An Integrated, Modular Research Architecture for the Transformation of Systems Engineering

Jon Wade
Stevens Institute of Technology, School of Systems and Enterprises, Babbio Center, 5th Floor, Castle Point on the Hudson, Hoboken, NJ 07030
jon.wade@stevens.edu

Colin Neill
Pennsylvania State University, School of Graduate Professional Studies,
Malvern, PA 19355
cjneill@psu.edu

Azad Madni
University of Southern California, Daniel J. Epstein Department of Industrial and Systems Engineering, Los Angeles, CA 90089-0193
azad.madni@usc.edu

Abstract

As systems continue to grow in size and complexity, it has become clear that existing Systems Engineering (SE) methods, processes and tools are becoming increasingly inadequate. Addressing these challenges will require the development of a new paradigm for Systems Engineering that incorporates systems science advances in the areas of Enterprises and Trusted Systems. Also, advances need to be made in the area of Human Capital Development to educate and train a workforce capable of supporting the new paradigm. This paper focuses on the transformation of Systems Engineering and describes a research framework necessary for its implementation.

Introduction

As systems continue to grow in size and complexity, it has become clear that existing Systems Engineering (SE) methods, processes and tools are becoming increasingly inadequate. A number of trends collectively accelerate this challenge. Growing system complexity and criticality raise vulnerability. The ascendancy of software as the preferred solution continues in the face of significant gaps in our ability to understand, validate and manage large evolving software ecosystems. Systems themselves are dramatically increasing in scope to include Enterprise level considerations in decentralized governance and distributed stakeholders. As a result, the human element is becoming an agent of major system importance. The increasing speed of technological change, the rapid evolution of threats, and the decreasing schedules for development all lead to the sense that time itself is compressing. Thus, complexity, uncertainty, criticality and rate of change all present critical systems challenges. Finally, there is a growing gap in human capital necessary to address the challenges that these systems pose.

A transformation of Systems Engineering is necessary to address these gaps and satisfy the rapidly changing needs for complex systems through their life cycle. Accomplishing this transformation requires a fundamental rethinking of current SE practices (Carlini 2009; Crisp 2007;
Eremenko 2009; Friedenthal 2010; Watson 2009) as well as the creation of foundational principles in a number of critical areas:

1. **Systems Engineering and Management Transformation**: Classical Systems Engineering methods, processes and tools (MPTs) are not sufficient to address the challenges of complex systems with rapidly changing requirements and technology, while being deployed into evolving legacy environments. Decision making capabilities to manage these systems are also critical as determining how and when to apply different strategies and approaches is as important as the actual strategies and approaches that are to be deployed. This area of research should result in the creation of MPTs that leverage the capabilities of computational, visualization, communication and IT technologies to keep systems engineering and management on the technology curve. In addition, these MPTs should provide support for each of the research areas noted below.

2. **Enterprise Systems and Systems of Systems**: This area of research addresses the evolving needs of Enterprise scale systems, also known as Systems of Systems. These are systems in which the classical systems approach of deterministically engineering the system based on relatively static requirements and specified human interactions is insufficient. These are complex systems in which the human behavioral aspects are critical and emergent behavior is the norm (Madni 2010; Madni 2011). Research is necessary to determine the foundational principles which can then be used to develop the MPTs that can manage such massive interdependence and emergence.

3. **Trusted Systems**: This area of research addresses the challenges in conceiving, developing, deploying and sustaining systems that are safe, secure, dependable and survivable. These are all emergent properties for which it is essential that the entire system is considered, once again, including the human element. Foundational systems principles are needed so that system architects and developers can design these properties into systems and monitor them throughout the system lifecycle.

4. **Human Capital Development**: The combination of the retirement of the baby boomer generation, the reduced number of people entering the technical workforce, the attributes of the new workforce, and the new systems challenges facing our technical staff have made human capital development a critical challenge that must be addressed if there is to be success in future systems. Research is needed to determine the critical knowledge and skills required for our workforces as well as determining the most efficient and effective means by which this can be instilled in our workforce over their entire careers. Nothing short of a transformation will be required to address these goals.

This paper will focus on Systems Engineering and Management Transformation which will address a number of the high level needs in the other areas.
Systems Engineering and Management Transformation

Ultimately, Systems Engineering and Management MPTs should provide the most efficient and effective means to facilitate the transformation of systems needs, to concepts, through architecture, design, development, deployment and sustainment. The amount of transformational work should be minimized and parallelized as much as possible, and decision making should be removed from the critical path all while trading off cost, schedule and risk. Achieving this will require the development and adoption of a new set of MPTs based on a solid theoretical basis and supported by visualization, modeling, computation and information technology.

2.1 Gaps

The following is a compilation of the major gap areas that are the major obstacles to the necessary transformation (Turner 2009; Wade et. al. 2010) to address the systems challenges described earlier:

- **Risk/Opportunity Management** - tools which can assist in the assessment of program risk and value creation to allow for the proper tradeoffs between these competing goals based on the capabilities of the organization and the challenges of the system under development
- **System requirements** - creation, validation, prioritization, resolution of conflicting requirement, managing changing and emerging requirements & decision making; in particular the creation of a collaborative environment that facilitates tradeoff resolution and creation of a mutually understandable description of the desired system concept
- **Low-Overhead Communication** - the ability to provide the essential communication to keep a large organization synchronized throughout a system lifecycle with a minimum amount of overhead to provide scalable agility
- **Architectural Design Support** - processes and tools to support the development of an architecture which can support the attributes of maintainability, upgradeability (flexibility) and extensibility, along with reliability, availability, security and other emergent properties
- **Verification & Validation** - an integrated set of processes and tools which can provide verification and validation throughout the lifecycle process
- **Legacy Integration** - the capability to monitor and characterize the current legacy system to ensure that the addition of new applications and services have the desired capabilities, and the ability to integrate independently evolving components into a larger interoperable system
- **Human Aware/Self-Adaptive** - the capability to optimize the use of humans in the system to take advantage of self-adaptive human capabilities

The following is a compilation of the opportunity areas:

- **Complexity Handling Capabilities** - tools and techniques which leverage technological advances in computation, visualization, information technology and communication that allow systems engineers to comprehend increasingly complex problems yet build parsimonious solutions.
- **Cycle Time Reduction** - a suite of processes and tools, including those noted above, which can increase the quality of the systems while compressing latency through the life cycle; these include tools which not only accelerate new development, but also eliminate unnecessary work by facilitating reuse and providing correct by design construction.

2.2 Concept

Meeting the challenges presented by the critical system trends, addressing the gaps identified in the previous section, and transforming Systems Engineering and Management into a successful, relevant and timely discipline, requires a new paradigm. This new paradigm must be:

- **Agile**: Allowing for quality, timely development with an incomplete and changing set of system requirements.
- **Integrated**: Part of the main development process and not an additional set of discretionary tasks.
- **Efficient**: Providing the greatest amount of benefits with the minimal number of steps and least amount of effort.
- **Leveraged**: Enabling exponential capability growth through the leveraging of computational, visualization, communication and information technologies, and prior systems experience.
- **Extensible**: Providing the ability to expand and enhance capabilities for future growth without having to make major changes in the infrastructure.
- **Deployable**: Enabling widespread impact through workforce education and broad application.

And yet, it must be sufficiently rigorous to ensure our systems are thoroughly engineered and will work as intended, satisfying the stakeholder’s needs and vision.

The proposed concept, as shown in Figure 1, is one termed Interactive Model-Centric System Engineering. In many ways, this approach is inspired by the automation and extensive use of computation, visualization, information and communication technologies used in the electronics industry.
The critical attributes are that each activity of the lifecycle, and communication between these activities, are accomplished with an optimal mix of technology and human capability, through the interactive use of a consistent set of data and models, with visualization that is optimized for the particular user. The use of graphical models has the potential to provide consistent meaning to all the stakeholders and bridge these gaps.

The four key elements are:
- Interactive - Interactive, iterative design, execution and re-design
- Continuous - The activities take place continuously and in parallel, e.g. verification and validation happen throughout the lifecycle
- Modeling - The representation of information that can be processed by computation for analysis and on-the-fly simulation
- Multi-Modal/Sensorial Visualization - The visual representation of information, personalized to the needs of the user

The adoption of an interactive model-centric system lifecycle model is necessary to transform systems engineering from a sequential, document based process to an interaction model-based one. In addition, rather than assuming a linear, waterfall process, the transformed discipline needs to take advantage of an opportunistic approach in which solutions are simultaneously being generated by all interacting stakeholders, yet remain consistent. Finally, humans must play a central role in the system such that entire system is optimized rather than just the technological systems and subsystems.

The tools and technology, which include models and simulation, can be used to facilitate understanding & decision making, improve development efficiency and automate processes. At the front end of the lifecycle, much of the effort is in the area of very abstract, multi-dimensional analysis and decision making across multiple domains. This is the area in which the human mind can be productively applied if it can be given the appropriate means of viewing the critical attributes. This is likely to be too broad of a space for design automation. However, it is an area in which visualization, and other multi-media, multi-modal means of presenting information can greatly improve the ability of human trade space analysis and decision making. As the system representation is transformed and refined through the lifecycle into less abstract and more concrete information, increasing design efficiency becomes a major focus. Finally, as these representations start to fit into established patterns and technology, automation can be applied.

In the four activity life cycle process, much of the human value-add occurs at the front end of the process, in the strategic areas of value recognition and concept creation. In these areas, tools can be used as a means to capture ideas and concepts, and translate these into representations which can be recognized by a variety of stakeholders and contributors. As such, tools can be used to facilitate the iterative creation of shared mental models, and provide a means by which to evaluate the behaviors and attributes of these models to facilitate decision making. Tools can be used to assist in the creation and analysis of architecture by visualizing systemic properties and emergent behavior so that change impact can be assessed and opportunities for extension and adaption can be readily identified. Tools can provide developers with the ability to ensure that their designs can be successfully integrated to form a system that is in compliance with and supports the envisioned value proposition. These tools can be used to automate the development of
system verification and validation. Finally, these tools can assist in the validating the desired usage models and support the training of personnel necessary for deployment.

It is critical that the models used in this lifecycle are capable of supporting the required level of detail and fidelity for each of their users, while being integrated for use through the entire lifecycle. Limitations in their representational detail, views (for different users) and ability to be integrated and updated for consistency will greatly restrict their value. Thus, these are required characteristics. While all of the capabilities need not appear at once, the overall value of the tools is increased as additional tools are added to the suite.

In addition, the critical elements necessary for the transformation of SE noted above are integrated into a set of clustered areas of innovation which are described below. It is expected that the research results from each of these modular clusters also can be integrated together to provide a wider set of capabilities.

2.3 Integrated Research Roadmap

The resulting eight research focus areas, also called modules due to their intended modular nature, and their relationships to the 4-stage lifecycle are shown in Figure 2. The sum total of these research areas provides for an integrated, yet modular architecture. While each of the individual areas can be pursued independently and provide incremental value, each provides additional benefit to the other areas in which the collective research provides more value than the sum of the individual parts. Each of these research areas is described in more detail below.

![Figure 2. Relationship of Research Areas to 4-Stage Lifecycle](Source: Wade et. al. 2010)
The **Prioritization and Tradeoff Analysis** module provides the capability to input the particular factors relating to the relative value and priority of high-level capabilities of the system under development. The output of this module is the creation of models which are invoked during subsequent Concept Engineering, Architecture and Design Analysis, and Design and Test Reuse and Synthesis work. The creation of a central set of models enables each subsequent development effort to work under the same set of valuation and prioritization constraints. In addition, this module provides visualization capabilities to enhance the user's ability to understand and assess the validity of these value and prioritization models.

The **Concept Engineering** (Carlini 2009; Cloutier et. al. 2009) module provides an interactive, collaborative, multimedia environment for multiple stakeholders to rapidly construct concepts of operation and other high-level abstract models of the system under development. Within the environment is a library of concept modules, a variety of scenarios, and Reuse and Synthesis capabilities. Models are simulated against scenarios in the repository while the Prioritization and Tradeoff models are employed to determine the relative value of each concept. Models are also supplied by the Human-System Integration module for the scenarios being investigated and also for the actual system models. The Human-System Integration modules may also be useful in the interactive concept development process by enhancing the ability of the stakeholders to develop a shared mental model by analyzing the behavior of their interactions and noting shortfalls to the appropriate users. Design and Test Reuse and Synthesis may also guide the user concepts towards more time, effort, cost and risk optimal solutions due to availability of reusable or synthesizable design and test. In addition, these capabilities can be used to construct a number of conceptual views of the systems with increasing levels of fidelity.

The **Architecture and Design Analysis** module provides the system architect with the ability to design and optimize an architecture which meets the needs of the operational concept while providing an optimal solution based on the Prioritization and Tradeoff Analysis models described earlier. The Design and Test Reuse and Synthesis capabilities provide the Architectural and Design Analysis module with the capability to quickly perform what-if analysis across a large set of trade spaces. Some of this work can be done through computationally automated means, but much can be done by providing visualizations which reveal system interdependence, highlight fragile regions where change comes at increased risk, and identify opportunities where system capability can be extended or adapted easily (Sangwan et. al. 2010). This is an area in which human capabilities can be greatly extended.

**Design and Test Reuse and Synthesis** provides the means, by leveraging existing assets and utilizing computational capabilities, to rapidly translate high level abstractions into lower level ones. These capabilities can be used across the entire range of design and test abstractions from concept to implementation. While it is improbable that synthesis and reuse can be effectively used in a turnkey manner for the entire system through all the various levels of abstraction, these capabilities certainly can decrease design and test development time, and reduce system development cost and risk if applied in areas of greatest leverage. Reuse and synthesis will be guided, both automatically and with human guidance, based on the information and analysis capabilities from the various research areas. For example, the models created from the Prioritization and Tradeoff Analysis module provide optimization guidance for Reuse and Synthesis decisions. Architectural and Design Analysis capabilities can also be used to provide direction for Reuse
and Synthesis decisions. Human-System Integration models provide the fidelity necessary to ensure that the entire system can be optimized, not just the individual technology and human subsystems and agents. The models and test scenarios developed in the Concept Engineering module can be used as an entry point into this module.

**Active System Characterization** has the role of providing feedback between the virtual and physical system domains. While many of the simulations that support the above work can take place using virtual or hybrid simulations with physical components, it is very difficult to understand and model the actual deployed environment with a high degree of fidelity. Understanding is increasingly difficult when this environment is a complex system of systems where there may be no centralized control or where human agents play a significant role. This module constantly monitors the actively deployed system and feeds back this information into the model and data repository ensuring that that this information is up to date in near real time. This information not only provides updates to the models of technical systems, but also of human behavior and system usage both for the system that is being developed and the system that is doing the developing. For example, performance attributes of the deployed system can be used to update the performance expectations of the system being developed with a new set of capabilities. The behavior of the developers can be used to determine potential changes in the development processes, or can be used to determine the effects of making changes to the system in both time, effort (exactly who is being impacted), cost and risk. Much of this work can be done through computational data mining. The modules in this area provide the necessary feedback path to effectively synchronize the virtual and physical worlds.

**Human-System Integration**, true to its name, is integrated throughout the system lifecycle activities. In particular, this module provides inputs to the rest of the modules to ensure that the human factor is properly taken into consideration and modeled with the end goal of optimizing the entire system, not just individual technical and human subsystems and components (Madni 2010; Madni 2011). Specifically, this is not limited to ergonomics and task analyses. This module takes inputs from the Active System Characterization module to ensure that its models are kept up to date and accurately reflect the behavior of the human agents in the existing system which may change over time. Not only is this module needed for the optimal development and deployment of the system being created, but also for the system which is creating the system. Thus, Human-system Integration provides critical information to the Agile Process Engineering module to ensure that these processes are properly optimized.

**Agile Process Engineering** is necessary to provide the processes and governance to enable productive parallel development in each of the aforementioned areas. Without such processes, these parallel developments would either be chaotic and counterproductive, or unnecessarily constrained through forced sequential activities. In addition, it is critical that the processes themselves are agile and tuned for the particular mission, system being developed and environments in which they are both being developed and being used. This module will use the models from the Prioritization and Tradeoff Analysis module to determine the relative importance of various system attributes to tune the processes used to develop them. The models from the Human-System Integration module will also provide input on how best to use this organization. In addition, processes will be reused and/or synthesized for improvement. It should be understood that the development system should be architected, designed and optimized with many of the
same techniques used for the systems that it is developing. These Agile Processes will act as the control system which governs how each of the research areas interact. This module and the Modeling Environment Infrastructure together comprise the environment, processes and governance that supports the SE activities.

Finally, there is the **Modeling Environment Infrastructure**. This infrastructure not only provides a central model and data repository substrate, but it also supports all of the aforementioned modules and infrastructure while providing the most effective interface to the users of the system who may involve a broad range stakeholders. This environment provides the means by which the Agile Processes are realized in operation. This environment plays a critical role in moving SE from an oversight role into an integrated, embedded capability in the engineering and support of systems throughout their lifecycle.

**Conclusion**

An integrated, modular framework composed of eight critical research areas supporting the transformation of Systems Engineering has been presented. Each of the eight research areas were described with respect to their capabilities. These descriptions note how these research efforts are integrated, such that they interact closely with one another providing value that is greater than the sum of their parts, yet remain modular such that each area can proceed and provide value independently. Each of the research areas has capabilities which leverage the current state of the art in computation, visualization, communication and information technologies. Future advances in these areas will only increase the capabilities of the technologies developed in these research areas, thus keeping Systems Engineering “on the curve”. However, success in these areas is not dependent on future technology advances. Taken separately, these research areas have the potential to significantly advance the state of the art of Systems Engineering. Taken together, they have the potential to transform Systems Engineering.

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**References**


Biographies

Jon Wade is a Distinguished Service Professor in the School of Systems and Enterprises at the Stevens Institute of Technology and currently serves as the Associate Dean of Research. Dr. Wade has an extensive background in leading research and development organizations and managing the development of Enterprise products at International Game Technology, the UltraSPARC V based Enterprise Server family at Sun Microsystems, and supercomputer development at Thinking Machines Corporation. Dr. Wade received his SB, SM, EE and PhD degrees in Electrical Engineering and Computer Science from the Massachusetts Institute of Technology.

Azad Madni is a Professor in the Daniel J. Epstein Department of Industrial and Systems Engineering, and the Director of the Systems Architecting and Engineering (SAE) Program in the Viterbi School of Engineering of the University of Southern California. His research interests include integrating humans with adaptable systems, engineering resilient systems, game-based simulations for education and training, and complexity management in large-scale systems. Dr. Madni received his B.S., M.S., and Ph.D. degrees from the University of California, Los Angeles. He is a Fellow of IEEE, INCOSE, SDPS, IETE, and an Associate Fellow of AIAA.

Colin Neill is an Associate Professor of Software and Systems Engineering at Penn State’s School of Graduate and Professional Studies. His research focuses on MPTs for design and architecture and investigating how engineers comprehend and reason about complex systems. Dr. Neill received his B.Eng, M.Sc. and Ph.D. degrees from the University of Wales, Swansea.