International Journal of Complex Systems – Computing, Sensing and Control
Vol. 3, No. 1, pp. 67-78, 2015

A MODEL OF ENTERPRISE SYSTEMS ENGINEERING CONTRIBUTIONS TO ACQUISITION SUCCESS

JILL L. DRURY[1], GARY L. KLEIN[2], MARK S. PFAFF[1], AND CRAIG BONACETO[1]

[1]The MITRE Corporation
202 Burlington Road
Bedford, MA 01730
{jldrury,mpfaff,cbonaceto}@mitre.org

[2]The MITRE Corporation
7515 Colshire Drive
McLean, VA 22102
gklein@mitre.org

ABSTRACT—This paper presents a conceptual causal model of enterprise systems engineering (ESE) impact on systems acquisition success. The model takes the form of a directed acyclic graph and its major components consist of collaboration support, ESE technique application, system characteristics, and organizational characteristics. As initial validation, we converted this conceptual model to a computational model using our Descriptive to Executable SIMulation (DESIM) modeling method. We obtained data based on subject matter experts' (SMEs') mental models so that we could determine the degree to which SMEs agreed with the model's components and relationships.

Key Words: Enterprise systems engineering, cognitive systems engineering, participatory design, organizational change management, collaboration support, modeling.

1. INTRODUCTION

Despite the fact that Systems Engineering (SE) is a mature profession, there is no consensus regarding the factors that lead to successful acquisition of complex systems [1]. Elm and Goldenson [2] undertook a large study aimed at understanding SE success by developing case studies of systems engineering practices in different companies. While they assessed systems engineering efforts as being successful or unsuccessful, they did not examine the impact of individual factors, such as those related to organizational characteristics and culture, that led to success or failure. Without a firm underpinning of those factors, it is not surprising that current SE practices are suboptimal for handling complex systems of systems [3]. We believe that a validated model of success factors would be useful to the SE community.

Difficulties in achieving successful SE efforts are attributed to many different causes, such as very short development cycles, disparate stakeholder needs, mismatches between technology and organizational needs, and rapid rate of technological change. Thus a model of success would need to take into account a broad view of the possible factors that could affect SE outcomes. Such a view has been taken by Enterprise Systems Engineering (ESE). The MITRE Corporation's Systems Engineering Guide (SEG) notes that ESE "encompasses and balances technical and non-technical aspects of the problem and the solution.…In performing enterprise systems engineering, we engineer the enterprise and we engineer the systems that enable the enterprise. In particular, we help customers shape their enterprises, aligning technology to support goals. We support their business planning, policy-making, and investment strategies" [4, p. 34].

The SEG cites the need to consider non-technical factors such as business planning and policy-making. It highlights "engineering the enterprise" in collaboration with enterprise members, going beyond simply engineering the technical systems that support the enterprise. ESE considers the effects of the new technologies on the stakeholder organization(s) and includes possibly redesigning workflows, staff member responsibilities, or policies in conjunction with developing the technologies. We believe that a model of ESE success for systems that involve user interaction would need to take into account the factors that are a part of ESE practice. Additionally, we envisioned that a useful model ideally would be:

- *applicable to systems that include direct user interaction,* because there is an additional design challenge when systems must be understood and utilized by human operators,
- *appropriate for complex systems* as defined by Snowden's [5] Cynefin framework (note that systems of systems often fall into the complex and chaotic quadrants of this framework),
- *general-purpose*, in the sense that the model would include the factors important for complex systems that allow for direct user interaction,
- *tailorable,* so factors could be altered to make the model applicable to a specific system,
- *sufficiently detailed* to provide guidance regarding which SE techniques or methods should be applied in the course of the engineering process, and
- *causal,* such that the relationships between the different success factors are made explicit.

Before deciding to develop our own model, we surveyed the landscape of SE models to determine if an existing model could be instantiated, extended, and/or validated. Three modeling approaches are described here: the V Model [6], the Enterprise Systems Engineering Model [7], and Model Based Systems Engineering [8].

The V Model is a high-level description of systems engineering activities performed across a system's lifecycle. It consists of the following steps: concept of operations, requirements and architecture, detailed design, implementation, integration, test, and verification, system verification and validation, and operation and maintenance. The V Model describes categories of activities rather than the techniques for executing those activities and their consequent outcomes.

The Enterprise Systems Engineering Model is broader in scope than the V Model. It includes three layers: the top layer being enterprise management, the middle layer being restructure the enterprise, process improvement and design, implement, transition, and the bottom layer being enterprise assessment. The middle layer acknowledges that the enterprise itself may need to be re-engineered as part of the SE process. Rather than identifying success factors, however, the purpose of this model is to show the relationships between traditional SE, ESE, and business processes.

Recently, there has been a movement towards Model Based Systems Engineering (MBSE), which is "the formalized application of modeling to support system requirements, analysis, design, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases" [8, p. 5]. Sometimes cited as an outgrowth of frameworks such as the US Department of Defense Architecture Framework (DoDAF; [9]), MBSE replaces documents specifying the system under development with functional, performance, component, and other models specific to that particular system. In other words, a set of MBSE models is not general purpose, but is specific to a given system.

Based on the literature, we saw the need to develop an ESE Success Model. The following sections describe the model, its initial validation, and directions for future work.

2. THE ESE SUCCESS MODEL

In an earlier work [10], we described how we scoured the literature for "ESE Success Variables": SE techniques and methods that, based on the evidence provided in the literature, appear to contribute to successful acquisitions of systems that fall into the complex quadrant of Snowden's [5] Cynefin framework.

2.1 ESE Success Variables

Much literature points to the importance of stakeholder involvement during all phases of the acquisition (e.g., [11,12]). As a consequence of the geographically diverse nature of many large-scale acquisition teams, having an appropriate suite of collaboration methods and tools is vitally important. Thus, collaboration, and the associated means of working together across time and space, becomes a foundational ESE Success Variable.

Another ESE Success Variable is SE technique application, meaning that four categories of supporting ESE techniques are critical for engineering complex systems, as follows.

- *Systems-of-Systems Engineering (SoSE)* techniques deal with "planning, analyzing, organizing, and integrating the capabilities of a mix of existing and new systems into an SoSE capability greater than the sum of the capabilities of the constituent parts" [13]. SoSE techniques are needed to help ensure that a new system will function effectively as a part of a larger set of interoperating systems.
- *Cognitive Systems Engineering (CSE)* is "an approach to the design of technology, training, and processes intended to manage cognitive complexity in sociotechnical systems. In this context, 'cognitive complexity' refers to activities such as identifying, judging, attending, perceiving, remembering, reasoning, deciding, problem solving, and planning" [14, p. 263]. CSE is needed for designing user interaction that accounts for cognition.
- *Participatory Design (PD)* "is a set of theories, practices, and studies related to end-users as full participants in activities leading to software and hardware computer products and computer-based activities" [15, p. 1125]. PD can help to ensure that users' needs are taken into account during all performance trade-off and design decisions.
- *Organizational Change Management (OCM)* includes activities pertaining to "defining and instilling new values, attitudes, norms, and behaviors within an organization that support new ways of doing work and overcome resistance to change" [16]. OCM is needed to ensure that technology adoption occurs smoothly, and that the enterprise's members are aided in adapting their business processes, roles, responsibilities, and/or policies to complement the new system.

Another ESE Success Variable includes characteristics of the system that is being acquired. Examples of these characteristics are complexity, size, performance demands for throughput or security, and degree of maturity of constituent technologies. Honour [17] observes that engineers often make tradeoffs among these factors, and collaboration with users can generate valuable input for decision-making as well as help users understand why solutions were selected.

A final ESE Success Variable concerns organizational characteristics, such as the degree to which technology users are dependent on each other as they accomplish tasks. To ensure success, ESE teams should determine the type(s) of interdependence that the new system needs to facilitate, since different types require different technology support.

Earlier, we used these ESE Success Variables to develop an overview model of ESE's contribution to systems acquisition success [10]. In this paper, we describe for the first time how we have evolved the overview model to be more detailed, such that it meets the criteria listed in the introduction.

2.2 Model Structure

The model's structure, as shown in Figure 1, takes the form of a directed acyclic graph. It has four clusters of light gray nodes, one for each of the four critical supporting categories of ESE techniques. These clusters represent the basic proposition that the quality of SE will affect its impact on acquisition success.

For each of the ESE technique categories, the quality of the result is affected by whether the specific techniques used are effective for the circumstances and whether they were executed correctly. Subsequently, the quality of the result affects whether use of the techniques will have a positive impact. There are "+" operators between these nodes to indicate a positive relationship between factors, such as the better the execution of the technique, the higher the likely quality of the outcome.

A blue node interacts with each cluster and represents the need for each technique category. Obviously, no matter how well a specific technique is executed, if it is not pertinent to the systems acquisition effort, it will have little or no impact. For example, systems or subsystems that require significant amounts of judgment or decision making would benefit more from CSE than those that require pattern matching followed by routinized interaction from a playbook or set of standard operational procedures. The model shows "*" (multiplicative) operators on edges from "Need" to "Impact" to indicate this interaction, such that if the need is zero, the impact will be zero.

The pink nodes represent major characteristics of the system being acquired that define the need for ESE techniques. In this case, the degree of user-system interaction and the amount of technical interoperability is shown, but the model can be tailored to show additional characteristics that are relevant to the system being acquired. For example, the extent of user-system interaction affects the need for PD and CSE; and the degree of technical interoperability affects the need for CSE, OCM, and SoSE.

The orange nodes represent organizational characteristics of the system being acquired, and also affect the need for the ESE techniques. For example, the type of coordination and degree of interdependencies among the members of the organizations that will be using the new system will affect the needs for different ESE technique categories. Similarly, the task environment and processes affect the complexity of the organization acquiring a system and therefore the system's complexity. As such, they play roles in the need for ESE techniques. Unsurprisingly, many of these nodes feed into the need for OCM.

The yellow nodes represent collaboration support. The greater the "Support for Asynchronous Collaboration," the greater the "Collaboration Quality" and "Collaboration Impact," as long as there is a "Need for Collaboration."

3. INITIAL VALIDATION

Originally, we had hoped to validate the model by taking many case studies from the literature, mapping their characteristics into the model and evaluating the studies' outcomes. With enough case studies, we aimed to tease apart the effects of the different ESE Success Variables. However, the complexity of the model meant that we would need thousands of case studies before being able to understand the contributions of each of the Success Variables. Thus we needed a different tactic for validation. That tactic, and its results, are summarized below.

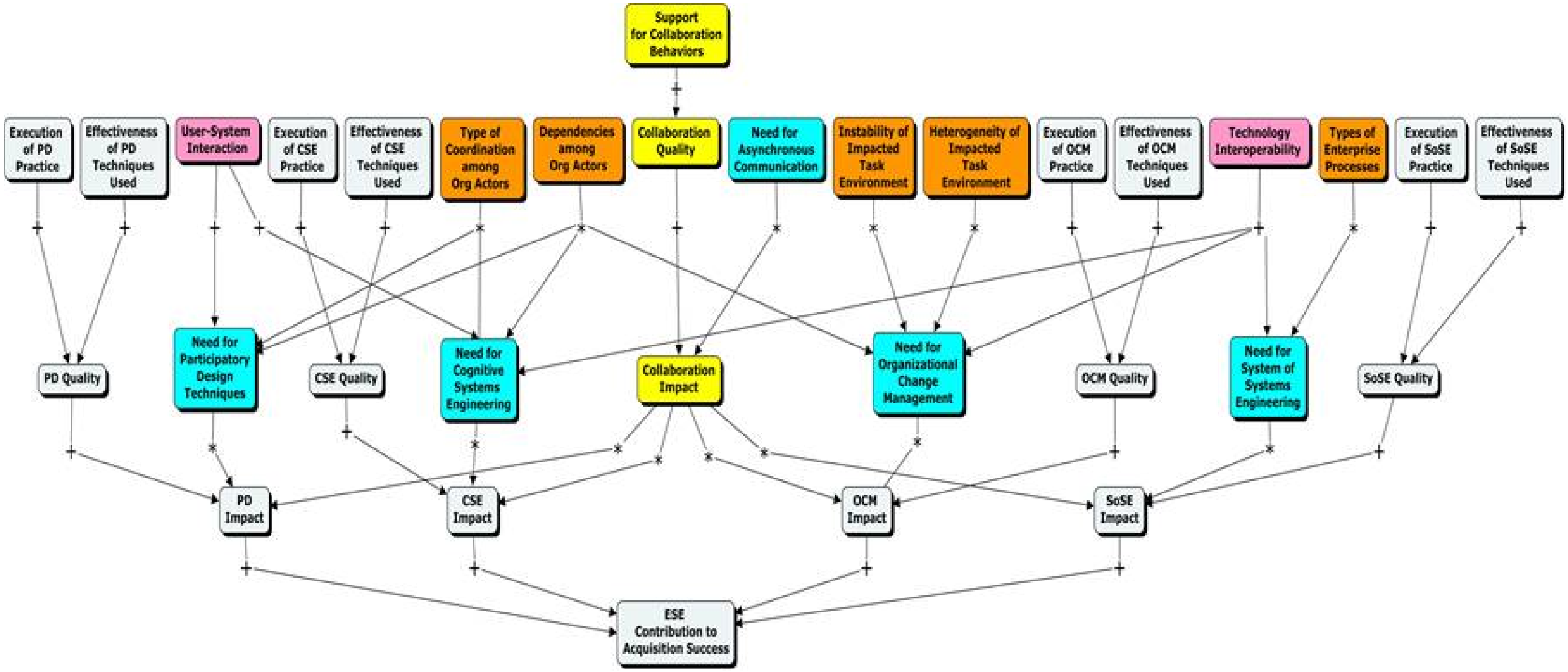

Figure 1. ESE Success Model

3.1 Validation Approach

As an initial approach, we put our model through a peer review with seven senior systems engineers. Prior to that effort, we composed definitions for every node in the model. These engineers suggested some changes, which we incorporated in the model presented in this paper. The node definitions are detailed below:

Systems Engineering Techniques (grey)

Participatory Design (PD)

1. **Effectiveness of PD Techniques Used** refers to how well the selected PD methods perform in contributing to the success of an engineering process. Note: this refers to the quality of the methods in general, not for a specific acquisition effort, which will depend on several factors.
2. **Execution of PD Practice** refers to the consistency and proficiency with which the selected PD methods are applied.
3. **PD Quality** refers to the effectiveness of PD for a specific engineering process, given the methods selected and the proficiency with which they are applied.
4. **Need for Participatory Design Techniques** refers to the appropriateness of using PD methods for the engineering task; for example, if users do not interact with the system, Participatory Design is unnecessary because PD focuses on ways to engage users in co-designing the system.
5. **PD Impact** refers to the contribution of PD efforts to the success of a specific acquisition.

Cognitive Systems Engineering (CSE)

6. **Effectiveness of CSE Techniques Used** refers to how well the selected CSE methods perform in contributing to the success of an engineering process. Note: this refers to the quality of the methods in general, not for a specific acquisition effort, which will depend on several other factors.
7. **Execution of CSE Practice** refers to the consistency and proficiency with which the selected CSE methods are applied.
8. **CSE Quality** refers to the effectiveness of CSE in a specific engineering process, given the methods selected and the proficiency with which they are applied.
9. **Need for Cognitive Systems Engineering** refers to the appropriateness of using CSE methods for the engineering task; for example, if users do not interact with the system, CSE is unnecessary because CSE focuses on how users think about their tasks and how those tasks fit into the overall work process.
10. **CSE Impact** refers to the contribution of CSE efforts to the success of a specific acquisition.

System of Systems Engineering (SoSE)

11. **Effectiveness of SoSE Techniques Used** refers to how well the selected SoSE methods perform in contributing to the success of an engineering process. Note: this refers to the quality of the methods in general, not for a specific acquisition effort, which will depend on several other factors.
12. **Execution of SoSE Practice** refers to the consistency and proficiency with which the selected SoSE methods are applied.
13. **Need for SoSE** refers to the appropriateness of using SoSE methods for the engineering task; for example, if the system is not a system of systems, SoSE is unnecessary.
14. **SoSE Quality** refers to the effectiveness of SoSE in a specific engineering process, given the methods selected and the proficiency with which they are applied.
15. **SoSE Impact** refers to the contribution of SoSE to the success of a specific acquisition.

Organizational Change Management (OCM)

16. **Effectiveness of OCM Techniques Used** refers to how well the selected Organizational Change Management methods perform in contributing to the success of an engineering process. Note: this refers to the quality of the methods in general, not for a specific acquisition effort, which will depend on several other factors.
17. **Execution of OCM Practice** refers to the consistency and proficiency with which the selected Organizational Change Management methods are applied.
18. **Need for Organizational Change Management** refers to the appropriateness of using Organizational Change Management methods for the engineering task; for example, if users do not interact with the system, Organizational Change Management is unnecessary because Organization Change Management focuses on how organizations do their work and on helping modify the organization.
19. **OCM Quality** refers to the effectiveness of Organizational Change Management for a specific engineering process, given the methods selected and the proficiency with which they are applied.
20. **OCM Impact** refers to the contribution of Organizational Change Management efforts to the success of a specific system acquisition.

Collaboration (yellow)

21. **Support for Collaboration Behaviors** refers to the tools that are used to facilitate collaboration among participants in the engineering process. These may include email, SharePoint, and other collaboration spaces that support collaborative behaviors such as notifying that new communications have been contributed, confirming that communications have been received, and representing shared understandings.
22. **Need for Asynchronous Collaboration** refers to the appropriateness of using asynchronous collaboration methods (communication and collaboration spaces that do not require simultaneous interaction) in the engineering process; for example, if there are only a few co-located participants participating in the engineering process, then asynchronous collaboration may not be necessary.
23. **Collaboration Quality** refers to the effectiveness of collaboration among participants in the system acquisition effort.
24. **Collaboration Impact** refers to the contribution of collaboration efforts to the success of a specific system acquisition.

Organizational Characteristics (gold)

25. **Type of Coordination between User Org Units** refers to the highest level at which users may need to synchronize their activities. There are three levels.
    a. standardized rules: following rules that have been previously agreed upon.
    b. planned coordination: following procedures that have been previously agreed upon.
    c. continual mutual adjustments: jointly developing and agreeing upon new rules or procedures to use either in a specific case or in general.
26. **Dependencies among Actors in User Org** refers to the highest level of interdependence in how work products of individuals or groups contribute to the final goals, with three levels:
    a. Pooled -- each individual or group provides discrete contributions to the goal
    b. Sequential -- the product of each individual or group depends on the output of another individual or group

c. Reciprocal -- when people experience the need for real-time negotiation or interaction

27. **Types of Enterprise Processes** refers to the kinds of business processes in which the users' organization engages, such as serial processes like assembly lines (called "long-linked"), brokerage processes (e.g., connecting buyers and sellers), or intensive processes that change the state of a person, place or thing with repeated actions (e.g., medical actions to a patient, attacks upon a target).
28. **Instability of Impacted Task Environment** refers to whether the enterprise task environment that is impacted by the acquired system tends to be stable or changing. The task environment includes those source environments that provide materials and resources, the operating environment in which the organization functions (regulations, competition), and the "market" into which the organization delivers products.
29. **Heterogeneity of the Impacted Task Environment** refers to whether elements in the enterprise task environment that is impacted by the acquired system tend to be similar or not. For example, does the acquired system affect just one product line or many dissimilar ones?

Characteristics of system use (pink)

30. **User-System Interaction** refers to properties that affect how end users will interact with the system being acquired. It includes the number of different user groups, the frequency of the system's use, the number of tasks that users will perform with the system, the complexity of those tasks, the extent to which users take actions via the user interface to achieve their goals, the time sensitivity for completing tasks, and the degree to which tasks are safety-critical or that mistakes would result in adverse financial consequences to users.

31. **Technology Interoperability** refers to how widely the system being acquired is used throughout the end users' organization(s), and technological interdependencies among the organizational units using the technology. It includes the e**xtent of technology impact on how organizations achieve their goals, the** extent to which modifications to existing systems will affect the new system and vice versa.

Outcome

32. **ESE Success for System Acquisition** refers to the satisfactory performance of a systems engineering effort to generate a usable product that meets requirements with reasonable costs in an appropriate period of time.

Next, we compared the mental models [18] of 85 subject matter experts (SMEs), who have collectively seen hundreds of SE successes and failures, to the model. A challenge in doing so, however, is to ensure that the data is gathered in an minimally biased manner. We gathered SME data in a way that does not bias their responses via our novel (patent pending) Descriptive to Executable Simulation Modeling (DESIM) process [19].

The DESIM process for transforming causal descriptive models expressed as directed graphs into computer simulation models is based on information obtained from crowdsourcing (or rather, "expertsourcing" from our SMEs). DESIM uses feedback obtained from experts to quantify the strength of causal relationships between variables in descriptive models to provide a minimally biased distribution of estimated weights for each causal relationship, which enables mathematical processing of the descriptive models on a computer. This process results in a distribution of weights rather than an averaging of weights, so that variations in responses are revealed.

To obtain this feedback, the causal descriptive model was decomposed into a set of pairwise comparisons and presented to experts via a graphic interface. Applying the analytic hierarchy process [20], experts were presented with pairs of relationships in the model and were asked to rate which one is stronger and by how much. From this data the system computed unbiased edge weights for each relationship between nodes in the model, resulting in a distribution of values for each edge representing the range of beliefs of the experts in the crowd. If the experts agreed with relationships in the model, we conjectured that this would result in non-zero edge weights, which therefore would validate the relationships among the concepts.

Before making the comparisons, participants were presented with one of two scenarios. The fictitious Airborne Command and Control System (ACCS) was described as having many subsystems and interfaces to numerous other systems, and requiring a wide variety of tasks performed interactively by a large cadre of operators. The fictitious Translator Document Feed (TDF) subsystem was described as an embedded capability of a larger translation management system. The subsystem manages lists of documents assigned to each translator, and documents processed in the TDF subsystem are retrieved by a single process in the larger system. We expected higher ratings for all four ESE impact variables for the ACCS scenario, but high ratings only for the SoSE variable for the TDF scenario.

Edge weights were elicited in the context of the specific scenario shown to the participant. Finally, participants holistically rated the impacts of the four main ESE variables described above (PD, CSE, OCM & SoSE) on success given the scenario, on a scale of 1 to 10. Participants also self-rated their expertise in the human, technology, and organizational domains, also from 1 to 10.

3.2 Validation Results

85 participants (68 males, 17 females) evaluated the causal relationships in the model. We hypothesized that domain expertise in the human, organizational, and technology domains would correlate with their holistic ratings the impact of their corresponding ESE variables (PD, CSE, OCM & SoSE) on "Contribution to Acquisition Success", but this was not the case, with one exception. In the ACCS scenario, the participants' technology domain self-rating was significantly correlated with the system-of-systems ESE variable's estimated impact ($r_s = .33$, $p = .03$). Further, we hypothesized that domain expertise would correlate with the pairwise comparison resulting edge weights of the bottom four edges in the model (Figure 1),.However, this also was not supported.

Overall, Friedman's ANOVA found significant differences in the participants' ESE impact ratings across both scenarios ($\chi^2(3) = 40.27$, $p < .001$), with SoSE having the most impact (Mdn = 10), followed by CSE and PD (both Mdn = 8), and OCM (Mdn = 7). When split by scenario, however, SoSE had significantly more impact on success in the ACCS scenario (Mdn = 10) than the TDF scenario (Mdn = 8.5), $U = 604.00$, $z = 2.90$, $p = .004$. The remaining three impacts were not significantly different between scenarios.

To test the extent to which experts agreed with the model, we examined the distribution of edge weights for each relationship in the model by looking for mean edge weights close to zero. The lowest mean edge weight was .08, though this was from a bimodal distribution with some experts reporting no relationship, and a cluster of others with a weight of approximately .15. The non-zero edge weights validated expert agreement with the model.

4. DISCUSSION AND FUTURE WORK

The results of the validation efforts indicated that SMEs believe that SoSE has the most important impact on acquisition success of the four SE techniques we asked them to consider. As expected, of the two scenarios, SoSE was judged to have more impact on the ACCS scenario. (This scenario clearly included systems of systems, whereas the TDF scenario did not.) Because of the ACCS system's greater degree of direct interaction with users, we expected that the other SE techniques would also show statistically significant differences between the two scenarios, but they did not. On one hand, the SMEs' assessment for the need for different ESE techniques was not biased by their backgrounds. On the other hand, this meant that SMEs seemed to undervalue the need for OCM, PD, and CSE techniques for the ACCS scenario versus the TDF scenario.

A limitation is the fact that we were comparing the model to the combined opinions of SMEs rather than to ground truth, which is notoriously difficult to determine for a complex ESE effort. Based on the historical attention of systems engineers to technical issues rather than people-oriented issues, it is possible that the SMEs did not recognize the increased importance of the other SE techniques for a scenario that required more cognition and interactivity.

To obtain additional empirical data, we plan to provide the model to real-world SE teams and assess the resulting SE activities' contributions to acquisition success. Further, we aim to design a controlled experiment in which two groups solve a SE problem, with only one given the model's recommendations. The goal would be to assess the quality of the SE products generated.

We feel that additional work to validate and refine the model will pay dividends. During the peer review, several of the SMEs volunteered that they plan to use the model to provide guidance to their teams when planning their upcoming SE efforts. They felt that the model could act as a communications aid when conveying to their customers the value of undertaking the recommended activities. Of particular interest was the fact that the model explicitly calls out techniques relating to "engineering the enterprise" and ensuring that technology meets the needs of users and their organizations so that the new system will be successfully adopted.

ACKNOWLEDGMENTS

We would like to thank Sherri L. Condon for her contributions to earlier work on the model. This work was supported by the MITRE Corporation Innovation Project 19MSR083-CA under the Systems Engineering Investment Area.
Approved for Public Release; distribution unlimited; case #15-0187.

REFERENCES

1. M. Emes, A. Smith, and D. Cowper, "Confronting an identity crisis—How to 'brand' systems engineering," Systems Engineering, Vol. 8, No. 2, pp. 164 – 186, 2005.
2. J. Elm and D. Goldenson, "The Business Case for Systems Engineering Study: Results of the Systems Engineering Effectiveness Survey," CMU/SEI-2012-SR-009. Available: http://resources.sei.cmu.edu/library/asset-view.cfm?AssetID=34061, 2012.
3. H. Hawley, J. Kruse, S. Landsman, P. Smyton, A. Dziewulski, M. King, "The POET approach." Presentation at 17th Int. Command and Control Research and Technology Symposium. Available: http://www.dodccrp.org/events/17th_iccrts_2012/post_conference/presentations/064.pdf, 2012.
4. The MITRE Corporation, Systems Engineering Guide. [Online]. Ebook published 5 June 2012 under ISSN 2169-9372. Available: http://www.mitre.org/publications/ systems-engineering-guide/systems-engineering-guide
5. D. Snowden, "Cynefin: a sense of time and space, the social ecology of knowledge management", in Despres, C. & Chauvel, D. (Eds), Knowledge Horizons: The Present and the Promise of Knowledge Management, Butterworth-Heinemann, Oxford, 2000.

6. International Council On Systems Engineering (INCOSE), Systems Engineering Handbook Version 3.1, August 2007.
7. J. K. DeRosa, G. Rebovich, and R. S. Swarz, “An Enterprise Systems Engineering Model,” Proceedings of the INCOSE International Symposium, vol. 16, No. 1, pp. 1423-1434, 2006.
8. International Council On Systems Engineering (INCOSE), “INCOSE Systems Engineering Vision 2020,” INCOSE-TP-2004-004-02, September 2007.
9. Department of Defense Chief Information Officer (DoDCIO), “DoD Architecture Framework Version 2.02.” Available: http://dodcio.defense.gov/TodayinCIO/DoDArchitectureFramework.aspx, 2010.
10. G. L. Klein, J. L. Drury, and S. L. Condon, “Understanding Asynchronous Distributed Collaboration in an Enterprise Systems Engineering Context,” ICSEng 2014 International Conference, June 2014.
11. M. A. Harris and H. R. Weistroffer, H.R., “A New Look at the Relationship between User Involvement in Systems Development and System Success,” Communications of the Association for Information Systems, Vol. 24, No. 42, pp. 739-756, 2009.
12. A. Pyster, D. H. Olwell, N. Hutchison, N., S. Enck, J. F. Anthony Jr, & D. Henry, Guide to the Systems Engineering Body of Knowledge (SEBoK). Available: http://www.sebokwiki.org/wiki/Enterprise_Systems_Engineering, 2012.
13. Department of Defense (DoD), “System of Systems Engineering,” in Defense Acquisition Guidebook, Washington, DC, October 14, 2004.
14. L. G. Militello, C. O. Dominguez, G. Lintern, and G. A. Klein, “The role of cognitive systems engineering in the systems engineering design process,” Systems Engineering, Vol. 13, No. 3, pp. 1-13, 2010.
15. M. J. Muller and A. Druin, “Participatory Design: The third space in HCI,” in The Human-Computer Interaction Handbook, 3rd ed., J. Jacko, Ed., Taylor & Francis, New York, 2012.
16. Government Accountability Office, BPR Glossary of Terms. [Online]. Available: http://www.gao.gov/ special.pubs/bprag/bprgloss.htm, undated.
17. E. C. Honour, “Understanding the value of systems engineering,” In Proc. of the INCOSE International Symposium, pp. 1-16, 2004.
18. K. J. W. Craik, The nature of explanation. Oxford: University Press, Macmillan, 1943.
19. M. S. Pfaff, J. L. Drury, and G. L. Klein, “Crowdsourcing Mental Models using DESIM (Descriptive to Executable Simulation Modeling),” Proceedings of the 12th Naturalistic Decision Making Conference, 2015.
20. T. L. Saaty, “How to make a decision: The analytic hierarchy process,” European Journal of Operational Research, Vol. 48, No. 1, pp. 9-26, 1990.

ABOUT THE AUTHORS

Dr. Jill Drury holds a BA in Physics from Macalester College, an MS in Business Administration from Boston University Overseas Program, an MS in Computer Science from Boston University, and a Doctorate of Science (Sc.D) in Computer Science from the University of Massachusetts Lowell. Drury has been at The MITRE Corporation since 1980 and has taught as an Adjunct Assistant Professor at the University of Massachusetts Lowell since 2002. Currently, Drury is a department head, systems engineer, and researcher of technologies that support human collaboration and decision making. She has published 100+ journal articles, conference papers, book chapters, and magazine articles.

Gary L. Klein is a Senior Principal Scientist in cognitive science and artificial intelligence in MITRE's Information Technology Center. Dr. Klein's work has focused on facilitating how people acquire and use information. He leads a number of projects on using decision spaces to improve decision makers' "option awareness" under deep uncertainty. This work led to a patent application for a process of using crowd sourcing to translate descriptive causal models into simulation models. In addition, Dr. Klein has numerous publications on decision support and a book on sociocultural sense making. Dr. Klein received his BA in Psychology from the University of California, Los Angeles in 1974, and his PhD in cognitive social psychology from Texas Tech University in 1982.

Dr. Mark S. Pfaff is a lead human-centered engineer in the Collaboration and Social Computing Department at the MITRE Corporation. He received his Ph.D. in Information Sciences and Technology from The Pennsylvania State University in 2008. Dr. Pfaff's research background is in mission-critical decision making in stressful and technologically complex environments, such as crisis management, emergency medicine, and command-and-control. His expertise is in human-computer interaction, computer-supported cooperative work, decision making under stress, and interactive design.

Craig Bonaceto is a Lead Information Systems Engineer in MITRE's Software Engineering Technical Center. Craig specializes in modeling and understanding complex cognitive work and user requirements, and using this understanding to design, develop, and improve capabilities to simplify complexity and enable users to perform work safely, productively, and efficiently. He has a multidisciplinary background in both cognitive engineering and psychology, as well as in computer science and software engineering. Craig holds a B. S. degree in Computer Science and Psychology from Rensselaer Polytechnic Institute.