INSIGHT

This Issue's Feature:

Social Dimensions of Systems

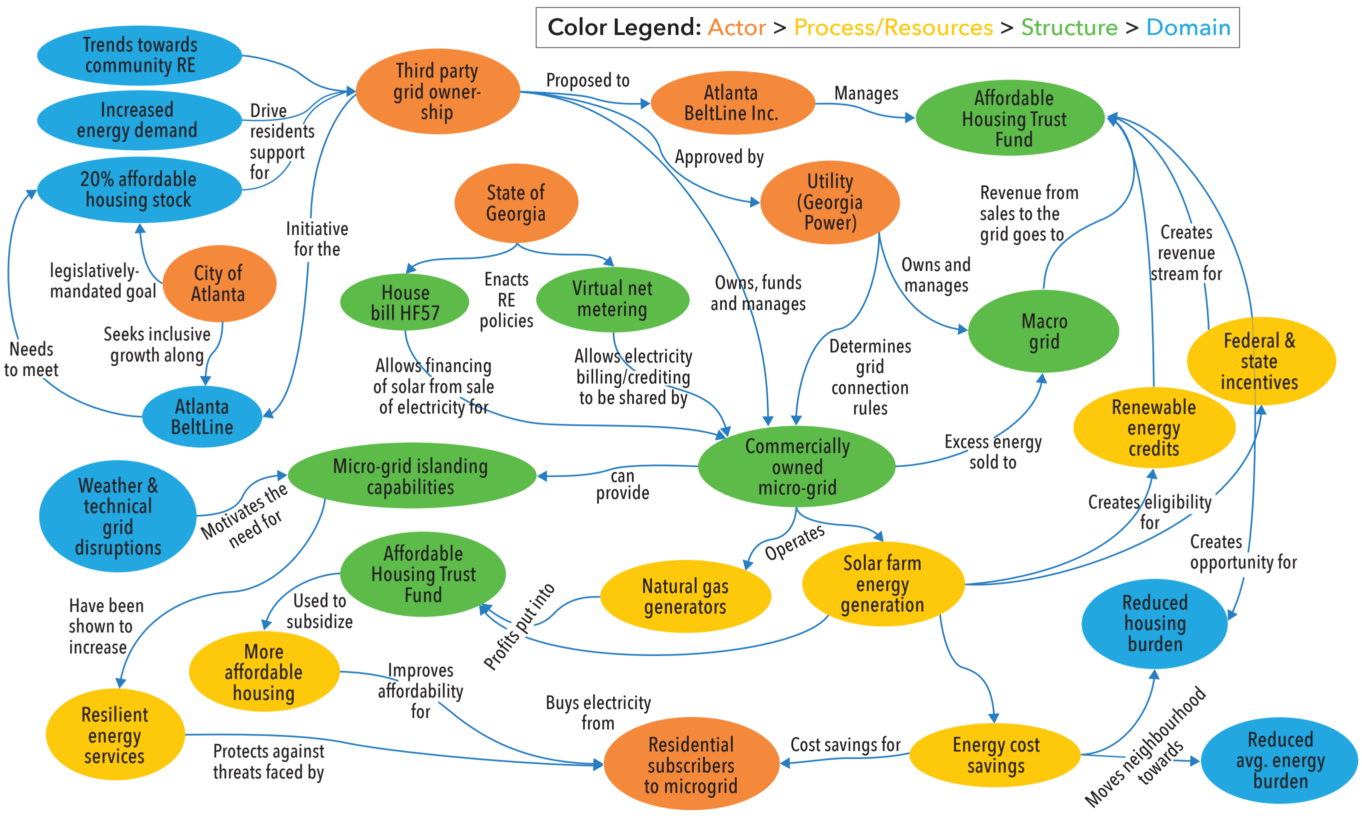

Illustration credit: from the article
To Get Systems Engineers Interested in Social Dimensions, Give Them a Social Optimization Problem
by Tom McDermott and Molly Nadolski (see page 27)

SEPTEMBER 2021
VOLUME 24 / ISSUE 3

INCOSE

A PUBLICATION OF THE INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING

Systems Engineering: The Journal of The International Council on Systems Engineering

Call for Papers

The *Systems Engineering* journal is intended to be a primary source of multidisciplinary information for the systems engineering and management of products and services, and processes of all types. Systems engineering activities involve the technologies and system management approaches needed for

- definition of systems, including identification of user requirements and technological specifications;
- development of systems, including conceptual architectures, tradeoff of design concepts, configuration management during system development, integration of new systems with legacy systems, integrated product and process development; and
- deployment of systems, including operational test and evaluation, maintenance over an extended life cycle, and re-engineering.

Systems Engineering is the archival journal of, and exists to serve the following objectives of, the International Council on Systems Engineering (INCOSE):

- To provide a focal point for dissemination of systems engineering knowledge
- To promote collaboration in systems engineering education and research
- To encourage and assure establishment of professional standards for integrity in the practice of systems engineering
- To improve the professional status of all those engaged in the practice of systems engineering
- To encourage governmental and industrial support for research and educational programs that will improve the systems engineering process and its practice

The journal supports these goals by providing a continuing, respected publication of peer-reviewed results from research and development in the area of systems engineering. Systems engineering is defined broadly in this context as an interdisciplinary approach and means to enable the realization of successful systems that are of high quality, cost-effective, and trustworthy in meeting customer requirements.

The *Systems Engineering* journal is dedicated to all aspects of the engineering of systems: technical, management, economic, and social. It focuses on the life cycle processes needed to create trustworthy and high-quality systems. It will also emphasize the systems management efforts needed to define, develop, and deploy trustworthy and high quality processes for the production of systems. Within this, *Systems Engineering* is especially concerned with evaluation of the efficiency and effectiveness of systems management, technical direction, and integration of systems. *Systems Engineering* is also very concerned with the engineering of systems that support sustainable development. Modern systems, including both products and services, are often very knowledge-intensive, and are found in both the public and private sectors. The journal emphasizes strategic and program management of these, and the information and knowledge base for knowledge principles, knowledge practices, and knowledge perspectives for the engineering of systems. Definitive case studies involving systems engineering practice are especially welcome.

The journal is a primary source of information for the systems engineering of products and services that are generally large in scale, scope, and complexity. *Systems Engineering* will be especially concerned with process- or product-line–related efforts needed to produce products that are trustworthy and of high quality, and that are cost effective in meeting user needs. A major component of this is system cost and operational effectiveness determination, and the development of processes that ensure that products are cost effective. This requires the integration of a number of engineering disciplines necessary for the definition, development, and deployment of complex systems. It also requires attention to the lifecycle process used to produce systems, and the integration of systems, including legacy systems, at various architectural levels. In addition, appropriate systems management of information and knowledge across technologies, organizations, and environments is also needed to insure a sustainable world.

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INSIGHT

A PUBLICATION OF THE INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING

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Inside this issue

About This Publication

INFORMATION ABOUT INCOSE

INCOSE's membership extends to over 18,000 individual members and more than 100 corporations, government entities, and academic institutions. Its mission is to share, promote, and advance the best of systems engineering from across the globe for the benefit of humanity and the planet. INCOSE charters chapters worldwide, includes a corporate advisory board, and is led by elected officers and directors.

For more information, click here:
The International Council on Systems Engineering
(www.incose.org)

OVERVIEW

INSIGHT is the magazine of the International Council on Systems Engineering. It is published four times per year and features informative articles dedicated to advancing the state of practice in systems engineering and to close the gap with the state of the art. ***INSIGHT*** delivers practical information on current hot topics, implementations, and best practices, written in applications-driven style. There is an emphasis on practical applications, tutorials, guides, and case studies that result in successful outcomes. Explicitly identified opinion pieces, book reviews, and technology roadmapping complement articles to stimulate advancing the state of practice. ***INSIGHT*** is dedicated to advancing the INCOSE objectives of impactful products and accelerating the transformation of systems engineering to a model-based discipline.
Topics to be covered include resilient systems, model-based systems engineering, commercial-driven transformational systems engineering, natural systems, agile security, systems of systems, and cyber-physical systems across disciplines and domains of interest to the constituent groups in the systems engineering community: industry, government, and academia. Advances in practice often come from lateral connections of information dissemination across disciplines and domains. ***INSIGHT*** will track advances in the state of the art with follow-up, practically written articles to more rapidly disseminate knowledge to stimulate practice throughout the community.

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FROM THE EDITOR-IN-CHIEF

William Miller, insight@incose.net

We are pleased to present the September 2021 *INSIGHT* issue published cooperatively with John Wiley & Sons as the systems engineering practitioners' magazine. The *INSIGHT* mission is to provide informative articles on advancing the practice of systems engineering and to close the gap between practice and the state of the art as advanced by *Systems Engineering*, the Journal of INCOSE also published by Wiley. The issue theme is the social dimensions of systems. We thank theme editors Randy Anway, Rick Dove, Erika Palmer, and the authors for their contributions that span multiple INCOSE working groups.

Several of the articles address security from the social dimension. Security is very much social! Your editor worked with the late Bob Morris decades back in time at Bell Labs. (Bob is the father of Robert Tappan Morris who unleased the first Internet worm in 1988 while a graduate student at Cornell University.) The elder Bob collaborated with Unix operating system co-creator Ken Thompson (Morris and Thompson 1979, Password Security: A Case History, Communications of the ACM, 22(11): 594-597) on password security and performed social engineering to crack peoples' passwords by getting to know them and using known personal information. This led to rules for enforcing stronger passwords for accessing Unix time-sharing systems. Bob's skill in hacking led to his being authorized a "burglars license," that is, permission to crack into any computer at Bell Labs, by Bell Labs late beloved executive vice president Sol Buchsbaum; Bob's successful hacking into the payroll computer is particularly entertaining, a masterpiece of social engineering.

"Perceived Conflicts of Systems Engineering in Early-Stage Research and Development" by Michael DiMario, Gary Mastin, Heidi Hahn, Ann Hodges, and Nick Lombardo discusses the difficulty of introducing systems engineering to the research and early development process and the inclination perspectives of researchers, engineers, and managers. The article offers potential means to manage the cultural transformation of early adoption of right-sized systems engineering in ESR&D and reverse the attitudinal positions.

"Incorporating the Role(s) of Human Actors in Complex System Design for Safety and Security," by Elizabeth Fleming and Adam Williams outlines the system context lenses to understand how to include various roles of human actors into systems engineering design. Several exemplar applications of this organizing lenses are summarized and used to highlight more generalized insights for the broader systems engineering community.

"An Agile Systems Engineering Analysis of Socio-technical Aspects of a University-built CubeSat" by Evelyn Honoré-Livermore, Joseph L. Garrett, Ron Lyells, Robert (Rock) Angier, and Bob Epps presents the results of an exploratory case study on a university CubeSat team developing an earth observation satellite. Formal analysis of agile systems engineering helps improve success throughout the CubeSat lifecycle. The authors apply the INCOSE Agile SE WG decision guidance method for applying agile system engineering method to identify areas in which the project organization can improve to become more agile in three specific problem spaces: customer problem space, solution space, and product development space. The analysis process leads to valuable insights about how the project organization of an academic project differs from that of industry. Additionally, the results indicate that areas such as stakeholder management and support environment can be factors that would benefit more from agile responsiveness.

"To Get Systems Engineers Interested in Social Dimensions, Give Them a Social Optimization Problem" by Tom McDermott and Molly Nadolski present a case study on student-led implementation trades for urban electrical microgrids that optimize community sustainability and resilience. In this case study, the students used formal models of non-traditional socioeconomic variables such as availability, energy burden on residents, and local jobs created. The case study presents a straightforward process that considers social requirements and metrics in systems engineering design that are typically overlooked. The authors present this as both an example learning framework and a broader call to define and standardize systems engineering methods, processes, and tools for increased integration of social dimensions as functional requirements in future systems.

"Applying Behavioral Science to Agile Practice Evolution" by Larri Rosser and Brian Ganus state that certain approaches work well in agile realization of products and services is not accidental, but rooted in the study of psychology, sociology, and human performance. For example, the "ideal agile team size" of 7 plus or minus 2 not only works but is supported by psychosocial theories such as the Ringleman effect, social channel capacity and short-term memory limitations. Examples of similar relations between behavioral science and agile patterns abound – preferred planning horizons, methods of estimating effort and approaches to scaling agile all relate to our understanding of human behavior individually and in groups. This article explores such relationships with the intent to provide agile practitioners with information about the underpinning of practices, and social scientists with examples of how their work contributes to the improvement of agile practices.

"Detecting and Mitigating Social Dysfunction within Systems of Systems" by Mike Yokell elaborates on a means of assessing the managerial relationships between the organizations that own constituent systems within a system of systems (SoS), with a goal of detecting social dysfunction that could adversely affect operations. For each of the relationship types, or affinity options, tangible, actionable guidance is offered that could help mitigate the social and operational dysfunctions. Results from a case study are included to illustrate the application, detection, and successful mitigation of social dysfunction within a system of systems.

"The emergent properties of an ethical leadership when aligned with the Systems Engineering Handbook and Code of Ethics" by Anabel Fraga analyzes the definitions found in the current Code of Ethics and Handbook regarding ethical leadership, its implications, and its application is explained and aligned to the ethical systems engineering idea. Also, examples of ethical behavior are introduced to explain emergent properties. It exemplifies that applying ethical leadership works in favor of the development of successful systems.

"Application of Model-Based System Architecture Process (MBSAP) to a Complex Problem with Social Dimensions: Utilization in Outpatient Imaging Centers" by Jill Speece and Kamran Eftekhari Shahroudi provides a comprehensive and visually understandable framework for system development. The primary social dimensions in outpatient imaging are the customer dimension, planning dimension, operations dimension, and technical dimension. Each of these dimensions has stakeholders with a diverse set of needs that must be well-understood and incorporated into the requirements. This paper presents an architecture for a system that utilizes all available exam time slots without a dependency on modifying patient behavior to prevent same day missed appointments. The MBSAP artefacts are the starting point for making the system a reality with stakeholders and finding the right balance between separate social dimensional measures.

"Bridge the Partisan Divide and Develop Effective Policies with Systems Engineering" by Jim Hartung describes a simple six-step systems engineering process for optimizing social, economic, and political systems. Second, he illustrates this process with two examples: (1) development of a nonpartisan tax reform proposal that balances the federal budget and addresses key societal problems without increasing the economic burden on taxpayers and (2) development of a nonpartisan plan for the United States to achieve the United Nations Sustainable Development Goals and address other urgent problems. Third, he discusses how lawmakers and policymakers can incorporate systems engineering into the lawmaking process. Many of the ideas presented here also apply to other countries.

We hope you find *INSIGHT*, the practitioners' magazine for systems engineers, informative and relevant. Feedback from readers is critical to *INSIGHT*'s quality. We encourage letters to the editor at insight@incose.net. Please include "letter to the editor" in the subject line. *INSIGHT* also continues to solicit special features, standalone articles, book reviews, and op-eds. For information about *INSIGHT*, including upcoming issues, see https://www.incose.org/products-and-publications/periodicals#INSIGHT. For information about sponsoring *INSIGHT*, please contact the INCOSE marketing and communications director at *marcom@incose.net*. ■

Perceived Conflicts of Systems Engineering in Early-Stage Research and Development[1]

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1 This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not represent the views of the U.S. Department of Energy or the United States Government.

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3 Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

ABSTRACT

Early Systems Research and Development (ESR&D) is one of the most crucial phases in the product development process. It both blends and blurs the lines between science and engineering, and requires a risk-based, disciplined, and graded approach to effectively manage scope, cost, and complexity of the final product. Many leaders, program managers, and scientists are unwilling to involve systems engineering because of the perception that systems engineering is heavily process oriented, adds unnecessary costs, and should be applied only to mature technologies. The value of systems engineering as applied to ESR&D is unclear to these key individuals. The unfortunate result is that system engineering is not applied to ESR&D. This results in R&D efforts that may have solved the wrong problem, selected the wrong architecture, require technical rework, have difficulty transitioning later maturity levels, and result in higher R&D costs and extended development timelines. This article discusses the difficulty of introducing systems engineering to the research and early development process and their inclination perspectives of researchers, engineers, and managers. The article shall offer potential means to manage the cultural transformation of early adoption of right-sized systems engineering in ESR&D and reverse the attitudinal positions.

INTRODUCTION

Early-Stage Research and Development (ESR&D) is one of the most crucial phases in the product development process, blending and blurring the lines between science and engineering. Early-Stage Research and Development is defined in traditional definitions of Technology Readiness Levels (TRLs) between TRL 1 and TRL 5. The readiness levels 1-2 define basic technology research and readiness levels 3-5 define research to prove application feasibility.

The value proposition for applying systems engineering and systems engineering management to the early stages of R&D is that the cost to extract defects or the cost of nonconformance rises exponentially throughout a project, increasing three to six times between the concept and design phases but up to a thousand times in the production/test phases (Walden et al. 2015).

This value proposition is unclear to many leaders, program managers, and scientists, who are unwilling to use practices of systems management and engineering because of the perception that systems engineering is heavily process oriented, adds unnecessary costs, and should be applied only to mature technologies. In addition, it is viewed as only used in the defense and space industry sectors to meet government requirements. As a result, systems management and engineering are typically not applied to this critical R&D phase. This results in R&D efforts that may have solved the wrong problem, selected the wrong architecture, required technical rework, had difficulty transitioning to later maturity levels, and resulted in higher R&D costs, low return on investment, and extended development timelines.

The benefits of systems management and engineering processes are well documented for manufacturing, for the development of complex systems and complex integration activities, but not for ESR&D. There have been investigations and studies of R&D quality and engineering performance, but with little broad institutional adoption such as Kodak's Robust Technology Development Process that led to many successful products from research to consumer production (Endres 1997).

It is important to recognize the distinction between systems engineering and systems management as this is critical for R&D, though the two terms are frequently combined under the heading of systems engineering. From a systems engineering perspective, systems management encompasses practices including planning, monitoring and control, risk and opportunity management, decision management, business and enterprise integration, acquisition and supply, information management, and configuration management (Sillitto et al. 2019). The very foundation of systems management began in R&D with the early United States (US) Space Program and US Department of Defense (Johnson 2002).

It can be argued that the benefits of systems engineering discipline have eluded R&D, and there are several reasons for this. One is the perception of onerous process and documentation that garners negative perceptions of systems management and engineering across R&D. Systems management traditionally grants organizational managers, who may not be technical leaders, authority over scientists and engineers. If systems managers lack technical domain knowledge, they tend to rely primarily upon cost and schedule metrics as performance measures which can fall short of what is required for project success. Further, traditional systems management design reviews may emphasize important topics like project management, configuration control, and artifact documentation while overlooking critical system development risk that are key to R&D success. This creates the perception that systems management imposes an unnecessary hierarchy over technical teams and inhibits the creative autonomy associated with innovation that is critical to successful research.

The systems engineering, and systems management community needs to move beyond negative perceptions, to take a fresh look at potential frameworks that can provide the structured thinking and repeatable approaches that will most benefit the breadth of government, commercial, private, and academic R&D our society requires. The R&D community needs repeatable and sharable approaches across multiple technical domains for optimizing success. It is time for developing repeatable, sharable, and adaptable approaches to support ESR&D.

This article discusses the difficulty of introducing systems engineering to the research and early development R&D process and the inclination perspectives of scientists, engineers, and project and technical managers toward systems engineering and systems management. We assert that the issue we confront today is not the absence of constructive processes–for many years successful R&D enterprises developed and sustained their own. Today the lack of a commonly understood and accepted framework for ESR&D inhibits collaboration of researchers, engineers, and managers. Our hypothesis is that a common process framework to enable a tailored system engineering approach for ESR&D is needed.

SYSTEMS MANAGEMENT, SE, AND THE STATE OF R&D

What we think of as "traditional systems engineering activities" are represented by the technical processes that comprise the systems engineering Vee Model as well as the systems management processes described previously, while research is more closely aligned with the systems engineering core competencies of systems thinking, critical thinking, systems analysis, and capability engineering (Presland 2018).

A fundamental difference between R&D and more traditional systems engineering activities depends upon our ability to decompose complex systems into fundamental components that have manageable complexity, bounded development costs, and highly predictable completion schedules. In this sense, traditional systems engineering, particularly as it is represented in the left side of the Vee Model, is a "reductionist" activity, in which the goal is to reduce uncertainty and "perceived complexity" by establishing shared and valid models of the system (Clymer 1994).

To understand complexity, reductionism requires compartmentalization of the system. This drives further decomposition into discrete elements and parts. systems engineering, systems management, and Total Quality Management are all processes and methodologies of reductionism where systems are decomposed into smaller elements to be understood and managed before they are integrated to form a holistic system.

ESR&D, however, is different. Innovation does not happen by reduction processes. Rather, it depends upon the creativity and discovery that leads to "expansionism," which tends to be greater complexity at the outset rather than reducing it. Reduced or narrowly bounded systems restrict freedom of action.

A different mindset engages in the "expansionist" process, and the organizational culture is distinct. Profoundly different skills, both technically and managerially, are required for "expansionist" challenges compared to "reductionist" or traditional systems development challenges. As with other creative problem-solving methods, such as Design Thinking (Ideo.org 2015), it also uses a balance of divergent and convergent thinking to arrive at a solution.

An additional key difference between traditional systems engineering, systems engineering management, and R&D involves "capabilities" versus "requirements" or, from a slightly different perspective, "point solutions" versus "performance envelopes." For example, when the Wright brothers performed their flight research in the early 20th century, they were focused on the "point solution" of a heavier-than-air vehicle sustaining flight with its own power and maneuvering. Only after that critical "point solution" was accomplished and matured did the Wright brothers explore the "performance envelope" solution of a military aircraft capable of executing a mission. When the Wright brothers were interested in demonstrating powered flight, they were pursuing a "capability need." Only after flight capability had been proven did they consider a broader spectrum of "performance requirements."

Addressing a capability need is, by design, the focus of most ESR&D. Creating a point solution, while contending with the multitude of new discoveries that redirect or derail a research or technical investigation, is a large challenge. It calls for special discipline. If we move away from simply meeting the capability need and move prematurely toward satisfying requirements or demonstrating a performance envelope earlier in development, we create even bigger issues.

CREATIVE TENSION

As was alluded to in the Introduction, the imposition of systems engineering and systems engineering management in the early stages of R&D is a source of conflict among the various groups of ESR&D stakeholders. Creative tension – "a situation where disagreement or discord ultimately gives rise to better ideas or outcomes" (creative tension 2021) – is the term that best describes this conflict. This tension is fueled by cultural differences with divergent and potentially conflicting values, conventions, and practices. One example of this, based on the authors' experiences and expressed by Craver (2015), is that scientists do not see the need for requirements and other processes that systems engineers advocate for. Further, scientists are comfortable with ambiguity and the unknown, or indeterministic expansionism, whereas engineers expect established knowledge and certainty, or deterministic reductionism (Wiley 2010). Finally, scientists have minimal consequences of being wrong when pursuing a solution; failure is expected. For engineers, there is a high risk if they are wrong because resources and deadlines are at stake (Helmenstine 2019).

Management of the creative tension, and thus the structural tension of conducting research, has been described for R&D in the context of ESR&D (Rogers 2003, Hahn et al. 2020, Senge et al. 1994 p 593). The typical bureaucratic structure of an organization is not conducive to managing creative tension and promoting successful technological innovation and research. Something more, something that balances a common vision that reflects a collective sense of what is important and why against the reality of constrained resources and desired timeframes is required. This is the role of systems management and engineering.

The structural tension is amplified in the acronym R&D where "research" precedes "development." The interplay between research and development in an organizational structure is stressed, and becomes even more taxed, by the introduction of systems management and early systems engineering. There is competition for resources with the scientists wanting to generate basic knowledge and the engineers wanting to apply the knowledge (Wiley 2010). It is common for scientists and research-oriented engineers working at low technology readiness levels (TRL 1-3) to avoid being controlled by process or programmatics because they believe it interferes with their expansionist creativity. However, as the project's TRL rises, technical disciplines are more readily accepted because the project enters accepted engineering processes.

Creative tension may be resolved with an iterative process of research, development, and evaluation that cycles back to research (Forsberg 1995). This provides an environment that continues to enable researchers while providing sufficient support to build a bridge to higher levels of maturation, represented in Figure 1, and continuously improving the value of the end product (Ring 2000). ESR&D frameworks enable the transformation of fundamental research into engineered products. Limitations within the application space, or subsequent technologies requiring development, become the drivers for future research. There are many examples of this organizational dichotomy and associated creative tension in organizations such a Lockheed Martin Skunk Works, Toshiba, Apple, and Bell Laboratories (Rogers 2003, Gertner 2012, Rich & Janos 1994). These are organizations whose researchers and early developers have made progress moving past what would be considered as antagonistic, bureaucratic, and destructive organizational processes.

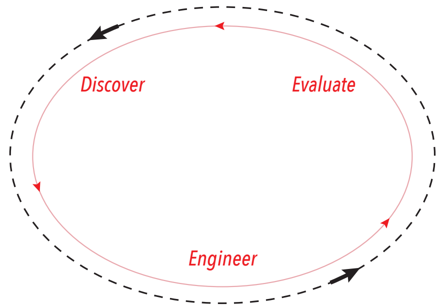

Figure 1. Research and Development Iterative Cycle (Ring 2000)

In these evolving R&D organizations, systems engineering, and research are complementary. systems engineering is inherently a requirements-driven process triggered by a systems engineering process event such as a user need statement or a requirements document. Similarly, the research cycle is triggered by research and early technology development goals that are like the systems engineering triggering events.

Role ambiguity is another source of conflict among systems engineers and other ESR&D stakeholders. This is particularly true between systems engineers and project managers. The ambiguity exists due to overlaps between systems engineering and project management (PM) responsibilities that can create problems if not effectively managed (Hahn 2016). In traditional R&D processes, there are domain-specific distinctions relative to the items in the bullseye in Figure 2. The systems engineer, for example, has responsibility for technical planning while the project manager has responsibility for budget and schedule planning. The same distinction can be made regarding risk management: the systems engineer is primarily concerned with product risks while the project manager is concerned with project risks. Finally, project managers and systems engineers deal with different sets of stakeholders, with project managers being concerned with business executives and organizational PM functions and the systems engineers interacting with users, maintainers, and technical staff involved in the R&D. There are variations to this description such as researchers may not be interested in the resultant project maturation above TRL 3, and the project manager is not interested in the project below TRL 3. There are also good examples in R&D organizations whereby the project manager and the systems engineer are the same individuals, or the various project managers, systems engineers, and researchers work side by side versus restricted in their respective domains (Gertner 2012, Rich & Janos 1994).

Closely related to role ambiguity is the tension between management authority, depicted by the roles in Figure 2, and technical influence maintained by the R&D technical leaders. Successful R&D projects rely upon a delicate balance. The technical influence of the scientific leadership team must be on par with the authority of the management team. When this balance is compromised, poor programmatic decisions occur that can compromise the success of R&D outcomes. Processes must address maintaining this balance.

Of course, technical problems, budgets, and schedule issues are highly interrelated. In modern projects, SEs may also have significant responsibilities in resource, scope, and schedule management, and procurement while PMs may have increased

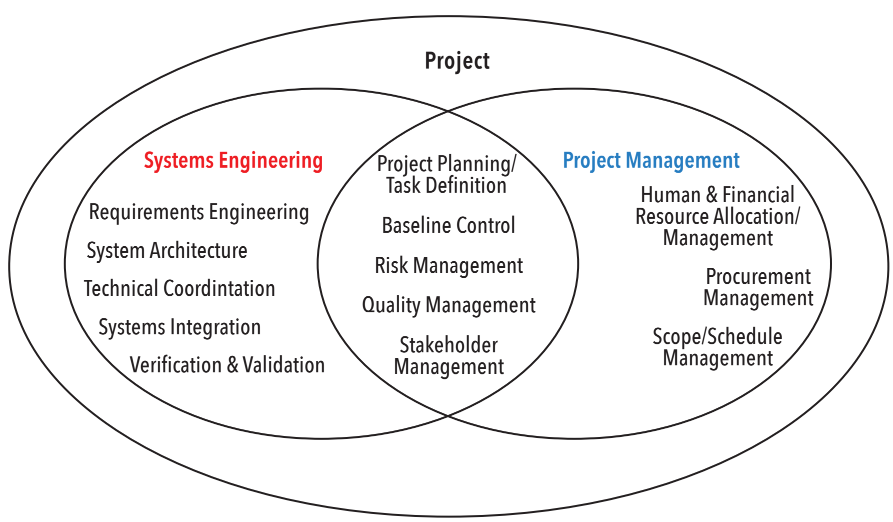

Figure 2: Overlap Depiction of Systems Engineering and Project Management (Adapted from Haskins 2007)

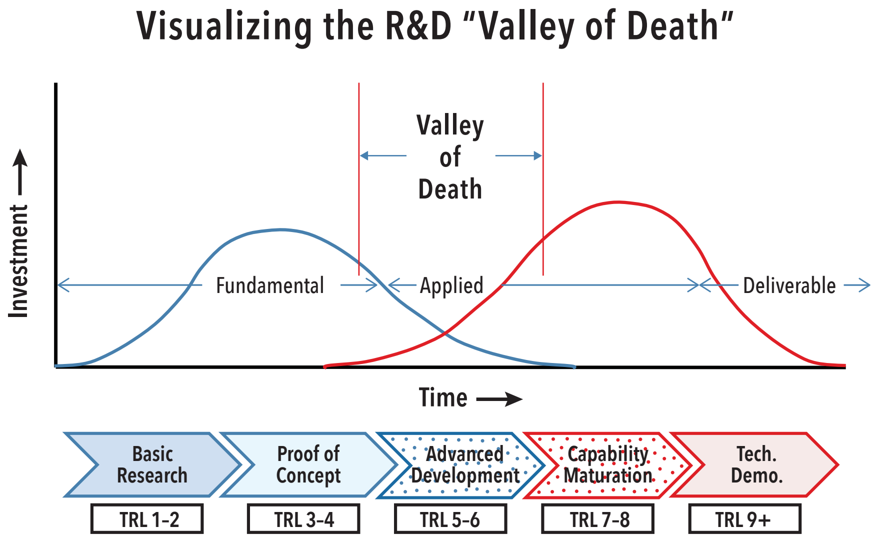

Figure 3: The R&D Valley of Death

responsibility in systems integration. Additionally, SEs and PMs share several "soft factors" including the need for practitioners to possess process competence, similar value propositions, application of processes using a graded approach, and many of the professional competencies cited in the *INCOSE Systems Engineering Competency Framework* (Presland 2018).

An ESR&D framework can help clarify roles and responsibilities if it serves to integrate systems engineering and PM functions at the appropriate level for the project. Because early R&D, unlike invention, is planned, scheduled, and budgeted, inclusion of some PM elements in the frameworks is a logical extension.

Responsibility for conquering the Valley of Death, shown in Figure 3 as occurring at TRLs 5 and 6, is a source of conflict between engineers engaged in ESR&D and development engineers operating at TRLs 7 and higher. Death often occurs because of funding or technical performance issues to satisfy the bridge between Research and Proof of Concept on one side of the bridge and Advanced Development and Capability Maturity at the other. Death also occurs for a host of other reasons such as neglect in the form of stakeholder failures to concisely define R&D objectives, bound acceptable risks, or to plan collaborative transitions of maturing R&D developments between responsible organizations and the misapplication of processes, resulting from ignorance, poorly defined or inappropriate performance metrics, power plays between technical and managerial leadership, or unconscious organizational culture biases. The greatest cause, however, is simply failing to build a bridge and its associated supports, including assigning responsibility for managing the Valley of Death, to prepare for the challenges in maturing early R&D.

FRAMEWORKS FOR GUIDING IMPLEMENTATION OF SYSTEMS ENGINEERING ON ESR&D PROJECTS

All R&D projects are a balance of estimated and quantified risk against tolerable organizational risk. The purpose of a process framework is to manage the unknowns, particularly at those instances where risks are the highest. The differences between R&D activities as compared to systems engineering processes imply a need for greater process flexibility to accommodate the various R&D maturity levels. The "expansionist" nature of R&D may appear to imply a demand for an inordinate amount of flexibility in a R&D framework, but not as much as one may assume; the amount of flexibility allowed is highly dependent on organizational context.

When carefully chosen, process frameworks can be suitable tools for right sizing systems engineering activities for ESR&D. While the very issue of adopting a framework for implementing systems engineering in ESR&D may itself be contentious, frameworks may also be useful in resolving tensions among stakeholder groups because they aid in communication by clarifying viewpoints and providing a basis for discussion.

Some considerations in selecting a framework to manage ESR&D include:

- Can the framework address the types of projects of interest?
- Does the framework address the cultural gap between systems engineering and ES&RD?
- Does the framework support the range of internal and external stakeholders?
- Can the framework support different funding levels and funding allocation strategies?
- What is an acceptable level of process documentation, tools, and templates required by the framework?
- And most importantly, will the framework support the transition to more formal systems engineering should the effort move beyond the TRL level for ESR&D?

Some candidate framework types include:

- Standards-based
- Risk-based
- Maturity-based
- Project Type-based

ISO/IEC 29110 *Systems and Software Life Cycle Profiles and Guidelines for Very Small Entities* (VSE) is a standards-based framework, a scaled down version of the ISO/IEC 15288 standard for traditional systems engineering. Although ISO/IEC 29110 was developed specifically to meet the needs of small commercial organizations, which often do not employ systems engineering, the VSE standard is perceived by some as still being too process-heavy and inflexible to be implemented in their organizations. Because it mimics ISO/IEC 15288 closely, ISO/IEC 29110 does not eliminate any processes; it only simplifies their implementation.

At least three of the Department of Energy's (DOE) national laboratories, all of which are Federally Funded Research and Development Centers (FFRDC), have developed risk-based frameworks. Pacific Northwest National Laboratory (PNNL) evaluated several potential frameworks against a previously developed set of requirements. A set of trigger questions was developed for identifying projects in the "systems engineering track." PNNL adopted, with slight modifications, the ISO/IEC 15288 standards-based systems engineering framework developed by Battelle Memorial Institute for projects requiring "formal" systems engineering resulting in the development of a systems engineering management plan. For the vast majority of the lab's projects, however, this was too process heavy and a risk-based approach consisting of 20 discrete risk elements addressing the complete project lifecycle was developed for projects requiring "semi-formal" systems engineering. This process-light, risk-based framework for assessing system development risk aligned well with the Laboratory's risk-based approach to project management, conceptually facilitating its widespread use.

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Table 1. Project Types

Activity	Knowledge Products	Basic/ Applied Research	Technology Development: Proof of Concept	Technology Development: Advanced Development	Technology Development: Capability Maturity	Technology Demonstration
Description	Project whose resulting knowledge benefits operational needs or guides S&T's research agenda. Includes assessments, roadmaps, information, databases, standards, and training.	Systematic study directed toward gaining a greater knowledge of the fundamental aspects of a physical phenomenon with the intent of filling a capability gap that meets a need.	A proof of concept (POC) or proof of principle project is a realization of a certain method or an idea to demonstrate its feasibility, or a demonstration in principle. POC purpose is to verify that some concept or theory has the potential of being used. Basic components are integrated to establish that they work together.	Expands/ matures POC methods and techniques into a well-defined, repeatable process or system. Initially, basic components are integrated with realistic supporting elements to be tested in a simulated environment. Components will advance to where they can be demonstrated in a near or representative operational environment.	Addresses the transition of a system into an operational environment where it can be applied by end users to address a capability gap or need.	Enables the direct examination of emerging capabilities against scenarios and use cases that are of operational interest to users/ clients.
TRL	N/A	TRL 1-2	TRL 3-4	TRL 5-6	TRL 7-8	N/A

Sandia National Laboratories also developed a risk-based graded approach framework to the application of systems engineering, quality management, and project management with activities based on standards including the systems engineering life cycle standard ISO/IEC 15288, Project Management Institute's *Project Management Body of Knowledge* (PMBOK), and the AS9100 quality management standard (Hahn et al. 2020).

Los Alamos National Laboratory's approach is like Sandia's in that it uses ISO15288 and the PMBOK as its foundation. To deal with the issue of applicability in early-stage R&D and to address the cultural issues, their framework uses ANSI/ ASQ Z 1.13-1999, *Quality Guidelines for Research* as it's quality management standard and transitions to relevant industry standards at later development phases (Hahn 2016).

In these frameworks, a questionnaire is used to determine the inherent risk level based on complexities related to product, project, and coupled with impact of failure. Responses to the questionnaire result in activities that help to minimize the identified risks. These frameworks are candidates for FFRDC-like organizations, especially those that have explicit expectations regarding the use of systems engineering and PM on projects they fund. How these frameworks translate to ESR&D in large and small commercial organizations remains to be seen.

The Technology Program Management Model (TPMM) is an example of a maturity-based, stage-gate framework (Craver 1994). TPMM uses systems engineering methods to manage technology development to successfully transition technologies to TRL 7 and beyond. In this model, Science and Technology development follows through TRL 6, a bit higher than what we consider to be ESR&D and puts responsibility for overcoming the Valley of Death squarely on the scientists and technologists. Like the Project Type frameworks discussed below, TPMM aligns its criteria to TRLs; it also defines deliverables which, along with other factors, are used as metrics to make decisions as to whether projects progress to later stages. The TPMM criteria align with TRLs as follows: (1) Discovery; (2) Formulation; (3) Proof of Concept; (4) Refinement; (5) Development; (6) Demonstration and Transition.

TPMM is consistent with the DOD5000 acquisition process and, as such, is process-heavy, standardizing the development, assessment, and transition processes and providing tools and templates for implementation. It was developed by the US Army and is only to be adopted by US military organizations and their defense contractors, who may be contractually obligated to do so.

TPMM employs a Technology Strategy Document, which is believed to establish a common language and shared vision. It is unclear whether it sufficiently addresses the cultural aspects of systems engineering and ESR&D.

By grouping similar projects by Project Type, one can attempt to standardize systems engineering, PM, and quality management activities and deliverables, based on the implicit and explicit project risks associated with the product and project characteristics. An exemplar Project Type framework, which tracks the Project Types to TRLs, is shown as Table 1.

The benefit of processes aligned with

Project Types is flexibility for prescribing development methodologies and for monitoring progress for a variety of technical, cost, and schedule profiles. Further, if processes are designed and implemented properly, R&D tasks should be allowed to be paused for a time and restarted when risk profiles improve with minimal losses to earlier investments.

If the ontology of Project Types can be clearly understood and recognized by the ESR&D community, their use, combined with processes, templates, and associated tools that are tailored for each Project Type, can bridge the social and cultural chasm between systems engineering and ESR&D and the various roles of personnel in the ESR&D process.

Project Types not only define the phases of development required to attain technological objectives, but they also identify broad classes of skills required for R&D maturity, allude to facility and infrastructure needs, and identify transition points where progress frequently stalls. Project Types provide a historical record – based upon the history of others as well as our own personal experiences performing, leading, and leveraging R&D – of where changes in discipline are demanded. The Valley of Death provides a contemporary cultural, managerial, and technical assessment of where the probabilities of failure are greatest. R&D Project Types offer a description, and a leading indicator of where careful attention is demanded to achieve success and is of mutual importance to project and technical managers, scientists, and engineers.

SUMMARY AND CONCLUSIONS

Systems engineering process applied at an inappropriate level of rigor for any project is especially toxic for ESR&D because it can interfere with the creative environment for successful research and hinder the researcher with perceived excessive processes. The key to success is adopting the logic of the system engineering management and systems engineering processes, then tailoring the rigor to the specific environment.

The standards, risk, and project-based frameworks described in this paper can be effectively applied to ESR&D. Which framework is appropriate for a particular organization is dependent on organizational business models and context; selection of a framework having such consistency is key to successful implementation and acceptance. The framework should not constrain the creativity of the researchers and the early developers. In fact, the appropriate degree of tailoring and formalism is essential for successful research. A good process will help provide early detection of project failures and avoid difficulties in the maturation process. Of course, moving to a framework-based model is, of itself, a change that requires careful management. Ignoring the need to manage the cultural transformation to support the switch to a framework such as the Project Types will put the success of the effort at peril. To ensure the success of change, multiple levels of the organization need to be influenced and engaged in the change – from executives to the staff – in not only the systems engineering and technical organization lines, but also in the project management organization. ■

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Incorporating the Role(s) of Human Actors in Complex System Design for Safety and Security

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ABSTRACT
Traditional systems engineering demonstrates the importance of customer needs in scoping and defining design requirements; yet, in practice, other human stakeholders are often absent from early lifecycle phases. Human factors are often omitted in practice when evaluating and down-selecting design options due to constraints such as time, money, access to user populations, or difficulty in proving system robustness through the inclusion of human behaviors. Advances in systems engineering increasingly include non-technical influences into the design, deployment, operations, and maintenance of interacting components to achieve common performance objectives. Such advances highlight the need to better account for the various roles of human actors to achieve desired performance outcomes in complex systems. Many of these efforts seek to infuse lessons and concepts from human factors (enhanced decision-making through Crew Resource Management), systems safety (Rasmussen's "drift toward danger") and organization science (Giddens' recurrent human acts leading to emergent behaviors) into systems engineering to better understand how socio-technical interactions impact emergent system performance. Safety and security are examples of complex system performance outcomes that are directly impacted by varying roles of human actors. Using security performance of high consequence facilities as a representative use case, this article will outline the System Context Lenses to understand how to include various roles of human actors into systems engineering design. Several exemplar applications of this organizing lenses will be summarized and used to highlight more generalized insights for the broader systems engineering community.

INTRODUCTION

The USS Stark incident of 1987 exemplifies the need for a broader understanding of human interactions with technology. The attack on the USS Stark resulted in the deaths of 37 US Navy personnel (Cushman Jr 1987). An active monitoring system detected hostiles on radar, however the audible advisory system had been turned-off by a human operator due to nuisance alarms (Cushman Jr 1987). Retired general Donn Starry said, "treating the human factor as an afterthought was never a good way to do business, and it is even less good in this day and age." The New York Times amplified this sentiment:

> *"The tale is a nightmare for the manufacturers of sophisticated electronic weaponry, who find increasingly that the systems they are building have become too complex for soldiers and sailors to operate properly. Moreover, maintenance and repair of the electronic weapons are also often beyond the ability of most military personnel, despite the investment of enormous amounts of training time, according to experts both inside and outside the Government." (Cushman Jr., 1987)*

Complex systems involve many interacting elements and often has dynamic and emergent features. Effective system design considers the complex interactions among technology, stakeholder and mission needs, cost, schedule, and the state of the industry. Following construction, the system operates in an equally complex context, with system performance dependent on the quality of the design, the operational environment, and stakeholder behaviors (operators and maintainers). Thus, system design requires an understanding of its technical and performance components as well as the needs and limitations of the stakeholders within the operational context. However, designers can struggle to consider the full operational context or stakeholder requirements early enough in the design process, which can lead to safety and security risks (Coso 2014; Proctor and Zandt 1994). The importance of incorporating various human actor roles into complex systems to ensure desired performance is evidenced not only in such historical examples as the 1986 Space Shuttle Challenger disaster and the 9/11 terrorist attacks but also in more recent cases like the 737 Max aircraft safety issues (Campbell 2019), the 2012 break-in at

Y-12 National Security Complex (Schlosser 2015), and even more recent cyber-attacks on the electric grid (Sobczak 2019).

Within complex systems, such as the ones presented above, humans interact with system operations at varying levels of supervisory control to maintain desired safety and security performance levels. This can range from monitoring, intermittent programming, and active controlling. Human supervisory control is a vital consideration in the design and operation of complex technology (Sheridan and Ferrell, 1974). Therefore, the system requirements are influenced through the designer's understanding of what tasks a human actor will perform in steady-state—and "off-normal"—operations. In the same vein, it is important to consider the level of autonomy of the machine (Parasuraman, Sheridan, and Wickens, 2000). The process of determining the appropriate level of automation can also be described as function allocation or determining the distribution of responsibility over tasks between human operators and systems (de Winter & Dodou, 2014; Joe, O'Hara, Hugo, and Oxstrand, 2015; Price, 1985).

More traditional approaches to function allocation in aerospace applications stem from foundational Human Factors research in the 1950's (Fitts 1951), which is more generally referred to as "humans are better at – machines are better at", or HABA-MABA. Within this model of humans versus machines, humans are better at detection, perception, judgement, induction, improvisation, and long-term memory. Machines are better at speed, power, computation, replication, simultaneous operations, and short-term memory. The Fitts list, though slightly outdated for today's technologies (de Winter and Dodou, 2014), can be used as a foundation to improve methods for integrating humans within the design of complex systems.

For example, as we move toward future system integration, designers will increasingly incorporate autonomous designs and technologies. Given the HABA-MABA model, the design of an autonomous, or partially autonomous, system must be approached with careful consideration of the goals of the system. The system goals must be defined and contextualized through careful input by a variety of stakeholders, including, but not limited to, users, managers, affected members of the public, and designers. Once the goals are understood, the functions for how those goals are achieved can be decomposed and allocated to components within the system. Those functions are then connected with human-driven tasks for how to complete the function in the desired manner of the designer. At this stage, a designer must consider how much they want the human to control in the system versus how much they want the machine to control—in other words, the designer must decide how human actors will engage with the system.

At the lowest automation level, a human actor makes all the decisions with no help from the automation. From this perspective, the machine may offer recommendations or different decision-paths to aid the human actor with their task. At the highest level, the machine—including inherent physical characteristics and supporting analog or digital control systems—receives input signals, manipulates that data according to an algorithm, and executes the assigned task, potentially with no (or little) input or supervision from a human actor.

Returning to the electric grid as an example, modern power grid operations have been an exercise in disjointed automation integration, with varying levels of automation dependent on geographic region and entity modernization. Recent cyberattacks, such as the significant 2015 Ukraine cyberattack (Zetter 2016) and the less consequential, yet revealing, 2019 cyberattack on the North American Electric Reliability Corporation (NAERC) (NAERC 2019, Sobczak 2019), demonstrate the potential for malicious actors to disrupt critical infrastructures by exploiting poorly designed human and technology interactions. As American providers move to integrate more automation through the Smart Grid, it is critical to understand the role of technology and humans and vulnerabilities of each.

Inadequately designed systems can harm safety and security performance. As demonstrated by the cases introduced earlier (the 1986 Challenge Shuttle Accident and the 9/11 terrorist attacks), systems that inadequately account for human interactions can lead to catastrophic consequences including significant loss of property, financial resources, and human lives. In response to the growing need to consider the full scope of design performance and operational context, Sandia has explored the integration of systems engineering concepts with the application of human factors methodologies. By investigating how humans' impact various aspects of system design, development, and use, system designs can more fully account for the various roles of human actors in achieving desired levels of safety and security in complex systems.

COMPLEX SYSTEM ORGANIZATION

Systems Engineering and the Fitts list emerged around similar timeframes. First deployed by Bell Telephone Laboratories in the 1940s, systems engineering focuses on interactions between components, incorporates lifecycle properties (and performance), and provides conceptual foundations for understanding how technical components and human users can be incorporated into design. Similarly, the Fitts list, first published in 1951, introduced a consensus understanding of the differences between humans and machines within system operations. How systems can be "buffeted, constricted, triggered, or even driven by outside forces"

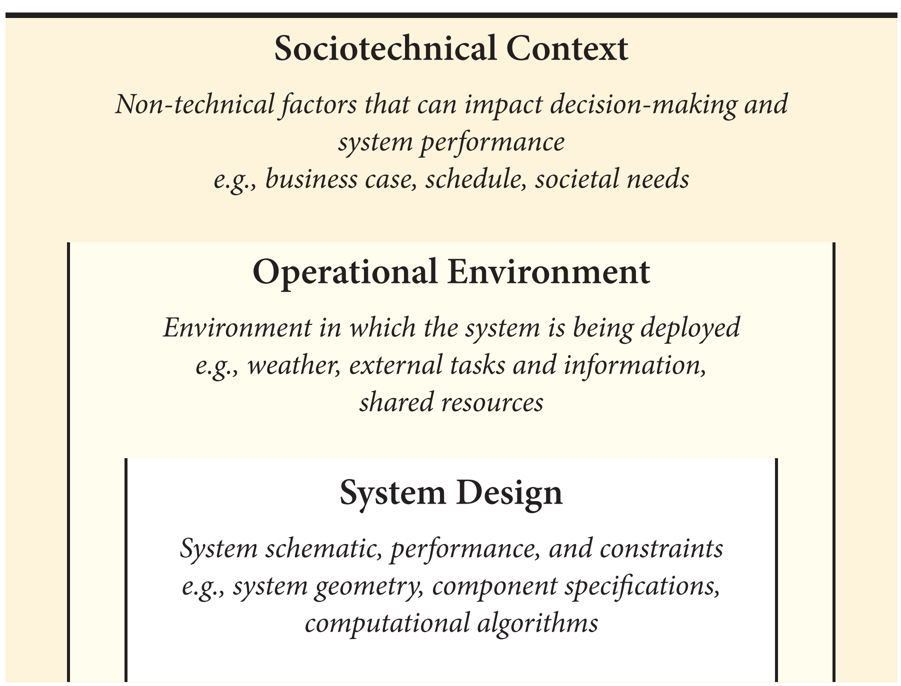

Figure 1. System Context Lenses

Table 1. System Context Lenses for decomposing design contributors

System Context Lenses	Definition	Example Questions for Designers
System Design	Structure based on system architecture, (desired) behaviors, and (expected) constraints necessary to meet a minimum level of performance requirements	• What is the primary technical goal of the system? • What technologies need to (can, or should) be integrated to meet that goal?
Operational Environment	The physical and social environment in which the system is expected to be deployed and achieve a minimum level of performance requirements	• How might the system perform differently in this real context? • What external dependencies drive system performance?
Sociotechnical Context	Non-technical factors that can impact decision-making and system performance, including business case, development schedule, societal needs/ perspectives	• What are the competitor's capabilities? • How does existing partnerships impact component design and development? • What are the driving societal impacts and perceptions? • How can this system be (or be perceived as being) misused or harmed?

Table 2. Representative design impacts per System Context Lenses, as related to an example aircraft design

System Context Lenses	Example Design Requirements	Example Design Impacts
System Design	• Meets maximum required velocity • Mitigates Loss of Control situations • Mitigates intruder entry to flight deck	• Engine design meets required performance characteristics • Inclusion of Maneuvering Characteristics Augmentation System • Access-controlled entrance to flight deck
Operational Environment	• Provides guidance on flight path monitoring and correction • Maintains adequate separate from nearby traffic • Avoids unsafe weather conditions	• Communication capability with Air Traffic Control • Inclusion Aircraft Collision Avoidance Systems • Inclusion of Aircraft Meteorological Data Relay
Sociotechnical Context	• Meets or exceeds competitor range and payload capabilities • Uses existing manufacturing contracts • Minimizes environmental impact	• Engine design has preferable performance characteristics compared to competitors • Incorporate specific materials and Commercial-Off-The-Shelf components • Inclusion of "green" materials in the design and operations

(Meadows 2008, p. 2) is well known and is being incorporated in recent engineering design trends that note the importance of "context" to system performance (Williams 2019). This perspective is also consistent with Dove and Willet's (2020a) use of social contracts to explain how a technical system remains viable and relevant "to the extent to which is it operationally compatible with the current order." Within Systems of Systems literature, the ROPE (Resources, Operations, Policy, Economics) lexicon framework allows engineers to include a diverse and holistic approach to design, highlighting the importance of both engineered and sentient systems within the problem definition (DeLaurentis & Callaway 2004).

The focus on system design context extends to the role of human interaction within the broader system environment, thus a frame is needed to consider those impacts. In considering human interactions, consider framing the roles of human actors in terms of three main lenses (Figure 1). By organizing a complex system into system design, operational environment, and sociotechnical context, a designer can more completely identify the full scope of the design context (Table 1) and the associated design impacts (Table 2, as based on a representative aircraft system).

HUMAN INTERACTIONS

Embedded within the lenses for understanding system context is the impact of human interactions. Understanding the dimensions of human interactions is essential to successful system performance (Table 3). Each lens highlights specific human stakeholders, their decision-making impacts, and how those decisions influence system design characteristics. Further, the decomposition of human actor interactions—in addition to identifying specific human actor tasks—also lends to an improved understanding of how automating tasks can impact system performance. Thus, safety and security impacts are driven by human interventions on the design, which then impacts how human actors directly engage with the designed system—as well as how elements of the designed system might be manipulated for unplanned use.

Consider the recent safety issues related to the Boeing 737 Max, for example. In the design of the Boeing 737 Max, the business case for the aircraft was at least partially driven by the surprise release of the Airbus A320neo. Boeing rushed to

Table 3. Human interactions across System Context Lenses

System Context Lenses	Example Human Stakeholders	Example Human Decision-Making Influences	Example Design Impacts
System Design	• User • Maintainers • Designers • Adversaries	• Tasks/workload • Information sensing and processing	• Human-machine interface • Control instrumentation • Tooling • Access panels
Operational Environment	• User • Maintainers • Designers • Team members • Design entity • Adversaries	• Situation awareness • Communication • Teamwork/crew dynamics • Training • Procedures	• Human-machine interface • Communication networks
Sociotechnical Context	• Designers • Regulators • Partnering entities • Competitors • General public • Adversaries	• Regulations and assessments • Competitor public relations • Public perception of technology implementation • Adversarial interest in technology	• Meets verifiable technical, regulatory and business requirements • Increases social acceptability of system deployment • Potentially accelerates "in-domain" system advancement

Table 4. Example System Context Lenses decomposition of the 737 Max accidents

System Context Lenses	Human Stakeholders	Human Decision-Making Influences	Design Impacts
System Design	• Pilots • Maintainers • Designers • Passengers	• Modernize existing fleet	• Updated analog to digital instrumentation • Inclusion of the Maneuvering Characteristics Augmentation System (MCAS)
Operational Environment	• Pilots • Maintainers • Designers • Air Traffic Control	• Known MCAS error	• Limited guidance on MCAS error
Sociotechnical Context	• Designers • Regulators (FAA) • General Public • Boeing • Airbus • Purchasing airlines	• Airbus capabilities • Improved fuel efficiency • Shortened design cycle • Standardization with existing 737 fleet	• New propulsion system • Modified aerodynamic characteristics • Limited 737 Max training • Limited FAA oversight

modify its same class of existing narrow body aircraft, the 737, to offer customers a new generation aircraft with comparable/preferred performance characteristics to the Airbus A320neo. However, the rushed development of the aircraft and prioritized customer goals led to Boeing cutting corners within the development process (Campbell 2019). Potential customers also valued fast development time, optimized fuel efficiency, standardization with the existing fleet, and minimal new training for fleet pilots. Thus, the updated 737 Max had a shortened design cycle, new propulsion system to meet fuel requirements, limited design modifications from the original 737, and minimal added training (Campbell 2019). As a result, according to (Campbell 2019), the Federal Aviation Administration's (FAAs) failure to provide complete regulatory oversight on the updated aircraft led to blind spots in system safety.

From the System Context Lenses perspective, the competitor's surprise announcement and customer-driven desire for reduced development timelines are examples of how the sociotechnical lens reinforced embedded human factors issues. The shortened design cycle led to inadequate (and incomplete) communication by human actors on design decisions (including the mitigation of critical design errors) and was supported by reduced oversight from the FAA. Similarly, the desire to minimize alterations from the existing fleet led to minimal pilot training, even as the 737 Max presented significant differences from the original 737. Thus, human actors were expected to safely operate the 737 Max in an operational environment that included a known error in the automated flight control law software and with limited experience with a new aircraft. Examples of design impacts at the system design lens include updates to digital controllers and sensors, in part driven by aircraft modernization decisions. Additional elements of the 737 Max safety example are summarized in Table 4.

As exemplified through the Systems Context Lenses perspective, the socio-technical lens of the 737 Max business case drove the implementation of technical design requirements without robust inclusion of how those added requirements might be constrained by the prior 737 variant's system design and operational environment. This echoes what a designer might see through a ROPE framework by explicating the resources and operations of prior 737 variants with the policy and economics of the desired variant modifications (DeLaurentis & Callaway, 2004). Through the System Context Lenses you are also given insights regarding the driving stakeholders behind each design impact and how those stakeholders have the capacity to influence

Table 5. Example System Context Lenses decomposition of the 2012 Security Incident at the Y-12 National Security Complex

System Context Lenses	Human Stakeholders	Human Decision-Making Influences	Design Impacts
System Design	• ARGUS system designers • Security guards • Y-12 employees	• Requirement to mesh "new" design into "old" (existing) system	• > 2000 false alarms *per day* • Inappropriate use of pan/tilt/zoom cameras • Partial/piecemeal implementation of new systems
Operational Environment	• Y-12 management • Security guard union • Security contractor (WSI)	• Security personnel complacency • Ambiguity in executing established security procedures • Drawn-out security union contract negotiations	• Long-standing broken/malfunctioning security cameras • Limited response/correction to personnel ignoring sensors that captured intruders' movement
Sociotechnical Context	• Oversight (NNSA) • Protestors (Nuns)	• Reduced oversight • Security standardization across facilities • Moral opposition to nuclear weapons activities	• Insufficient vulnerability assessments • Regulations not compared/aligned with site policies to ensure compliance

the implementation and verification of design requirements.

For a security example, consider the 2012 breach of the Y-12 National Security Complex (Y-12). Constructed in 1943 as part of the Manhattan Project, the Y-12 supports the U.S. nuclear weapons stockpile, international efforts to encourage peaceful uses of nuclear energy, effective nuclear naval propulsion systems (Schlosser 2015). From the mid-2000s to 2012, Y-12's security contractor—Wackenhut Services Inc.-Oak Ridge (WSI)—had received annual National Nuclear Security Administration (NNSA) regulatory and oversight evaluations of outstanding (Schlosser 2015). Around 2010, the NNSA identified ARGUS enterprise security system as the primary component of the mandated program to standardize security operations across its facilities. Additionally, in February 2011, the NNSA initiated its governance transformation project to enhance security performance by reduced oversight that relied on security contractor self-reporting (DOE/IG 2012). The resulting deterioration of security performance—and reliance on using human actors to replace malfunctioning security technologies—aligned with the efforts of three protestors to successfully infiltrate Y-12 security systems and damaged the $549 million dollar crown jewel of Y-12, the Highly Enriched Uranium Materials Facility (Schlosser, 2015). After vandalizing the HEUMF (by throwing human blood around, spray painting Bible verses on the walls and using a hammer to chip away at the walls in protest of nuclear weapons), the intruders were detained, handcuffed, and escorted to local jail, and the HEUMF area was secured (DOE/IG 2012).

While security performance cannot control for the actions of potential adversaries, the System Context Lenses perspective is instructive for explaining how Y-12's security performance became more susceptible to the intruders. In the sociotechnical context lens, the desire for standard security systems across NNSA facilities and reduced oversight are human decision influencing factors that resulted in security operations misaligned with both desired goals and regulations. Extended contract negotiations with the security union helped create an atmosphere of complacency and ambiguity that constitute the operational environment lens and resulted in long-standing malfunctioning security components and ignoring of alarms from functioning security components. This environment incubated elements within the system design lens that allowed the mandated implementation of the ARGUS security system to result in a patchwork installation process and a significant increase in false alarms. Additional elements of the Y-12 security example are summarized in Table 5.

As summarized above, the inability of the designed security system to protect Y-12 assets or ensure normal operations emerged from how "socio" aspects impacted the ability for "technical" components to meet system objectives. This matches systems security intuition offered by Dove and Willett (2020a) who used a social contract perspective to explain the reinforcing nature of external (human or socially driven) governing laws on the emergent self-preservation behaviors of technical components in systems. Here, the framing of the System Context Lens, the depiction of associated representative human interactions, and the related questions for system designers provided in this article can help achieve systems capable of "mutual protection behaviors among systems technical components" (Dove and Willett 2020a).

CONCLUSIONS AND IMPLICATIONS

Thirty-four years after the catastrophic USS Stark incident, events continue to show the safety and security consequences from designers still struggling to incorporate human actors more effectively within complex system design. Both historical and recent examples demonstrate how designers have failed to incorporate human factors across the full design context of increasingly complex systems. The System Context Lenses introduced in this article seeks to provide one mechanism for connecting useful insights from the human factors and systems engineering communities. Similarly, where Dove and Willett (2020b) argue that the "social dimension will play a major role in the future of systems engineering," the System Context Lenses approach summarized in this article provides one approach for system engineers to achieve "a cyber-physical-social appreciation that includes people, process, technology, and environment." In short, these three lenses—and the interactions between them—are offered as mechanism for better organizing the "socio" portion of socio-technical systems.

The organizing lenses we offer provides a solution to the problem of connecting technical and social design influences. In addition, the System Context Lens was developed in part to clarify and extend other approaches used within systems design. For example, within systems engineering, requirements and functional analysis methods transform technical capability needs into system design requirements and provides an approach to verify implementation of those requirements. When used together, many of the systems engineering approaches provide a formal connection between technical system design and the operational environment (Model-Based Systems Engineering). Yet, without detailed and intentional inclusion of the human component throughout all design phases, nuances of human interactions in practice may reduce overall system effectiveness.

Human factors methods (task analyses, process diagrams) strives to address system engineering's gaps by revealing human-system interactions and connecting those interactions with design requirements. Persona definitions and journey mapping can also be used to describe system user types and expected human-system interactions. Commonly missing from these various approaches is the inter-dimensional impacts for how one stakeholder might impose design requirements that impact another stakeholder—even more so when those impacts are extended from the rarely emphasized sociotechnical context. Thus, an approach is needed to explicitly incorporate the role of humans in the complex systems design process and highlight how those interactions are impacted by the system design, operational environment, and sociotechnical context.

The System Context Lenses offers an approach through which designers can explore the integration of systems engineering concepts and the application of human factors considerations throughout the full context of complex system design. By investigating how human actors interact within (and across) the system design, operational environment, and sociotechnical context lenses provides opportunities to identify influences on human decision-making and optimize related impacts on design to achieve desired system performance goals. In this manner, system engineers can better account for the impacts of various roles of human actors and more fully address sources of system complexity necessary to achieve desired levels of safety and security performance. ■

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An Agile Systems Engineering Analysis of Socio-technical Aspects of a University-built CubeSat

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ABSTRACT

System development teams often face challenges outside of pure technical problems. There are unpredictable circumstances in many areas including customer needs, personnel changes, and sociotechnical issues that can span across the development organization such as knowledge management and goal alignment. This paper presents the results of an exploratory case study on a university CubeSat team developing an Earth Observation satellite. Formal analysis of agile systems engineering helps improve success throughout the CubeSat lifecycle. We apply the INCOSE Agile systems engineering WG decision guidance method for applying agile system engineering method to identify areas in which the project organization can improve to become more agile in three specific problem spaces: customer problem space, solution space, and product development space. The analysis process led to valuable insights about how the project organization of an academic project differs from that of industry. Additionally, the results indicate that areas such as stakeholder management and support environment could be factors that would benefit more from agile responsiveness.

INTRODUCTION

The academic CubeSat projects may have the same expectations to the performance and functionality as industrial CubeSats but face vastly different challenges, especially when viewed through a sociotechnical lens. An academic team consisting of students have a "natural" high turnover based on the school calendar and graduation, the students must balance coursework and project work, often based on volunteer participation, and lack of prior experience in both teamwork and in the specific discipline.

The Norwegian University of Science and Technology (NTNU) recently started their own CubeSat team, which has the goal of delivering their first CubeSat to the launch provider in the end of 2020. There is an overarching goal for the team to develop a framework and organization that can deliver integration of scientific payloads onto CubeSats, and that the CubeSats can work together to form a concert of multi-agent systems for maritime surveillance. The first CubeSat took 3.5 years from concept ideation to delivery, while the original schedule was 2 years, with a goal of shortening the time to 1 year on average.

We hypothesized that an academic team could benefit from an agile and responsive approach and used the "Agile Decision Guidance (ADG)" (Lyells et al. 2018) method to identify which factors in their system can become more effective by applying agile principles.

The systemigram in Figure 1 highlights the sociotechnical complexity of the academic CubeSat development environment. Students need to balance their course and thesis work concurrently with the CubeSat project work. Furthermore, there is a turnover of 9 months for how long the students join the team. They typically join in September and graduate in June, and December is lost to exams and from mid-May focus on finishing the write-up of their thesis. Managing these sociotechnical challenges requires a holistic approach and understanding of their interconnectedness and effect on the organization.

Academia builds CubeSats both for education and scientific purposes. Increasingly popular in industry, most CubeSats launched in the last 5 years were for non-academic purposes (Kulu 2020). Unlike their larger counterparts, CubeSats share launch opportunities with other missions. In 2017, the Indian Space Research Organization (ISRO) launched 104 satellites using a single rocket. It is simple for launch integrators to integrate the CubeSats because of their standard size and design, and they can be easily deployed using "pods." Additionally, if a CubeSat is not ready for launch, substitutions of the same form factors are simple, optimizing the launcher's risk and return on investment.

CubeSats are small satellites consisting multiples of 10 cm * 10 cm *10 cm units

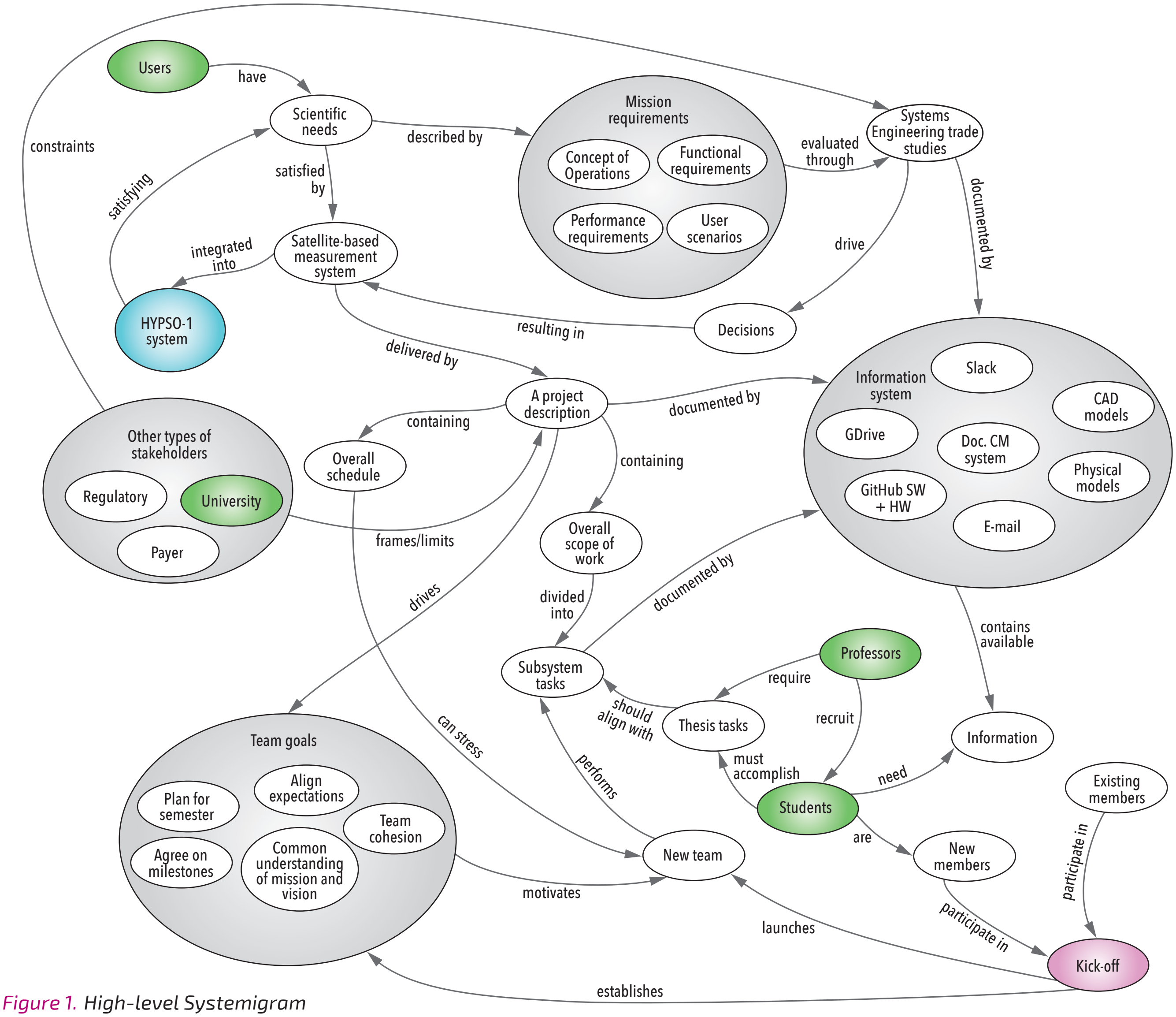

Figure 1. High-level Systemigram

(1U) and can come in sizes of any multiple of this unit, such as 3U, 6U, or 12U. The CubeSat unit was introduced in collaboration by California Polytechnic State University (Cal Poly) and Stanford University through the CubeSat Design Specification, with the purpose of educating the future engineers through a hands-on satellite project. In comparison to large monolithic satellites, CubeSats use Commercial-Off-The-Shelf (COTS) components for most of their subsystems. COTS components have lower reliability, but the lifetime in space of a CubeSat is also lower because of the lower altitude. This significantly lowers the cost and time needed to develop a satellite.

Students can get hands-on experience with systems engineering and space technology development through CubeSat projects, like Project Based Learning (PBL) courses (Savery and Duffy 1995). However, a systematic approach on how to teach systems engineering through the CubeSat project is still pending. The degree of space technology learning is higher but needs systemization.

UNDERSTANDING THE PROBLEM SPACE

As mentioned in the referenced paper, this method uses the OODA (Observe, Orient, Decide, Act)-loop as a model for learning and adaption. The focus of this application case study is on the first three activities of the OODA-loop model, effectively providing situational understanding of the HYPSO problem space. The assessment (Inquiry/Observe phase) took place over several months during the spring-fall of 2020. The project manager and one of the software team leads participated in most of the workshops together with the assessment team. After that, we discussed (Orient phase) the results with some more of the team members, to build the same mental model of the situation and organization. At the end of the Orient phase, some factors were decided (Decision phase) to focus on to apply agile principles to.

The following sections will describe each of the activities and how they contributed to putting the CubeSat team on the path to becoming more agile. All meetings took place virtually, both because of different geolocations and because of the COVID-19 pandemic.

OBSERVATION: ASSESSMENT QUESTIONNAIRE AND DISCUSSIONS

The ADG method uses an assessment questionnaire divided into three observation spaces: (1) the customer problem space, (2) the solution space, and (3) the product development system space, and a team-oriented agile response capability assessment. While the first three describe the organization and the context, the fourth observation space concerns the agility of organization's capabilities. The questions are formulated to give insight into: (1) the stability or instability of a factor, (2) the variety or range of a factor, and (3) how predictable or how well we have observed changes of the factor. A to-

Table 1. Observation Space Factors and Shorthand Notation

Customer Problem Space		Product Development Space		Solution Space	
Factor	Shorthand Notation	Factor	Shorthand Notation	Factor	Shorthand Notation
Customer set	CusSet	Product Development Team Membership	PDSTeam	Solution architecture	SolnArch
Stakeholders	StkHld	Construction environment	ConsEnv	Module set	ModSet
Mission environment	MsnEnv	Integration environment	IntEnv	Solution interfaces	SolnI/Fs
Customer's mission	CusMsn	Operational environment	OpEnv		
Mission challenges and constraints	ChlgCon	Support environment	SuptEnv		
Customer's goals	CustGol				
Target System Major Reqs.	SysRqt				

tal of 36 factors were assessed through over 100 questions and scored between 1-7. Some of the factors have an assessment spread, because of the complexity of the system. For example, software and hardware modules have different experiences with the support environment factor. The factors assessed are given in Table 1.

In the customer problem space, some interesting discoveries were made about the project organization, which highlight the differences between academic and industry projects. For example, the customer set is both highly varied and very predictable. The customers (shown in green in Figure 1) include the researchers interested in the end data products from the satellite, operators, students, and professors. Each group of customers has different needs, although they are all in knowledge-intensive areas. For the customer group of students, these change every year. While the project team is aware of this, each group of students is different and may have different expectations of the project delivery.

The customer problem space also addresses the mission challenges and constraints ("other types of stakeholders" in Figure 1). Here, the nature of academia is the source of most challenges. For example, the pool of resources (students) is limited to those who want to join the project, and they may not have the experience needed at that point of the project schedule. There are few incentives that can be used to encourage team members to work harder when it could benefit from more resource-time, and the project schedule needs to adapt to the university schedule with exams and holidays. Universities are not set up for making products, which makes supplier management, procurement, quality control, and related activities ad-hoc and person-dependent.

The project has a low observation capability for the changing mission challenges and constraints, as shown in Figure 2, have not been good at recognizing upcoming changes beforehand. For example, the testing setup was developed late because of lack of resources. This led to the discovery of missing performance and capabilities, which in turn resulted in the change of the mission to compensate for it.

In terms of project goals, the project has not experienced them changing much. As a research project, it is the main goal to "Publish research and educate students," which is quite different from industry. Students have a common overarching goal in "Graduate on time" but may have individual goals that should be aligned with the project. One of the challenges highlighted by the team was the importance of goal-alignment with student thesis, ensuring that for example engineering work could be turned into something relevant for their master or bachelor thesis.

Some of the areas discussed such as system requirements have previously had a low observation record, but the team hypothesized that this may be due to doing

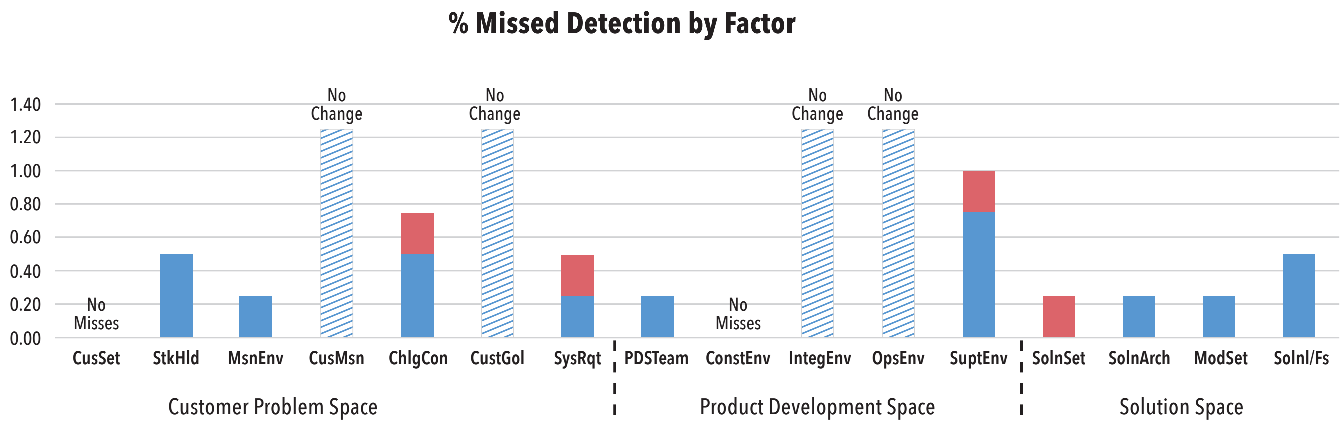

Figure 2. Missed Detection by Factors (The Red Band Indicates the Spread in the Assessment)

Table 2. Agile Response Factors and Shorthand Notation

Decide		Act		Observe Results	
Factor	Shorthand Notation	Factor	Shorthand Notation	Factor	Shorthand Notation
Collaborative decision making	Collab_Decis	Modular response capabilities	Mod_Capab	Ability to observe actions	Observ_Actions
Clear org. responsibilities for decisions	Org_Respons	Scope of influence to implement actions	Influence_Scope	Ability to observe results of actions	Observ_Results
Latitude to make changes	Latitude_Chg	Speed of implementing consequential actions	Action_Speed	Lag between actions and observation of effectiveness	Lag_Act-Observ
Ability to renegotiate commitments	Negot_Commit	Actions timely enough for effective results	Timely_Action		
Speed of conse-quential decisions	Decis_Speed				
Decisions timely to achieve results	Timely_Decis				

it for the first time and learning on the go. Since there was no previous knowledge of building CubeSats, getting an overview of all regulatory regulations, launch procedures, and other external requirements necessitated extra effort.

The modularity of how software is developed has created some friction for the overall product development. When students do their thesis work, they normally must do this individually to be able to hand in individual thesis reports. In practice, this is often translated to working on single modules of the software product. There had been instances where students had made small changes to the interface of their module, which resulted in the integrated software malfunctioning, and other modules needing adjustment, or the original module being reset. Sometimes, this interface change was not detected before the student graduated, and the knowledge of exactly how the module was implemented was partially lost.

For the product development space, the focus was on understanding the construction, integration, operational, and support environment in addition to the team itself. Although there is a high rate of change of the product development team (every university semester), it is predictable unless a student drops off unexpectedly. The biggest difference with industry is how the university CubeSat team cannot choose its own members and "fill the gaps" if someone is missing, they are dependent on students wanting to join the team and volunteering.

The support environment had already been indirectly mentioned in the mission constraints – as a university there are certain regulations that need to be followed, and there is a lack of coordinated support to individual research projects. Most funding for universities is directed for educating students, not necessarily for the support infrastructure needed to develop products. Research project funding may not always plan for the engineering need either, so then they are not given priority at the department. The availability of the support environment has been changing at a high frequency and is exceedingly difficult to plan with for the team.

PRODUCT DEVELOPMENT AGILE RESPONSE CAPABILITY

The final factors to be assessed are related to identifying in which areas the organization has agile capabilities to respond, given in Table 2. One focus area was how the team collaborates. The team has multiple arenas for collaborating such as Slack, e-mail, GitHub, in-person meetings and shared online drives, with a combination of push and pull flow of information. Both subjects highlighted how they felt that all the needed information existed, but that the assimilation of multiple information sources was ineffective. The effectiveness increased with project work experience (for example among PhD members or if the students had worked in complex projects previously), and with time (the spring semester usually better than the fall semester). Another challenge was how the onboarding and offboarding process worked, where many students join at the same time in the fall semester, but there might not be enough mentors to follow up with them individually to the same degree that you might at in industry.

In terms of the product development culture, the team members made it clear that it was positive and collaborative, especially within each subsystem. For example, the team responded rapidly to the COVID-19 outbreak by adjusting work routines quickly and looking for alternative solutions to doing their tasks. There is an overall culture of openness to new viewpoints and ideas, which may be because of the nature of academia where people are there with the express intention of learning new things.

There have been some issues with decision-making because it is unclear how the responsibilities lie, and the decisions are not communicated well enough. This was mentioned in the Project story (an artifact of the agile decision guidance method) and confirmed in the assessment. Furthermore, it is sometimes difficult to see the result of the changes because the satellite has not been launched yet and there are some choices that will be verified once operational.

SOCIOTECHNICAL ASPECTS AND HOW TO MANAGE THEM

The AD G method uncovered some specific sociotechnical issues:

1. **Differing customer goals:** There is a wide variety of customers, ranging from students to professors to the end-users of the satellite Earth Observation (EO)-data. The

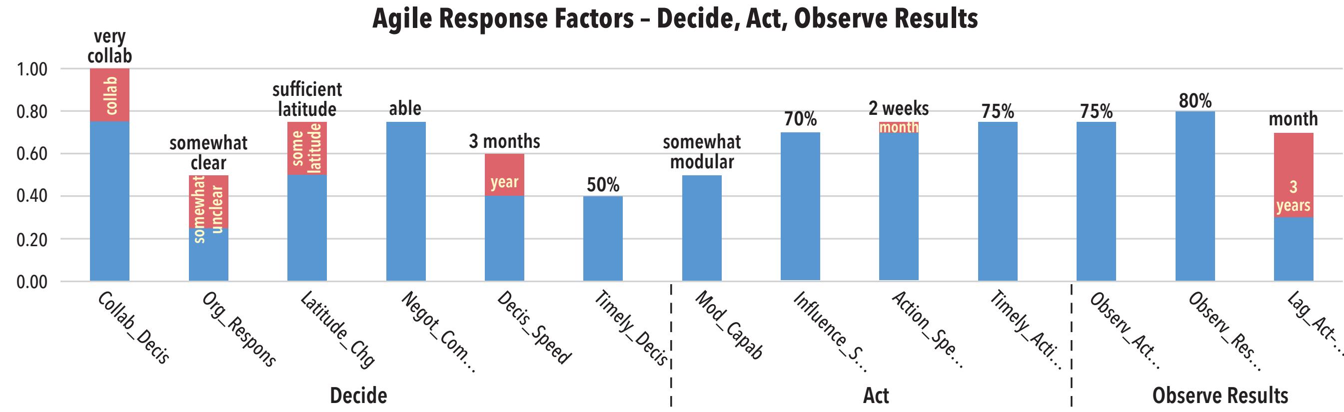

Figure 3. Agile Response Factors Assessment

students have a goal of graduating on time, and the end-users want to get their satellite EO-data. What a thesis consists of may not always be what is needed to get the product from the satellite, for example, building firmware to interface with a camera is not necessarily a good scientific master thesis.

2. **Mission challenges and constraints:** Students often do not have experience with projects nor space technology, which is challenging to plan the development effort with.
3. **Support environment:** This is not shown in the systemigram, but the analysis showed that the support environment was unpredictable, unstable, diverse, and difficult to see changes of. This factor includes machining, purchasing support, logistics, test facilities, electronics engineering support.

An updated version of the systemigram, in Figure 4, includes the Support environment as an actor and how it relates to the system and team.

EDUCATIONAL ASPECTS

A recurring theme in the discussions was how the team consists of students with little or no experience in neither project work nor systems engineering. Furthermore, most of the technical problems appear during the integration, or verification and validation. On one hand, it may be because the requirements have changed frequently. On the other hand, the lack of integration planning and understanding of how a thesis task may work in the final system have created problems.

There is an opportunity to increase the probability of meeting the schedule objectives of the project, and to train students in systems engineering by aligning the CubeSat project work as a PBL course. The learning objectives can be two-fold, one centered in systems engineering capability, and another in the specific discipline of the student. The student then can take ownership of developing these skills through application in their thesis, which is applied to the CubeSat project and contributes to the overall system.

CONCLUSION

Application of the ADG method was able to uncover sociotechnical challenges and identify factors which could benefit from an agile approach in a university CubeSat project. The ADG method uses a questionnaire and supporting discussions as the basis for analysis, to help organization determine where to concentrate agile efforts.

CubeSats are increasingly being used for advanced scientific research missions both in industry and in universities, and

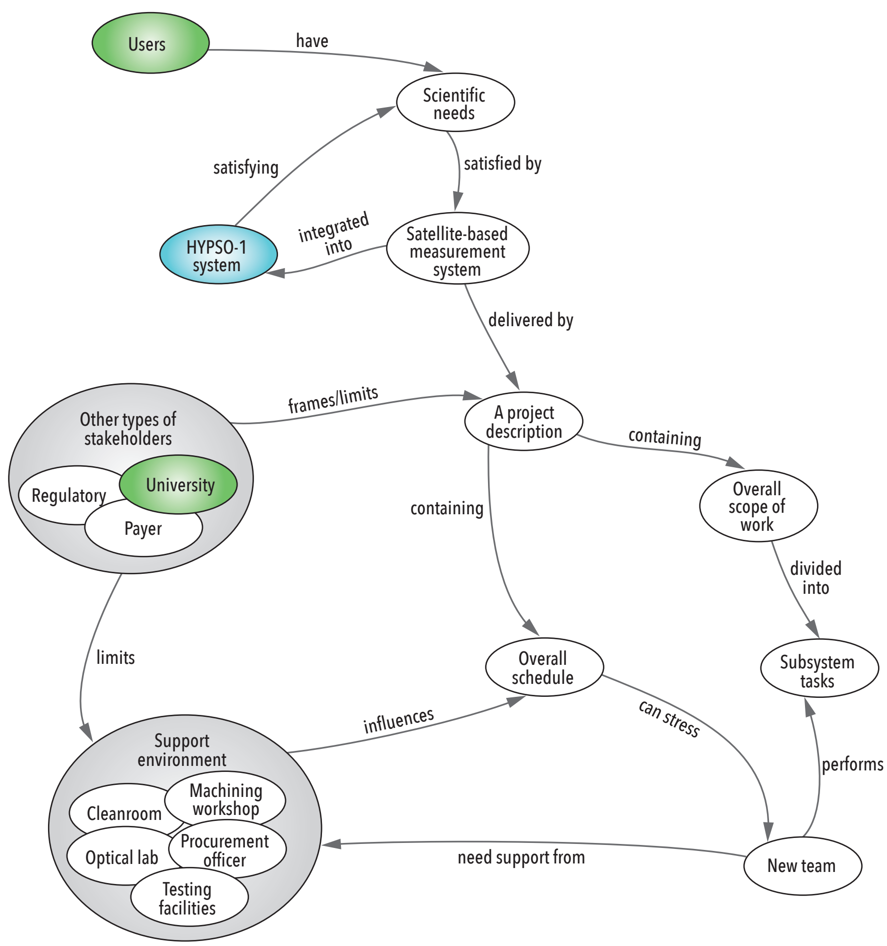

Figure 4. Updated Systemigram with Support Environment

there is a need to understand how this can be done in the context of university and its organizational structures. The university CubeSat project has unique sociotechnical challenges such as an unpredictable support environment, a resource base with little project or systems engineering knowledge, misalignment between project work and coursework, and unclear decision-making processes. There are also unique benefits like not being "set" in a way of working, both due to lack of previous work experience, and because the team changes every year. This gives an opportunity for introducing new ways of working, methods for collaboration, tools, etc. Finally, there is a strong sense of team cohesiveness and positive attitude towards change, partly because the student team is already in a learning environment. ■

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To Get Systems Engineers Interested in Social Dimensions, Give Them a Social Optimization Problem

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ABSTRACT

Systems engineering provides methods and tools to model and design the engineered system jointly with the external context of the system, specifically including social, economic and policy models. This article provides an example approach to formally model the system to optimize around social constructs (recognized social variables). In an educational program, this challenges engineering students to work through an optimization problem that considers social, economic, and technical requirements and conduct trades equally across all dimensions. We present a case study on student-led implementation trades for urban electrical microgrids that optimize community sustainability and resilience. In this case study, the students used formal models of non-traditional socioeconomic variables such as availability, energy burden on residents, and local jobs created. The case study presents a straightforward process that considers social requirements and metrics in systems engineering design that are typically overlooked. We present this as both an example learning framework and a broader call to define and standardize systems engineering methods, processes, and tools for increased integration of social dimensions as functional requirements in future systems.

THE INCOSE IMPERATIVE FOR SOCIALLY RESPONSIVE SYSTEMS

Students in systems engineering programs often are given assignments to optimize system requirements across business and technical drivers. They may consider broader socioeconomic and sociotechnical aspects but are seldom required to consider these in system optimization trades. However, socially related optimization variables are readily available and can be formally incorporated into system requirements and performance trades. We present an example case study to provide an impetus for the educational community to incorporate more formal evaluation of social aspects into future systems design and practices.

INCOSE Vision 2025 states an imperative to apply systems engineering to help shape policy related to social systems and it identifies several societal grand challenges, including energy security and sustainability. Vision 2025 further states a future where "the addition of a formal systems approach helps decision-makers to select cost effective, safe, and sustainable policies that are more broadly embraced by the stakeholder community." It specifically identifies eight key characteristics of future systems: sustainable, scalable, safe, smart, stable, simple, secure, and socially acceptable (INCOSE 2014). Each of these "8S" characteristics is an architectural attribute of a system that is responsive to wider system viewpoints and can be explored to enhance holistic learning skills. Table 1 relates the 8S attributes to the socio, technical, and economic dimensions of a system. Designing to satisfy each of these attributes should be a goal of future systems. When educating systems engineering students, attempting to optimize across these goals provides a learning opportunity that encourages sustainable development, systems thinking, and the use of systems engineering tools.

EXPLORING THE SOCIAL DIMENSIONS OF AN ARCHITECTURE LEADS TO SYSTEMS THINKING

We have explored, educated, and reported on a body of work that addresses sociotechnical analysis in large engineered systems and have consequently developed frameworks that help the engineering community think through the "socio" aspects of engineered systems (McDermott et al. 2018, McDermott and Nadolski 2018, McDermott and Freeman 2016, McDer-

Table 1. "8S" Architectural Attributes of Socially Responsive Systems

Attribute	Socio	Technical	Economic
Sustainable	Support community livelihoods	Incorporate more sustainable technology	Maintain a successful business
Scalable	Support urban densities/ populations	Efficiency increases with scale	Scalable capital and operational costs
Safe	Minimize hazards & loss	Minimize risks	Minimize liability
Smart	Involve community in operations	Incorporate data and information flows	Operate efficiently and optimally
Stable	Increase human access & wellbeing	Meet service quality objectives	Manage cost of service
Simple	Operate locally, create jobs	Elegant technical architecture	Repeatable business model
Secure	Ensure privacy	Protect operation	Protect operation
Socially Acceptable	Improve standard of living & wellbeing	Design for aesthetics and equal access	Promote distribution of equities

mott and Nadolski 2016). Encouraging systems engineering students to consider the broader socioeconomic, sociotechnical, and sociopolitical environment requires the use of systems thinking methods and tools that are designed to incorporate and encourage exploration of these elements. The students learn two fundamental processes: first, creating appropriate models of the system and its wider context, and second, facilitating agreement and decision-making that the models accurately represent the behavior of the system in the real world. The systems thinking mindset shifts the disciplinary focus in systems engineering from project level processes and synthesis of function to domain level processes and optimization of architectural attributes. The systems engineer as a facilitator of group knowledge requires skills related to leadership, creativity, and self-mastery. Creating appropriate models requires knowledge of the correct theories, concepts, principles, and patterns that reflect the wider system behaviors. Godfrey, Deakin Crick, and Huang recommend immersing students in a context-driven problem, then having them develop a systems architecture that captures the system and context as a multi-disciplinary exploration. The fact that a solution cannot be known up front exercises their ability to learn and builds competence in the use of systems tools (Godfrey, Deakin Crick and Huang, 2014).

Case studies related to sustainable and resilient development contribute significantly to the student learning process. They learn to be holistic by exploring a system architecture that is outside their experience (Godfrey, Deakin Crick and Huang, 2014), and they develop analytical and computational skills through analytical methods for decision making. Systems and critical thinking are encouraged through an instructor facilitated process that begins with research, develops narratives, creates conceptual models, and defines data parameters to support structuring of models for decision making (McDermott and Nadolski, 2018).

Most learning frameworks aim to simplify complexity of these large systems. We believe it is integral to development of systems thinking to study how different factors interact with one another in a complex system to enable or inhibit beneficial change. To support this work, we combined three frameworks that link policy models and decision models to better capture the context and the system, shown in Figure 1.

We use a conceptual "three-systems" model to encourage breadth of analysis. This model is extended from Larsen's "universal mental model of a system" and encourages one to view the problem to be solved as a situation in a system-of-systems, the solution as an innovation system responding to a business opportunity, and the coupling of these as a change to a sociotechnical system of some complexity (Lawson, 2010). The students are encouraged to view this as a layering of phenomena at different social levels in a multi-level modeling problem as derived from the work of Rouse, shown in Figure 2. This provides an enterprise analysis methodology for capturing aspects of complex systems and their context (Rouse, 2015). A human capital modeling framework is provided to the students – this was developed by Hutto and organizes a complex model of human standard of living and social wellbeing (Hutto, 2017). This framework is shown in Figure 3 and represents research on structure equation modeling of human capital development core to social resilience.

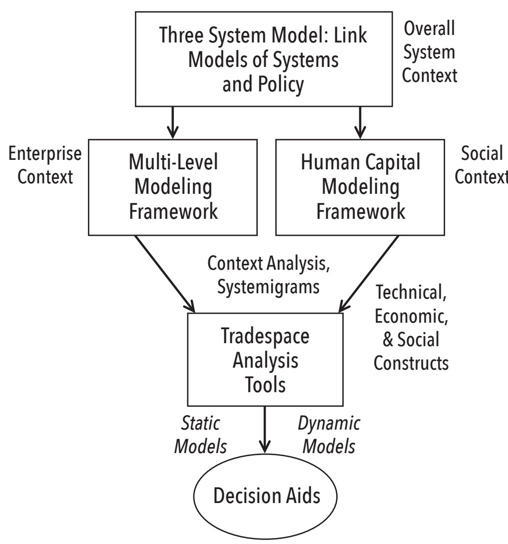


Figure 1. Frameworks and Methods [1].

The resulting insight provided by these systems analysis frameworks is then captured into a set of model-based systems engineering (MBSE) tools that provide knowledge management and trade-space analytics in multiple contexts (McDermott and Nadolski, 2017). This provides more holistic understanding, by not only visualizing critical social, technical, behavioral, and economic aspects, but also capturing emergent properties, interdependencies, and relationships, which existing models and tools often fail to capture. In the learning process, the students quickly develop understanding of the multi-disciplinary nature of the problem, then must make decisions on how to effectively model the system to maximize stakeholder outcomes.

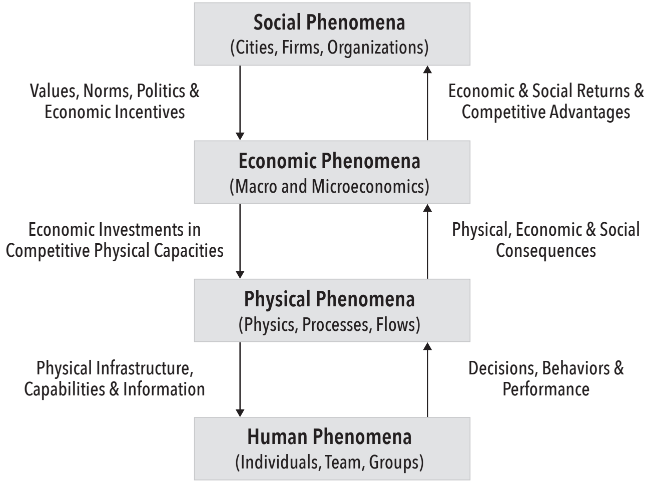


Figure 2. Multi-level Hierarchy of Phenomena (Rouse, 2015).

CASE STUDY: RESILIENT URBAN MICROGRIDS

We use a case study of a student-led, multi-year project to model the feasibility of electrical micro-grids to improve community sustainability and resilience to present our methods and tools. This case study involved a team of five students in a systems engineering capstone project and two other students from a public policy program, all at the post-graduate level. The students were asked to model more sustainable infrastructure while also improving human community resilience for residents using that infrastructure. The students in this case were directed to create decision support tools that explore the possibility of micro-grid application in urban Atlanta, Georgia neighborhoods, using more holistic views of technology, policy, economics, and social wellbeing. The case study was developed as part of a longer-term National Science Foundation project to create families of model-based decision analysis tools that better inform engineers, investors, policymakers, and city planners on the complexity of urban infrastructure systems (Crittenden et al.). The case study explores a framework that combines these activities within the context of urban electrical power infrastructure. Several metrics and models exist to evaluate various subsystems in electrical micro-grids. However, few tools consider their performance and function working together as a whole and in the context of social, technical, and economic decision making as shown in the 8S dimensions of Table 1.

The public policy students created the following contextual narrative. In 2017, Atlanta experienced one of its worse power outage events. At the same time, it also became the 27th city in the United States to commit to operating on 100% clean and renewable energy. Recent events and changing trends like these are often “innovation moments” where technical and social transformation can come together and when informed communities work together to both ends. An Atlanta City Council plan includes a goal of 100% renewable across all city operations by 2025 and a community-wide transition by 2035. The resolution aims to prioritize more sustainable energy sources such as solar power, and more efficient delivery systems such as smart meters and microgrids. The City also aims to create structured mechanisms to include low- income citizens in the benefits to be derived (City of Atlanta, 2017).

However, Atlanta is also constrained by a franchise agreement with Georgia Power through the year 2064 that authorizes the utility’s occupation and use of streets to install, operate, or upgrade equipment. Therefore, any city initiative to improve the resiliency of Atlanta’s energy system and pursue more renewable sources will have to involve Georgia Power. This is a good example of the economic and political constraints that make systems-focused change difficult. Solutions that benefit both the city and its primary utility are needed, and tools that evaluate a balance of infrastructure and community improvements are needed. Chief among these is an increase in community resiliency, which is highly dependent on the city’s infrastructures as well as the human communities using them.

Energy burden is a variable that can be used to feed a social optimization problem in this domain. Energy burden is a measure that spans all four phenomena in the sociotechnical enterprise layers of Figure 2. It is also a well-established indicator of

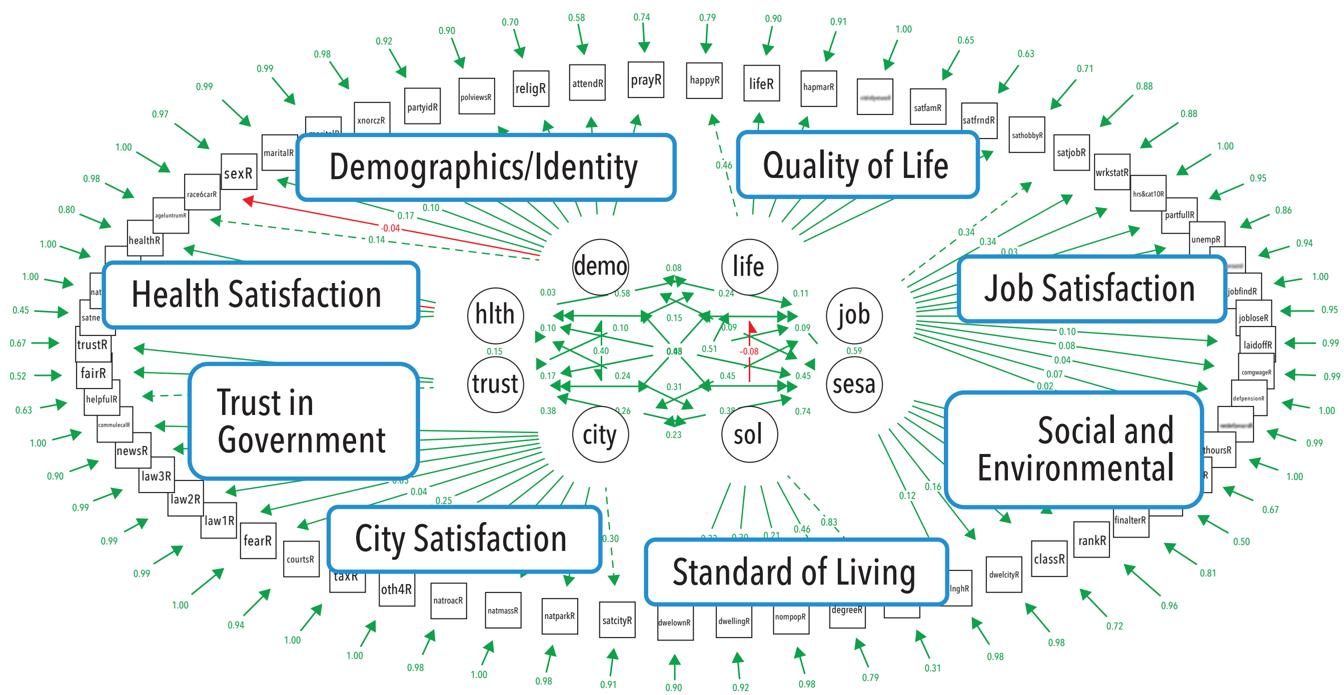


Figure 3. Human Capital Factors Associated with Community Resilience (Hutto, 2017).

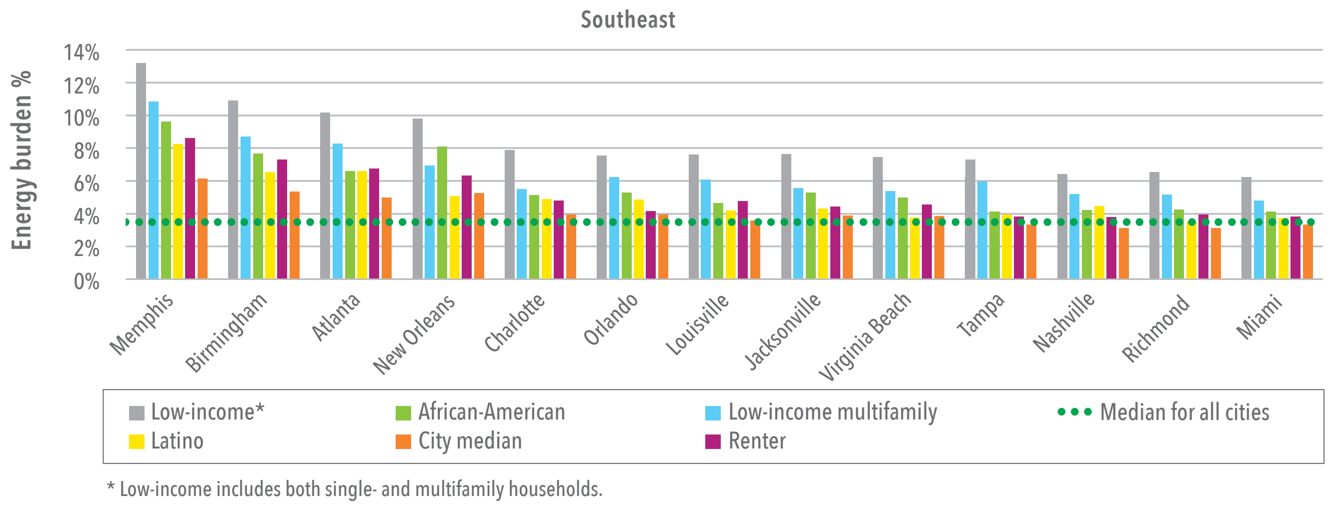


Figure 4. Energy Burden in the Southeast (Drehobl and Ross, 2016).

well-being of a household, linked specifically to standard of living and city satisfaction factors in our human capital model of Figure 3. Energy burden is the proportion of total household income used to pay home energy bills, which includes electricity, natural gas, and other heating fuels. Median US energy burden across all cities is 3.5% while low-income household's burden is twice as high at 7.2% (Drehobl and Ross, 2016). Households that experience high energy burdens (above the metro area median) experience many negative impacts on health, economic well-being and have less capacity to withstand the impacts of shocks such as extreme weather events (Fisher, Sheehan, and Colton, 2020; Heyman, Harington, and Heyman, 2010). High energy burdens can also perpetuate the cycle of poverty by requiring families to devote a disproportionate amount of income to utilities. As shown in Figure 4, many of the metro areas in the Southeast U.S.—a region with low electricity prices and lower average incomes—faced higher energy burdens compared with metro areas nationally, suggesting that low electricity prices do not equate to low burdens. Electricity use is high in these regions due to the warmer climates and amount of air conditioning.

THE SOCIAL OPTIMIZATION ANALYSIS

The public policy and systems engineering students were provided with conceptual tools that helped them think through the enterprise layers and the human capital models of Figures 2 and 3. They were given a scenario in the context of urban community microgrids and the optimization variable of energy burden but were left to explore the holistic system and outcomes on their own.

The students explored three ownership models for a microgrid with renewable energy generation in an urban context in the city of Atlanta: A Public Utility Owned Model, a Community Owned Model, and a Commercially Owned Model. All three scenarios were conceptually modeled, and structural case studies examined to understand the incentives and motivations for stakeholders as well as stakeholder financial involvement. The option for the creation of a community-scale microgrid through the financing of a private investor (commercial entity or non-profit) was selected. The case study had the students taking the role of a theoretical grid operator.

Two Atlanta neighborhoods were selected and analyzed as case studies for the models.

Table 2. Neighborhood Energy and Cost Data (McDermott et al., 2018)

Neighborhood/ Region	Grid size: # of Households (HH)*	Energy Consumption (KWh/HH/Yr)*	Residential $/KWh*	Energy Cost ($/Yr/HH)*	Median annual HH Income ($)**	Energy Burden
King Memorial	1,388	13,951	$0.116	$1,618	$23,407	6.91%
Lindbergh Center	4,162	17,116	$0.116	$1,985	$69,721	2.85%
Georgia	*4,191,209*	*13,464*	*$0.115*	*$1,554*	*$61,250*	*2.54%*
South Atlantic	*26,787,726*	*13,416*	*$0.117*	*$1,575*	*$55,030*	*2.86%*
US	*129,811,718*	*10,812*	*$0.127*	*$1,368*	*$56,500*	*2.42%*

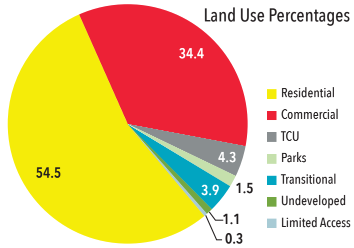
*data from Georgia Power **data from itsmarta.com HH=Households; KWh=Kilowatt Hours; Yr=Year

Table 3. Example Microgrid Energy and Cost Sizing Data (McDermott et al., 2018)

Neighborhood/ Region	Grid size: # of Households (HH)	Size of the Microgrid (Megawatt)	Energy Output (KWh/Yr)	Energy Value/Year ($)	Solar Panels/ Smart meters needed	Capital Cost ($)
King Memorial	1,388	13.5	19,664,620	$2,556,401	13,880/1388	$56,144,600
Lindbergh Center	4,162	49	71,375,293	$9,278,788	41,620/4162	$168,352,900

Lindbergh Center Station Area Profile

Land Use Within 1/2 Mile

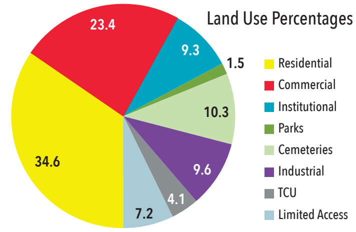


Sources:
MARTA GIS Analysis 2012 & Atlanta Regional Commission LandPro 2009.

Residential Demographics 1/2 Mile	
Population	7,640
Median Age	30.7
Households	2,436
Avg. Household Size	3.14
Median Household Income	$69,721
Per Capita Income	$28,567

King Memorial Station Area Profile

Land Use Within 1/2 Mile



Sources:
MARTA GIS Analysis 2012 & Atlanta Regional Commission LandPro 2009.

Residential Demographics 1/2 Mile	
Population	6,678
Median Age	37.1
Households	3,198
Avg. Household Size	1.94
Median Household Income	$23,407
Per Capita Income	$19,642

Figure 5. Community Demographic Data (MARTA, 2017)

Each are within a ½ mile radius of a Metro Atlanta Rapid Transit Authority (MARTA) rail station that lays in the border of the community. Selection of these neighborhoods was based on available data. Besides demographic and population estimates, the project had access to detailed energy cost and models of solar energy capacities in each area. King Memorial was selected as a representative low-income neighborhood, while Lindbergh Center was indicative of an average income community. Neighborhood energy use and cost data is shown in Table 2. Examples of the grid sizing and costing data is shown in Table 3. Residential demographic data is shown in Figure 5.

The students used a systemigram (Boardman and Sauser, 2008) to map out the relationships between the social, technical, and economic aspects of the situation, sociotechnical context, and solution space. This is shown in Figure 6. A systemigram is a useful approach to visualize the complex relationships across political, economic,

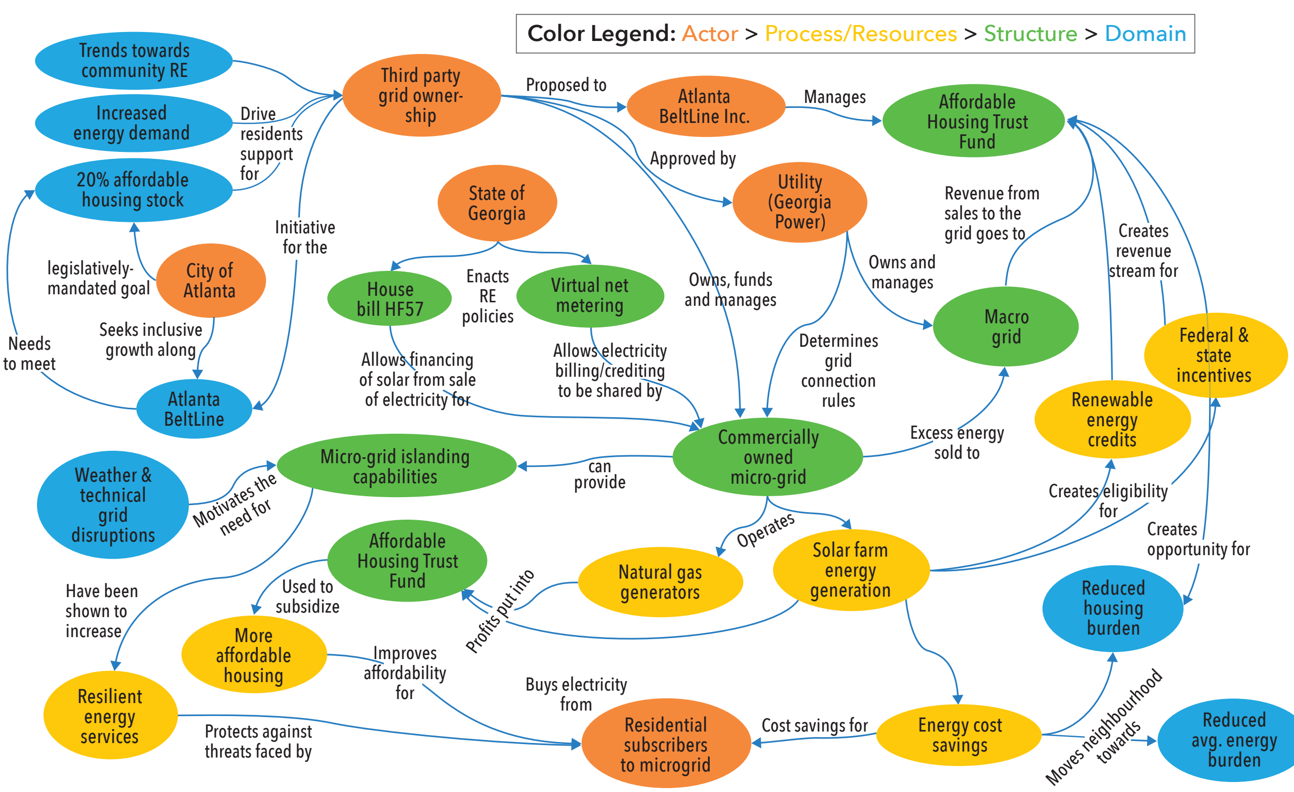


Figure 6. Systemigram diagram of a commercially owned microgrid (McDermott et al., 2018).

Table 4. Weighted Requirements Model (McDermott et al., 2018)

Category	Relative Weight	Requirement	Engineering Characteristics/ Measures
Technical (50%)	14%	System shall deliver power with high **reliability**	Downtime (total minutes/year)
	14%	System shall deliver power with high **quality**	Voltage and frequency variation and waveform distortion
	8%	System shall use multiple power sources to increase energy security	Connect to Macro-grid with islanding capability, mix of fuel sources
	8%	System shall utilize solar as primary power source	Commercially available solar panels
	1%	System shall enable interoperable component level integration	Use non-proprietary components
	1%	System shall enable sharing of power amongst customers	Enable two-way flow of energy and information
Financial (25%)	10%	System economic value shall be greater than cost	Revenue > Capital +Operating Cost
	8%	Price of microgrid-generated electricity shall remain stable over time	Change in price over time
	3.5%	The system shall engage available customer segments in the community for power generation	Power generation aggregate penetration %
	3.5%	There shall be minimal upfront capital expense for disadvantaged customers	Upfront capital expense per sliding scale
Community (25%)	7%	Microgrid owner shall use local labor for construction and operations	Employment per Megawatt
	7%	Microgrid owner shall use local materials	Economic Development/Megawatt
	5%	System shall reduce energy burden for disadvantaged end-users	$ gained through incentives (tax credits/ subsidies)/ surplus power to the grid
	4%	Microgrid owner shall include an energy efficiency education and awareness component	% of members who engage in energy efficient behavior
	2%	System shall be located on marginal-use lands	Acreage of marginal land repurposed

social, technological, legal, and environmental (PESTLE) factors of a system. The diagram starts with a set of motivations that would drive a potential residential grid owner (Atlanta Beltline Inc.) to engage in the development of a renewable energy microgrid. Stakeholders from Atlanta Beltline Inc., a non-profit urban renewal enterprise, supported this case. The systemigram visually articulates the impacts of this development on the residential community. The students envisioned use of part of the profits for the electrical services to help fund a trust dedicated to affordable housing in the grid area, which could be used to offset energy burdens directly using credits for low-income participants. Two key enablers, one policy related (Ga House Bill HF57) and one technological (virtual net metering) are prerequisites for a commercially owned microgrid in the state. The house bill allows private entities to finance capital investment in the system. The capital investment cost and years to break even was a key aspect of the decision space evaluated by the students, as well as funding an affordable housing trust from the resulting revenues from microgrid sale of excess energy back to the city grid.

With this visual scenario in hand, the students used stakeholder interviews to establish high level requirements and engineering characteristics across technical, economic, and community social domains, as shown in Table 4. Each requirement was ranked, and the students used Quality Function Deployment (QFD) to produce weighted requirements ranking for the trades.

Use cases were used to further derive the system requirements such that the structure of the microgrid model and stakeholder roles were identified in detail. The use cases identified the community role of the grid customer in generating, maintaining, and controlling the system. A systems dynamics model was developed to create a dynamic model of solar microgrid energy and cost flows on an hourly basis to estimate various energy demand and production scenarios at scale. The revenue model integrated into the systems dynamics tool is shown in Figure 7. This is one of many views in the model but is relevant as the community control of "Surplus Energy revenue per Year" as related to Total Available Energy vs. Demand % are the primary means to generate community support from the system. These must be modeled within a longer-term capital model highlighted as "#Years to break even."

Not shown are components of the systems dynamic model associates with grid

Figure 7. Revenue portions of the system dynamics model (McDermott et al., 2018).

resilience (dynamic energy output versus demand) and jobs created (associated with operations cost in the model). To understand job creation, additional use cases were created associated with customer staffed generation, operations, and maintenance roles that modeled staffing sizes for the system associated with operations cost. The model generated data fed into a decision-aiding tool using multi-attribute analysis techniques to evaluate the decision space. The primary decision variables were years to break even (capital costs and operating costs/revenues), energy resilience (ability to maintain available energy during shocks), and local jobs created.

Resilience scenarios included technical, economic, and environmental factors such as failures, weather events, and price shocks in energy costs. Grid options included a standalone microgrid with battery storage, a dedicated connection to the (city) macrogrid, and a macrogrid connected system with the capability to island off the city grid. Fuel options included solar, natural gas generation, diesel generation, and macrogrid sources. The model investigated resilience to both environmental/technical disruptions and to fossil fuel price shocks, with price shocks representing the primary community impacts in standard of living and energy burden. The highest resilience solutions are unaffordable in years to break even, but microgrid subsidy credit models require a 20-year operating commitment, so this is a convenient set point for "# Years to break-even." With that assumption various mixes of energy generation sources can be optimized. Given a grid implementation size and mix, the energy generation, demand, revenue, and job generation can be calculated. With these quantified, a "Surplus Energy revenue per Year" calculation can be used to, for example, justify funding a trust for low-income customers to address energy burden.

Using today's technologies in the models, neither diesel or battery backup options met a base constraint of a 20-year breakeven cost, and battery technology at this time is unaffordable at urban community scales. Optimal solutions are solar with either natural gas generation or macrogrid backup or a combination. A combined micro- and macro-grid solution with islanding is preferred because of the opportunity to sell excess energy to the city grid as a revenue source and use the city grid as a backup for resilience. A natural gas source with secondary solar generation is optimal at this time but increasing solar generation will improve revenues to the housing trust as prices come down and provide more resistance to fossil fuel price shocks. All these options must deal with policy constraints specific to a region. However, the models provide decision tools for policy makers, energy providers, and community leaders to evaluate options locally.

The models indicate a more sustainable and resilient community level microgrid can improve energy burden and other social factors associated with community resilience. The students learned in the process that the technical and cost trades associated with an urban microgrid are straightforward but required a dynamic simulation for accurate assessment. Combined solar/ natural gas generation on a community scale (1000-5000 households) is technically feasible and financially feasible looking at a 20-year breakeven model. It offers higher energy resilience than the macrogrid and would produce local jobs. However, generating revenues for subsidies requires significant (city) financial investment in the capital costs of the operation. Finding approaches to directly impact energy burden through subsidies and tiered pricing models is difficult. Also, the regulatory issues with local implementation are a barrier.

The students demonstrated that it is feasible to model and conduct analyses of alternatives for a system considering a broad range of social, economic, and technical requirements. All these factors can be investigated with normal systems engineering tools, given the right support. From an instruction point of view, systems engineering educators should know that such analyses are possible in a systems engineering case and that broad social, economic, and technical trades in an INCOSE "8S" framework can be designed and taught.

CONCLUSIONS

Case studies that encourage learners to model the system, its business goals, and the external context together are necessary for development of good systems thinking skills. Systems engineering can formally adopt approaches where the engineered system is modeled jointly with the external context of the system, particularly to include social, economic, and policy models. Using the series of models, tools, and frameworks presented in this case study and approach allows students and systems engineers alike to link policy models and decision models to better capture the context and the system. This over time will make systems engineering more relevant to non-engineering domains.

A systems engineering approach uses tradespace analysis methods and tools for analyzing requirements and performance trades addressing both engineering design and social aspects of human and infrastructure systems. In this case, a standard systems engineering process is used, augmented by enterprise level methods and tools developed help the systems engineer capture and manage the complexity of a sociotechnical problem. The enterprise system views provided both qualitative and quantitative methods for capturing aspects of complex systems and their context.

Systems thinking skills are encouraged by having a case study specifically related to sustainable and resilient development, forcing evaluation of these architecture characteristics, as opposed to just technical design characteristics. By incorporating policy analyses, technical energy components, financial budgeting, weighted requirements and socio-economic studies of resilience and energy burden, the students were able to create a dynamic systems model that could be invaluable to policy makers focused on improving city-wide resilience or initiating the transition to fossil-fuel free economies. The exercise encouraged the students to work through an optimization problem that considers social, economic, and technical requirements and conducts trades equally across all dimensions. Beyond creating socio-technical models of the system, they additionally learned how to facilitate interdisciplinary discussions by facilitating agreement and decision-making to create accurate models that represent the behavior of the system in the real world. ■

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Applying Behavioral Science to Agile Practice Evolution

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ABSTRACT
Early agile practices developed by trial and error and are retained "because they work." The fact that certain approaches work well in agile realization of products and services is not accidental – it is rooted in the study of psychology, sociology, and human performance. For example, the "ideal agile team size" of 7 plus or minus 2 not only works but is supported by psycho-social theories such as the Ringleman effect, social channel capacity and short-term memory limitations. Examples of similar relations between behavioral science and agile patterns abound – preferred planning horizons, methods of estimating effort and approaches to scaling agile all relate to our understanding of human behavior individually and in groups. This article will explore such relationships with the intent to provide agile practitioners with information about the underpinning of practices, and social scientists with examples of how their work contributes to the improvement of agile practices.

INTRODUCTION

Agility in engineering and science is in a period of growth and change, both in our understanding of how to engineer systems that are agile and how to perform engineering and science in an agile fashion. The software development community adopted agile practices and design patterns early, but those patterns are now fanning out into a broader range of engineering and scientific endeavors. SpaceX (Denning, 2020) and SAAB Aeronautics (Lindlöf, L, 2018) design and develop complex hardware systems using agile methods, and Thermo Fisher Scientific (Scrum Alliance, 2016) applies a variant of scrum, an agile framework, to realize medical devices.

As agile practices branch out into a broader range of engineering and scientific work, the frameworks should change and evolve to support new circumstances, informed by consideration of how humans interact and work together individually and in how they perform in groups. Fortunately, behavioral science has studied many of the principles underlying current agile practices and can collaborate with the engineering community to define effective practice variants for additional domains. In this article, we explore patterns in behavioral science that can provide "reusable components" of agile engineering in the same way modular components enable agile technical systems.

In *Lean and Agile: Synergy, Contrast, and Emerging Structure* (Dove 1993), Dove describes agility as "The ability to thrive in an environment of continuous and unpredictable change". In the context of engineering and science, both the systems and the people developing them must demonstrate this ability. Practices that exhibit agility tend to share a set of attributes that enable success in such environments. *Managing Complexity with Agility and Openness* (Rosser 2019) identifies the following enabling attributes for agile practices:

- Move from the unknown to the known in short cycles
- Assume unpredictability, design to deal with it
- Value responding to change over following a pre-defined path
- Focus on valuable outcomes, be flexible in intermediate steps

Each of these attributes enhance performance in a changing and unpredictable environment. As practitioners explore alternative practices for agile science and engineering, they should be mindful to retain these valuable attributes.

The majority of current used agile development and design patterns were codified in the software development domain, with some forays into the acquisition and configuration of commodity information technology hardware. As agile practitioners begin to apply these patterns in other domains, adjustment is sometimes needed. The challenge is to adapt to the new circumstances without violating the underlying principles of the pattern.

An example of this in the technical pattern space is the practice of encapsulation. To enable short learning cycles, rapid testing, and early delivery of value, implemented elements may only have minimal dependencies on one another. In the software development realm, the principle of encapsulation is implemented in the form of capabilities, features, and stories which are increasingly smaller elements of loosely coupled functionality. Hardware realization does not always lend itself to this type of encapsulation and decomposition due to the need to provide packaging, power, and physical interfaces. Because of this, hardware agilists may encapsulate and decompose using systems, products, and components taking a structural rather than a functional approach. While this may "look funny" to the typical software agilist, it does not violate the principles of encapsulation and loose coupling. It may very well constitute a valid variant of agility for some domains.

Alternative applications of agile patterns occur in the process space as well as the technical architecture and design spaces, and in these arenas, the underlying patterns are less universally understood by engineers. In most cases, agile process patterns (often referred to as frameworks) were developed empirically and accepted because they succeeded in their original domain. While this is a valid approach to defining a practice, it is not illuminating when modifying the practice for alternate uses.

For example, consider the application of *timeboexes*. These short, fixed length planning and work periods feature in many agile frameworks, but when practitioners are unaware of the science behind their effectiveness, misapplications may occur. It is common for practitioners to decide to fit timeboxes to accounting periods, milestone dates or other externalities, not recognizing that such variability reduces the effectiveness of timeboxes in developing work habits and rhythms and honing the team's ability to estimate completion effort. Varying timebox length also complicates planning and increases cognitive loads (Cohn, 2017). So, while it is reasonable for practitioners to modify the standard length of timeboxes to match their circumstances – periods from hours to months may be appropriate- creating variable timeboxes is not usually advisable.

In the following section, we examine common process patterns embedded in current agile frameworks, drawing on research in the behavioral science of human interaction and performance to identify key concepts that should be maintained when modifying agile practices.

COMMON HUMAN PATTERNS USED IN AGILE FRAMEWORKS

Integrated work teams are a key element of most agile frameworks for product development, with significant attention on their formation, structure, and operation. *Team Composition and the ABCs of Teamwork* (Bell et al. 2018) explains, "Teams are a means of organizing work so that individuals can accomplish more than they can on their own.[…] The value of organizing work into teams is that a team member does not need to be able to do everything on his or her own: a team provides access to a broader pool of perspectives, capabilities, and efforts." Cross functional teams are integral for many agile frameworks, providing a foundation for rapid learning, design for unpredictability, response to change, and flexible implementation, enabling true agility.

While teams facilitate a broader perspective, higher capacity, and rapid checks and balances, teamwork also has its own issues and challenges. Research shows that working in teams inevitably creates some overhead in the form of communication and coordination (McMillan, et al. 2014). Team assignments can also provoke social loafing (Simms and Nichols 2014), in which individuals exert less effort as their contribution becomes less obvious in team outputs. Because of these and other potential negative characteristics of teamwork, it is important that the structure of the team itself, as well as the division and reporting of work and team activities, be tuned to the sweet spot in which the benefits of teams significantly exceed the drawbacks.

One pattern for agile teaming is the commonly recommended individual team size of seven plus or minus two (Hetherington 2020). This number is large enough to access team virtues of capacity and diversity, but small enough for individuals to maintain close relationships and for their individual efforts to show.

In addition to team size, there are certain aspects of team activity shown to contribute to success. One characteristic of successful teams is a common understanding of their team charter, environment, goals, and capabilities, sometimes described as a shared mental model (McMillan, et al. 2014). This is the genesis of the agile pattern of team planning, which leads the team to commit to a well understood set of objectives for the team. The basic pattern of agile team planning includes several other common characteristics.

A short tactical planning horizon plays to the human capacity to plan details effectively, and the human propensity to procrastinate when deadlines are vague and far in the future. From the perspective of agility, this short horizon also promotes rapid learning and the ability to adjust quickly to changes.

Relative estimation acknowledges that humans are much more effective at evaluating relative characteristics of size and duration than at providing accurate numerical estimates of the same characteristic. This approach helps teams quickly get to a reasonably accurate plan without spending excessive time fretting over a level of accuracy that is difficult to achieve and highly likely to change.

Team decomposition of tasking ensures a common understanding of the team's work and at the same time allows each team member to select short individual tasks for which they are responsible to complete. This allows for team innovation and responsibility but also leaves room for individual performance. These atomic tasks also limit multitasking, promote flexibility, and enhance the ability to modify plans when needed.

Visual Representation of Work is another common pattern in agile science and engineering. Examples include *Visual Information Radiators*, which make clear, simple visualizations of key information continuously available to teams, and *Andons*, which provide simple shared visual indications of progress or problems. These visual representations focus teams on both outcomes and process by providing easily interpreted information about the work to which the team has committed and its current state of progress. This provides a common abstraction of the state of work to which the team can respond and develops the team's shared mental model of their work.

The patterns described above are formalized in basic agile frameworks such as scrum, XP, and Kanban. They have proven effective in agile team operation and are also validated by research in the social sciences. Practitioners would do well to bear these patterns and the behavior science behind them in mind when adapting agile practices to new types of work.

AN EXAMPLE OF AGILE PRACTICE EVOLUTION – LARGE SCALE PROJECTS

One area of evolution in agile practices is the application of agile to exceptionally large projects. As the number of practitioners involved in a project exceeds the nominal team size of 5 to 9, productivity issues quickly appear. This may lead the project to form multiple agile teams, but practitioners have found that not all proven agile practices scale directly (Butkus 2020). For example, projects requiring more than five or so agile teams of five to nine people each may find that creating multiple instances of the basic team structure does not meet their needs for integration, communication, or dependency management. This leads to the development of additional patterns for scaling that should be informed by the behavior of humans in larger numbers.

The Scaled Agile Framework (SAFe) introduces the concept of the Agile Release Train (ART) to address the needs of larger projects, and it includes several additional patterns to support the more complex team structure.

The size of an ART is capped at 150 participants, in line with research on social channel capacity (Dunbar 1992) (Scaled Agile 2019). In addition, specific roles for participants who support multiple teams are defined to be filled by people comfortable and skilled at bridging networks.

Additional visualization elements such as the program board are introduced to provide a common context for milestones and dependencies for all participants, and the program increment planning event provides a regular opportunity to ensure that the entire team of teams maintains a shared mental model of their work.

These examples illustrate the value of applying knowledge of behavioral science to the evolution of agile practices, enabling adaptation while retained effective constructs for human iteration.

ADDITIONAL AREAS FOR IMPROVEMENT

In addition to addressing the challenges of large project teams, there are other areas were evaluating agile practices in the context of both a range of project domains as well as human behavior and performance may also be beneficial. For example, while agile product development values working capabilities over comprehensive documentation, what level of documentation, and of what type of information is necessary for people to effectively develop and mature systems using agile engineering? How does the necessary documentation change based on project size, duration, or complexity? How can interactive models and visualization of performance and interdependencies be applied to enhance team performance? How should agile practices evolve to better support distributed and culturally diverse teams?

Agile product development focuses on both quality and innovation, and the combination of these attributes requires active engagement of human ingenuity and teamwork. In the same way that technical patterns provide the underpinnings of agile technical systems, engagement with the human and social sciences offers us the opportunity to enhance agile practices to meet the evolving goals of agility in the engineering and scientific work required in our ever-changing world. ■

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Detecting and Mitigating Social Dysfunction within Systems of Systems

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ABSTRACT
What are systems engineers supposed to do when social dysfunction leads to operational dysfunction? This article elaborates on a means of assessing the managerial relationships between the organizations that own constituent systems (CS) within a system of systems (SoS), with a goal of detecting social dysfunction that could adversely affect operations. For each of the relationship types, or affinity options, tangible, actionable guidance is offered that could help mitigate the social and operational dysfunctions. Results from a case study are included to illustrate the application, detection, and successful mitigation of social dysfunction within a system of systems.

KEYWORDS: system of systems, SoS, operational independence, managerial independence, social dysfunction

INTRODUCTION

ISO/IEC/IEEE 21839:2019 defines a system of systems (SoS) as a "set of systems and system elements that interact to provide a unique capability that none of the constituent systems (CS) can accomplish on its own," while noting that each CS is a "useful system by itself, having its own development, management, utilization, goals, and resources, but interacts within the SoS to provide the unique capability of the SoS." Sometimes, organizations and their systems do not function together properly. Detecting and then mitigating social dysfunction between organizations that own CS within SoS is an important aspect of SoS engineering.

By rating the importance of the exchanges in the relationships between systems and the organizations that manage them, the strength of alignment or affinity can be assessed. SoS Operational Affinity provides insight into the extent to which systems share common interests, while SoS Managerial Affinity provides insight into the extent to which organizations that own CS share common interests.

SoS Managerial Affinity provides a means to detect social function and dysfunction between organizations or people responsible for CS within an SoS. In the cases of dysfunction, the next step is to mitigate those dysfunctions. SoS Managerial Affinities, their implications, and summary guidance to both the supplier and acquirer are available to understand and mitigate the dysfunctions.

The approach has been applied successfully with positive results. A case study illustrates the approach. Unfortunately, acknowledging dysfunctions as well discussing them to facilitate resolving them are exceptionally difficult.

BACKGROUND ON SYSTEMS OF SYSTEMS

SoS are not just collections of systems. Additional characteristics, often referred to as operational and managerial independence, are what distinguish SoS from systems (Maier 1998). Constituent systems (CS) within SoS can and do operate independently. The organizations are independent, but somehow interdependent. The systems the organizations own are independent but must interoperate with each other. ISO/EIC/IEEE 21840:2019 provide a more thorough exploration of these differences and their implications.

To explore these concepts, say Organization A owns System V, which takes inputs and produces some outputs (Figure 1).

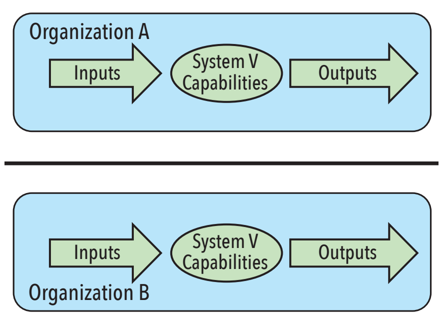

Figure 1. Systems that do not interact are not part of an SoS

Likewise, Organization B owns System W, which takes inputs and produces some outputs. The organizations could be separate corporations, governmental agencies, or business units within a larger organization. Because these systems do not interact with each other, there is not an SoS here. Organizations exert managerial control over their respective systems through goals and objectives, which are subject to laws, regulations, and other constraints. This is nothing new – organizations leverage humans to manage programs or projects that oversee systems.

An essential characteristic of CS within an SoS is that they remain operationally

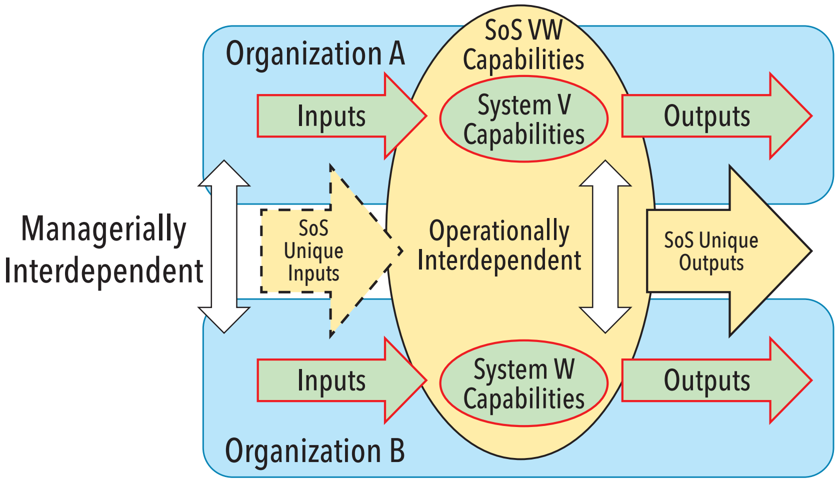

Figure 2. A set of systems and system elements interact to provide a unique capability

independent. That is, they fulfil some number of purposes on their own separate from the SoS. However, CS are also operationally interdependent as they work together to produce the SoS outputs. This seems contradictory. Something that is independent does not depend on something else. Yet here we are. CS are never independent, yet they are also never subservient to the SoS (ISO/EIC/IEEE 21840:2019).

Another essential characteristic is that CS within the SoS are managerially independent. This means that organizations that own CS, plus the people within the organizations, could have goals and objectives that differ from those of the SoS. Recall that Organization A manages System V and Organization manages System W. If these systems interact, an SoS emerges (Figure 2). The SoS, called VW or WV, provides something unique that systems V and W did not provide on their own. These systems are now operationally interdependent. The organizations are now interdependent as well. We have a conundrum. The organizations are independent, yet interdependent because their systems are independent, yet interdependent.

DETECTING FUNCTION AND DYSFUNCTION WITHIN SYSTEMS OF SYSTEMS

Relationships between systems and organizations can be explored using a framework of affinities (Yokell 2018A). SoS Operational Affinity provides insight into the extent to which systems share common interests, while SoS Managerial Affinity provides insight into the extent to which organizations that own CS share common interests. In both cases, a simple Likert-type scale can be used to assess the importance of the exchange.

From the perspective of the systems, the consuming system can assess the importance of the operational input while the producing system can assess the importance of the operational outcome using a scale:

- 2 = highly important in a positive way
- 1 = somewhat important in a positive way
- 0 = not important
- -1 = somewhat important in a negative way
- -2 = highly important in a negative way

By mapping the producer's perspective to the consumer's perspective as a matrix or grid, the relationship between the systems can be characterized (Figure 3) to create the SoS Operational Affinity. Using the same approach, the organizations can assess the importance of the exchanges between them. By mapping the supplier's perspective to the acquirer's perspective as a matrix or grid, the relationship between the organizations can be characterized (Figure 4) to create the SoS Managerial Affinity. The framework assigns names to clumps of boxes to facilitate understanding the relationships.

Because the focus of this article is on social dysfunction, the SoS Managerial Affinity will be used. While the terms *supplier* and *acquirer* reflect organizations, we can also interpret them to mean the managers in those organizations. That is, we also may be making an assessment here of the affinity between people. Determining operational priorities for a system or a CS within an SoS is a managerial function of a person within an organization, which is subject to governance (Yokell 2018B).

MITIGATING SOCIAL DYSFUNCTION WITHIN SYSTEMS OF SYSTEMS

SoS Managerial Affinity provides a means to detect social function and dysfunction between organizations or people responsible for CS within an SoS. In the cases of dysfunction, the next step is to mitigate those dysfunctions. Table 1 on the next page summarizes the SoS Managerial Affinities, their implications, and summary guidance to both the supplier and acquirer (Yokell 2018A).

Affinities on the diagonal of the matrix reflect known alignment of perspectives. Understanding these affinities is straightforward and the suggested mitigations obvious. However, the affinities off the diagonal reflect misunderstandings and potential misalignment of objectives or incentives. Recall that a key characteristic of SoS is that organizations are independent, yet interdependent because their systems are independent, yet interdependent. As in any relationship, conflicts can occur.

CASE STUDY

There have been several applications of the approach. Unfortunately, acknowledging and discussing dysfunction is difficult. To facilitate publication, the case outlined here is abbreviated and intentionally vague.

A complex system was being developed. From some perspectives, it was seen as a

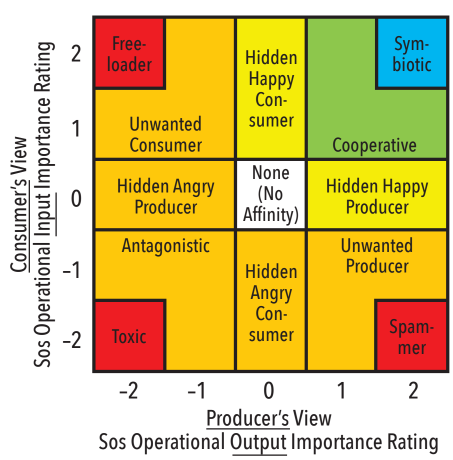

Figure 3. SoS Operational Affinity

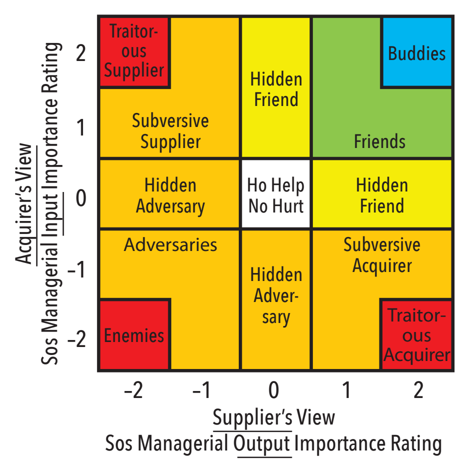

Figure 4. SoS Managerial Affinity

system with many system elements. The term SoS was not used, at least initially. For simplicity, this case study describes just two of the system elements, System V and System W. The overall system was contracted with a prime (Organization A) who used multiple subcontractors to complete the work. One of the system elements, System W, explicitly identified as a system itself, was allocated to a sister business unit (Organization B) within the prime's corporation. The customer and the prime drew the system structure with one system shown as subsidiary or a sub-element to the other.

Although the term was not applied at the time, this structure aligns well with a Directed SoS–SoS created and managed to fulfill specific purposes and the constituent systems are subordinated to the SoS (ISO/IEC/IEEE 21841:2019). It seemed reasonable that System W was subordinate to System V and that Organization B was subordinate to Organization A. Both organization A and B were business units within the same corporation, but Organization A was the prime.

During development and initial transition to operations, the operational interaction between the two systems was

Table 1. Summary of SoS Managerial Affinities, Implications, and Guidance

SoS Managerial Affinity	Meaning	Implications	Guidance to Supplier	Guidance to Acquirer
No Help, No Hurt	Priorities and Incentives in both organizations are not aligned, either positively or negatively.	The organizations may not help each other because they have no incentive to do so, but they also won't hurt each other because they have no incentive there either.	Monitor for changes over time.	Monitor for changes over time.
Friends	Priorities and Incentives in both organizations are somewhat aligned in a positive way.	The organizations are likely to collaborate fairly effectively. Note that positive alignment can exist without formal agreements.	Cultivate the relationship. Monitor for changes over time.	Cultivate the relationship. Monitor for changes over time.
Buddies	Priorities and Incentives in both organizations are strongly aligned in a positive way.	This is a special case of "Friends." The organizations are likely to collaborate effectively. Note that strong positive alignment can exist without formal agreements.	Prioritize and cultivate the relationship. Monitor for changes over time.	Prioritize and cultivate the relationship. Monitor for changes over time.
Adversaries	Priorities and Incentives in both organizations are aligned, but in a negative way.	The organizations are not likely to collaborate. The relationship between the managers or organizations may be adversarial. The managers or organizations may be undermining each other, threatening the operational outcomes of the SoS.	Reconsider or improve the relationship, not just organizationally but between systems. Seek alternative Acquirers and Consumers.	Reconsider or improve the relationship, not just organizationally but between systems. Seek alternative Suppliers and Producers.
Enemies	Priorities and Incentives in both organizations are strongly aligned, but in a negative way.	This is a special case of "Adversaries." The organizations will fight collaboration. The relationship between the managers or organizations may be toxic. The managers or organizations may be actively undermining each other, threatening the operational outcomes of the SoS.	Terminate the relationship, not just organizationally but between systems. Seek alternative Acquirers and Consumers.	Terminate the relationship, not just organizationally but between systems. Seek alternative Suppliers and Producers.
Hidden Friend	One side didn't care about the other, who really is a friend.	This relationship is potentially beneficial, representing a lost opportunity. Cultivating the relationship could reduce risk to operations.	Cultivate the relationship and consider adjusting to the friendly ground.	Cultivate the relationship and consider adjusting to the friendly ground.
Hidden Adversary	One side didn't care about the other, who really is an adversary.	This relationship is potentially dangerous. A hidden adversary is a risk to operations.	Reassess the relationship and consider improving or adjusting to the common ground if possible. If not, plan to terminate the relationship.	Reassess the relationship and consider improving or adjusting to the common ground if possible. If not, plan to terminate the relationship.

Table 1. Summary of SoS Managerial Affinities, Implications, and Guidance (continued)

SoS Managerial Affinity	Meaning	Implications	Guidance to Supplier	Guidance to Acquirer
Subversive Supplier	The acquirer thinks the supplier's priorities and incentives are aligned in a positive way, but they really are aligned in a negative way.	This relationship is dangerous. A subversive supplier is a risk to acquirer's operations.	Reassess the subversive aspects of the relationship and consider ways to improve it if possible.	Reassess the subversive aspects of relationship and consider ways to improve it if possible.
Traitorous Supplier	The acquirer thinks the supplier's priorities and incentives are strongly aligned in a positive way, but they really are strongly aligned in a negative way.	This is a special case of "Subversive Supplier." This relationship is very dangerous. A traitorous supplier is a high risk to the acquirer's operations.	Anticipate being replaced as soon as the acquirer finds an alternative.	Terminate the relationship and replace the supplier immediately.
Subversive Acquirer	The supplier thinks the acquirer's priorities and incentives are aligned in a positive way, but they really are aligned in a negative way.	This relationship is dangerous. A subversive supplier is a risk to the supplier's operations.	Reassess the subversive aspects relationship and consider ways to improve it if possible.	Reassess the subversive aspects relationship and consider ways to improve it if possible.
Traitorous Acquirer	The supplier thinks the acquirer's priorities and incentives are strongly aligned in a positive way, but they really are strongly aligned in a negative way.	This is a special case of "Subversive Acquirer." This relationship is dangerous. A traitorous acquirer is a high risk to the supplier's operations.	Anticipate being replaced as soon as the acquirer finds an alternative.	Terminate the relationship and replace the supplier immediately.

inconsistent and problematic. That is, the system (or SoS) experienced operational dysfunction. The customer and corporate leaders had difficulties understanding how this could be – both systems were being built within the same corporation, subject to common corporate governance.

Organization A's SoS architect reviewed the paper on managerial and operational affinity (Yokell 2018A) and made some observations. Using the SoS operational affinity matrix (Figure 4), the SoS architect examined each of the systems within the larger ecosystem. Many of the operational affinities were positive and the matrix merely provided a means of expressing those relationships. However, when the SoS architect examined the operational affinity between System V and System W, the architect noted the dysfunction immediately, highlighting the struggles to get the systems to function properly.

Moving to the SoS Managerial Affinity matrix, the SoS architect found a match for the managerial relationship between the organizations, a traitorous supplier. Although the organizations were indeed within the same corporation with common overall governance, the business units were behaving differently. Organization B's perspective of the system structure was different from Organization A's perspective. Organization B perceived the structure with System W as a peer to System V, not as a subordinate. Organization B aspired for System W beyond its relationship with System V.

It is common for business units with a corporation to have some objectives in common, supporting the overall corporate mission, plus some objectives that are unique, with each business unit advocating their own products and services. In this case, the business units had a common but conflicting goal – to grow their business units. The leaders of the business units were incentivized to do so. For business units that do not overlap or do not strongly depend on each other, this goal or incentive structure makes sense. However, when the business units are interdependent, the pursuit of the goal at the business unit level can conflict with the overall objective. As is well known in systems engineering, optimizing a part rarely optimizes the whole.

Using the SoS Managerial Affinity, Organization A's SoS architect identified that the organizations and, specifically, the leaders within them, had competing goals and incentives. While most thought that the common governance within the corporation would drive collaboration and mutual support, leading to reduced cost, the leaders in the respective organizations were undermining each other as they each sought to maximize their own business unit's objectives for growth. The corporation's incentives had been intended to optimize the parts assuming a benefit to the whole but ended up harming the parts as well as sub-optimizing the corporation.

Following the guidance in Table 1 to mitigate managerial dysfunction, the SoS architect began socializing his discovery. It took quite a bit of time, but the corporation eventually moved System W along with the people working it from Organization B to Organization A, resolving the conflicting priorities. With alignment in goals and incentives, the people began working together more harmoniously (or less contentiously). Improvements in the operational affinity began to follow as the systems reduced the dysfunction.

CONCLUSIONS

Operational and managerial independence are key characteristics of SoS. CS within SoS can and do operate independently. The organizations are independent, yet interdependent because their systems are independent, yet interdependent. By rating the importance of the exchanges in these relationships, the strength of alignment or affinity can be assessed. SoS Operational Affinity provides insight into the extent to which systems share common interests, while SoS Managerial Affinity provides insight into the extent to which organizations that own CS share common interests.

SoS Managerial Affinity provides a means to detect social function and dysfunction between organizations or people responsible for CS within an SoS. In the cases of dysfunction, the next step is to mitigate those dysfunctions. SoS Managerial Affinities, their implications, and summary guidance to both the supplier and acquirer are available to understand and mitigate the dysfunctions. The approach has been applied successfully with positive results. However, acknowledging dysfunctions much less discussing them to facilitate resolving them is exceptionally difficult. However, making the effort to improve relationships can be beneficial, not just in harmonious exchanges but also in fostering successful outcomes. ■

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Application of MBSAP to a Complex Problem with Social Dimensions: Utilization in Outpatient Imaging Centers

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■ **ABSTRACT**
Outpatient imaging centers struggle daily to manage the negative impact of same day missed appointments. The technical component of outpatient imaging centers includes a complex IT infrastructure and advanced medical imaging equipment. The social component of outpatient imaging centers includes stakeholders that regularly interact with these technologies and one another all to help physicians diagnose their patients. The effectiveness of the technology used in outpatient imaging is dependent on operator ability and stakeholder collaboration. Problems in this type of system require intentional systems thinking to understand stakeholder needs. The Model-Based System Architecture Process (MBSAP) provides a visually understandable framework for system development in an industry unfamiliar with Systems Engineering methods. The primary social dimensions in outpatient imaging are the Customer Dimension, Planning Dimension, Operations Dimension, and Technical Dimension. Each dimension has stakeholders with a diverse set of needs that must be well-understood and incorporated into the requirements. This paper presents an architecture for a system that utilizes all available exam time slots without a dependency on modifying patient behavior to prevent same day missed appointments. The MBSAP artefacts are the starting point for making the system a reality with stakeholders and finding the right balance between separate social dimensional measures.

■ **KEYWORDS:** outpatient imaging, same day missed appointments, model-based system architecture process

THE NEED

Outpatient imaging centers, like most service-based organizations, struggle daily to manage the negative impact of same-day missed appointments. Engineering a solution for this problem is complex due the "diverse, clashing interests and goals" (Garcia-Diaz & Olaya, 2018) of the stakeholders that make up this sociotechnical system. The technical component of outpatient imaging centers includes complex IT infrastructure and advanced medical imaging equipment. The social component of outpatient imaging centers includes stakeholders that regularly interact with these technologies and one another all to help physicians diagnose their patients. The effectiveness of the technology used in outpatient imaging is dependent on operator ability and stakeholder collaboration. Problems in this type of system require intentional systems thinking to completely understand the needs of each stakeholder. In *Systems Thinking for Social Change*, the author argues that systems thinking in practice covers the spiritual, emotional, physical, and mental dimensions of a social system (Stroh, 2015). A way system thinking can be intentionally practiced in a sociotechnical system is through use of the Model-Based System Architecture Process (MBSAP) (Borky, 2009-2018). MBSAP provides a comprehensive and visually understandable framework for system development in an industry unfamiliar with Systems Engineering methods. Using systems thinking and Model-Based Systems Engineering (MBSE) to solve this type of problem in healthcare is new. In fact, a search for the terms "MBSE" and "Radiology" or "Outpatient Imaging" yielded zero results in both the Engineering Village and the ABI/INFORM Complete databases. The MBSAP methodology includes three viewpoints – Operational Viewpoint, Logical/Functional Viewpoint and Physical Viewpoint – that are each organized into Behavioral, Structural, Data, Service and Contextual Perspectives.

Outpatient imaging centers are not alone in their need to proactively manage utilization, most service-based organizations are actively employing various methods to modify customer behavior to reduce the impact of no shows (Speece & Shahroudi, 2019). However, for outpatient imaging centers, methods to change patient behavior to reduce same day appointments have had minimal impact (Speece, 2019). In healthcare, efforts to change the system are a better and more reliable option than trying to change patient behavior. This paper presents an architecture for a system that utilizes all available exam time slots without a dependency on modifying patient behavior to prevent same day missed appointments. The data and information presented in this paper is primarily pulled from an outpatient imaging center in California that lost $1.5M in 2017 and $1.8M in 2018 to same day missed appointments (Radiology Associates, 2015–2019). This problem spans the healthcare industry with the national impact to the total United States healthcare system estimated to be $150 billion (Gier, 2017).

The primary social dimensions in outpatient imaging are the Customer Dimension, Planning Dimension, Operations Dimension, and Technical Dimension. Each of these dimensions have stakeholders with a diverse set of needs that must be well-understood and incorporated into the requirements. Empathy for all stakeholder needs in requirements development in the healthcare world is key to the success of the system. The goal is to develop a system that works alongside and supports each of the stakeholder groups without requiring manual interventions in their workflows. The role human users will play in the system will be minimized to current job requirements with adjustments being made primarily to the systems they are using. Users will be trained to understand how the dynamic adjustments will affect their workflow but should not be expected to remember the nuances of the system to perform their job. The system itself should be invisible to the staff members. To design an "invisible" system architecture, the needs of each social dimension must be understood. Artefacts from the Operational Viewpoint for a system that minimizes the impact of same day missed appointments in an outpatient imaging center are presented in this paper.

STRUCTURAL PERSPECTIVE OF THE OPERATIONAL VIEWPOINT

The proposed system is envisioned to have two domains – Center Exam Status and Cancellation Prediction. The Center Exam Status domain breaks down further into the Patient Status and Wait Room Notification subdomains. The Patient Status subdomain will track patient status–early, on time, late or exam not completed–and automatically feed the data to a dashboard and predictive model. Patients who have not arrived by their table time will be assigned a status of "exam not completed." This will trigger front office receptionists to contact the patient and determine a reason. The Wait Room Notification subdomain is the system that automatically notifies patients who have arrived of their approximate wait time and place in the queue. In an outpatient imaging setting, there are multiple queues for the different modalities however patients usually do not understand that, and multiple complaints have been received about wait time. The Waiting Room Notification system will use check-in time information pulled from the Patient Status subdomain or Radiology Information System (RIS) as well as exam cycle time data. This system is necessary to reduce the unnecessary burden of asking front office staff to track everyone in the waiting room and notify them continuously of their approximate wait time.

The Cancellation Prediction domain will be an independent model that predicts the probability of a patient cancelling their exam and either triggers an alternative workflow or enables double-booking for patients with a high cancellation probability. This domain will receive scheduled patient data from RIS and calculate cancellation probability and cancellation reason regardless of whether the patient has been seen before or not. The model will need to self-update by regularly incorporating data received from the Center Exam Status System. After each patient analysis, the model will send a signal to RIS to either trigger a change to the scheduler's workflow, enable double-booking or do nothing. See Figure 1 for a concept of operations that shows the system domains and how they interact with the different social dimensions in outpatient imaging. See Figure 2 for a use case objectives diagram that shows the needs of each major stakeholder group.

THE CUSTOMER DIMENSION

Patients and referring physicians need a quick turnaround on imaging orders. In outpatient imaging, an actionable item on the Pareto for cancellation reasons is "scheduled elsewhere." Often this means they were able to schedule at another facility sooner and forgot to call and cancel the appointment they scheduled first. This is the justification for requirement 1.1 (see Figure 3: Mission Level Requirements for AUM) that the system shall minimize the number of unused exam time slots.

Minimizing unused exam time slots can be accomplished by either proactively preventing the same day missed appointment before it occurs or overbooking. Part of the concept for the AUM came first from realizing

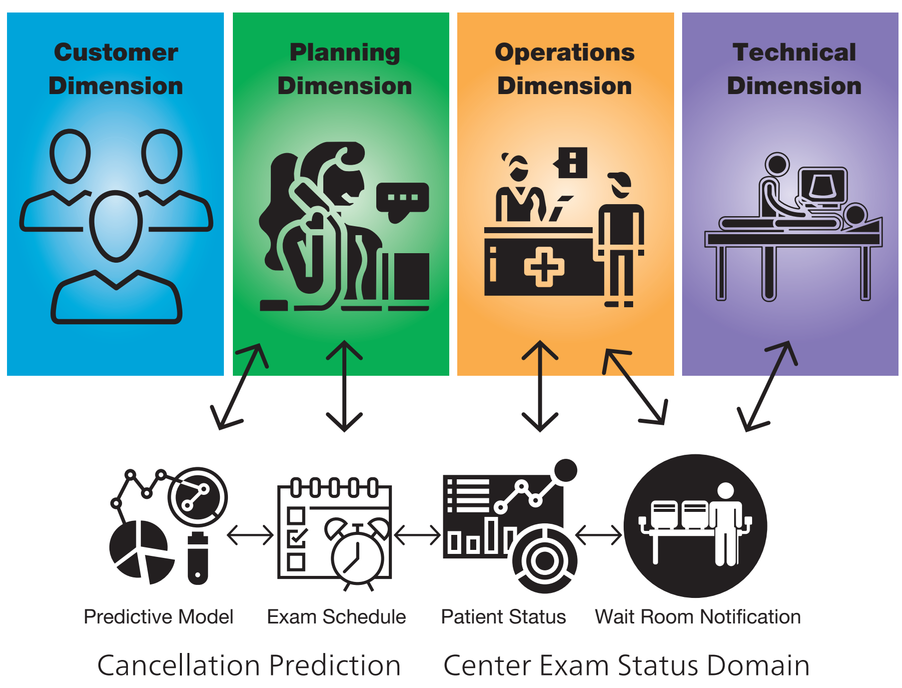

Figure 1: Concept of Operations for AUM with Stakeholder Social Dimensions

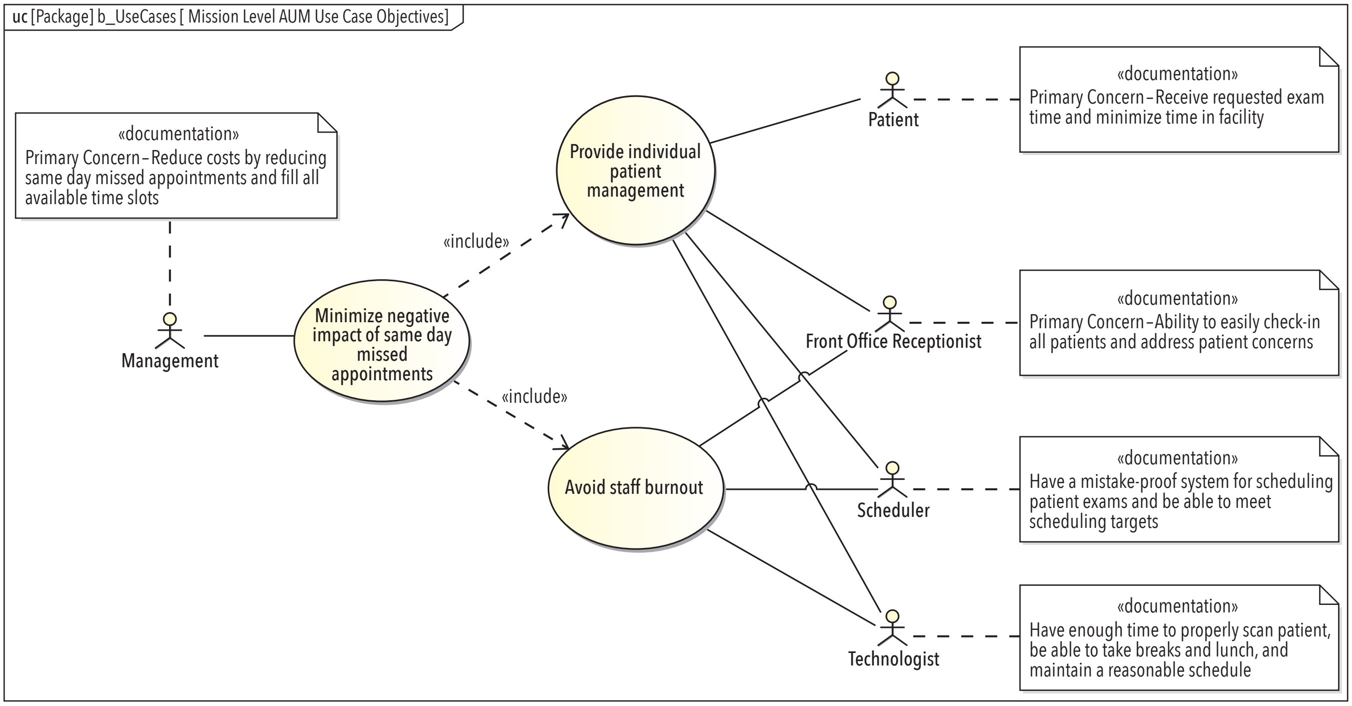

Figure 2: Mission Level Use Case Objectives

that the healthcare industry is not the only service-oriented industry suffering from the impact of same day missed appointments. Benchmarking other service-oriented industries to understand their best practices on how they manage this issue helped further evolve the system-level requirements. An automated utilization management system with individualized workflows to prevent same-day cancellations and optimize modality utilization is a patient-friendly and industry-friendly option. See Figure 4 (next page) for a sequence diagram of automatically modifying scheduler workflows based on the potential cancellation reason.

THE PLANNING DIMENSION

Schedulers need a solution that does not increase their current scheduling cycle time. Upon scheduling a patient exam, relevant information is transferred into the Digital Radiography (DR) system. When staff members schedule an exam, the system only provides them with the next available time slot and a high-level view of the schedule for the day. Schedulers are unable to quickly see the necessary details like phone confirm status, insurance, and

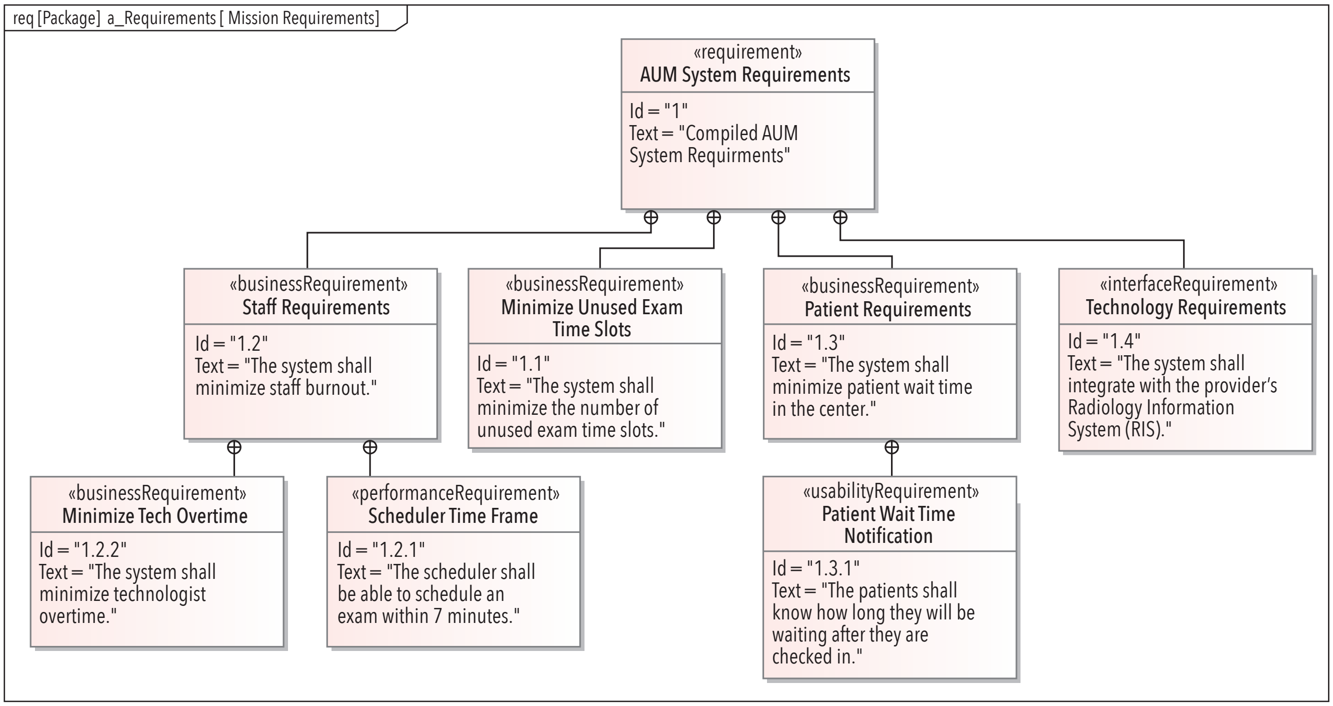

Figure 3: Mission Level Requirements for AUM

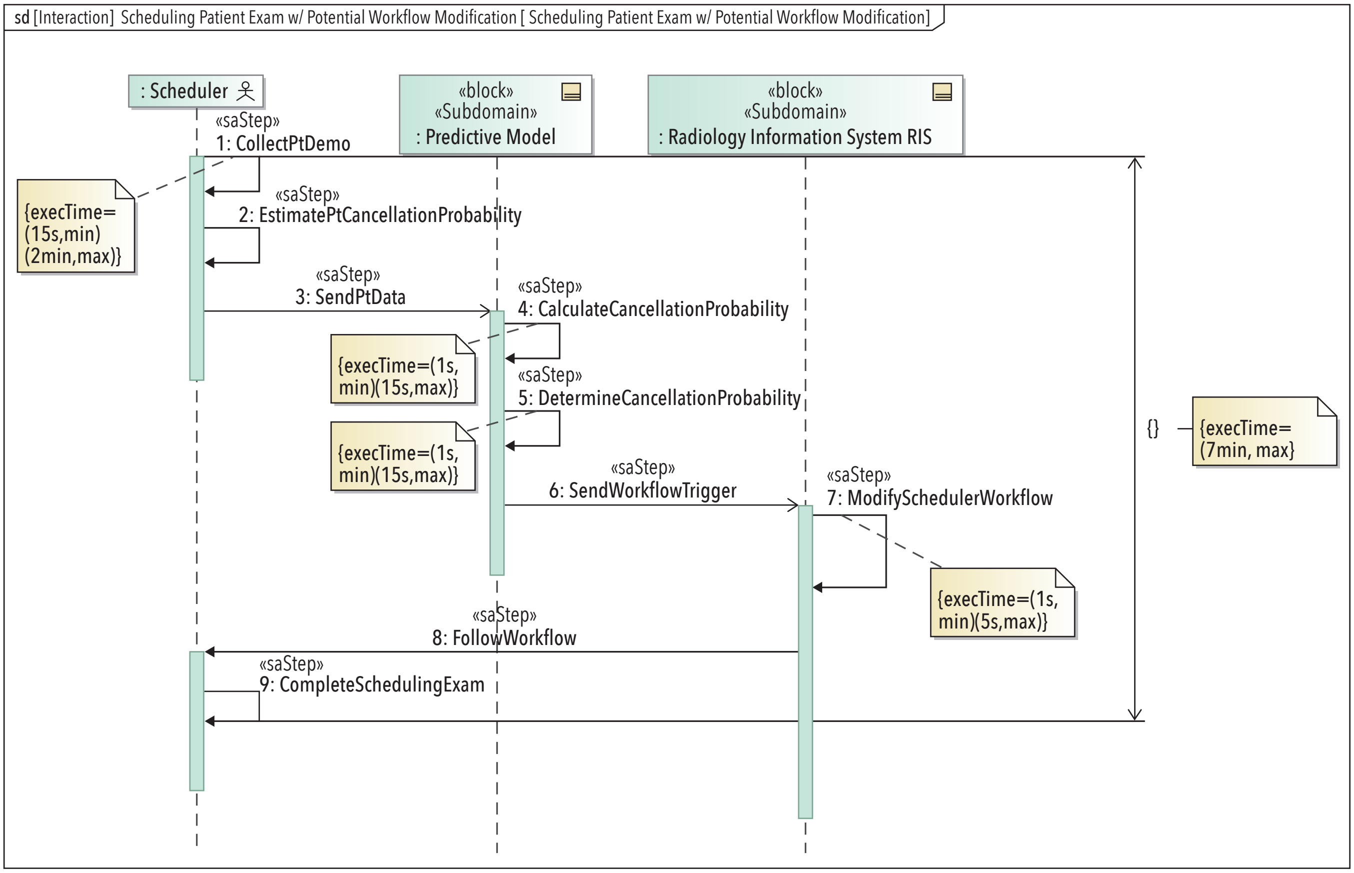

Figure 4: Sequence Diagram of Scheduling Patient Exams w/ Potential Workflow Modification

more, to efficiently double book. This is the justification for the requirement 1.4 that the system needs to integrate with the provider's Radiology Information System (RIS).

Schedulers are required to follow the RIS workflow that is presented while scheduling a patient's exam. If the patient's cancellation probability is high and an actionable cancellation reason has been identified, then the predictive model will send the RIS system a trigger to modify the scheduler workflow to fit the patient's needs. This process will be invisible to the scheduler as they will simply need to follow the system prompts. If the patient's cancellation probability is high and an actionable cancellation reason cannot be identified, then the predictive model will send the RIS system a trigger to allow the exam time to be double-booked, but the scheduler's workflow will not change.

THE OPERATIONS DIMENSION

Front office receptionists need a solution that allows them to provide the best possible customer service. A risk this type of system may create is a less rigid and more fluid schedule that makes patient-facing staff members uncomfortable, as they must deal directly with potentially angry patients. To alleviate this stress for the front office, the system itself needs to provide up-to-date status reports to the patient (requirement 1.3.1).

Front office receptionists are responsible for checking patients into the system. This is currently the only way the RIS knows if a patient has physically arrived for their exam. The check-in process involves confirming that the patient has arrived in the system, collecting any out-of-pocket amount due and ensuring the patient fills out necessary paperwork. If a patient has not checked in by their scheduled time, then the front office receptionist needs to be alerted to attempt to contact the patient and obtain a reason for the same day missed appointment. For each patient scheduled, the front office receptionists will either check them in or obtain a reason for the missed appointment. The system needs to provide the alert to reach out to no-show patients because the front office receptionists are too busy checking in current patients to keep constant tabs on the schedule. These needs are incorporated into the development of the Patient Status domain.

THE TECHNICAL DIMENSION

Technologists need a solution that does not put them at risk for burnout (requirement 1.2). There is a risk that a packed schedule will create required overtime for the technologists and staff. Overtime is one cause of burnout in healthcare (Genly, 2016) and the system must ensure that required overtime is minimized or not even required. To mitigate the risk of staff burnout and increasing turnover, the frequency of overtime will be tracked, and causes will be analyzed closely. If overtime exceeds a certain threshold, then modifications to the algorithm for determining when to double book will be made.

UNINTENDED CONSEQUENCES

Unintended consequences may arise from the implementation of this system. To detect these unknowns as they occur, the qualitative and quantitative feedback from both the patient and staff surveys will be monitored regularly. Patient surveys can be sent automatically post-scheduling and post-exam so feedback can be collected and analyzed daily. Staff surveys are currently conducted quarterly at Radiology Associates but would be recommended to send monthly after the implementation of the new system.

CONCLUSION

MBSAP has been invaluable in adding

systemic and systematic rigor to the complex real-world problem of same day missed appointments in an outpatient imaging center. The resulting systems architecture ensures that the needs of all stakeholders are met while anticipating potential unintended consequences of the new architecture that might appear in separate identified social dimensions. This system architecture is intended to minimize the impact of same day missed appointments on operations and improve exam availability for all patients without increasing workflow complexity for schedulers, front office receptionists, or technologists. The MBSAP artefacts are the starting point for making the system a reality with stakeholders and finding the right balance between separate social dimensional measures.

While the utilization management process is not identical for all healthcare providers, the high degree of similarities makes it possible to create a verified and validated system architecture that could blaze the path towards making a dent in the $150 billion dollar problem in healthcare. ■

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The Emergent Properties of an Ethical Leadership When Aligned with the Systems Engineering Handbook and Code of Ethics

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ABSTRACT

It is not easy to define leadership and the characteristics a leader must have. Some authors prefer one or another skill, but definitions are diverse. Some sources try to indicate what it means and its implications. A holistic ethical leadership model cannot be defined circularly, but it must be understood, such as a praxis.

Leadership means more than its common definition; it means truth, ethics, empathy, and much more. In this case, it is of importance the definition of leadership, and in particular the ethical leadership. Also, the role of the leader is important, their education, their skills, and their influence.

The need for ethical leadership in systems engineering is essential to be highlighted. The Code of Ethics of INCOSE and the Handbook do not merge the concept of leadership and ethics. That is why it is vital to show the need for alignment among both documents in terms of ethical leadership. Also, an explicit reference to this concept is needed in both documents because leadership needs to be honest, and ethics is a role to provide it.

In this paper, we analyze the definitions found in the current INCOSE Code of Ethics and INCOSE Handbook regarding ethical leadership, its implications, and its application is explained and aligned to the ethical systems engineering idea. Also, examples of ethical behavior will be introduced to explain emergent properties. It will exemplify that applying ethical leadership will work in favor of the development of successful systems.

INTRODUCTION

Leadership is a concept that must be considered a whole, holistically – means and diverse factors interfere and must be considered. A definition of ethical leadership, its implications, and its application on complex must be considered in a holistic approach. A leader is a person and a complex system at the same time. A holistic and ethical view must be incorporated into leadership skills when guiding a team. A leader shall do the right thing, at the right time, in the right way. It is important to consider the whole, the context, the person, the values, and the meaning. In the end, it is like knowledge management, in the sense of diverse concepts aligned and interrelated to build a trust model among people.

According to studies made by the Institute of Leadership and Management, 63% of managers have been asked to do something contrary to their ethical code, 43% have been told to behave in direct violation of their organization's own values statements, and 9% have been asked to break the law (ILM report). It means ethical leadership shall be improved among practitioners of systems engineering and we must promote the skills of an ethical leader among practitioners. Ethical leaders that follow ethical models will be followed by their team; it is in the spirit of people to act appropriately.

It is in the nature of the human being to be ethical and reflect their ethics in the actions they take. For this reason, while it is possible to lead people to perform unethical acts, the opposite is far easier. It is incumbent on the leader to ensure that their actions are ethical in themselves and are seen to be ethical by those they seek to lead. They need to be role models, and they must be open to questions and challenges from their followers and address them with an open mind for inclusion, diversity, and empowerment. This is the essence of integrity, and it is critical for the leaders, the projects, and the ethics model to succeed on any trend.

ETHICS AND LEADERSHIP SIGNS ON THE SYSTEMS ENGINEERING HANDBOOK AND RULES

According to the Code of Ethics of INCOSE (INCOSE Code of Ethics, 2006), *"Systems Engineers uphold and advance the integrity, honor, and dignity of the engineering profession by*:

- *Being honest and impartial.*
- *Maintaining the highest levels of integrity and keeping abreast of the knowledge of their disciplines.*
- *Striving to increase the competence and prestige of the engineering profession; and,*
- *Supporting the educational institutions, the professional societies, and technical societies of their disciplines."*

As stated in the (Walden et al., 2015), systems engineering leadership and systems engineering ethics concepts are introduced but not declared deeper. The INCOSE Handbook on page 23 indicates: "T*he practice of Systems Engineering can result in significant social and environmental benefits, but only if unintended and undesired effects are considered and mitigated*."

The practice of systems engineering shall consider the unintended and undesired effects and include the active search of educated skills of ethics on the systems engineers. If the systems engineers are educated and motivated to have ethical skills, the effects will be minimal on this aspect.

Reviewing the references in the INCOSE Handbook, the next reference to ethics in the INCOSE Handbook is on pages 141 and 143 to indicate that negotiations shall be conducted with ethics. But no more references were found in the chapters. Also, when searching in the Handbook for leadership it is located mainly in section 2.10 about Systems Engineering Leadership and some references, around five or six, in another section to indicate where the leader shall have a role. It is important to include more references and an adequate definition of a leader, leadership, ethical leadership, and its clear role in systems engineering. It is not possible from my point of view to conceive a leader without ethics, so it must be an ethical leader who applies ethical leadership thoughts and skills.

EMERGENT PROPERTIES OF ETHICAL LEADERSHIP

It is human to be ethical and reflect ethics in the actions one takes. For this reason, while it is possible to lead people to perform unethical acts, the opposite is far more manageable. For example, as stated in some studies (Tu, 2019), ethical leadership was positively related to team creativity. Consistent with the predictions of uncertainty reduction theory, psychological safety climate mediated the relationship between ethical leadership and the three forms of team-level creativity. Furthermore, supervisor support for creativity positively moderated the effect of ethical leadership on psychological safety climate and the indirect effects of ethical leadership on the three forms of team-level creativity through psychological safety climate. The analysis offers significant theoretical and practical implications on ethical leadership and creativity in organizations. Using complex system leadership theory wherein leadership is defined as changing the rules governing local interactions, the theory links shared identity and ethics to those local rules (Hazy, 2012). As said by Professor Hazy, because leadership impacts collective identity and thus the rules of interaction, and sometimes does so opaquely, creating and maintaining such a system is an ethical challenge for leadership (Hazy, 2012).

It is incumbent on the leader to ensure that their actions are not only ethical in themselves but are seen to be ethical by those they seek to lead. They need to be role models, and they must be open to questions and challenges from their followers, addressing them with an open mind for inclusion, diversity, and empowerment. This is the essence of integrity, and it is critical for the leaders, the projects, and the ethics model to succeed on any trend.

Once concepts of ethics and leadership are reviewed in the INCOSE Handbook it is crucial to identify and point out that a need for a nexus between ethics and leadership is important, not only the code, and for both to be aligned.

An emergent property in a system refers to the attributes that appear due to the interaction or synergies between the actors or components. Ethics is presented as emergent from the behavior of systems engineers or leaders following micro and local rules. The possibilities of emergent synergies by acting as an ethical leader are diverse and might emerge as: recognition of the engineer by the organization because of the values and skills, promoting better teamwork because of ethical and moral boundaries, being asked to lead a project because of the ethical leadership skills, and more. Keep in mind that it is in the human being's foundations to be ethical and reveal their ethics in the behaviors they have, so in the end, the human (the system engineer) intrinsically looks for a mirror–more people believing the same and having the same roots.

On the European Projects (European Commission Ethics Appraisal Procedure, 2020) one of the interesting facts is that ethics requirements might become contractual obligations and will be assessed. Proposals have an ethics review to continue its evaluation.

For instance, as explained by Reed Hastings, Netflix hires and promotes only people who display their nine valued behaviors. For example, one such value is communication. Those who listen well, are concise and eloquent, treat people with respect regardless of their status, and maintain calm in stressful situations are rewarded and promoted within Netflix (Hastings, 2013). This value is linked to their performance assessments at the recruitment stage and throughout their careers there – if a person does not align with their values, Netflix 'probably isn't the right place for them' (ILM report) (Goncalves, 2018).

CONCLUSIONS

Definition of ethical leadership, its implications, and its application to systems engineering must be considered holistic. The leader is, at the same time, a person, and a complex system.

To guide a team, a holistic and ethical view must be incorporated into leadership skills. The leader shall do the right thing, at the right time, in the right way.

It is in the human condition to be moral and consider their ethics in their choices. For this reason, while it is possible to lead people to conduct unethical acts, the opposite is much easier.

Systems engineering shall consider not only the unintended and undesired effects but also the active search for the systems engineers' ethical skills. If system engineers are educated and motivated to have ethical skills, the effects will be minimal, if any.

The potential for emerging synergies by acting as an ethical leader is varied and might emerge as an organization's recognition of the engineer on the grounds of values and skills, promoting better teamwork on the premise of ethical and moral boundaries, developing a project in terms of ethical leadership skills, or even creating and sustaining relationships of trust as a systemic capacity of the entire organization.

Once concepts about ethics and leadership are reviewed in the INCOSE Handbook it is important to identify and point out that a need for a nexus between ethics and leadership is important, not only the code; an improvement of the concept of ethical leadership might be included in the revisions of the INCOSE Handbook. ■

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Bridge the Partisan Divide and Develop Effective Policies with Systems Engineering

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ABSTRACT
The United States is a divided country. This is sometimes a strength when we consider diverse viewpoints before deciding. However, it is often a weakness, when hyper-partisan politics divides us and prevents us from addressing serious problems. In this article I discuss how lawmakers and policymakers can use systems engineering to bridge the partisan divide and develop practical, nonpartisan solutions for complex societal problems. First, I describe a simple six-step systems engineering process for optimizing social, economic, and political systems. Second, I illustrate this process with two examples: (1) development of a nonpartisan tax reform proposal that balances the federal budget and addresses key societal problems without increasing the economic burden on taxpayers and (2) development of a nonpartisan plan for the United States to achieve the United Nations Sustainable Development Goals and address other urgent problems. Third, I discuss how lawmakers and policymakers can incorporate systems engineering into the lawmaking process. Although this article uses the United States as an example, many of the ideas presented here also apply to other countries.

INTRODUCTION

Systems engineering is a powerful process for managing the definition, design, development, operation, and retirement of complex products and systems. It is well established for optimizing physical products and systems and documented in handbooks published by organizations such as NASA (*Systems Engineering Handbook*, 2017), the Department of Defense (*Systems Engineering Fundamentals*, 2001), and the International Council on Systems Engineering (*Systems Engineering Handbook*, 2015).

However, the systems engineering process is not so well established for optimizing *intangible* systems. This article summarizes work I have been doing to adapt and simplify the systems engineering process so lawmakers and policymakers can use it to address complex societal problems (see JimHartung.com).

I believe systems engineering can be used to address complex societal problems for three reasons. First, it is an objective, nonpartisan process that considers the needs of all stakeholders and uses facts and data to optimize a product or system. Second, it balances opposing interests, conflicting objectives, and many constraints. Third, it is used on large, complex, and politically charged programs such as the International Space Station, which involved 15 countries including the US and Russia. On such programs, systems engineering enables diverse participants with divergent objectives, constraints, and capabilities to work together for the common good. Lawmakers and policymakers need a process such as this to develop good solutions for difficult societal problems.

THE SYSTEMS ENGINEERING PROCESS

The systems engineering process used by engineers to develop physical products and systems is often complex. However, a simpler process is needed if lawmakers and policymakers are to use it to address societal problems. Figure 1 shows the simplified systems engineering process I developed for this purpose. This six-step process encourages development of practical, nonpartisan solutions for the following reasons:

Steps #1 and #2 require anyone using this process to put aside ideology, at least for a while, and focus on (1) understanding the needs and desires of all stakeholders and (2) synthesizing these needs and desires into top-level objectives. This broadens the mind and increases empathy for opposing viewpoints.

Step #3 requires creative thinking to develop a strategy that achieves the top-level objectives and key stakeholder needs and desires. This forces one to reject ideological strategies that focus on just one or two objectives and develop a balanced approach that all stakeholders can support. [FIG 1 GOES HERE]

Steps #4 and #5 use the strategy developed in step #3 to define the new or improved system. To optimize the system, it is evaluated against the objectives, key

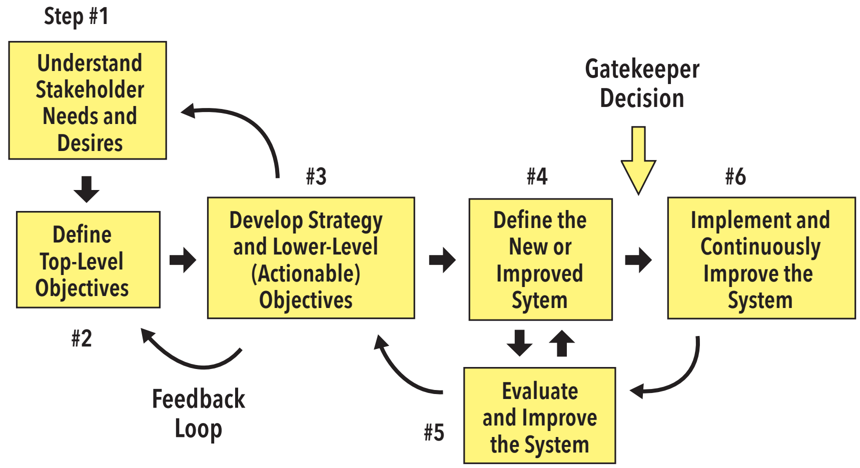

Figure 1. The systems engineering process, simplified to address societal problems

stakeholder needs and desires, and other potential solutions. This forces one to consider alternatives, address deficiencies, and improve the proposed solution. Often, this leads to changes in the strategy developed in step #3.

Step #6 is implemented only after a gatekeeper (such as Congress and the president) approves the solution. To provide a check and balance, the gatekeeper must be different from the group that is developing the solution. The first five steps of the systems engineering process are repeated (ideally, as rapidly as practical) until the gatekeeper approves implementation.

After a solution is implemented, the entire six-step process is repeated periodically to continuously improve the solution, using lessons learned from experience and new facts and data as they become available.

TAX REFORM EXAMPLE

I used this six-step process to develop a comprehensive, nonpartisan tax reform proposal (Hartung, 2020). I chose tax reform for two reasons. First, the tax code is a complex system with numerous stakeholders' needs and desires, many conflicting objectives and constraints, and strongly held differences of opinion. Therefore, it is a good test of the systems engineering process. Second, the last major US tax reform (the Tax Cuts and Jobs Act of 2017) was enacted recently, so it provides a good baseline for assessing the value of systems engineering for developing better solutions than with current political processes.

Table 1 shows the top-level objectives and key stakeholder needs and desires established for tax reform (steps #1 and # 2 in Figure 1). These are the requirements that drove development of the tax reform proposal.

Table 2 shows the strategy and lower-level (actionable) objectives used to develop the proposed tax reform (step #3 in Figure 1). The following three key considerations led me to adopt this strategy:

- **Expert opinion:** Most tax experts want to broaden the tax base and lower tax rates (Reid, 2018 and Gale, 2019). Many developed countries have used this strategy with satisfactory results. So, I used this strategy for all three major taxes: individual income taxes, corporate income taxes, and payroll taxes (strategies #1, #2, and #3 in Table 2).
- **System optimization:** The tax system cannot be optimized by itself but must be optimized in the context of other societal goals. Many important synergies can be achieved by addressing healthcare, climate change, and tax reform together, so my strategy tackles all these problems at once, to provide an integrated system solution (strategies #4 and #5 in Table 2).

Nonpartisan approach: To develop a nonpartisan solution, my goal was to combine the best ideas from Republicans, Democrats, and others across the political spectrum. Strategies #4 and #5 illustrate this: Medicare Choice combines the best features of Medicare for All (favored by many progressive Democrats) and premium support (favored by many conservative Republicans). Carbon dividends address climate change (a priority for many Democrats) using a market-based approach (supported by many Republicans).

To develop the new tax system (steps #4 and #5 in Figure 1), I performed many evaluations and considered many alternatives. Table 3 summarizes the proposed tax reform and compares it with

Table 1. Top-level objectives and key stakeholder needs and desires for tax reform

Top-Level Objectives	Key Stakeholder Needs and Desires
1. Fiscally responsible	• Balance the federal budget and reduce the national debt (as % of GDP) • Control spending (make government more effient and effective) • Decrease the cost of healthcare (for both individuals and society) • Restore Social Security to financial health without cutting benefits
2. Pro-growth	• Encourage sustainable and inclusive economic growth • Create more good jobs, especially for low-income and middle-class taxpayers • Reduce tax rates without cutting government services
3. Simple and fair	• Address the problem of inequality without damaging wealthy taxpayers • Provide a strong social safety net, including universal healthcare • Decrease tax avoidance, tax evasion, and political corruption • Reduce tax preferences, loopholes, itemized deductions, and tax credits
4. Nonpartisan and comprehensive	• Achieve the most important objectives of both political parties • Address all key issues with the current tax code • Use realistic assumptions to evaluate the proposed tax reform

the current tax code, enacted in late 2017. Its key features are as follows:

- **Balanced budget:** The proposed tax reform balances the federal budget and funds universal healthcare without increasing the economic burden on taxpayers or decreasing other government services. It does this by (1) reforming the healthcare system to make it better and more efficient and (2) using the resulting cost savings to balance the budget.
- **Medicare Choice:** The proposed tax reform includes a novel approach for universal healthcare, which I call Medicare Choice. With this system, those who want Medicare will receive it. Those who do not want Medicare can opt out and receive premium support instead, to purchase any healthcare insurance they choose. Medicare Choice will improve healthcare, reduce cost, and maximize personal choice and competition.
- **Social Security:** The proposed tax reform restores Social Security to financial health without reducing benefits by (1) eliminating the cap on wages subject to the payroll tax and (2) using all payroll tax revenue to fund Social Security (no diversion for Medicare).
- **Individual income tax:** The proposed tax system simplifies the tax code. All income is taxed at the same (progressive) rates. Itemized deductions are eliminated and replaced with a larger standard deduction. Every taxpayer and dependent receives a $1,000 refundable tax credit. All other tax credits are eliminated. Individual income tax rates are slightly lower than in the current tax code.
- **Business tax:** The corporate income tax (currently 21%) is eliminated and replaced with a broad-based value-added tax (VAT) with a lower tax rate (13%). The VAT is an efficient tax that inherently taxes corporate profits as well as other business costs and expenses. It provides sufficient revenue to fund Medicare Choice. Eliminating the corporate income tax will stimulate business investment and create jobs.
- **Payroll tax rate:** The payroll tax is reduced from 15.3% to 14%. Nevertheless, it provides sufficient revenue to fully fund Social Security, since the cap on taxable income is eliminated and no payroll tax revenue is diverted to fund Medicare.
- **Bipartisan:** The proposed tax reform achieves the most important objectives of both Republicans and Democrats.
- **Carbon dividends:** Revenue-neutral carbon dividends are included to address climate change. With carbon dividends, oil, natural gas, and coal companies will pay a steadily increasing fee on their products and all fees collected will be

Table 2. Strategy and lower-level (actionable) objectives for tax reform

Top-Level Objectives	Key Stakeholder Needs and Desires
1. Broaden the individual income tax base, reduce tax rates	• Eliminate all itemized deductions and most tax credits, tax preferences and loopholes • Provide a large standard deduction and refundable tax credit for all taxpayers and dependents • Tax income from all sources at the same time (progressive) rates
2. Broaden the business tax base, reduce tax rates	• Replace the corporate income tax with a broader and more efficient value-added tax • Use all value-added tax revenue to fund universal healthcare
3. Broaden the payroll tax base, reduce tax rates	• Eliminate the cap on taxable income • Use all payroll tax revenue to fund Social Security
4. Implement "Medicare Choice" to improve healthcare and reduce cost	• Provide Medicare for everyone who wants it, premium support for those who opt out • Use the resulting cost savings to balance the federal budget without increasing the economic burden on taxpayers
5. Implement "Carbon Dividends" to address climate change and inequality	• Collect a fee from fossil fual companies • Return all revenue to Americans with quarterly or monthly carbon dividends

Table 3. Key features of the proposed tax reform and the current tax code

Feature	Key Features	
	Current Tax Code	**Proposed Tax Reform**
Balanced budget?	No	Yes
Funds universal health care?	No	Yes
Social Security benefits sustainable?	No	Yes
Payroll tax rate	15.3%	14%
Individual income tax • Tax rates • Itemized deductions • Standard deduction • Tax credits • Tax preferences	 12% to 37% Many Yes Many Many	 10% to 36% None Larger One Few
Corporate income tax • Tax rate • Itemized deductions and credits	 21% Many	No Corporate income tax
VAT tax rate	No VAT	13%
Bipartisan?	No	Yes
Carbon dividends?	No	Yes
Balanced budget feedback mechanism?	No	Yes
Public disclosure rules?	No	Yes

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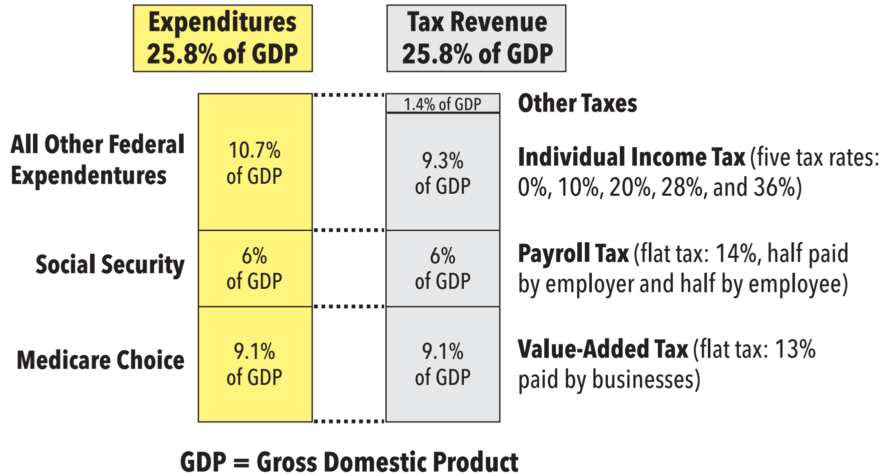

Figure 2. The proposed tax reform balances the federal budget

returned to the American people with quarterly dividend checks. This should reduce net US greenhouse gas emissions to near zero by 2050, while providing every taxpayer and dependent with carbon dividends ranging from about $500 to $1,500 annually.

- **Balanced budget feedback mechanism:** The proposed tax reform includes an automatic feedback mechanism to encourage Congress and the president to control spending and balance the federal budget.
- **Tax transparency:** All candidates for high-level public office must disclose their tax returns. This is done to promote good governance and reduce corruption.
- **Investment in future growth:** The proposed tax reform increases investment in the seeds of future growth, especially education and infrastructure. It does this by increasing funding for the Highway and Mass Transit Trust Funds and creating (and funding) an Education Trust Fund.
- **Inequality:** The proposed tax reform includes many features to reduce inequality. Three of the most important are as follows: First, it is a progressive tax system that taxes all sources of income at the same (progressive) rates and provides a large refundable tax credit and carbon dividends for all taxpayers and dependents. Second, it includes a strong social safety net anchored with universal healthcare (Medicare Choice) and a financially sustainable Social Security system. Third, it creates jobs, especially for low-income and middle-income taxpayers because it eliminates the need for businesses to fund their employees' healthcare, increases investment in education and infrastructure, and replaces the corporate income tax with a more efficient value-added tax.

Figure 2 shows how the proposed (new) tax system balances the federal budget. Medicare Choice is funded by the value-added tax. Social Security is funded by the payroll tax. All other federal expenditures are funded by the individual income tax and other taxes such as the estate tax and excise taxes. The federal budget is balanced with both expenditures and revenue slightly less than 26% of Gross Domestic Product.

The last step in the systems engineering process (step #6 in Figure 1) is to implement and continuously improve the

Figure 3. United Nations Sustainable Development Goals

Table 4. Lower-level (actionable) objectives and strategy

Strategy Matrix

- X = Primary solution 0 = Secondary solution
- Horizontal rows show how the objectives and targets are achieved
- Vertical columns show how the top actions achieve the objectives

			Top 10 Actions									
			Medical Choice	Life Skills & Career Education	Living Wage Labor Policies	Carbon Dividends	Smart Land & Water Use Policies	Comprehensive Tax Reform	Nonpartisan Good Government	Pragmatic Justice System	Points-Based Immigration System	Lead a United and Multipolar World
Problem Areas	**Lower-Level (Actionable) Objectives**	**Targets**	**Strategy Matrix**									
Inequality and discrimination	Reduce economic inequality withhout harming the wealthy	4	X	X	X	0		X	0	X	X	X
	Increase gender equality in a way that benefits everyone	2	0	X	0			0	0			0
	Reduce racial and ethnic inequality in a way that benefits everyone	3	0	X	0			0	0	X	0	0
	Reduce crime and the number of persons held in prison	2	0	X	0				0	X	)	
Healthcare and education	Provide high quality, affordable healthcare for all	3	X					0	0	0	0	0
	Improve public health and safety	2	X	0		0			0	0	0	0
	Provide high quality, affordable education and job training for all	2		X	X				0	0	0	0
Jobs and economic opportunities	Encourage robust, sustainable, and inclusive economic growth	2	0	X	0	0	0	X	0	0	0	0
	Create more good jobs for those with low and moderate incomes	2	0	0	X	0		X	0		0	0
Environment	Address climate change without slowing economic growth	2				X	0	0	0			0
	Use resources sustainably without hurting the economy	6				0	X		0			0
	Protect biodiversity without stunting economic growth	3				X	X		0			0
Governance	Make government more competent, efficient, and nonpartisan	3	0	0	0	0		X	X	0	0	0
	Promote global peace, prosperity, freedom, and friendship	4		0		0	0		0	0	X	X

system. This step requires Congress and the president to act. This is obviously a long shot, but I am actively promoting the key features of this tax reform and the associated healthcare reform (Medicare Choice) and climate action (carbon dividends). Even though this proposal was developed before the COVID pandemic, it is as up to date today as it was before the pandemic and these reforms are needed now more than ever.

SUSTAINABLE DEVELOPMENT GOALS EXAMPLE

After developing this tax reform proposal, I used the same six-step systems engineering process to address a broader set of societal problems. For this work, I used the United Nations Sustainable Development Goals (SDGs) as the starting point. In 2015, the United Nations adopted 17 SDGs (shown in Figure 3) and 169 targets to guide global development through 2030. I used these SDGs and targets as the stakeholder needs and desires.

In 2020, Sachs et al published a report (Sustainable Development Report 2020) that identifies the gaps each country must overcome to achieve the SDGs. This report also ranks all countries in terms of SDG compliance. The top six countries are Sweden, Denmark, Finland, France, Germany, and Norway, with SDG scores of 80 to 85 on a 100-point scale. The United States is ranked 31st in the world, with an SDG score of 76.4. We have much work to do to achieve the SDGs.

After studying the SDGs, I chose the following two top-level objectives for this work: The United States should (1) achieve the SDGs by 2030 or as soon thereafter as practical and (2) address other serious problems on the same time scale, even if they are not covered by the SDGs. The first objective reflects my belief that the SDGs are appropriate targets for the United States but recognizes that it will be impossible to achieve them all by 2030. The second objective was added because the SDGs do not address some of America's most serious problems such as political polarization, racial discrimination, nuclear weapons control, and the national debt. Tackling both objectives at the same time encourages development of a cost-effective, integrated systems solution.

Table 4 summarizes the lower-level objectives and strategy developed to achieve these top-level objectives. The lower-level objectives are shown in the second column. The strategy (which includes ten key actions) is shown in the ten columns and the matrix on the right.

For each objective, two or more quantitative targets were established as shown in the third column of Table 4. For example, 11 quantitative targets were defined for inequality and discrimination (4+2+3+2). These 11 quantitative targets are shown in

Table 5. Quantitative targets for inequality and discrimination

Problem Area: Inequality and Discrimination				
Objectives	**Quantitative Measure**	**SDG Target**	**My Target**	**Current Value**
Reduce economic inequality without harming the wealthy	Poverty rate after taxes and transfers (%)	<10	same	17.8
	Palma ratio (income of top 10%/income of bottom 40%)	<1	same	1.8
	Gini coeffient (best 0–100 worst)	<30	same	46.1
	Wealth of top 10% of households/wealth of bottom 90%	—	<1	3.9
Increase gender equality in a way that benefits everyone	Gender wage gap (% of male median wage)	<7.5	same	18.9
	Seats held by women in Congress (%)	>40	same	23.8
Decrease racial and ethnic inequality in a way that benefits everyone	Black wage gap (% of white median wage)	—	<7.5	39
	Hispanic wage gap (% of white median wage)	—	<7.5	26
	Seats held by minorities in Congress (%)	—	>40	22
Reduce crime and the number of persons held in prison	Homicides (per 100,000 population)	<1.5	same	5.3
	Persons held in prison (per 100,000 population)	<100	same	671.1

Table 5. They were chosen to be representative rather than comprehensive, but complete enough to guide policy development. The other 29 quantitative targets are similar, but they are not shown here because of space limitations. Most of the quantitative targets came directly from the SDGs, but I added a few (as shown in Table 5) to address problems not covered in the SDGs.

Developing the strategy and top ten actions in Table 4 was difficult and required several iterations. Fortunately, I discovered during this process that the same systems engineering principles I learned while developing physical products and systems also apply when addressing intangible societal problems. Table 6 summarizes 11 systems engineering principles that proved most useful for developing the strategy and top ten actions in Table 4.

Table 7 shows the top ten actions identified in Table 4. While developing these actions, my goal was to develop practical, nonpartisan solutions that can be implemented today and completed in ten years. Three of the top ten actions in Table 7 were discussed previously: Medicare Choice, Carbon Dividends, and Comprehensive Tax Reform. The other seven actions are summarized in the following paragraphs. All ten actions are described in more detail on my website.

- **Life Skills and Career Education:** To improve the education system, I propose adding a new course of study to primary and secondary schools to teach students the generic skills they need to achieve success in life and in a career. These skills can be taught, and they are just

Table 6. Key systems engineering principles used to develop strategy and lower-level objectives

1. Systems approach (optimize the whole, not the parts)
2. Address root causes, not symptoms
3. Nonpartisan (win-win solutions, achieve all key stakeholder objectives)
4. Learn from experience (best practices, natural experiments)
5. Simplify (KISS = keep it simple and smart)
6. Fact-based solutions (in God we trust, all others bring data)
7. Historical perspective (optimal solutions depend on history)
8. Systems models (both qualitative and quantitative models)
9. Requirements flowdown and allocation (requirements traceability)
10. Provide information and incentives to motivate action
11. Input from subject-matter experts (and non-experts)

Table 7. Top ten actions to achieve the objectives

- Healthcare .... Medicare Choice
- Education .... Life Skills and Career Education
- Economy .... Living Wage Labor Policies
- Climate Change .... Carbon Dividends
- Environment .... Smart Land and Water Use Policies
- Taxes .... Comprehensive Tax Reform
- Governance .... Nonpartisan Good Government
- Justice System .... Pragmatic Justice SYstem Reform
- Immigration .... Points-Based Immigration SYstem
- International Relations .... Lead a United Multipolar World

Table 8. The top ten actions achieve the 17 Sustainable Development Goals

Top Ten Actions		Sustainable Development Goals																
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Healthcare	Medicare Choice	X		X		X					X							
Education	Life Skills and Career Education	X	X	X	X	X			X	X	X	X						
Labor Policies	Living Wage Labor Policies	X	X		X	X			X	X	X	X						
Climate Change	Carbon Dividends							X			X		X	X	X	X		X
Environment	Smart Land and Water Use Policies		X				X						X	X	X	X		
Taxes	Comprehensive Tax Reform	X							X		X							
Governance	Nonpartisan Good Government	X				X	X				X	X						X
Justice System	Pragmatic Justice System Reform	X	X								X						X	
Immigration	Points-Based Immigration System	X	X								X							X
International Relations	Lead a United Multipolar World													X			X	X

as important as academic subjects, especially for disadvantaged students.

- **Living Wage Labor Policies:** To give everyone a good opportunity to earn a living wage, I propose two actions: (1) expand work-study programs, career and technical education, and national service programs, especially for the young and the disadvantaged, and (2) increase the minimum wage to 50 percent of the median household income in each state or region (for high school graduates) and 40 percent of median household income (for those who have not graduated from high school).
- **Smart Land and Water Use Policies:** To address environmental problems, I propose to (1) expand national and state parks and federal wilderness areas, (2) enact laws to require sustainable use of water resources (including aquifers), forests, and farmland, (3) discourage construction of houses and other high-value buildings in areas that are most susceptible to natural hazards such as flooding and fires, and (4) make infrastructure investments to build resiliency against human-caused and natural hazards.
- **Nonpartisan Good Government:** To make government more effective and efficient, I propose several actions to (1) help Congress and the president overcome hyper-partisan politics and enact better laws, (2) create a more informed and engaged citizenry, (3) improve elections, (4) make the Supreme Court less partisan, and (5) encourage the media and opinion leaders to exercise free speech more responsibly.
- **Pragmatic Justice System Reform:** To reduce crime and incarceration, I propose several actions to improve our laws and prosecutorial systems, reform our police forces and prisons, and develop better alternatives to prison, using best practices from around the world.
- **Points-Based Immigration System:** To improve our immigration system, I proposed to reform it using Canada's points-based system as a guide. My proposal increases merit-based immigration, decreases extended family immigration, expands temporary work permits to reduce the incentive for illegal immigration, and addresses difficult problems such as how to deal with undocumented immigrants, asylum seekers, and refugees.
- **Lead a United Multipolar World:** To improve US foreign policy, I propose shifting from the current ad hoc decision-making process to a more rules-based approach and increasing international collaboration and assistance. My proposals are designed to encourage development of a united multipolar world, where global leadership is shared, collaboration and competition are based primarily on soft power rather than military power, a written code of conduct guides international relationships, and international agreements and institutions are aligned so every country has a strong incentive to comply with the code of conduct.

Table 8 shows how these ten actions achieve the SDGs. I am continuing to evaluate and improve these actions (step #5 in Figure 1) with the help of others. The last step in the systems engineering process (step #6 in Figure 1) is to implement and continuously improve the system. As with tax reform, this step requires Congress and the president to act. My ten proposed actions contain about 50 specific recommendations, which are an *integrated systems solution* for many of America's most urgent problems. It is good to have an objective such as this in mind when developing public policies. However, these actions and recommendations do not need to be implemented together; they can be evaluated separately and enacted sequentially over a period of several years.

INCORPORATING SYSTEMS ENGINEERING INTO THE LAWMAKING PROCESS

Systems engineering has been used successfully in science, technology, industry, and business for over 80 years. The foregoing examples illustrate how systems engineering can also be used to develop practical, nonpartisan solutions for complex societal problems.

One of my most important recommendations is that Congress should incorporate systems engineering into their lawmaking process. How can they do this? The answer is quite simple: Congress should establish a new organization that will use systems engineering to develop nonpartisan proposals. This new organization will not make policy. Its proposals will only be the starting point for Congressional debate and discussion. Congress and the president are the gatekeepers who decide when the organization's proposals are good enough to be implemented. This is how industry uses the systems engineering process. Congress and the president should use the same approach.

This new organization should be patterned after the (nonpartisan) Congressional Budget Office and the systems engineering organizations in industries that develop complex products and systems. This organization might be named the Nonpartisan Solutions Office (NSO) because it will use systems engineering and other fact-based and data-driven methods to develop nonpartisan proposals to address America's most urgent problems.

This new organization's proposals will make Congressional discussion of America's top issues a routine process and promote rational discussion of alternatives. Once discussion of these issues becomes routine, compromise will be possible and practical, nonpartisan laws can be enacted and continuously improved.

Congress does not currently have a full-time professional organization dedicated to developing nonpartisan solutions. This a major reason Congress is so dysfunctional. Too often, each political party develops their own (partisan) ideas without much regard to the needs of other stakeholders. Once their (partisan) positions have been defined, it is difficult for the parties to compromise and overcome cognitive biases. An NSO could break the logjam by developing and proposing rational, nonpartisan solutions.

The Senate should also consider modifying its filibuster rules, so any nonpartisan bill sponsored by the NSO is exempted from the filibuster. The filibuster rules currently allow 40 Senators (out of 100) to block passage of most bills. These rules were designed to promote nonpartisanship, but in actual practice they have had the opposite effect. Exempting nonpartisan bills from the filibuster would make the Senate (and Congress) much more effective, while also ensuring that the majority party does not steamroll over the minority party.

All legislative bodies should have an organization(s) such as the NSO to develop nonpartisan proposals. If Congress leads in using systems engineering, state and local governments, public policy organizations, policymakers, and international organizations can follow their example. This will help bridge the partisan divide and improve the political process at all levels of government.

CONCLUSION

Throughout history, civilizations and countries that were too divided and did not solve their problems failed. To survive and thrive, the United States and the world need better processes for working together for the common good.

This may seem like an impossible dream, but if engineers can work together to develop complex products on highly political programs, why can't lawmakers and policymakers work together to address complex societal problems? They just need a better process—the systems engineering process. ■

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Jim Hartung has 40 years' experience as a systems engineer, manager, and executive, primarily at Boeing, United Technologies, Rockwell International, and the US Navy. Most of his career he used systems engineering to develop complex products and systems such as the International Space Station, clean and renewable energy technologies, and nuclear power plants for submarines and aircraft carriers. Since retiring, he has pioneered the use of systems engineering to address social, economic, environmental, and political problems. He is author of the book *Rational Tax Reform: Using the Systems Engineering Process to Fix America's Broken Tax System*. His website JimHartung.com provides additional information.

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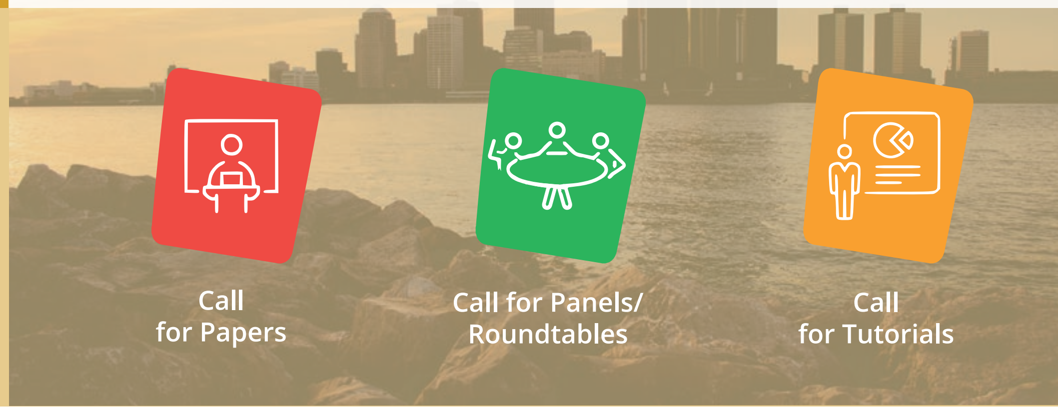

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