*Transitioning research into practice - crossing boundaries through integrative collaboration*

# RESEARCH TRANSITION REPORT

*– 2017*

SYSTEMS ENGINEERING RESEARCH CENTER

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## INTRODUCTION AND CONTEXT

Since 2008, the SERC has operated as the UARC chartered to perform systems engineering (SE) research for the Department of Defense (DoD) and the Intelligence Community (IC). The SERC mission is to enhance and enable the DoD's capability in systems engineering for the successful development, integration, testing, and sustainability of complex defense systems, services, and enterprises. This is done through research leading to the creation, validation, and transition of innovative SE methods, processes, and tools (MPTs) to practice. It responsibly manages impact while evolving and coalescing the number, connectedness, and responsiveness of the SE research community in the United States to the needs of the DoD and IC.

In coordination with its sponsors, the SERC has focused its research portfolio into four thematic areas with associated Grand Challenges, as shown in Figure 1 and described below.

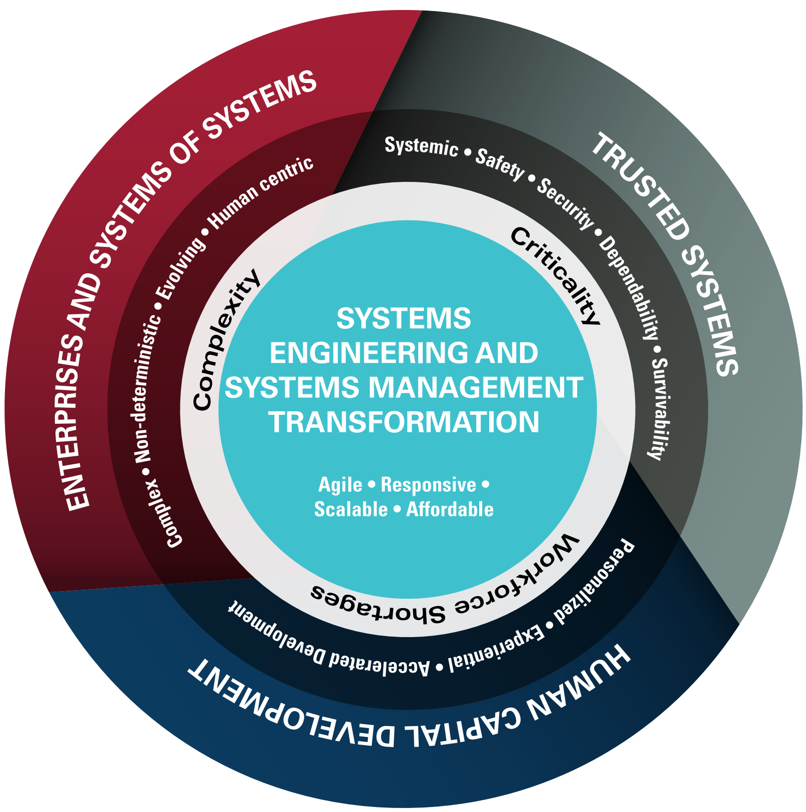


*Figure 1. The Four Thematic Areas Being Addressed by SERC Research Tasks.*

**ENTERPRISES AND SYSTEMS OF SYSTEMS:** Providing ways to develop, characterize and evolve very large-scale systems composed of smaller systems, which may be technical, socio-technical, or even natural systems. These are complex systems in which the human behavioral aspects are often critical, boundaries are often fuzzy, interdependencies are dynamic, and emergent behavior is the norm. Research must enable prediction, conception, design, integration, verification, evolution, and management of such complex systems.

> ***Grand Challenge:*** *Create the foundational SE principles and develop the associated MPTs that enable the DoD and its partners to model (architect, design, analyze), acquire, evolve (operate, maintain, monitor, adapt) and verify complex enterprises and systems of systems to generate affordable and overwhelming competitive advantage over its current and future adversaries.*

**TRUSTED SYSTEMS**: Providing ways to conceive, develop, deploy and sustain systems that are safe, secure, dependable, adaptable and survivable. Research must enable prediction, conception, design, integration, verification, evolution and management of these emergent properties of the system as a whole, recognizing these are not just properties of the individual components and that it is essential that the human element be considered.

> ***Grand Challenge:*** *Achieve much higher levels of system trust by applying the systems approach to achieving system assurance and trust for the increasingly complex, dynamic, cyber-physical-human net-centric systems and systems of systems of the future.*

**SYSTEMS ENGINEERING AND SYSTEMS MANAGEMENT TRANSFORMATION:** Providing ways to acquire complex systems with rapidly changing requirements and technology, which are being deployed into evolving legacy environments. Decision-making capabilities to manage these systems are critical in order to determine how and when to apply different strategies and approaches, and how enduring architectures may be used to allow an agile response. Research must leverage the capabilities of computation, visualization, and communication so that systems engineering and management can respond quickly and agilely to ensure acquisition of the most effective systems.

> ***Grand Challenge:*** *Move the DoD community's current systems engineering and management MPTs and practices away from sequential, document-driven, hardware-centric, point-solution, acquisition-oriented approaches; toward concurrent, portfolio and enterprise-oriented, hardware-software-human engineered, model-driven, set-based, full life cycle approaches. These will enable much more rapid, flexible, scalable definition, development and deployment of the increasingly complex, cyber-physical-human DoD systems, systems of systems and enterprises of the future.*

**HUMAN CAPITAL DEVELOPMENT:** Providing ways to ensure that the quality and quantity of systems engineers and technical leaders provide a competitive advantage for the DoD and defense industrial base. Research must determine the critical knowledge and skills that the DoD and IC workforce require as well as determine the best means to continually impart that knowledge and skills.

> ***Grand Challenge***: *Discover how to dramatically accelerate the professional development of highly capable systems engineers and technical leaders in the DoD and defense industrial base and determine how to sustainably implement those discoveries.*

## OBJECTIVE OF THIS RESEARCH TRANSITION REPORT

All research within the SERC is conducted with an objective of transitioning that research into practice, as appropriate. This aspect of the SERC continues to grow in impact through our collaboration with a number of FFRDCs, National Laboratories, and DoD Industry. To further support this process of transitioning research into practice, this report highlights completed or on-going research tasks that are at a reasonable point of maturity to support such a transition. SERC research faculty have published over 300 technical papers and reports over the past eight years and transitioned the research into numerous courses across the SERC universities and beyond. We encourage organizations to review the research tasks highlighted in this report, and to contact us if we can assist in the necessary discussion and engagement to support the transition of relevant research into practice.

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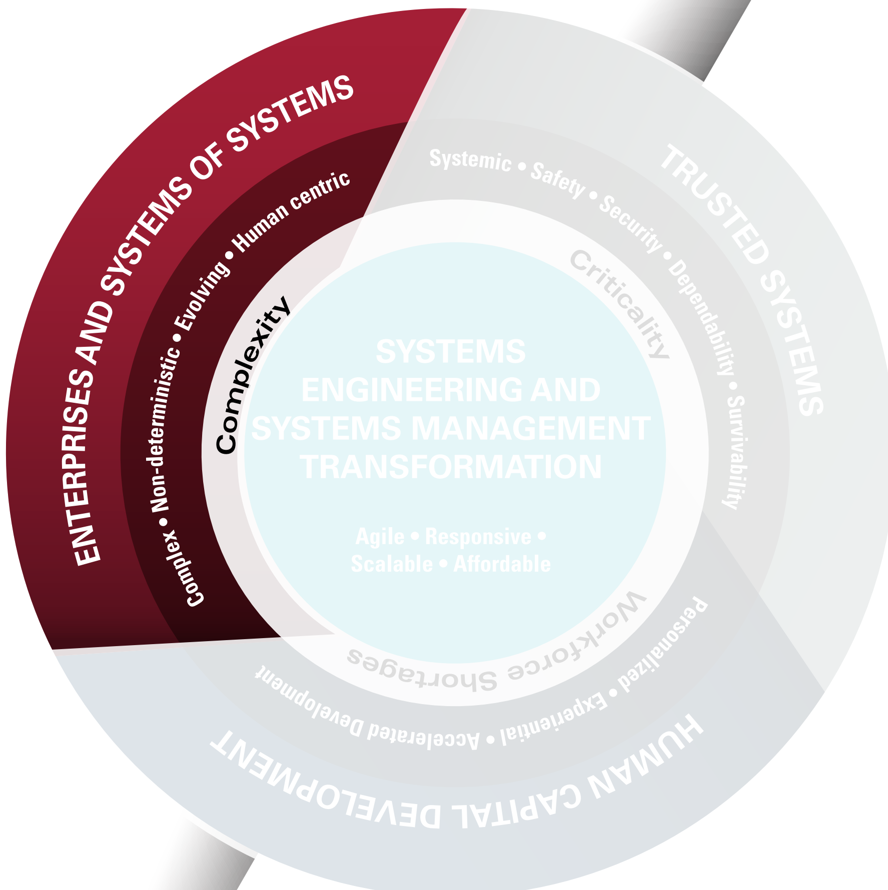
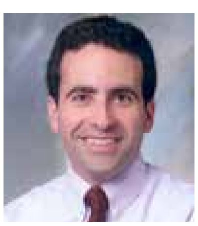
# ENTERPRISES AND SYSTEMS OF SYSTEMS



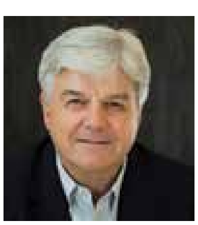

*Providing ways to develop, characterize and evolve very large-scale systems composed of smaller systems, which may be technical, socio-technical, or even natural systems. These are complex systems in which the human behavioral aspects are often critical, boundaries are often fuzzy, interdependencies are dynamic, and emergent behavior is the norm. Research must enable prediction, conception, design, integration, verification, evolution, and management of such complex systems.*

## RESEARCH COUNCIL MEMBERS FOCUSED ON THIS THEMATIC AREA:



**Daniel A. DeLaurentis**

*Professor, Director, Institute for Global Security and Defense Innovation (i-GSDI), Purdue University*



**William B. Rouse**

*Alexander Crombie Humphreys Chair in Economics of Engineering, Stevens Institute of Technology*

## ASSESSING THE IMPACT OF DEVELOPMENT DISRUPTIONS AND DEPENDENCIES IN ANALYSIS OF ALTERNATIVE SYSTEM OF SYSTEMS (SOS), SOS ANALYTIC WORKBENCH (AWB)

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**Sponsor:** DASD(SE)
**Project Page:** http://www.sercuarc.org/projects/assessing-the-impact-of-development-disruptions-and-dependencies-in-system-of-systems-sos/

### 1. What was the problem being addressed? Why was it hard and is it important?

The task of evolving and refining a System of Systems (SoS) presents significant decision-making challenges across both technical and programmatic domains. SoS generally involve integrating multiple independently managed systems to achieve a unique capability, therefore requiring collaboration, negotiation, and control. The large number of interdependencies that exist, among and between such systems, makes objective assessment of the impact of SoS architectural decisions, very difficult. Handling the large number of variables involved rapidly goes beyond the immediate mental faculties of decision-makers. Furthermore, the complex relationships that exist between systems makes the nature of an SoS hard to understand. These challenges, among others, fuel the inability to make effective decisions, which can lead to developmental cost and schedule overruns, reduced operational capabilities, and increased risks. Over the past four years, we have been funded by the SERC to develop an SoS Analytic Workbench, addressing some of these challenges.

### 2. What was new in the approach and why do we think it will be successful?

The SoS Analytic Workbench idea was inspired by our recognition that SoS design and operation involves asking and answering many questions, which, on the surface, may appear unique to the SoS context, but, upon further examination, reveal similarities and commonalities across SoS. By their nature, these questions cannot be answered by a single analysis method or tool, and in thinking about the best framework to attack the challenge, we were inspired by the workbench metaphor offered by SERC Technical Advisor Judith Dahmann from MITRE Corporation to encapsulate the concept of a set of theories and methods that we have adapted and expanded to support answering these archetypal SoS questions. We developed a candidate suite of methods based on observations of previous case studies and subject matter expert opinions on the most pressing needs for analysis-based decision support. These methods relegate the complexities of SoS related decision-making to the methods and delegate the decision-making elements to the decision-maker. Our growing success in the development of the SoS Workbench has been fueled by collaborative exchanges with potential users from government, industry and academia.

### 3. Who should care about this problem?

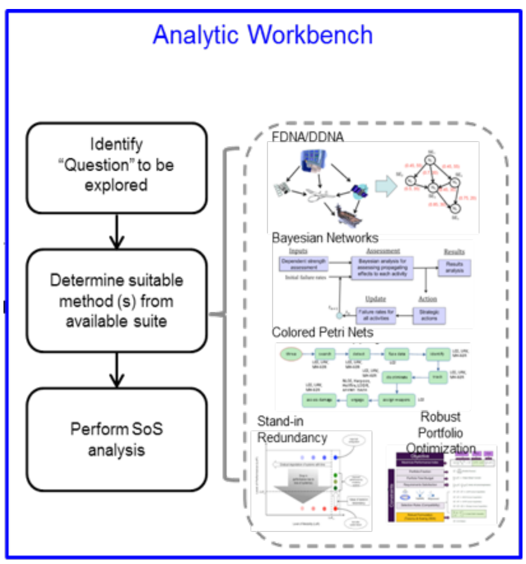
While our work focused on the needs of the US-Department of Defense, the problem of evolving an SoS is relevant to all factions of our broader industrial ecosystem. System-of-system problems exist across a great range of areas, ranging from air transportation to financial ecosystems. Our methods, processes and tools developed in this effort are domain agnostic, with the very reason of being translatable and usable across a wide range of problems.

### 4. What are the risks and payoffs?

The risk of this endeavor was rooted in the ability of the methods chosen of our workbench to be effective against a wide array of potential problem faced by SoS decision-makers. Furthermore, there was also the risk of adoption of the tool, in terms of usability and suitability of the methods to be able to provide actionable insights to stakeholders. However, our deep exchanges and iterations with a large array of collaborators form MITRE Corporation, Johns Hopkins Applied Physics Labs (JHUAPL), U.S. Army Research Labs, Naval Surface Warfare Center Dahlgren Division, Naval Warfare Center Crane (NSWCC), NASA Marshall Spaceflight Center (NASA-MSFC), and others have enabled us to mitigate these risks towards providing a well posed prototype product that has been used by several of our partners and collaborators in native environments. The payoff was an SoS Workbench toolset that not only provided an innovative suite of methods, but was tailored to meet the needs based on a wide array of inputs from the System Engineering and SoS community.

**5. What difference will this research make?**

Immediate and continued benefits of the research have been rooted in our research transition strategy plan with some of our collaborators. One of our most successful exchanges, resulting in effective use of our AWB, was with the Johns Hopkins University Applied Physics Laboratory (JHUAPL), who saw utility in merging dependency metrics (strength, criticality, and impact), from the SoS Workbench, with their own model of system effectiveness to measure network performance in real-time. Collaborations with NASA Marshall Space Flight Center (MSFC), culminated in a Cooperative Agreement to use selected tools in the SoS-AWB (SODA, RPO, SDDA) to analyze aspects of space exploration architectures, with particular focus on the impact of different technological choices. NSWCC applied the SoS Workbench's SODA tool to a restricted project on risk analysis of critical defense infrastructure and assets. Furthermore, there have been 58 users of the AWB on Purdue's NanoHUB system who have successfully run 692 instances of our tool provided at: (**NanoHUB Link: http://nanohub.org/resources/plottool**). Our years of research in the development of these tools have provided an excellent set of documented successes of impactful application of the SoS Workbench tools, and, lessons learned both in development and transition of analytic tools to native SoS environments.



## ENTERPRISE SYSTEMS ANALYSIS: MULTI-LEVEL SOCIO-TECHNICAL MODELING

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**Sponsor:** DASD(SE)
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### 1. What was the problem being addressed? Why was it hard and is it important?

Developing and applying Systems Engineering (SE) techniques to enterprises would be of great value to DoD. DoD expends substantial funding on managing enterprise activities, from health care to transportation to energy management. SE methods, processes, and tools that allow DoD stakeholders to better understand the impact of incentives and their policy decisions could significantly improve the performance of DoD enterprises, saving money while increasing DoD's ability to deliver high-quality systems and services to the warfighter. Addressing enterprise systems is especially challenging because it is the interaction of social, behavioral, and organizational factors with technological systems that is the major driver of enterprise behavior. Addressing these types of issues cannot be accomplished with technical means alone. Rather, technical solutions must be carefully coordinated with policies and strategies that consider individual, economic, and organizational incentives. One key challenge to achieving such solutions is that traditional engineering approaches to modeling and analysis have difficulty with these social aspects. Traditional design and optimization techniques depend on having a relatively complete description of the system. The complexity introduced by differing stakeholder values, incomplete knowledge, and social dynamics calls for new analytic approaches.

### 2. What was new in the approach and why do we think it will be successful?

Historically, engineering models have often treated human and organizational factors as an afterthought. When they are included, it is often in a highly constrained manner. Such constraints limit the ability of any model to detect the sometimes surprising behavior of an enterprise system as the real human or organization in question has far more degrees of freedom than the model would suggest. To better incorporate the human, social, and behavioral factors, this effort employed a deliberately multi-level approach to constructing models of enterprise systems. From this perspective, the technical system is just one "level" of system. Organizational, political, economic, and behavioral views of the system are each assigned to a different level ensuring equal status in the modeling effort. However, implementing this approach entails a number of technical challenges with regard to how each of these levels should be modeled and how the levels should interact with one another. The research approach was to investigate and develop methods to address these challenges via a series of case studies, each a real world enterprise problem relevant to DoD.

### 3. Who should care about this problem?

DoD and other federal agencies such as Health and Human Services and Veterans Affairs that face challenges where organizational and social factors play a substantial role.

### 4. What are the risks and payoffs?

From a technical perspective, there are two major risks. The first risk is that efforts to develop computational models that involve multiple scales or perspectives often encounter difficulties coordinating information flows among the scales or perspectives. If the resolution of these difficulties are case specific, it could limit the utility of the resulting methods. The second risk is that theories from the behavioral and social sciences are rarely formulated to support computational modeling. If key theories are not amenable to integration within a multi-level computational model, certain enterprise behaviors could be missed. However, if these risks are addressed, the resulting methods could enable federal agencies to detect potential unintended or counter-productive consequences to proposed policies and technical solutions.

### 5. What difference will this research make?

The primary output of this research is an enterprise modeling methodology that enables organizations to evaluate potential policy options or technical solutions when behavioral, social, or organizational factors are significant drivers of realized outcomes. More specifically, the methodology is designed to enable the detection of unintended or counter-intuitive results triggered by these factors. The methodology was developed through the performance of two cases studies: the detection of counterfeit electronic parts in the defense supply chain and the protection of critical infrastructure.

## FLEXIBLE INTELLIGENT LEARNING ARCHITECTURES FOR SYSTEMS OF SYSTEMS (FILA-SOS)
### - An Advanced Computational Approach to SoS Analysis and Architecting using Agent-based Behavioral Modeling

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**1. What was the problem being addressed? Why was it hard and is it important?**

Evaluating the effectiveness of SoS solutions in representative mission level scenarios is now presenting a new challenge, as mission level models such as: Advanced Framework for Simulation, Integration and Modeling AFSIM and Suppressor, are difficult to optimize for SoS applications. The current models were designed to demonstrate optimal use of one single force architecture at a time (usually to highlight one member of that architecture), not to evaluate a multitude of architectures. Analysts traditionally fine-tune the tactics within an evaluation scenario to show how well the chosen architecture (and the highlighted system) succeeds at the mission goals.

The system-of-systems analysis requires identifying not only which systems are present in the architecture and how many of each (including their interactions), but the best way to use those systems. For example, increasing communication links may improve SoS effectiveness, but also increases SoS vulnerability to different methods of attack. Adding the dimension of choosing-the-players has uncovered a weakness in the current evaluation process: the problem is now unbounded. Three major challenges confront those attempting Mission Level System of Systems analysis with the current model set.

The first challenge is finding optimal solutions within the near infinite potential set of force architectures. Secondly, the fact that systems behave and perform differently depending on which other systems exist within a chosen architecture makes accurately predicting outcomes tentative at best. Currently, predicting mission success is more art than science and each potential architecture must be evaluated within the mission model to determine effectiveness.The interactions between systems, numbers of systems, and their potential synergistic effects can only be realized in detailed mission modeling. Lastly, each mission scenario presents its own unique set of interactions and effects. Force structures and tactics that work in one scenario may be completely ineffective in a different scenario. The three challenges of modeling combat effectiveness of System of Systems at a mission level – ineffectiveness of detailed mission models for assessment, complex systems interactions, and scenario dependencies combine to create the demand for a new form of mission level modeling.

**2. What was new in the approach and why do we think it will be successful?**

Flexible and Intelligent Learning Architectures for SoS (FILA-SoS) integrated modelling as developed in this research task provides a decision making aid for SoS manager based on the wave model of SoS development. The modelling approach called the FILA-SoS does this by using straightforward system definitions methodology and an efficient analysis framework that supports the exploration and understanding of the key trade-offs and requirements by a wide range system-of-system stakeholders and decision makers in a short time. FILA-SoS and the Wave Process address four of the most challenging aspects of system-of-system architecting, namely: dealing with the uncertainty and variability of the capabilities and availability of potential component systems, providing for the evolution of the system-of-system needs, resource and environment changes over time, accounting for the differing approaches and motivations of the autonomous component system managers, and optimizing system-of-systems characteristics in an uncertain and dynamic environment with fixed budget and resources. The proposed approach provides evaluation of the effectiveness of SoS solutions in representative mission level scenarios over time with different defense and commercial applications. Its unique approach will bring powerful synergy to bear on the problem and produces an effective set of practical tools to facilitate SoS analysis and architecting.

**3. Who should care about this problem?**

The DoD, or any commercial organization, faced with the necessity of developing cyber physical systems and /or complex SoS architectures can make use of the FILA-SoS approach.

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**4. What are the risks and payoffs?**

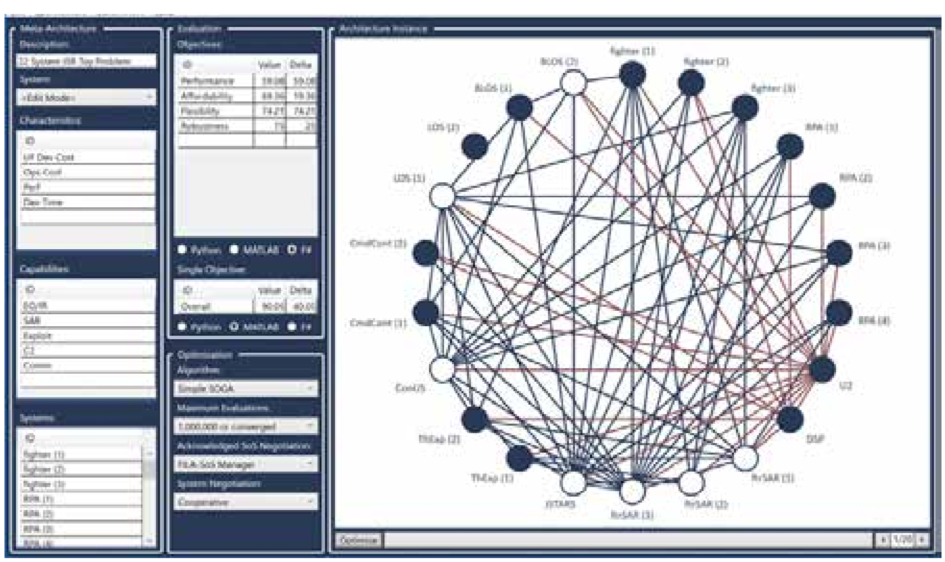
This project builds upon earlier work by the SERC. Because it was an extension and improvement upon existing work, the risks were minimized. The basic issue was being able to successfully model the multiple complexities of SoS. The task can now be accomplished for different applications domains through the SoS Explorer software tool developed recently by the Engineering Management and Systems Engineering Department at Missouri S&T. It provides a framework for defining system of systems/cyber-physical systems capabilities for complex problems such that optimal architectures may be produced computationally. The overall performance of the architecture is determined by the objectives defined for it. These objectives may be defined using one of three languages: Python, MATLAB, or F#. The selected optimizer can then be used to generate optimal architectures which are displayed in the GUI and may be interactively adjusted by the user. Solutions may be stored as Excel Open XML files (".xlsx") or graphically as Portable Network Graphics (".png") images. Stored files may be reloaded and analysis continued by adjusting capabilities or constraints further.

For evaluation, the objectives require an architecture which, in this framework, is a set of systems and interfaces and information about the systems in terms of their characteristics, capabilities, and feasible interfaces. The objectives are evaluated by an optimizer, which may be selected from three evolutionary algorithms: NSGA-III, MaOEA-DM, and Simple SOGA. Both single and multiple objective optimization is supported. Furthermore, constrained optimization is supported and constraints may be added using Python, MATLAB, or F#. Availability of this capability is the basic payoff the research.

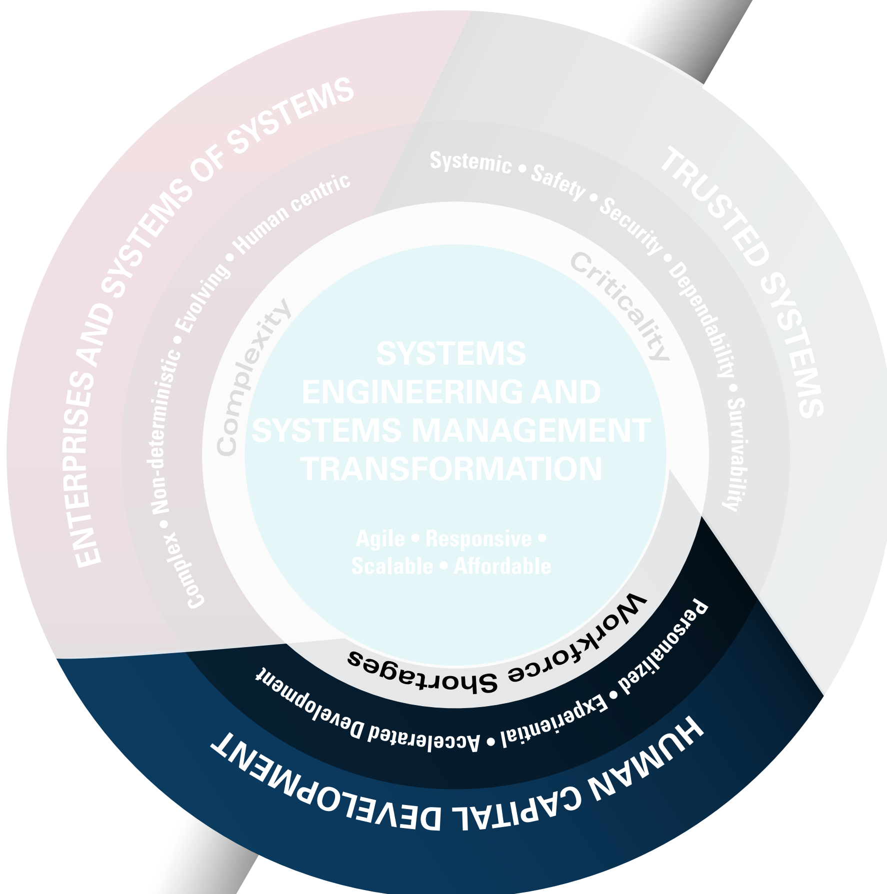
**5. What difference will this research make?**

The concepts developed in this research were transitioned through one of the Missouri S&T Systems Engineering PhD students from the Boeing Company to SoS Concept Development and Assessment in the DARPA SoSITE project. Architecture assessment and meta-architecture generation modules of FILA SoS were modified after the completion of the research task and converted to SoS Explorer software. Licensees will be available later in the year. This software is also being used in the Smart Engineering System Design course in the Systems Engineering program at Missouri S&T.

System of Systems and Cyber Physical Systems (CPS) are multi-faceted systems of the future entailing complex logic and reasoning with many levels of performance in intricate arrangement. They need to be engineered and operated in an evolutionary way through a web of connections demonstrating adaptability and discovered capability. They are designed for autonomy and may exhibit emergent behavior that can be visualized. Complex Adaptive Systems have dynamically changing meta-architectures. Finding an optimal architecture for these systems is a multi-criteria decision making problem often involving many objectives - on the order of 20 or more. This creates "Pareto Breakdown" which prevents ordinary multi-objective optimization approaches from effectively searching for an optimal solution; saturating the decision maker with a large set of solutions that may not be representative for a compromise architecture selection from the solution space. This requires a drastic change in the engineering methods and tools. Modelling and simulation of CPS is becoming a very important area of research. The need for test beds ensuring interoperability between CPS and for verification, (either of models or of the CPS themselves, inclusion of human factors in modelling and simulation, open frameworks for model interoperability, incorporation of security architectural features into models, combining formal verification and simulation technology) is an evolutionary approach to testing and evaluation of adaptive and resilient CPS. Big-data analytics modelling via machine learning have been recently identified as significant fundamental research themes. This research demonstrates that it is possible to solve some of these design problems with a model that can be transitioned to real world applications and open an avenue to the development of new approaches.



# HUMAN CAPITAL DEVELOPMENT




## RESEARCH COUNCIL MEMBERS FOCUSED ON THIS THEMATIC AREA:

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*Sam Nunn School of International Affairs,*
*Georgia Institute of Technology*

**Jon Wade**

*Distinguished Research Professor,*
*Stevens Institute of Technology*

*Providing ways to ensure that the quality and quantity of systems engineers and technical leaders provide a competitive advantage for the DoD and defense industrial base. Research must determine the critical knowledge and skills that the DoD and IC workforce require as well as determine the best means to continually impart that knowledge and skills.*

## THE HELIX PROJECT (WORKFORCE EVOLUTION)

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**1. What was the problem being addressed? Why was it hard and is it important?**

The Department of Defense has for years been concerned about the growth and development of its systems engineering workforce. A particular concern has been the anticipated retirement of senior systems engineers in the near future and an inadequate number of mid-level systems engineers to fulfill these positions. This resulted in the Helix project – which was initially developed to investigate what makes systems engineers effective.

The current task expands upon the research developed during the execution of earlier RTs supporting the Helix project. There are five main areas of focus for this task:

- While Helix has largely elaborated what enables individual systems engineers to be effective, it has not yet identified a career map for growing effective systems engineers, nor has it yet explained to nearly the same depth what enables organizations to be more or less effective in growing an effective systems engineering workforce.
- The Helix project has amassed a large dataset covering 363 individuals – systems engineers, their peers, and their leadership. In 2017, the team has conducted additional analysis for patterns and trends needed to provide a better understanding of effective system engineers' career paths and the typical position assignments used to get experience in a variety of systems engineering roles.
- The Helix team has collected data on the ways that organizations try to improve their systems engineers' proficiency and some basic trends have been identified. In order to better enable organizations to use *Atlas* – our theory of what makes systems engineers effective – the team is collecting new data around critical organizational characteristics.
- Prior to 2017, the Helix team focused primarily on a grounded theory-based approach. In 2017 and going forward, the Helix team will incorporate additional literature and will examine the potential uses of Helix findings on other SERC research tasks as well as the activities of professional associations.
- The Helix team has helped several organizations begin implementation of *Atlas* in a variety of ways. However, the end goal is for *Atlas* to be implemented more widely than can be done at present with only direct involvement with the Helix team. In order to do this, additional infrastructure must be put in place to enable widespread use by individuals or organizations.

**2. What was new in the approach and why do we think it will be successful?**

At the conclusion of the Helix FY16 work in December 2016, Helix project researchers have collected data from nearly 300 people at 20 organizations as of December 2017, Helix project researchers had collected data from over 360 people at 23 organizations, all with IRB approvals from Stevens Institute of Technology and the DoD to conduct research with human subjects. With the publication of *Atlas 1.0* in December 2016, the Helix project reached a critical milestone. *Atlas* is mature enough for earlier adopters with limited help from the Helix team, and is documented in a way that enables others to understand the motivations, methodology, principles, architecture, and details of the theory. Early methods and tools to apply *Atlas* have been developed and piloted with a small set of early adopters to help grow their systems engineers.

Despite the progress made to date, additional work is required to ensure that Helix and *Atlas* can fulfill their potential impact within the community. To this end, the research questions must be updated. Previous work on Research Questions 1 (What are the characteristics of effective systems engineers?) and 2 (What makes systems engineers effective and why?) have largely been answered, but can be refined.

The research questions that will guide Helix going forward are:

i. How can organizations improve the effectiveness of their systems engineering workforce?

ii. How does the effectiveness of the systems engineering workforce impact the overall systems engineering capability of an organization?

iii. What critical factors, in additional to workforce effectiveness, are required to enable systems engineering capability?
Five key research gaps were identified by SERC. The primary focus of the proposed Helix research will be to close these gaps and document them in a way that will enable others to adopt *Atlas* more readily. Further, Helix needs to be embraced and utilized by the overarching systems engineering community. The 2017 effort will include a strong focus on transition activities, including working with professional societies such as the International Council on Systems Engineering (INCOSE), the National Defense Industrial Association Systems Engineering Division (NDIA SED), and the Institute of Industrial and Systems Engineers (IISE) to endorse and recommend use of Atlas.

**3. Who should care about this problem?**

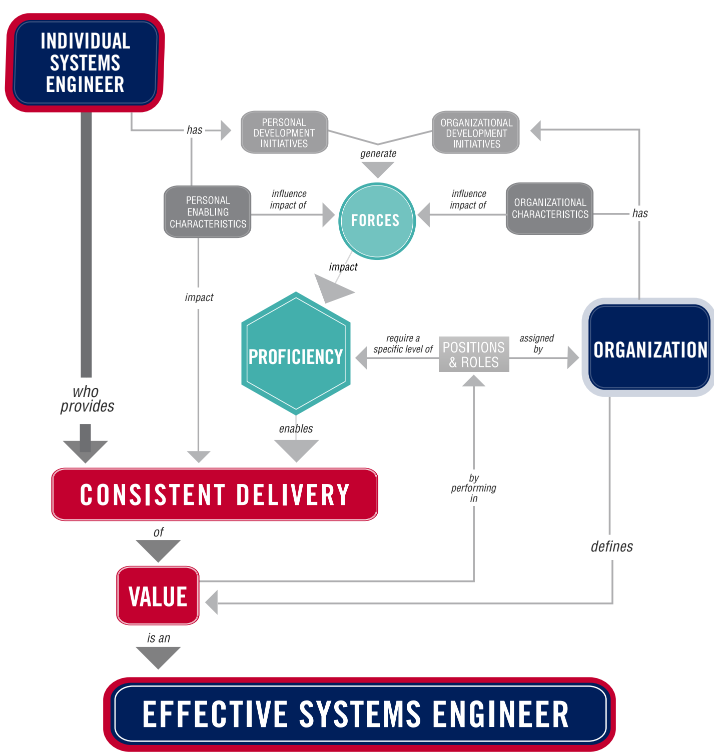
Any organizations concerned with growth, development, and effectiveness of their systems engineers or who want to develop products of increasing complexity will find useful principles in *Atlas*. Individual systems engineers will also find guidance that they can use to assess and guide their own development.

**4. What are the risks and payoffs?**

A risk is the adoption of *Atlas* and Helix research within the community for use. A payoff, however, has been proven with the customization of Atlas at MITRE. There has been significant positive feedback on the guidance and clarity the tools provides on growing the individuals within their organization, and thus growing their workforce. The Helix team is aware of six organizations that have utilized *Atlas* to assess or improve their own workforce development efforts for systems engineers.

**5. What difference will this research make?**

The 2017 effort has had a strong focus on transition activities, including working with professional societies such as the INCOSE to endorse and recommend use of *Atlas*. Additional early adopters need to be engaged and the Helix team needs to learn from the experiences of those early adopters, feeding those experiences into the evolution of *Atlas* and its supporting methods and tools. Coordination and collaboration with professional societies will be a critical step in enabling this. Successful impact will include individuals and companies having the ability to curate their ability to operate at a much more systems-oriented level to make a greater impact.



## CAPSTONE MARKETPLACE

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www.capstonemarketplace.org

**1. What was the problem being addressed? Why was it hard and is it important?**

A continuing challenge for engineering acquisition workforce is that a large portion is nearing retirement age and this workforce embodies the Department's systems engineering (SE) and analyst experience; nearly 45% of the engineering workforce is eligible to retire within the next 10 years. The complexity of modern defense systems drives a demand for systems engineering talent, rooted in classical engineering and science disciplines. Today's engineers must design and engineer systems that are adaptive and resilient to unknown missions and creative adversaries, while making trades between cost, schedule and a wide variety of critical design factors. They must balance agility with rigorous data analysis, safeguard critical information, and stitch together a variety of systems to accomplish a mission. With this in mind, the SERC pursued resetting SE in academia and invigorating the workforce. Previous SERC research has shown that multidisciplinary Capstone programs can enhance development of SE competencies. The Capstone Marketplace (CM) is an online tool intended to match multidisciplinary student teams with challenging engineering projects from sponsors along with mentors, and subject matter experts. Experiences gained in these projects coupled with an introduction to core SE tools and knowledge creates a valuable experiential learning platform to help address the looming workforce needs.

**2. What was new in the approach and why do we think it will be successful?**

The CM finds sponsor-driven needs and problems and is seen as a way to receive capabilities, defined by warfighters, from students and faculty at the universities. Sponsors also valued the rapidness of the design process from concept to test/fielding while students learn from the process by immersion into real world customer relationships. The CM encourages universities and teams to execute the Capstone work in a framework that uses a streamlined set of SE processes. Capstone projects represent an excellent platform for experiential learning, development of innovative solutions to real user needs. The fact that capstone projects are almost universal in undergraduate engineering curriculum creates an opportunity for organic growth of the CM in broadening SE competences in the emerging engineering workforce.

**3. Who should care about this problem?**

DoD and other organizations who desire to promote systems engineering skills through multidiscipline Capstone projects. Universities also care about the CM because it provides challenging projects for the students, and ushers the streamlined SE processes that benefit, not burden, the end result. Students are eager for real problems to solve and the added benefit of working with users and experts is desirable for experience resume building, and networking as the embark on their careers.

**4. What are the risks and payoffs?**

The risk may be insufficient involvement from sponsors, students, or faculty. If there is substantial participation, the CM will thrive with faculty and students gaining opportunity to work on real-world challenging problems, while the sponsors will be able to utilize the research realized during the project. In several instances this approach has led to solutions that have moved forward for additional research. As the number of CM projects grows, the number of emerging engineers with a core of basic SE knowledge also grows.

**5. What difference will this research make?**

The CM continues to be viewed as a success by the participants across all three groups: academic, sponsor, and mentors. The sponsors receive rapidly-prototyped concepts with lessons learned while simultaneously being able to recruit new, fresh talent. The success will also impact the student's ability to incorporate SE thinking into their respective workforce upon graduating.

## DEVELOPING SYSTEMS ENGINEERING TECHNICAL LEADERSHIP

**Principal Investigator:** Michael Pennotti (mpennott@stevens.edu)
**University:** Stevens Institute of Technology
**Sponsor:** DAU
**Project Page:** http://www.sercuarc.org/projects/developing-se-technical-leadership/

**1. What was the problem being addressed? Why was it hard and is it important?**

The technical complexity of today's defense systems continues to grow exponentially at a time when demographic trends are causing the accelerated departure of the most experienced professionals from the defense acquisition workforce. This presents a daunting challenge to those charged with ensuring that the country retains the technical superiority required to defend our national interests. There is a critical need, therefore, for a means to accelerate the development of the next generation of technical leaders who possess both the technical competency and the leadership skills required to meet this challenge.

In the past, such technical leaders have emerged naturally over a very long time in a much more slowly evolving technical world. The question addressed by this research is whether it is possible to create a set of experiences that would shorten this time, and if so, how best that might be accomplished. Building on experiences in academia and the private sector, the SERC sought to address this challenge.

**2. What was new in the approach and why do we think it will be successful?**

In a sequence of RTs over a six-year period, the SERC worked closely with the DAU sponsor to develop more than 100 lectures, case studies, exercises and group projects, and tested these in a series of pilots with mid-career and emerging technical leaders from across the defense acquisition community. Based on the results of these trials, three one-week workshops were developed and transitioned into DAU-conducted pilots. The results demonstrated that the technical leadership capabilities of high potential, senior DoD systems engineers and technologists can be accelerated through an educational program in technical leadership, and that such a program can be successfully delivered by members of the DAU faculty.

**3. Who should care about this problem?**

The DoD technical acquisition community, including the faculty and leaders within the Defense Acquisition University, has demonstrated their interest and commitment to the research by incorporating the results into their ongoing Key Leadership Development Program (KLDP). Beyond that, companies throughout the defense industry, and industry more broadly, should be interested in learning about the research and tailoring the results to their own domains.

**4. What are the risks and payoffs?**

The risks were that it might not be possible to accelerate the development of technical leaders through targeted educational experiences, or that if it was, the skills required to accomplish this could not be transferred to members of the DAU faculty. The research demonstrated that both of these risks have been overcome.

**5. What difference will this research make?**

DAU's ongoing KLDP has received outstanding reviews from both the participants and their acquisition sponsors. Numerous professionals who have completed the program have assumed positions of greater responsibility and have credited their participation in the program for that opportunity and for preparing them to be successful in their new roles.

## LEADERSHIP DEVELOPMENT FRAMEWORK FOR THE TECHNICAL ACQUISITION WORKFORCE

**Principal Investigator:** Wilson Felder (Wilson.felder@stevens.edu),
**University:** Stevens Institute of Technology
**Sponsor:** DASD(SE)
**Project Page:** http://www.sercuarc.org/projects/developing-se-technical-leadership/

### 1. What was the problem being addressed? Why was it hard and is it important?

Large and complex technical undertakings – sophisticated weapon systems, diverse research institutions, major programs of national importance, and the like – require unique skills of their leaders. These individuals must have both a strong technical background and a special ability to lead people of varying backgrounds and disciplines. The required skill set is not easily acquired after one has already been confronted with the difficulties inherent in these positions. These skills must instead be honed over a career of increasingly challenging assignments, starting as soon as the fledgling technical leader has graduated from a foundational engineering or science baccalaureate program. In the research, the team asked what such a career-long development journey might look like, and suggested an approach to acquiring the necessary skills while developing a framework for technical leadership development within the five technical acquisition career field in the DoD.

### 2. What was new in the approach and why do we think it will be successful?

The work is based on existing scholarship, which has largely focused on understanding the characteristics of successful technical leaders, particularly at the highest levels. However, the approach has been more deductive than previous efforts, in attempt to establish not what a typical career has been for successful technical leaders, but rather what it should be. The conclusions are based on an integrative understanding from extensive cumulative experiences from executives in industry and government, along with the insights of numerous colleagues from a diverse set of institutions. The team does not claim that this is the way others have developed great technical leaders, but the methods recommended have been demonstrated to be effective, and the sum of the recommendations represents a new approach.

### 3. Who should care about this problem?

Defense Acquisition University, DoD, and any organization looking to utilized a development framework for their leadership in the technical acquisition workforce.

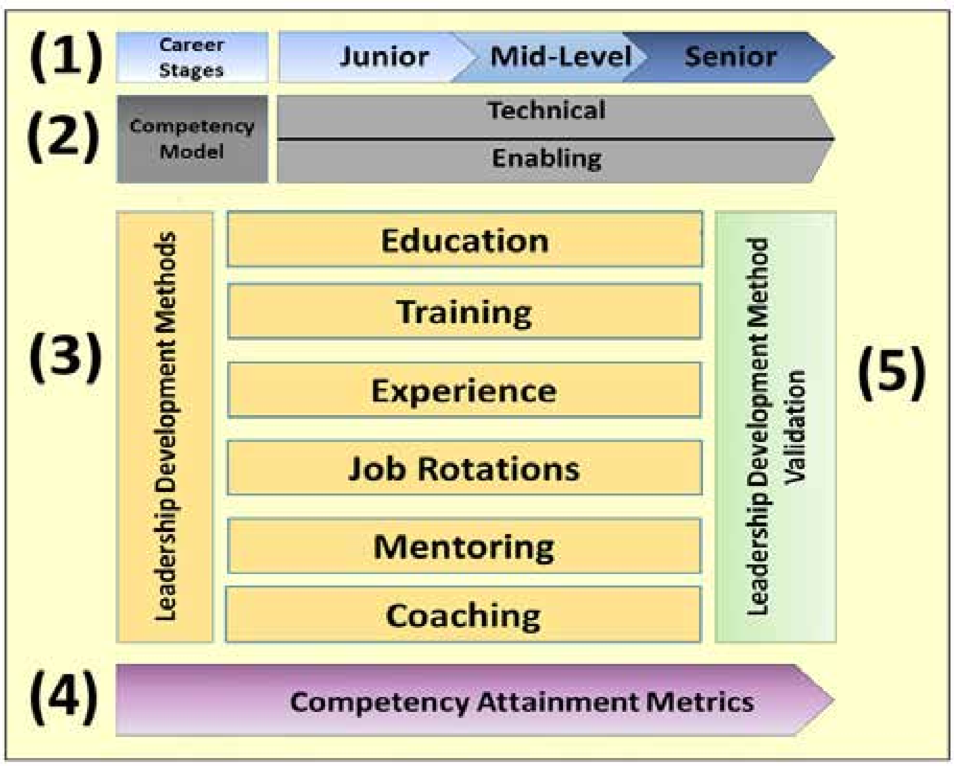
### 4. What are the risks and payoffs?

The study documented for the first time a comprehensive analysis of the relevant scholarly literature on the subject of technical leadership development, while the survey represents solid examination of our current understanding about how technical leaders have been, and are best, developed, and serves as a strong foundation for future work.

### 5. What difference will this research make?

The approach can be applied by aspiring individuals, supervisors or executive sponsors, as well as by entire agencies or subordinate commands at any level of the DoD. The successful application of the developed Framework and Career Model does not depend on a formal top-down program, and though focused on DoD, it can be applied in any technical leadership situation. The core of the Framework is a set of 24 carefully curated competencies that reflect the dual technical and leadership natures of the technical leader's role. The team defined six broad categories of development methodology to assist those applying the framework. The Framework application involves a cyclical process centered on the emerging technical leader, and incorporates a set of best practices derived from observations and analysis of programs at a variety of best-in-class companies and agencies. The team assembled these into a Career Model, combining a number of tools and practices into a single integrated whole, in some cases bringing practices together for the first time. A key finding was that leadership development must be associated with objective assessment techniques that are evidence-based and reflective of accomplishments, and not solely on capabilities. The team offers a tool allowing an individual to track personal progress towards attainment of all 24 competencies. It was also found that the best programs are highly tailored. Accurately framing the competencies within an organization and way in which they are applied is very important.

The implementation Guidebook delivered under this task is planned for conversion into a formal DAU document for DoD-wide promulgation. In the meantime, the draft Guidebook has been released for public use on the SERC website. In addition, the investigators have conducted a series of outreach efforts including presentation of the material at technical conferences and other venues, such as the recent AIAA Technical Committee on Management's Technical Leadership Development workshop in Cleveland, OH. Gratifyingly, there also appears to be a grass-roots movement to incorporate these ideas among employees, for example, at the Missile Defense Agency.



## SYSTEMS ENGINEERING EXPERIENCE ACCELERATOR (SEEA)


**Principal Investigator:** Jon Wade (jwade@stevens.edu)
**Co-PI:** Douglas Bodner (doug.bodner@gatech.edu)
**University:** Stevens Institute of Technology

**Sponsor:** DASD(SE)
**Project Page:** http://www.sercuarc.org/projects/system-engineering-experience-accelerator/

### 1. What was the problem being addressed? Why was it hard and is it important?

Moore's Law and the resulting exponential increase in the capabilities of computational, networking and software based systems, coupled with the growth of distributed dynamically evolving System of Systems, increasing societal dependence, criticality of security, and ever shortening development time have surpassed the capabilities of traditional Systems Engineering. Linear improvement cannot keep up with the exponential growing demands that are enabled by the underlying technologies and amplified by the aforementioned trends. Human capabilities simply are not improving at exponential rates. The net result of these trends is that systems engineers and management are being trained with subject matter that is out of sync with the demands of the work place using methods and processes from a bygone era that are ill suited to their needs. There are additional challenges in that the baby boomer generation of which many of our current Systems Engineers are members, is rapidly reaching retirement age, and there is not a ready source of Systems Engineers available to replace them. This is a particularly critical issue for staff in the acquisition of national defense oriented systems which experience all of the systems challenges noted above.

**Problem Statement:** Traditional Systems Engineering (SE) education is not adequate to meet the emerging challenges posed by ever increasing Systems and Societal demands, the workforce called upon to meet them and the timeframe in which these challenges need to be addressed.

**Program Goal:** Transform the education of SE by creating a new paradigm capable of halving the time to mature a senior SE while providing the skills necessary to address emerging system's challenges.

### 2. What was new in the approach and why do we think it will be successful?

The SERC shall update the deliverables from previous SEEA research. Specifically, the SERC shall: A.) Develop new content for the DAU unmanned aerial system (UAS) experience. SERC researchers shall develop content focused on using trade studies to make technical decisions, as well as making reliability decisions. B.) Improve the current DAU UAS experience. SERC researchers shall improve content for non-player characters and update student lecture materials, C.) Improve the user interface to accommodate learners with disabilities. As part of this process, the SERC shall migrate the Experience Accelerator (EA) infrastructure from Adobe Flash to HTML5. D.) Validate the research hypothesis. SERC researchers shall capture and analyze student learning results. E.) Support Deployment at DAU and Transition to Open Source Sustainment. The high-level goals for this program are two-fold. First, the researchers shall create a means of maturing Systems Engineers in a manner than will reduce the time it takes to reach the senior level of experience. This shall be achieved by the researcher piloting applications of the Systems Engineering Experience Accelerator tools, investigating the efficacy of the single player, multiplayer, classroom and other models of instruction and establishing any technical supporting needed to aid the deployment of the toolset. It is believed that creating new experience-based training, which is integrated with and complements more traditional means of knowledge acquisition, will be necessary to achieve this goal. Secondly, researchers shall provide the means by which these results can be obtained in an economically attractive manner.

In addition, tools have been developed for the SEEA. To date, the prior research has developed Simulation Builder and Tuner tools, an initial version of the integrated Experience Builder, and a prototype Learning Assessor tool. These tools are actively being used by developers outside of the EA research team to develop new experiences. While significant progress has been made in their development, additional work is required before these tools can be released to an open source community.

### 3. Who should care about this problem?

Defense Acquisition University, DoD, industrial organizations and educational organizations.

**4. What are the risks and payoffs?**

One risk is the difficulty in identifying appropriate measures for learning in the selected areas. The mitigation will be to review and model research in measuring learning outcomes in constructivist-based learning environments, such as those developed with case-based learning, problem-based learning, project-based learning, and discovery learning methodologies, in order to determine how best to measure critical thinking, problem-solving, and professional skills and competencies, measure learner perceptions of learning in these areas, and capture the EA experience of some learners in order to capture qualitative evidence of learning, as exhibited through user actions and strategies within the simulation. There are risks that the experiences do not provide significant learning that can be transferred to the on the job practice. There are also risks that the new developed tools are not effective for the target users.

In addition to the new capabilities, Task 2 will have a series of improvements in the current experience to ensure that the users of the EA have the opportunity to effectively learn the desired lessons. The current DAU experience will be extended in both scope and new capabilities. The experience was designed to support the UAV project from PDR to limited production. Past work addressed the first phase of the experience, namely up until the CDR. Four additional phases have been prototyped. There is significant payoff to having the Section 508 Compliance since it must be obtained before DAU or other federal agencies, or organizations that require accessibility, can use the EA in a classroom. Improvements to the DAU content will result in increased effectiveness in learning. The development and improvement of tools will greatly expand the number of available experiences and will provide the means to tune the experiences to the needs of individual instructors and students. The assessment and validation of learning will provide knowledge to increase the efficacy of future experiences and instruction.

**5. What difference will this research make?**

The SEEA User Interface has been revamped and upgraded to an HTML5 infrastructure to provide better capability and meet the web accessibility requirements of the US government for its use by government personnel. The SEEA Tools, while not required to meet all the accessibility requirements, are also evolving; new features are being added and new tools developed. Interest in using the SEEA technology has extended beyond the defense systems engineering community to include education, healthcare, and other industrial environments as well. The SEEA is currently being used in three academic environments. The US Defense Acquisition University, the University of Alabama Huntsville, Georgia Tech and the Air Force Institute of Technology are planning to collect additional metrics from their systems engineering classes. An updated learning assessment tool will be used to support and analyze the information from these classes, and will help determine if SEEA's immersive experience provides a measurable advantage over the traditional lectures.

The SEEA was used successfully by the UK Ministry of Defense (MoD) to create and deliver a new experience. Unlike the prototype experience, which was built around a complex system dynamics model, the UK MoD Tempest experience was primarily built around personal interaction. It also had a much shorter time frame and more limited scope. The SEEA team is continuing to test the tool set internally, and will continue to conduct tutorials and workshops in experience development to validate and improve the tools.

As an open source, openly available tool, the team is actively building a community of users and developers around the Experience Accelerator. As the community evolves, more types of simulations will become available and additional interaction techniques developed. For example, another SERC task, one developing simulations of agile, lean and similar adaptive governance mechanisms in systems development, is actively working to provide its capabilities within the SEEA environment.

## ARMY SYSTEMS ENGINEERING CAREER DEVELOPMENT MODEL

**Principal Investigator:** Val Gavito (vgavito@stevens.edu)
Please contact Dr. Dinesh Verma (dinesh.verma@stevens.edu) if you have an interest in this task.
**University:** Stevens Institute of Technology
**Sponsor:** Army
**Project Page:** http://www.sercuarc.org/projects/army-systems-engineering-career-development-model/

**1. What was the problem being addressed? Why was it hard and is it important?**

The Army requires a deliberate, continuous, and progressive SE career development model that provides engineers with the experience, education, and training to effectively support the acquisition community. The model additionally needs to address individual, organizational, and enterprise actions.

**2. What was new in the approach and why do we think it will be successful?**

This RT continues its findings from the first phase, and worked to provide incremental improvements on the Career Development System (CDS) to address the objectives outlined above. The research is divided into four subtasks:

Subtask 1: Education & Experience: Developing a productive link between the databases that comprise Army Career Acquisition Management.

Subtask 2: Tenure & Cross Functional Competencies: Expand on the recommendations and provide a recommended Personnel Rotational Model.

Subtask 3: Army Mentorship: Expand on the recommendations and conduct research on how best to incentivize the Army Mentorship Program amongst the engineering ACF workforce.

Subtask 4: Continuing Learning Modules (CLM): Expand upon FIPT CLM review to prioritize CLMs for KLP development, and provide a recommended CLM catalogue.

**3. Who should care about this problem?**

Any organization in the US Army which employs systems engineers; this model will likely have additional relevance to systems engineers in the other Services as well.

**4. What are the risks and payoffs?**

Because this RT utilized and built upon the results of the previous task phase, the risks are considered minimal. The project is broken into four main development areas, so that any risks or issues in one area will not impact the others and will still enable useful progress in these other areas.

**5. What difference will this research make?**

The model addresses individual, organizational and enterprise actions for career development, including a) allowances for an individual to tailor their career development, b) organizational elements to address organizational responsibilities for career development, and c) enterprise aspects to link policies and infrastructure changes to support career management at an enterprise level. The ultimate goal of the CDS is to ensure that the Army has the engineering talent to support the acquisition community and to create a cadre of future engineering leaders.

## MISSILE DEFENSE AGENCY (MDA) RESEARCH AND COURSE DEVELOPMENT – VERIFICATION, VALIDATION, AND ACCREDITATION (VV&A) AND MONTE CARLO SIMULATION

**Principal Investigator:** Mikel Petty (pettym@uah.edu)
**University:** University of Alabama Huntsville
**Sponsor:** Missile Defense Agency
**Project Page:** http://www.sercuarc.org/projects/mda-research-and-course-development-vva-and-monte-carlo-simulation/

### 1. What was the problem being addressed? Why was it hard and is it important?

Researchers shall investigate how models and simulations are used in the Missile Defense Agency (MDA), with a focus on Monte Carlo simulations, and verification, validation and accreditation (VV&A) of simulations and models. The researchers shall then develop course materials that address MDA's needs for VV&A and Monte Carlo simulations. The researchers shall pilot the course materials and make updates based on results of the pilot application. The researchers shall include novel research on VV&A and Monte Carlo methods that would be of particular use to MDA.

### 2. What was new in the approach and why do we think it will be successful?

The VV&A course shall include VV&A definitions and concepts, VV&A methods, VV&A case studies and exercises, and VV&A processes. The case studies shall be oriented around topics of particular interest to MDA, such as validating a ballistic missile flyout model using hypothesis testing, or validating a spacecraft propulsion system sizing model using regression methods. The Monte Carlo simulation course shall include Monte Carlo definitions and concepts, modeling and generation of inputs, statistical analyses of model outputs, Monte Carlo exercises and case studies, and the basic concepts and principles of experimental design. The case studies shall be oriented around topics of particular interest to MDA, such as attrition combat analysis and missile impact analysis. The course will have five distinct parts.

### 3. Who should care about this problem?

Missile Defense Agency, DoD, and other organizations in pursuit of transforming systems engineering through model-centric engineering and the verification and validation of system behaviors.

### 4. What are the risks and payoffs?

One risk is that the models provided contain insufficient functional specification to create a complete set of behavior models, but payoff would be that the research formalized provided behavior specifications into model-centric systems engineering architecture tools, demonstrated the use of the resulting architecture model for early V&V analysis of requirements and captured formalized patterns of common design flaws or other model properties in a patterns catalog.

### 5. What difference will this research make?

The verified and validated MP behavior model is a formal specification for an entire library of valid use case scenarios that exceeds the completeness of those generated using current methods. Such a model can be used as a solid set of source data for further architectural analysis, such as resource utilization and cost estimation.

## STRATEGIC PLANNING SCIENCE & TECHNOLOGY PORTFOLIO DEVELOPMENT

**Principal Investigator:** Robin Dillon-Merrill (Robin.DillonMerrill@georgetown.edu)
**University:** Georgetown University
**Sponsor:** DAU
**Project Page:** http://www.sercuarc.org/projects/strategic-planning-science-and-technology-portfolio/

**1. What was the problem being addressed? Why was it hard and is it important?**

The project sought to understand best practices for how the Department of Defense (DoD) was managing science and technology (S&T) portfolios and to transition this knowledge to improve the process by developing curriculum material for the Defense Acquisition University (DAU). Understanding an organization's strategy is a key component in evaluating a science and technology (S&T) portfolio, and teaching materials to convey the findings were developed in addition to multiple classroom exercises to improve DoD S&T professionals' skills in portfolio management. To do this, research was needed to develop, synthesize, and validate principles for formulation and executing a strategic plan for science and technology development with the goal of enhancing the capability of the DoD's acquisition workforce.

**2. What was new in the approach and why do we think it will be successful?**

The research was conducted in four phases:

Phase I: Identify relevant strategic planning and science and technology portfolio development content

Phase II: Course teaching content development

Phase III: Exercises and case study development

Phase IV: Research pilots and revisions

Numerous interviews were conducted to find the best practices in DoD organizations that focused on research and development (R&D) portfolios. The results of the project were over 100 PowerPoint slides, four detailed case studies, and several shorter case studies. The research findings were incorporated into a newly developed course at the Defense Acquisition University.

**3. Who should care about this problem?**

DoD and other agencies and warfare centers who care about technology development, which is the foundation for the DoD material acquisition process. Organizations responsible for this development include DoD laboratories and organizations such as the Army Research Development and Engineering Centers and the Navy Warfare Centers.

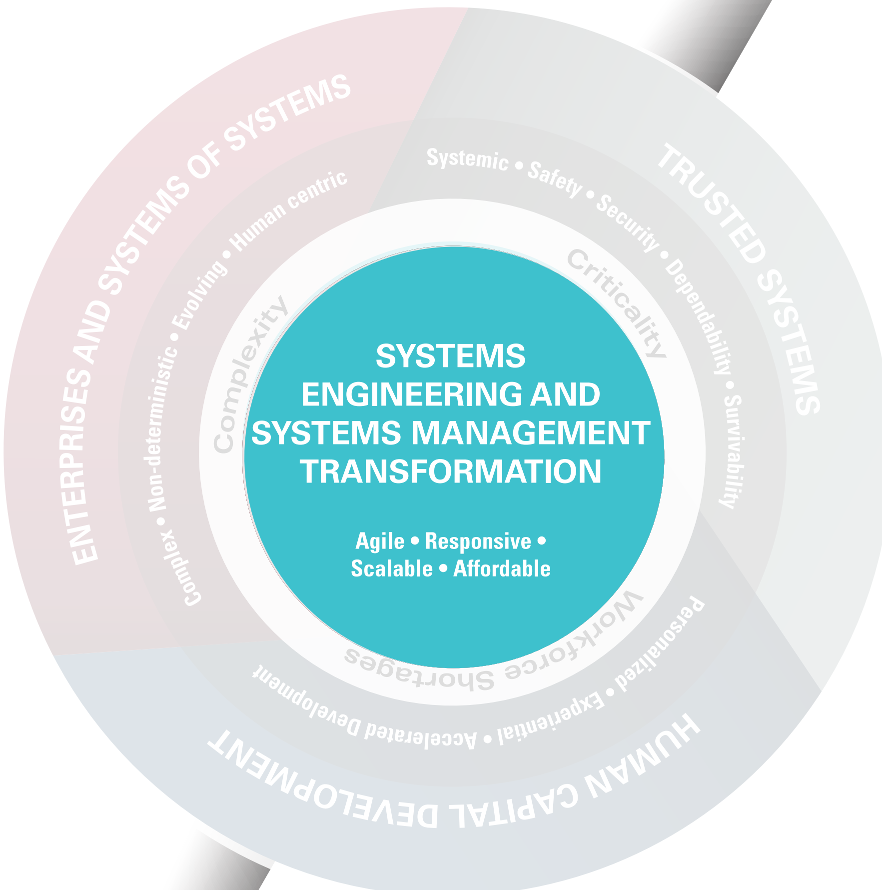
**4. What are the risks and payoffs?**

To maximize an organization's contributions for the warfighting mission, and to most effectively use resources, S&T managers in these organizations must capitalize on effective strategic planning to prioritize technology areas. Portfolio management is a challenge for an organization as distributed as the Department of Defense because portfolio management works best when there is a senior leader or leadership team with the decision making capacity to oversee many research portfolios and choose those that support the organization's strategy and cancel those that do not. The best strategy driven portfolio will balance near-term and long-term needs. Instead of a portfolio management approach, DoD's stove-piped governance structure where each service generally sets its own priorities is an impediment to using an integrated portfolio management approach.

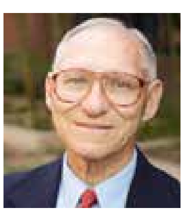
**5. What difference will this research make?**

The task specifically supported course development for DAU, and the pedagogy included case study review, method development lessons, and group exercises through a four-day course curriculum. Material was provided via literature and survey review for identified key skill areas. The coursework instruction material was provided to DAU, and is available on the projects webpage in the Technical Report. It helped those in the class understand strategic planning in S&T portfolio development, and showed the importance that within these areas, S&T managers must also develop and manage S&T portfolios to ensure the required technologies are matured for seamless transition to programs of record or directly to the warfighter.

# SYSTEMS ENGINEERING AND SYSTEMS MANAGEMENT TRANSFORMATION




## RESEARCH COUNCIL MEMBERS FOCUSED ON THIS THEMATIC AREA:

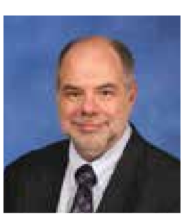


**Barry Boehm**

*Chair of the SERC Research Council*
*SERC Chief Scientist*

**Mark R. Blackburn**

*Associate Professor, Stevens Institute of Technology*



**Paul Collopy**

*Chair, Industrial and Systems Engineering and Engineering Management,University of Alabama in Huntsville*

*Providing ways to acquire complex systems with rapidly changing requirements and technology, which are being deployed into evolving legacy environments. Decision-making capabilities to manage these systems are critical in order to determine how and when to apply different strategies and approaches, and how enduring architectures may be used to allow an agile response. Research must leverage the capabilities of computation, visualization, and communication so that systems engineering and management can respond quickly and agilely to the characteristics of these new systems and their acquisitions.*

## SYSTEM QUALITIES ONTOLOGY, TRADESPACE AND AFFORDABILITY

**Principal Investigator:** Barry Boehm (boehm@usc.edu)
**University:** University of Southern California
**Sponsor:** DASD(SE)
**Project Page:** http://www.sercuarc.org/projects/tradespace-and-affordability/

### 1. What was the problem being addressed? Why was it hard and is it important?

This task builds upon previous phases of the research with three primary tasks. Task 1, Research and Develop SQ Scientific Foundations: The contractor shall continue to expand, coordinate, and evolve the two complementary ontologies for the SQs: the Product Quality, means-ends framework being evolved at USC, and the Quality-in-Use semantic framework for change-oriented SQs being evolved at MIT, with formal definitions for each being evolved at UVa. Task 2, SQ Methods, Processes, and Tools (MPTs) Piloting and Refinement: The contractor shall build upon previous engagements with DoD organizations to continue piloting the SERC methods and tools to address DoD-system SQ tradespace and affordability issues, particularly in the cyber-physical-human systems and economic analysis areas. The contractor shall continue to refine the methods and tools based on the results of the pilot applications. Task 3, Next-Generation, Full-Coverage Cost Estimation Model Ensembles: The contractor shall continue to perform cost estimation research, specifically developing the next-generation versions of the COCOMO model for software cost and schedule estimation and the COSYSMO cost model for systems engineering cost and early-phase schedule estimation.

### 2. What was new in the approach and why do we think it will be successful?

Task 1 will continue to expand, coordinate, and evolve two complementary ontologies for the SQs: a Product Quality, means-ends framework being evolved at USC, and a Quality-in-Use semantic framework for change-oriented SQs being evolved at MIT, with formal definitions for each being evolved at U.Virginia. Each will have compatible definitions of the key DoD SQs, and associated methods and tools for making formalizations accessible to the systems engineering research and practitioner communities for validation against the needs of practice. Task 2 will follow up on the engagements with DoD organizations pursued in Phases 2 through 4, to continue to pilot the application of SERC methods and tools to DoD-system SQ tradespace and affordability issues, particularly in the cyber-physical-human systems and economic analysis areas. The methods and tools will continue to be refined, based on the results of the pilot applications.
Beginning with work in the space domain with USAF/SMC and the Aerospace Corp., Task 3 has refocused on the two areas for which the needs and availability of data are the strongest: Overall-DoD next-generation versions of the COCOMO model for software cost and schedule estimation and the COSYSMO cost model for systems engineering cost and early-phase schedule estimation.

### 3. Who should care about this problem?

With the ontology, methods, processes, and tools, the research is of interest across the DoD and across the international and standards communities.

### 4. What are the risks and payoffs?

As resilience involves both agile flexibility and disciplined assurance, it is an excellent example of the importance of, and tradespace challenges involved in, simultaneously achieving multiple system quality factors. If successful, a payoff would be appropriately connecting systems engineering technical analyses from the financial community's cost analyses leading to technical specifications with more affordable costs.

### 5. What difference will this research make?

The Product Quality framework from Task 1 will continue to populate its synergy and conflict relationships among the SQs; to expand the quantification of the synergies and conflicts; and to refine the prototype tools for representing and applying the results. It will also develop complementary views for addressing DoD high-priority SQ-related issues dealing with uncertainties such as sources of change, early cost-effectiveness analysis, and Total Cost of Ownership analysis. It will also develop and apply scientific theories to validate the capabilities and consistency of the frameworks, models, methods, processes, and tools being researched and developed. A valuable impact would be developing more service-oriented and interoperable versions of current SERC SQ MPTs; developing approaches for better integrating MPTs primarily focused on physical, cyber, or human system SQ analysis; efforts to modify and compose existing SERC SQ MPTs to better interoperate with each other and with counterpart MPTs in the ERS community and elsewhere; and efforts to apply the MPTs to the ilities tradespace and affordability analysis of increasingly challenging DoD systems.

## INTERACTIVE MODEL-CENTRIC SYSTEMS ENGINEERING (IMCSE)

**Principal Investigator:** Donna Rhodes (rhodes@mit.edu)
**University:** Massachusetts Institute of Technology
**Sponsor:** DASD(SE)
**Project Page:** http://www.sercuarc.org/projects/interactive-model-centric-systems-engineering-imcse-program/

### 1. What was the problem being addressed? Why was it hard and is it important?

The transformation of systems engineering to a model-centric paradigm is progressing at a rapid pace. Models are increasingly used to drive major acquisition and design decisions, yet model developers, analysts, and decision makers are faced with many challenges. The systems community has made progress on standards, methods and techniques for model-based engineering, but has not fully considered complexities of human-model interaction. The IMCSE research program arises from the opportunity to investigate the various aspects of humans interacting with models and model-generated data and the human dimensions of model-centric enterprises. This is an important problem because human effectiveness in digital engineering and human acceptance of model-centric practice will be essential detriments of success of future acquisition programs. This is a multi-faceted investigation that involves both technical and social facets. Evidence-based findings are not readily found; but this is necessary to avoid failures grounded in using incorrect assumptions and ignoring cognitive and perceptual limitations. Open areas of inquiry include: how individuals interact with models; how multiple stakeholders interact using models and model generated information; facets of human interaction with visualizations and large data sets; how trust in models is attained; and what human roles are needed for model-centric enterprises of the future. This project is based on a belief that improving human-model interaction would significantly improve the effectiveness of digital engineering practice, quality of model-decision making, and cultural acceptance of a digital future.

### 2. What was new in the approach and why do we think it will be successful?

Building on prior phase work, the approach in this project uses case application, experiments and empirical studies to generate findings that are transferable into current and future practice. An ongoing activity to transform a method of evaluating systems under dynamic uncertainty through an interactive framework is applied in case applications. This method provides a means to explore design space, considering impacts of design choices. This case application tests usability and degree of interactivity, which reveals benefits and additional research needs. A designed experiment investigates the impacts of visualization and interaction in a decoupled manner. Findings of the experiment provide an empirical basis for making decisions on the design and use of model-centric environments for effective human interaction. The experimental findings give empirical evidence to make decisions regarding what manner to present data to decision makers (e.g., under what conditions visualization, interaction or both enhance human decision making). In a second activity an interview-based study of model-centric decision makers is generating an empirical body of evidence about trust in models, patterns in model-based decisions, and socio-technical factors. The study contributes foundational knowledge of current practice and strategies for using models in making decision, in support of the evolving practice of model-centric engineering. The outcomes of the study, augmented by investigation of other sources, are being used to develop a body of heuristics that will be used by practitioners and educators. Early validation indicates these heuristics will provide encapsulated guiding strategies to support transformation in model-centric enterprises and in educating workforce. Ongoing collaborative engagement with the model-based systems engineering community provides the means to connect the work with related efforts on principles and practices that are being developed. The knowledge generated in this project is being shared in numerous conferences, workshops, stakeholder briefings, webinars and academic courses. A third activity looks at human-model interaction from the enterprise perspective and explores the need for a curation capability in enterprises. Literature investigation and empirical knowledge gathering is used to formulate strategies, roles, and alternative forms for model curation. Semi-structured interviews and technical exchanges with executive leadership are informing the research approach and outcomes, as well as serving to identify potential transition partners.

*(continued on next page)*

**3. Who should care about this problem?**

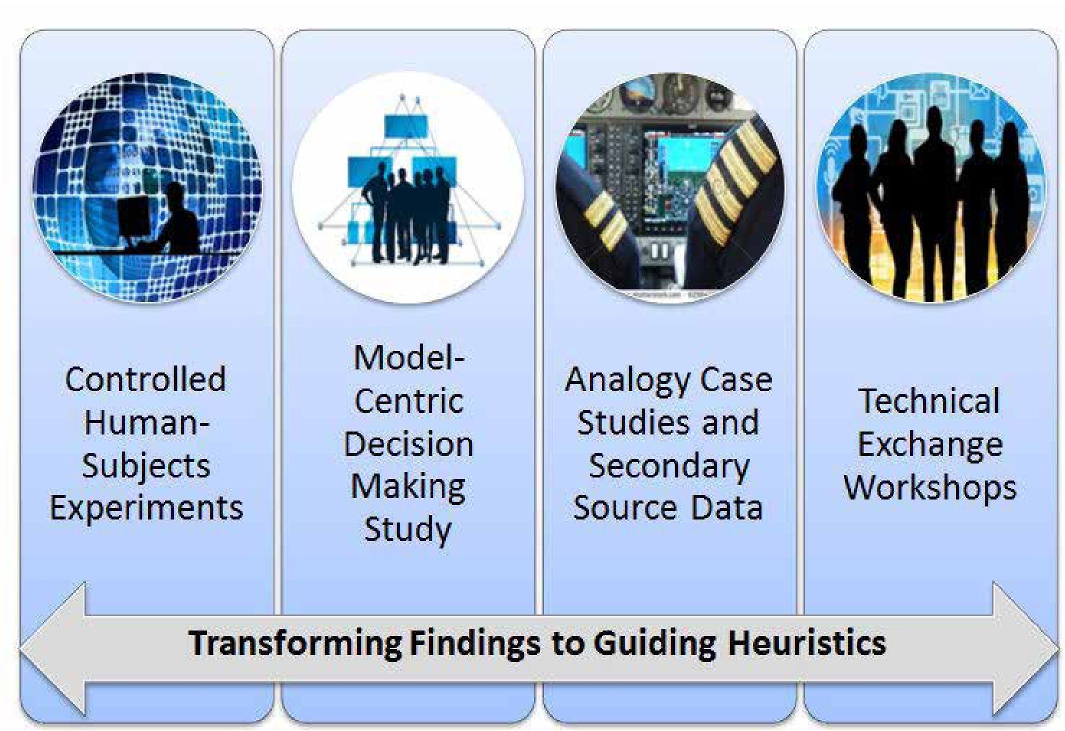
DoD, Defense Industrial Base, and organizations who have urgent need for a more powerful integration of humans and model-based systems engineering technologies, and who seek evidence-based strategies and enablers to support model-centric decisions and model-centric enterprise transformation.

**4. What are the risks and payoffs?**

Digital engineering is rapidly progressing, but there are risks related to acceptance and effective use of models and model-generated information that arise from the human dimensions (cognition, model trust, social factors in model-centric decisions, etc.). Payoff is in positive impact on model-centric practice and enterprise performance.

**5. What difference will this research make?**

The research can address essential human elements necessary for model-centric enterprises that have not been adequately investigated. Evidence-based strategies, heuristics and human-model interaction knowledge will directly impact effectiveness and acceptance of digital engineering. Wide dissemination and engagement of the systems community through various mechanisms raises visibility of this topic. Ongoing efforts are focused on transferable knowledge assets including model pedigree, curation guidelines, and heuristics for model-centric decision making.



## ENGINEERED RESILIENT SYSTEMS

**Principal Investigator:** Tommer Ender (tommer.ender@gtri.gatech.edu)
**University:** Georgia Institute of Technology
**Sponsor:** US Army Engineering Research and Development Center
**Project Page:** http://www.sercuarc.org/projects/engineered-resilient-systems-tradespace-tools/

### 1. What was the problem being addressed? Why was it hard and is it important?

This research involves development of decision support methods and a tradespace toolset framework architecture in support of the DoD's Science & Technology (S&T) priority for Engineered Resilient Systems (ERS). This effort includes research and development of methodologies to include Use Context based Utility Functions, and risk mitigation of uncertain future events through option buy-ins. The research involves various usability upgrades to tradespace toolsets, building on past experience in building web-based, collaborative systems engineering (SE) frameworks to address new stakeholder requirements. The research has also developed a series of ERS tradespace toolset concepts, primarily to include the ERS TradeBuilder. ERS focuses on agile and cost-effective design, development, testing, manufacturing, and fielding of trusted, assured, and easily modified systems. Its products are engineering concepts, techniques, and design tools. Its goal is to achieve a vitally needed transformation in Defense acquisition with the contribution of systems engineering throughout a system's lifecycle. This is essential to address a geopolitical environment marked by rapidly changing threats, tactics, missions and technologies. The pace of change renders current approaches unsustainable in both cost and time.

### 2. What was new in the approach and why do we think it will be successful?

Enhanced utility functions (to score alternatives that captured two components of a resiliency metric for a system design) to include data that describes the system's ability to deal with uncertainty and operate in multiple environments. The approach also specified the data should include understanding and correlating the system with a historical family of similar systems – this correlation will lay the foundation to assess portfolio trades across systems. Continue to develop and enhance usability of ERS architecture and the ERS Tradespace software. This tool is usable by variety of systems, e.g., ships, aircraft, and ground vehicles.

### 3. Who should care about this problem?

As the primary sponsor, the United States Army Corps of Engineers, and all affiliated organizations with Engineered Resilient Systems. But this would further include any DoD acquisition authorities tasked with developing systems that must be relevant under future, unknown operational environments.

### 4. What are the risks and payoffs?

The risk of a software development activity required to apply and transition the research will require that the SERC and ERDC teams maintain consistency in software. The relevance of the application of the case studies is another risk for the success of ERS TradeBuilder, while also certain restrictions may apply to hosting such toolsets. The payoffs, though, will be a proven systems engineering process with a notional design-execute-explore workflow, integrating enhanced toolsets into ERDC's broader ERS TradeStudio workflow.

### 5. What difference will this research make?

The tools and processes developed as a result of this research enable acquisition professionals to understand the impacts of variable operational scenarios on the decisions they make about the systems they define and deploy. This is done by enabling those decision makers to leverage under one framework the power of high fidelity modeling and simulation, high performance computing, model based systems engineering, and tradespace analytics.

## DEVELOPMENT AND APPLICATION OF FACT PORTFOLIO MANAGEMENT CAPABILITY; FRAMEWORK FOR ASSESSING COST AND TECHNOLOGY (FACT), APPLICATIONS OF PORTFOLIO MANAGEMENT TECHNIQUES TO SOFTWARE-HEAVY SYSTEMS OF SYSTEMS

**Principal Investigator:** Daniel Browne (Daniel.Browne@gtri.gatech.edu)
**University:** Georgia Institute of Technology
**Sponsor:** USMC Systems Command (MARCORSYSCOM)
**Project Page:** http://www.sercuarc.org/projects/development-and-application-of-fact-portfolio-management-capability/

### 1. What was the problem being addressed? Why was it hard and is it important?

The Systems Engineering Research Center (SERC) and Georgia Tech have participated in previous research efforts supporting the Marine Corps in the analysis and management of portfolios of systems and software solutions. In this research effort the SERC and GTRI expanded on that previous work to begin formalizing portfolio management methods into a reusable framework and explore new methods and strategies that are extendable to systems of systems. Standardized methods of tackling these problems have been developed over time, with a focus on sound Systems Engineering (SE) principles and tools. Although a standard process is commonly executed in solving these portfolio management problems, a standardized suite of tools is non-existent to support that process. Most often, new tools are developed by each SE team, sometimes leveraging a past tool utilized by the team, but often time not being reused for future efforts. A previous phase of the research began the effort of formalizing some of these methods into tools, and with the success of this research, have been enhanced and extended. Future improvements to the Portfolio Management Analysis Tool (PMAT) capabilities to support time-based portfolio management challenges were also identified in this research.

### 2. What was new in the approach and why do we think it will be successful?

Building upon work from previous research, new modeling approaches and methodologies need to be developed and applied to the Log IT War Room analysis. For the previous research, the focus was on the Global Combat Support System – Marine Corps (GCSS-MC) which is one system of many within the Log IT portfolio. For that challenge, portfolio management strategies were applied to evaluate how different components could be combined to offer a complete solution for GCSS-MC. In this challenge, the strategies applied for GCSS-MC need to be reviewed for how they scale to a more complex system of systems and modified as necessary. Additionally, evaluation and scoring methods were developed which are specifically geared towards software-heavy systems such as those within the Log IT portfolio. An initial task of the greater effort will require a complete functional decomposition of the tools and processes within the Log IT portfolio. In order to accomplish this effectively, a proper process, data collection, and organization strategy need to be defined and implemented for the team to operate.

### 3. Who should care about this problem?

Marine Corps Systems Command, DoD, and organizations interested in the management of a portfolio of capabilities.

### 4. What are the risks and payoffs?

The Log IT portfolio is composed of dozens, or even hundreds, of information technology systems. Additionally, the different systems may be owned and managed by different organizations, requiring time and effort to collect the information needed. Also, some of the visualization techniques identified may require the use of technologies incompatible with older web browsers, causing a disconnect between valuable visualizations and implementation techniques. The primary goal is to develop the evaluation framework, and document a strategy that could be implemented for the entire Log IT portfolio in future work, which is a large payoff for the Government to utilize.

### 5. What difference will this research make?

Proper execution of this task eased the transition from functional decomposition to portfolio re-aggregation and evaluation. The research goal is to identify the proper data elements that need to be collected for items within the Log IT portfolio so that modeling techniques can be applied. This will include developing a technique utilizing these data element inputs to identify overlaps and gaps in capabilities. Data visualization techniques need to be designed and implemented to offer insightful visualizations to decision makers. Visualizations will be required for inspecting the functional decomposition as well as the scoring methodology for the portfolio re-aggregation. Preferred implementation of these visualizations is within the same tool supporting the functional decomposition and data gathering.

## VIRTUAL COLLABORATIVE ENVIRONMENT FOR CONDUCTING PROJECT DESIGN AND TESTS

**Principal Investigator:** Daniel Browne (Daniel.Browne@gtri.gatech.edu)
**University:** Georgia Institute of Technology
**Sponsor:** USMC Systems Command (MARCORSYSCOM)
**Project Page:** http://www.sercuarc.org/projects/virtual-collaborative-environment-for-conducting-project-design-and-tests/

### 1. What was the problem being addressed? Why was it hard and is it important?

Multiple Systems Engineering (SE) toolsets are being developed by the military services to enable collaboration, requirements analysis, configuration management of data, and more extensive tradespace analyses. Two toolsets of note are USMC's Framework for Assessing Cost and Technology (FACT) and Army Research Labs' (ARL) Executable Architecture Systems Engineering (EASE). FACT is a framework which enables the definition of a design architecture using SysML and the ability to integrate various models; these are generally fast running models. EASE integrates various simulation tools together, and abstracts the input and configuration parameters so that non-subject matter experts can execute the simulation tools. Standalone, EASE provides a web-based interface for running executions. Previous work developed a Representational State Transfer (REST) API on top of EASE to enable the remote manipulation of the available executions. The REST API has been consumed by FACT, including a custom interface for tying the architecture definition within FACT to the inputs/outputs of an EASE execution. The current interface only allows for a single execution at a time and although users can retrieve the EASE output artifacts, the data loop is not complete, meaning output from an EASE simulation cannot be sent into another model by FACT.

### 2. What was new in the approach and why do we think it will be successful?

An overarching goal of the RT was to identify the best strategy for integrating analysis occurring within FACT with a constructive model. Initial tasking under this research effort explored the use of NAVAIR's Architecture Management Integration Environment (AMIE) and NUWC's Virtual World. Review of these technologies determined that they were not appropriate for realizing this goal at this time. However, the FACT-EASE interface offers an existing baseline capability for manipulating a constructive simulation from the FACT environment. This interface, however, needs to be expanded in order to become the preferred mechanism for stimulating constructive models. Specific areas for expanding the link between FACT and EASE include: (1) allowing for trade studies, as opposed to just single point designs, to be submitted to EASE via the API and updating FACT's consumption of the API to leverage this capability; (2) developing a Design of Experiment (DoE) generation tool within FACT which would inform what points need to be executed on a long-running simulation offered by EASE to adequately represent the design space; (3) providing semi-automated tools for the DoE capability developed in (2) and the analysis of the results to create fast-running surrogate models hosted within FACT.

### 3. Who should care about this problem?

Marine Corps Systems Command, DoD, and organizations interested in the aggregation of models and simulations into a single cohesive environment.

### 4. What are the risks and payoffs?

Research and development in the area of (semi-)automating the surrogate model development process could offer a valuable capability to the FACT tool suite, but the product could also more generally be a standalone tool and documented process for creating accurate surrogate models that is available to the SE community.

### 5. What difference will this research make?

Under this topic, researchers enhanced the link between FACT and Army Research Lab's Executable Architecture Systems Engineering, as a means to offer a reusable approach for exposing simulators to FACT users. Furthermore, the execution methodology of FACT was updated to offer a comprehensive set of Design of Experiment techniques as opposed to the previous Monte Carlo approach offered in FACT 1.x. Lastly, researchers began development of tools to support the semi-automated ability for creating surrogate models from higher fidelity simulations hosted on EASE. First completed was the ability for executing proper DoEs, which is required for the screening and regression processes of surrogate model generation. Additionally, an updated tradespace analysis dashboard has been integrated into FACT. As a road map for the continued research and development required for surrogate model generation, researchers captured the end to end Surrogate Modeling Process.

## EARLY WARNING QUANTITATIVE TECHNICAL RISK

**Principal Investigator:** Gary Witus (gwitus@wayne.edu)
**University:** Wayne State University
**Sponsor:** DASD(SE)
**Project Page:** http://www.sercuarc.org/projects/tradespace-and-affordability/

### 1. What was the problem being addressed? Why was it hard and is it important?

DoD development and acquisition programs sometimes experience adverse outcomes. From 1995 to 2013, 25 Major Defense Acquisition Programs (MDAPs) were cancelled before Initial Operating Capability (IOC). This was 10 to 15 percent of all MDAPs started in that time period. Sunk costs were over $45B. Of the MDAPs that entered production, less than 90-percent were rated as operationally effective, less than 70-percent were rated as operationally suitable. The Government Accountability Office (GAO) reported that in fiscal year 2012, of the 85 major defense acquisition programs under review, 39 percent had unit cost growth of 25 percent or more, the average delay in IOC was 27 months, on average development cost increased 49 percent from the initial estimate, and the average change in total acquisition cost from the initial estimate was an increase of 38 percent. The initial causes and chain-of-event mechanisms leading to the adverse outcomes had not been identified as significant risks in time to develop and apply effective proactive mitigation, or appropriate mitigations were known in time but not applied. The intent of DoD's risk management processes is to make decisions to mitigate risks early, and avoid the outcomes described above. It is clear that there are significant opportunities to improve DoD's risk management processes. Under the RT, the SERC was to build upon previous research phases to develop and deploy new, practical, and relevant risk management methods, processes and tools to complement and extend the risk management MPT currently in use with an ultimate goal of improving risk-informed decision-making in DoD development and acquisition programs.

### 2. What was new in the approach and why do we think it will be successful?

The research was to develop, pilot, evaluate, refine, and transition MPTs to detect and assess exposure created by decisions and actions made prior to the Engineering and Manufacturing Development (EMD) phase, detect and analyze elevated risk exposure generated during EMD, and diagnose sources, causal chains and mitigation alternatives. The team conducted empirical research to assess the practicality, specificity, and relevance of prospective risk leading indicators (RLI) via application to an ACAT I acquisition Program beginning at initiation of the Engineering and Manufacturing Development (EMD) phase. Doing this would help address whether RLIs for EMD-phase programs were practical, informative, relevant, and comprehensive -- proving system development leading indicators could be source of risk leading indicators. The prospective RLI began with the System Development Leading Indicators (SDLI), developed by the National Defense Industrial Association (NDIA) in cooperation with the Practical Software and Systems Measurement (PSM) organization, and the International Council on Systems Engineering.

### 3. Who should care about this problem?

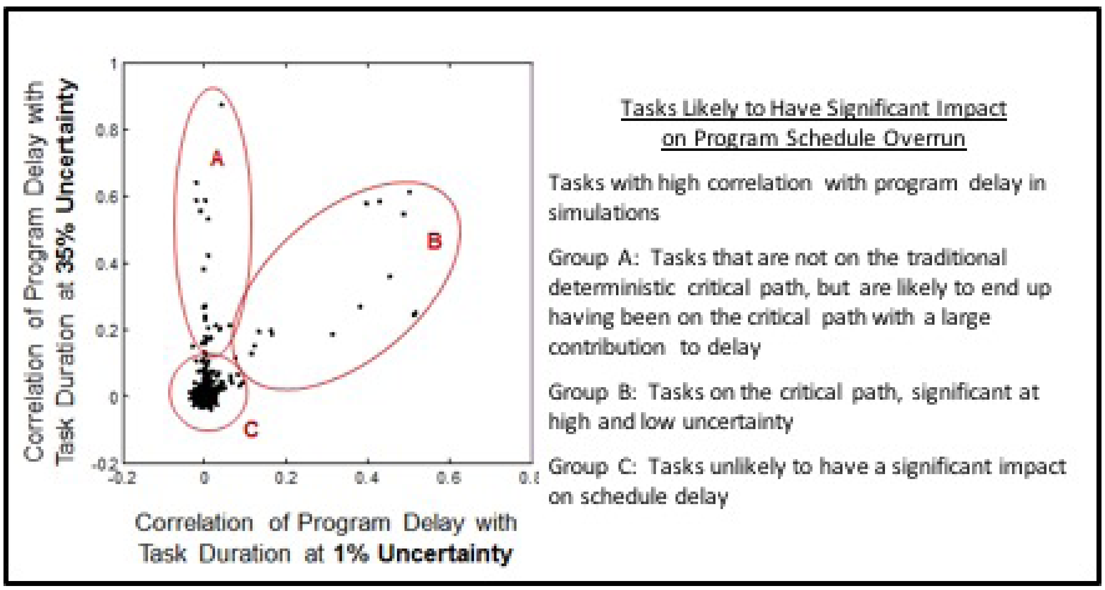
DoD, Defense Industrial Base, and organizations who seek to apply effective, proactive mitigation against risk in a complex environment.

### 4. What are the risks and payoffs?

There is the chance of not having sufficient data to evaluate the risk estimating relationships for risk leading indicators that can be evaluated given data reporting schedule. Leading indicators, by definition, lead the effects. The longer the lag in the effects, the less data there are in any timeframe. The purpose of the analysis is to estimate the strength of correlation, the length and dispersion of the lead-lag relationship. The greater the dispersion of the lead time, the longer the data time series are needed. The final risk is that the work packages do not have time and cost overruns. If there are no variances to explain, statistical analysis to evaluate correlations is impossible. If the variances are small and few in number, a larger sample is needed to evaluate correlations. When the data became available, the team could assess aspects of risk exposure and sources of data in an EMD program that were not addressed in the SDLI, therefore formulating additional, complementary RLI for EMD-phase programs.

**5. What difference will this research make?**

The overarching goal of this project is to develop a set of practical, informative, and relevant leading indicators of risk exposure DoD acquisition programs encompassing major types and source of risk exposure. Risk leading indicators (RLI) are evidence-based, quantitative metrics of existence of, proximity to, and trend toward "at risk" states – program conditions with causal or statistical relationship to elevated likelihood of future time and cost overrun. The Risk Management team found the metrics, analyses, conclusions and recommendations to be practical, informative and relevant. The Risk Management team also saw significant value in analyses of bias and uncertainty in time and cost estimating, and in the greater exploitation of probabilistic schedule risk analysis to identify the tasks likely to have significant impact on internal milestone delay. They concurred with the finding that further work was needed for practical "Interfaces and Architectures" metrics and risk indicators, and that "first-order" indicators and metrics would be valuable and are within reach.



## SYSTEMS ENGINEERING M&S INTEGRATION FRAMEWORK IN THE DIGITAL THREAD

**Principal Investigator:** Gary Witus (gwitus@wayne.edu)
**University:** Wayne State University
**Sponsor:** TARDEC
**Project Page:** http://www.sercuarc.org/projects/systems-engineering-ms-integration-framework-in-digital-thread/

### 1. What was the problem being addressed? Why was it hard and is it important?

The need for an agile SE enterprise presents a challenge for digitally-enabled SE workflow and M&S integration. The concern is that if the digital thread is rigid or brittle, it would not serve the needs of an agile SE enterprise, and could not reduce effectiveness, and ultimately be discarded. The challenge was to develop a vision for a digitally enabled agile SE enterprise. The researchers developed a framework and preliminary standards to define and document digital thread environments at DoD agencies. The researchers also developed a preliminary model of the transformation process from the current "as-is" organization to the completed digital thread, and transformation maturity model. The framework, standards, and models address SE M&S integration and high-level data flows, over the acquisition lifecycle, to enable rapid generation of system/produce models for integrated analysis in a co-simulation environment. The framework, standards and maturity model should be sufficiently robust to be applied to fragmented, manually intensive "as-is" organizations to mature, integrated model-centric engineering enterprises.

### 2. What was new in the approach and why do we think it will be successful?

The researchers verified the utility of the research product in an initial pilot application in a relevant DoD environment, such as the US Army tank and Automotive Research, Development and Engineering Center. The researches work with end-users and transition partners to demonstrate the capability to:

A.) Document the "as-is" SE/M&S elements and high-level data exchanges in a scientific workflow model

B.) Define and describe a "to-be" vision of an SE M&S integration framework that will integrate with SE and product development, to enable rapid generation of system/product models for integrated analysis in a model exchange and co-simulation environment

C.) Define a roadmap for near-term steps towards the digital thread that could enhance the "as-is" environment with current or emergent data exchange, model or simulation capabilities

D.) Identify the remaining gaps to achieve the "to-be" vision, including gaps in the state-of-the practice and efforts needed to bridge those gaps

### 3. Who should care about this problem?

The Army (TARDEC), DoD, and other organizations that are challenged with digitally-enabled SE workflow and M&S integration through their agile SE enterprise.

### 4. What are the risks and payoffs?

The research found that DoD Research Development and Engineering Command (RDECs) require an agile SE organization. The SE organization at a DoD RDEC have diverse roles and responsibilities on different programs, and a functional engineer-centric organization can adapt its interaction and process with a high degree of adaptability and versatility to accommodate the needs and constraints of an individual program. This poses challenges for digital SE and M&S integration, and also poses a challenge for the workflow data capture.

### 5. What difference will this research make?

A deeper knowledge and greater understanding into the enterprise with the use of SE M&S integration framework was developed. Stagnant methodologies were illuminated and greater rigor was introduced with a near-term solution roadmap. The researchers also formulated an alternative, evidence-based approach using a configuration management model, stamping work being produced with a unique ID and metadata with a unique ID of all work products which provided direct inputs to produce the product from a systems perspective. This was necessary and sufficient to reconstruct the entire engineering workflow.

## AGILE SYSTEMS ENGINEERING MANAGEMENT

**Principal Investigator:** Rich Turner (richturner.work@gmail.com)
Please contact Dr. Dinesh Verma (dinesh.verma@stevens.edu) if you have an interest in this task.
**University:** Stevens Institute of Technology
**Sponsor:** DASD(SE)
**Project Page:** http://www.sercuarc.org/projects/agile-lean-software-engineering-evaluating-kanban-in-se/

**1. What was the problem being addressed? Why was it hard and is it important?**

The challenge is to successfully apply systems engineering to evolving complex systems and systems of systems. The current systems development environment includes: A.) rapid change in threats, capability needs priorities, and technology/solution concepts and availability, B.) multiple powerful stakeholders with inconsistent win conditions, C.) legacy or component systems and platforms that are evolving independently with heterogeneous governance systems, D.) overall capability enhancement via continuous, interdependent software development.

It is difficult to schedule as well as efficiently apply resources to ongoing development and operation tasks in such an uncertain environment. Timely coherent communication and decision making are critical success factors - but often difficult. New ways of coordinating, valuing, and performing work across this complex development environment are needed. Organizational structures can have a significant impact on productivity; however, changing these structures can incur significant costs with uncertain benefits.

**2. What was new in the approach and why do we think it will be successful?**

The researchers improved the utility of DATASEM tool for building experiments and analyzing results, with the goal of informing decisions regarding the structure of the engineering work to be performed and the organizations doing the work. The researchers focused on improving the ease of use for both building experiments and analyzing outcomes. The researchers also investigated other organizational modeling tools to identify capabilities that complement DATASEM. Task 2: The researchers also looked at calibration and validation in their refinement of DATASEM. DATASEM was also validated through a set of rigorous experiments using the experimental validation framework developed in the previous research phase. DATASEM results collected from pilot efforts to calibrate and improve the DATASEM capability.

**3. Who should care about this problem?**

DoD, NSA, and other organizations desiring effective, integrated master schedules in rapidly changing operational environments with the proven use of Kanban and other adaptive governance mechanisms.

**4. What are the risks and payoffs?**

Some of the risks include creating models and simulations that are not of use, insufficient interest in adaptive concepts, and adoption support is unstable. Despite these risks, the ongoing research continues development of a flexible, web-accessible, agent-based modeling and simulation capability to investigate adaptive approaches through realistic experiments to understand governance models, a framework to calibrate assumptions of performance, conduct increasingly sophisticated experiements with stochastic support, and the ability to provide support for organizations considering adaptive approaches.

**5. What difference will this research make?**

DATASEM has attracted significant attention from the system of systems community as a way to not only investigate, but also demonstrate the impact of change on both existing and adaptive governance mechanisms, and to measure the effectiveness of various combinations. Infrastructure support for modeling organizational negotiation and communication activities related to SoS governance can improve management understanding of the critical nature of such activities to effective governance. Ultimately, DATASEM could be applied to acquisition governance processes to develop and test alternative governance approaches and to identify and create ways to mitigate incompatibilities between adaptive and traditional governance mechanisms. Industry has suggested the project consider the concept of technical debt in the DATASEM models and as a significant attribute for characterizing particular configurations of workflow, organization, and governance, leveraging other SERC research in this area.

## TRANSFORMING SYSTEMS ENGINEERING THROUGH MODEL-CENTRIC ENGINEERING

**Principal Investigator:** Mark Blackburn (mblackbu@stevens.edu)
**University:** Stevens Institute of Technology
**Sponsor:** US Army Engineering Research and Development Center, NAVAIR
**Project Page:** http://www.sercuarc.org/projects/transforming-systems-engineering-through-model-based-systems-engineering-ardec/ and http://www.sercuarc.org/projects/transforming-systems-engineering-through-model-based-systems-engineering/

### 1. What was the problem being addressed? Why was it hard and is it important?

The problem was a global scan assessing the technical feasibility of a radical change in the way that the government could use "Digital Models," or Model-Centric Engineering (MCE) and/or Digital Engineering (DE) to significantly reduce the time to delivery large-scale systems to the warfighter.

### 2. What was new in the approach and why do we think it will be successful?

The approach used an open-ended global scan spending more than 30 days of onsite effort with the sponsor asking leaders in industry, government (e.g., NASA/Sandia) to tell us about the most advanced holistic approach to MCE and DE. The results are 116 pages of proprietary/NDA meeting notes, Bayes Model of measures, and a traceability matrix, which was ultimately the easiest instrument to communicate with Senior leaders at NAVAIR about the breadth of everything heard. Also found was the need for more understanding about the key challenges in the research areas such as cross-domain model integration, which led to semantic technologies and ontologies as a means for interoperability versus strictly tool-to-tool integration, challenges of model integrity and the trust in model prediction when they were not integrated, and also modeling methods and how to model so that we can trust the results.

Both NAVAIR and ARDEC had similar challenges with assembling different type of analysis workflows across various domains that would be assembled for various types of programs. Tool-to-tool integration was either very challenging or simply not feasible, therefore Semantic Web Technologies and Ontologies are of high interest during this next phase of research as well as an Integration and Interoperability Framework. Another challenge in the transition is that sponsors are now more in models and code are provided, demonstrated, and taught, which goes beyond the more typical technical reports.

By leadership request, there was an acceleration of the Research Task, and currently the team is executing a Surrogate Pilot for a new operation paradigm for model-based acquisition that incorporates experiments for the Research Task.

### 3. Who should care about this problem?

ARDEC, NAVAIR, DoD, and other organizations in pursuit of transforming their systems engineering through model-centric engineering. While the Surrogate Pilot has synergy between the organizations, underlining its value, the research tasks are about a new operational paradigm for model-based acquisition – which several organizations, both government and industry, care significantly about.

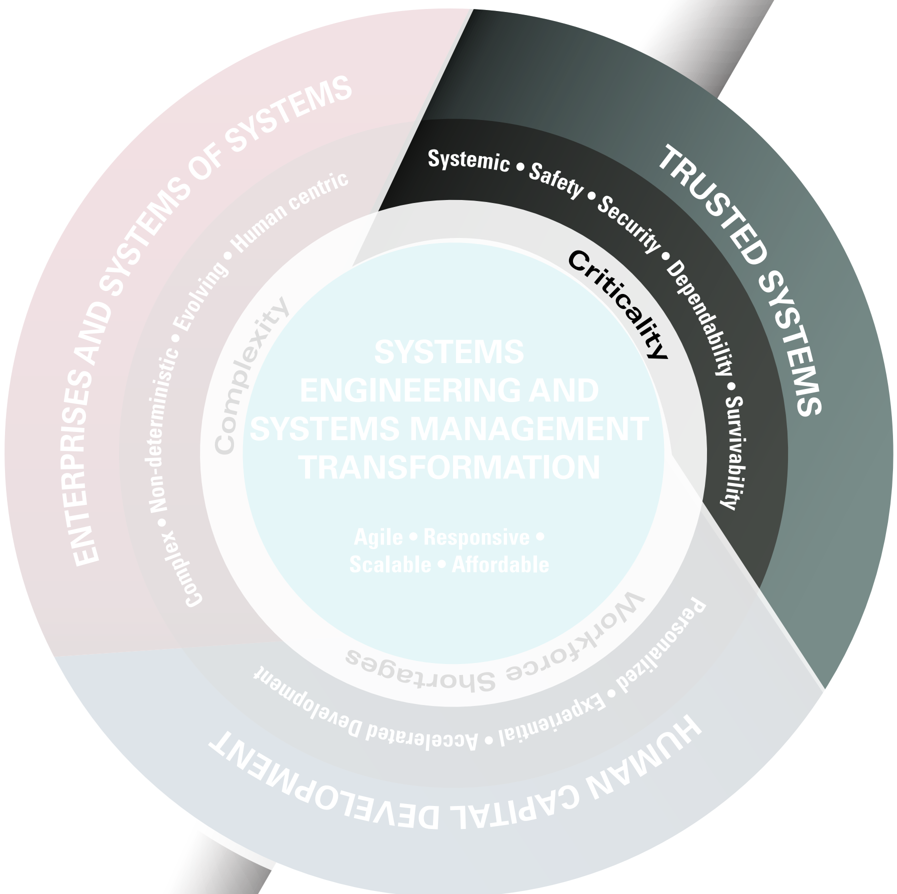
### 4. What are the risks and payoffs?

There are a few risks with such an immense task. The expectation that the team will be able to achieve all of the goals of Systems Engineering Transformation (SET) by 2020 is a risk, especially since the team members are building prototypes of the models, and the stakeholder that are involved expand far beyond any control or guidance of the SERC Principal Investigator. Also, SET defines working in an Authoritative Source of Truth through the research. This poses issues with cyber security when it is both classified and unclassified. Another risk is that SET requires significant workforce development, which needs to be explored and employed to perform efficiently in the new operational paradigm for model-based acquisition.

### 5. What difference will this research make?

This research will expand the current state of SE knowledge, documenting details about technologies that support evolving modeling frameworks with underlying sponsor-relevant digital system models, as well as lessons learned that apply to methodologies for transitioning engineering organizations from document-based to model-centric practices.

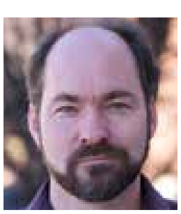
# TRUSTED SYSTEMS




## RESEARCH COUNCIL MEMBERS FOCUSED ON THIS THEMATIC AREA:

**Barry Horowitz**

*Munster Professor of Systems and Information Engineering and Chair, University of Virginia*



**Kevin Sullivan**

*Associate Professor in Computer Science, University of Virginia*

*Providing ways to conceive, develop, deploy and sustain systems that are safe, secure, dependable and survivable. Research must enable prediction, conception, design, integration, verification, evolution and management of these emergent properties of the system as a whole, recognizing these are not just properties of the individual components and that it is essential that the human element be considered.*

## SECURITY ENGINEERING – DESIGN PATTERNS AND OPERATIONAL CONCEPTS

**Principal Investigator:** Barry Horowitz (bh8e@virginia.edu)
**University:** University of Virginia
**Sponsor:** DASD(SE)
**Project Page:** http://www.sercuarc.org/projects/security-engineering/

**1. What was the problem being addressed? Why was it hard and is it important?**

The research efforts have been addressing the use of engineering model-based tools for supporting decisions regarding the design of cyber attack resilient cyber physical systems. The issues being addressed are: 1) The design of a tool set that can effectively be used by system designers and decision-makers for identifying and prioritizing potential resiliency solutions, and 2) the scalability of the use of such tools to account for the complex System-of-System (SoS) configurations employed by DoD. Critical issues being addressed by the researchers relates to the fidelity of information required by the tools and the degree of automation required in order to enhance user productivity in creating high quality designs. In addition, in preparation for transition into use, the researchers have started to develop organized processes for teams of users employing such tools.

**2. What was new in the approach and why do we think it will be successful?**

The ongoing cybersecurity effort has included the start of the transition process for the research efforts related to model-based tools, as well as transitioning into use the results of earlier system technology efforts involving system architectures that employ secure Sentinels for detecting cyber attacks and rapidly reconfiguring systems to reduce or eliminate the potential consequences of detected cyber attacks. Both of these areas of research represent leading edge approaches to addressing cyber attack resilient systems. Expanding the concepts that were initially focused on single system design and implementations to System of Systems (SoS) configurations has initiated a more challenging requirement for resilient mission capabilities, but with corresponding additions to the values that can be achieved. Research results have been encouraging and have been stimulating interest in a number of DoD organizations. Research plans include a focus on conducting initial technology and tool use experiments with the Army's Armament Research, Development and Engineering Center (ARDEC) to address weapon system resiliency and to identify transition opportunities with other DoD organizations as well.

**3. Who should care about this problem?**

Military organizations engaged in development of SoS-based weapon systems and operational groups that will use those weapon systems in warfighting environments where adversaries are likely to employ of cyber attacks

**4. What are the risks and payoffs?**

The payoffs for this research activity are: 1) the ability to include what are likely to be low cost but much needed cyber attack resiliency features to our weapon systems, and 2) the likely impact of resiliency feature serving to deter adversaries from employing what could be high consequence cyber attacks.

**5. What difference will this research make?**

This RT addresses the overall goal of the SERC's Systemic Security Research Program, which is to develop safe, secure, dependable defense systems that are resilient to cyber and other threats through systemic security approaches that complement today's current, incomplete perimeter/network methods. The approach is to reverse cyber security asymmetry from favoring our adversaries (small investment in straightforward cyber exploits upsetting major system capabilities), to favoring the US (small investments for protecting the most critical system functions using system-aware cyber security solutions that require very complex and high cost exploits to defeat).

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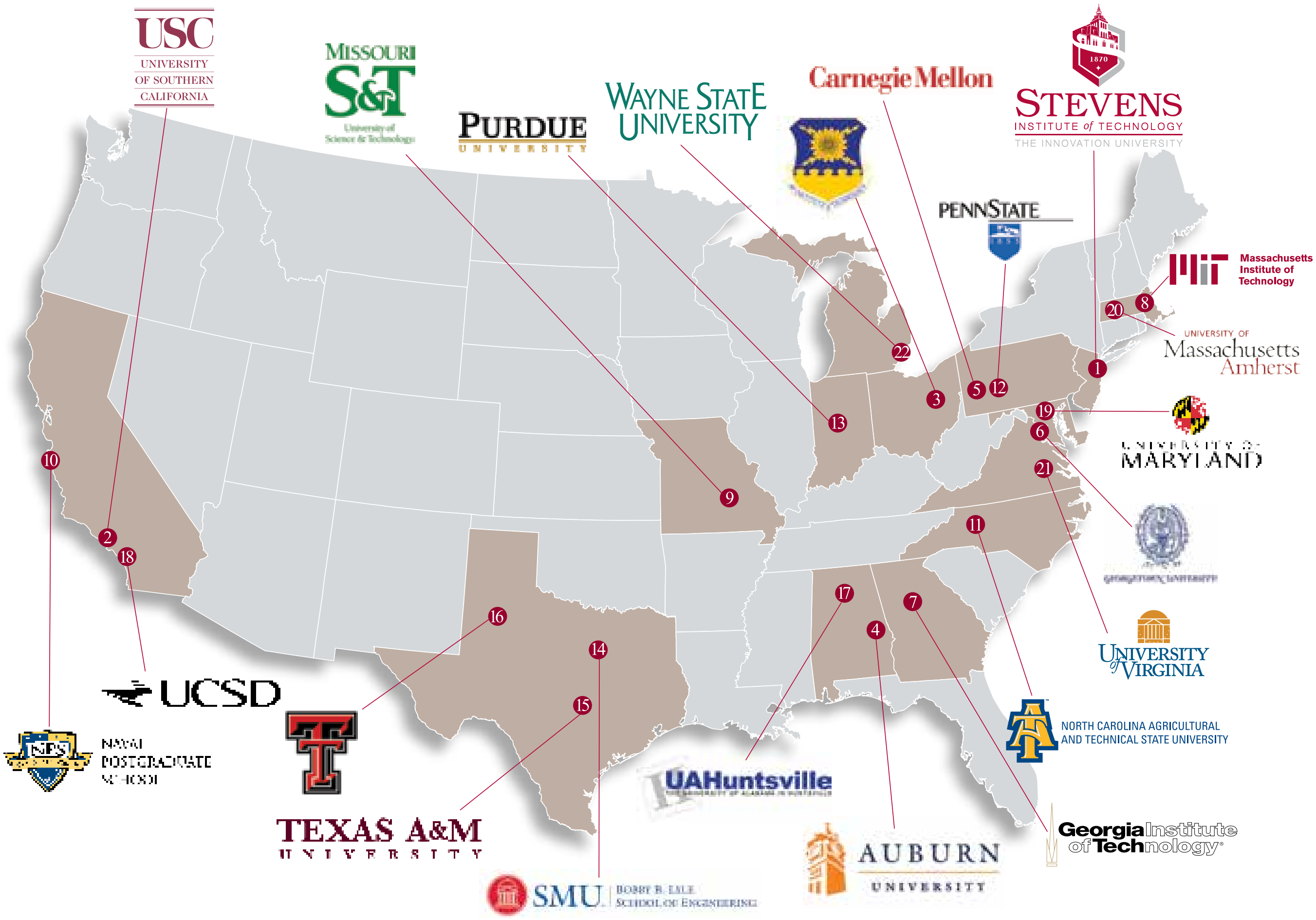

## University or Research Organization

1. Stevens Institute of Technology
2. University of Southern California
3. Air Force Institute of Technology
4. Auburn University
5. Carnegie Mellon University
6. Georgetown University
7. Georgia Institute of Technology
8. Massachusetts Institute of Technology
9. Missouri University of Science and Technology
10. Naval Postgraduate School
11. North Carolina Agricultural & Technical State University
12. Pennsylvania State University
13. Purdue University
14. Southern Methodist University
15. Texas A&M University
16. Texas Tech University
17. University of Alabama in Huntsville
18. University of California - San Diego
19. University of Maryland
20. University of Massachusetts Amherst
21. University of Virginia
22. Wayne State University

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