the original NASA study and this second study focusing on commercial and government focused projects. These included correlations between 6. Project Integration, 7. Project Verification, and 13. Technical Risk Management with the project success metrics. In the original study only overall project success was used as a success metric. In the new study this was broken out to overall project success (organization view) and overall project success (stakeholder view)."

Program/Engineering Decision Making (Utley, 2012 & 2013). The UAH research team was asked to observe SLS weekly meetings to assess the effectiveness and general characteristics of these meetings pertaining to the affordability of the next launch vehicle. The evaluation of the team was based on the work of Larson and LaFasto (1989) and Utley and Brown (2010).

The first evaluation of the meetings was based on the eight (8) tenets of effective teamwork from Larson and LaFasto (1989).

Purpose: There is no daily or weekly mention of the overarching purpose of the group. It is assumed the purpose is clear, but no mention of it leaves room for the purpose to atrophy.

Principled Leadership: There is highly respected and trusted leadership in the Chief Engineer. The culture he has established is indicative of an effective team.

Competent Team Members: While most members seem competent and all required elements/disciplines are represented, there is a large number of task deficiencies mentioned at this level.

Collaborative Environment: The general feeling is one of collaboration; however it is worrisome to have mention of several integration failures.

Unified Commitment: There is little direct evidence of a unified commitment and several cases of differences in interpretation of expectations.

Standards of Excellence: There is little direct evidence of high standards of excellence, but nothing to refute it.

External Support/Recognition: The is no evidence of external support and recognition from the meetings.

The second evaluation made was based on the criteria established by Utley and Brown (2010) in which 12 characteristics are judged as to their tendencies toward either teamwork or working group behaviors. Teamwork behaviors are more collaborative and interdependent, while working group behaviors are more independent and information is only exchanged at the interfaces between disciplines. The observations during the meetings indicate that culture, leadership, accountability and decision-making are all team like. Participation seems to be genuine, indicating teamwork tendancies, with minor improvements needed. Motivation is evenly split between team and working group behaviors. Communication within the group is good, indicating team tendancies; only outside the group needs improvement to move from working group to team behaviors. There is evidence of debate, albeit limited, and appropriate collaborative resolution, which indicates slight team tendancies. Although the atmosphere is very respectful, interpersonal relations are almost nonexistent indicating working group behaviors. Evidence of overt trust among members is missing, again indicating working group tendancies. The fact that purpose is absent from the discussion indicates more working group tendancies.

A series of recommendations was made to SLS management, based on the aforementioned analysis and further delineated by how much direct control or influence management has to affect change. These recommendations include:

1. The overarching purpose of the SLS mission can be stated at every meeting. One idea is to end each meeting with it so it is the last thing mentioned before people go back to their tasks. It should be elevating with an attribute, like affordability, attached to the mission.
2. Any positive mention of recognition from top management should be shared with the members. They in turn should be encouraged to share the message with their units.
3. The atmosphere reflects the trust in and respect for the leader. In turn the leader could offer overt displays of trust and respect. A mention of capability, past experience, or faith in a particular contributor could spark some additional enthusiasm for goal accomplishment.
4. Reminders that the group succeeds or fails together could offer some help in achieving a unified commitment.
5. In that vein, a common working approach and level of expectation could help instill the proper motivation.

A follow-on study (Utley 2013) was initiated with the objective of exploring how direction and guidance flow from chief engineers to design engineers and through the different approval boards using SLS as the test-bed. While formal systems engineering (SE) processes are documented, frequently engineers still do not fully understand the informal implementation or practices of SE. As follow-on to the previous year's work to understand decision-making and interactions, a more in-depth knowledge of decision-making and integration was conducted.

Three (3) Change Requests (CR) were identified and the decision process documented. A literature review was completed resulting in a framework for decision-making. A survey instrument was then developed, revised and approved for data collection. From the data analysis conclusions were drawn in two areas: Decision-making and Communication.

Decision Making: Evidence suggests that the decision-making process is less process dependent than typical systems engineers might expect. As long as the process matches the needs of the decision makers and an effort is made to get all needed individuals involved, different processes can be used effectively. In some instances more people were included than necessary, but in this case including extra people is a less riskier approach than not including enough people or the wrong people. The preponderance of evidence suggests that comments were dis-positioned effectively and efficiently. Most respondents agreed with the decisions and thought the overall decision-making process was effective and efficient.

<u>Communications</u>: Evidence suggests that a more formal approach is used to alert people of the initial CR communication and a more informal approach is used to alert people to the discussions to resolve comments. This seems appropriate and a good use of resources. However multiple areas were uncovered to suggest communication gaps

Recommendations were developed from the above mentioned analysis. They were

1. Include all involved parties in the discussion of the CR comments. This requires additional resources up front, but may solve issues in the long term.
2. Synchronize the decision schedules between contractor and NASA as much as possible.
3. Recognize that "faster" isn't always "better." In other words understand and practice the systems thinking law of "faster is slower" (Senge, 1994). Most natural and manmade processes have an optimal time frame for accomplishment and it is often not the fastest.
4. Institute a culmination meeting at the end of the CR decision to close the communication loop.
5. Make everyone aware that life cycle cost concerns are everyone's responsibility.
6. Make cost and schedule impact assessments with every comment.

Understanding Mission/Robustness

Design Robust Engineered Systems (Malak, 2013). The objective of this study is to create and demonstrate a methodology for defining engineered systems that are robust. This is motivated by the sense that robustness is a desirable system quality. However, the meaning of "robustness" is ambiguous at best. Various bodies of literature use the term in conflicting ways. Furthermore, several of the more widely-used definitions imply robustness measures that scale poorly to systems engineering problems. In light of this, the researchers concluded that robustness is inappropriate as a figure of merit for decision making, but could be useful heuristic for guiding the process of generating alternative system designs. The research team developed a methodology for system definition that relies on utility-based decision making in concert with a robustness-based analysis for prioritizing how engineers will seek to improve system utility. The team demonstrated the methodology on a systems engineering problem (system definition phases of entry, descent and landing functions for Mars Science Lab mission) [cite Ben's MS thesis and 2013 IDETC/CIE paper]. Current efforts are focused on how to incorporate the findings into the SysML model being developed by fellow consortium member, Dr. Stephen Johnson at the University of Colorado – Colorado Springs. Future work may include additional utility-based analysis and work on incorporating/evaluating unanticipated perturbations.

Physics Relationships – Performance/Robustness

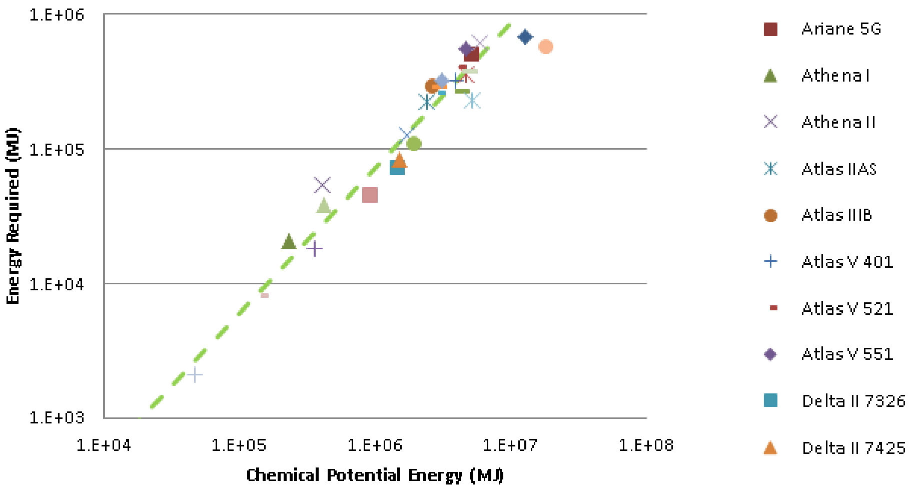
Affordable Decisions and Cost Implications (Colley, 2012). This objective of this research study was to develop the foundation for a non-parametric physics-based model for predicting the effect of technical design changes on total system life-cycle cost. The problem(s) that this study sought to address was that current mass-based parametric models can be misleading when used to guide design decisions, particularly in the presence of new technologies and materials. Our hypothesis was that because rockets are designed for essentially one task, to increase the kinetic energy of the payload, energy may be a better fundamental metric than mass. This study began by studying the correlation between the total chemical potential energy of a launch system (on the launch pad) and the actual net change in payload kinetic energy energy required/produced by a Launch System.

Exhibit 3 shows the results for several systems for a Space Station intercept orbit. Quite remarkably, aside from the Space Shuttle (whose efficiency is limited by the bulk of the also-launched orbiter), the efficiencies are quite tightly clustered around a simple power-law relationship, whose best-fit index is nearly one (1) (i.e., the fit is nearly a direct relation). That best fit is shown in equation 1 which has linear correlation coefficient of r = 0.974 (excluding the Shuttle).

$$E_{orb} = 0.0718\left(\frac{E_{chem}}{10^6\,\mathrm{MJ}}\right)^{1.08} \times 10^6\,\mathrm{MJ} \qquad (1)$$

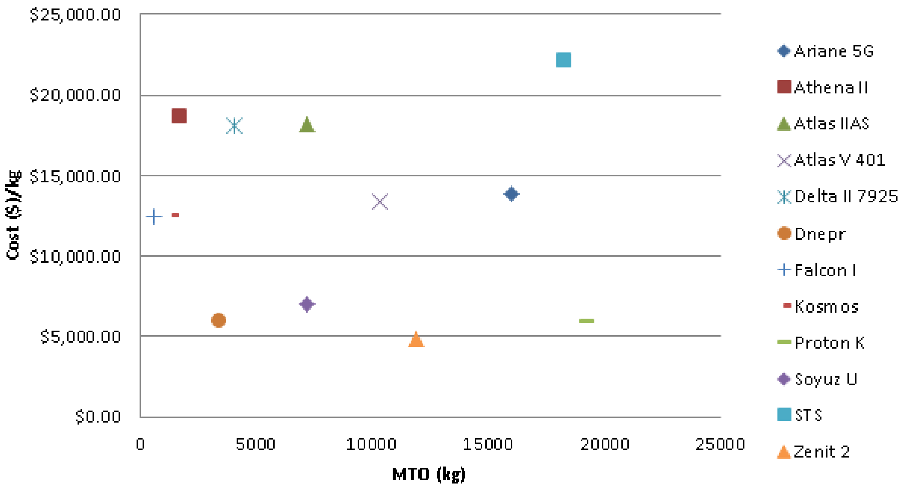
What this means, is that over a [illegible] energy, across the very wide variety of architectures and propellant types, rockets are surprisingly consistently efficient, at around 7%, in terms of delivered payload energy vs. input chemical energy.

Exhibit 3: Payload Energy Efficiency of Various Rocket Systems



The cost efficiency can be assessed simply by looking at the listed cost of launching a maximum payload to a Space Station, as according to the Futron report (Futron 2002). That report limits the number of systems available for cost analysis. Exhibit 4 6 shows the cost per payload kilogram for several systems. The systems divide, essentially, into nationality of the system. Namely, all the systems below $10,000/kg are Russian; those between $10,000/kg and $20,000/kg are US or European missions, and the only system above $20,000/kg is the Space Shuttle (which is hobbled in this metric by having to launch a large airframe into orbit, aside from the payload). Note that, in the figure, there is a very wide array of payload capability, ranging from hundreds of kg up to 20,000 kg, and yet these broad cost categories by nation hold fast. Because the costs were so straight-forward to interpret, we regard that, in the end, cost can be fairly well parameterized in terms of payload mass for any particular nation’s space program.

Exhibit 4: Cost of rocket systems per kg of payload to a Space Station orbit



It is clear from Exhibit 4 that the systems cluster into three bands. Russian engines which cost approximately $5,0000/kg, American/European Engines which cost approximately $15,000/kg, and Space Shuttle which was greater then $20,000/kg. Unfortuantely, there is currently no data available on private launch vehicles (ie., SpaceX).

Draft Systems Engineering Postulates

During the last year, in an attempt to better articulate some guiding principles and provide an under pinning for this research endeavor a set of statements have been postulated which are apparent in our research of elegant system engineering. They have been presented and reviewed by the membership of the consortium and are still being discussed. We are presenting the draft postulates in this paper (and at the 2014 ASEM IAC) in hopes of generating more discussion and feedback between both systems engineering practitioners and researchers. The current set of postulates is as follows:

1. System Engineering is product specific.
   It is the contention of the authors that systems engineering is (and should be) driven by the product and in particular the physics, logic, and cognitive relationships that are foundational to the specific product or system being designed.

2. There exists at least one optimal system engineering solution for a specific context.
   This posulate is proposing that for any given operational context there exists an optimal design for the system to accomplish the mission. The context is defined by postulates 6 and 7. This postulate makes no statement about a global optimum. Rather, we argue that there is a local optimum within the confines of the specific operational context.

3. System complexity ≥ optimal system complexity necessary to fulfill all system outputs.
   This postulate is stating that, in a given operational context, the minimum system complexity required to fulfill all of the system outputs is the optimal system complexity and that complexity of alternative system designs are equal to or greater than the optimum. This postulate asserts that less complexity is more optimal for a given context. This postulate is not a general statement that less complexity is better. Rather, we argue that 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. The definition of system complexity is a much debated topic. For our work, system complexity is defined as a measure of a system's intricacy and comprehensibleness in interactions within itself and with its environment. This definition points to two (2) factors in complexity: Physcial/Logical intricacy; human cognitive comprehension. There are a number of corollaries which can be fit under this and these will no doubt be the source of much debate in the definition of complexity. We are still identifying the corollloraries to this definition and will elaborate on this in a subsequent paper.

4. The System Engineering domain consists of subsystems and their interactions among themselves and with the system environment.
   Systems engineering encompasses a set of interacting subsystems. From a physical and logical structure sense, systems engineering is not a single mechanical, or electrical, or chemical, etc. system. System engineering encompasses systems with multiple subsystem of various physical and logical types. The interaction of these subsystems is the focus of the system engineer, not as a detailed designer, but as a well-versed integrator of all system ineractions. These system interactions include interactions with the system environment, which can drive the design as strongly as the subsystem interactions themselves and can be coupled with the subsystem interactions to create unexpected responses within the system.

5. The function of System Engineering is to integrate engineering disciplines in an elegant manner.
   The discipline domain is not one that is separate from all other engineering and social disciplines, but one that integrates and incorporates these in an elegant manner into a meaningful context. Any complex system consists of multiple engineering and social discipline domains and system engineering is discipline whose domain include all of these. Note that the focus is on basic understanding of each discipline with a more detailed understanding of the interactions among them. This incorporates various organizational integration aspects as stated in Postulate 6 below.

6. System Engineering influences and is influenced by organizational structure and culture.
   Systems Engineering does not operate in a vacuum, which focuses only on the technical aspects of design. How we organize the design process is driven by the system being designed and how we design the system has a corresponding influence on the structure of the organization. These factors also impact the culture of

the organization. The system engineer must be cognizant of these factors and effectively manage the organizational interactions.

7. System Engineering is constrained by budget, schedule, policy, and law.
   Every project has overarching constraints that go beyond the physical and environmental. Specifically, most (if not all) projects have a finite amount of funds (i.e., a budget) and time (i.e., schedule). All systems must conform to established organizational and government policy and laws. These policies and laws put real constraints on potential budget, schedule, and technical solutions.

These postulates were formulated to begin a discussion on the domain of Systems Engineering in hopes of laying a foundation for a more comprehensive, rigorous and scientific foundation for the discipline. As with any postulated statement, a statement assumed without proof to be true, the next step is to prove or disprove these postulates. The author’s welcome feedback and recommendations for modification and refinement of this initial set of postulates.

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