Research Issues Raised by the Guide to the Systems Engineering Body of Knowledge

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Abstract

As the world has evolved over the past half a century, so too has the discipline of Systems Engineering (SE). From one humble beginning at the Bell Telephone Laboratories as the discipline responsible for technical planning and control (Kelly, 1950), SE has evolved into an interdisciplinary approach responsible for the conception and realization of successful complex systems (INCOSE, 2004) across the system life cycle. However, the current standards and bodies of knowledge in SE have not consistently kept up with the evolving nature of the discipline.

A current effort to develop a guide to the Systems Engineering Body of Knowledge (SEBoK), part of the three-year Body of Knowledge and Curriculum to Advance SE (BKCASE™) project kicked off in the fall of 2009, offers an opportunity to identify and address gaps in SE knowledge and research. This paper addresses findings, research, and decision points reached by the four-dozen member author team during the first year of developing the guide and leverages community feedback to identify gaps in knowledge areas or needed research areas based on a limited review of version 0.25 of the guide, distributed in the fall of 2010.

Introduction

The Body of Knowledge and Curriculum to Advance Systems Engineering (BKCASE™) project is creating a guide to the Systems Engineering Body of Knowledge (SEBoK). The primary purpose of this work is to baseline the body of knowledge to help improve the practice of SE. The process of describing and reviewing this guide has identified a number of potential gaps in the knowledge and has raised other issues of interest to SE researchers.

In this paper we provide an overview of the content of SEBoK version 0.25 and introduce a discussion on the maturity of SE. Next, we do an initial analysis of these research related issues and use them to make suggestions about how BKCASE should address research issues in the future. We will also make some general observations about SE research and consider how a mature SEBoK can be used to facilitate new and evolving research areas going forward.

Overview of SEBOK

Background

The BKCASE team has successfully grown from a small core team of five members to a team of over 50 members, including both authors (mostly volunteer) and supporting team members, from around the world and from a variety of domains. The BKCASE project is supported by several professional societies including the International Council on Systems Engineering (INCOSE) and the Institute of Electrical and Electronics Engineers (IEEE) and by funding and sponsorship primarily from the U.S. Department of Defense. Two products, the SEBoK and the Graduate Reference Curriculum for Systems Engineers (GRCSE™), are being developed to inform SE education and practice. Initial drafts of these products were released in late 2010 for limited review; second drafts are planned for release in late 2011 for open review; and the final versions of the products will be released to the public in late 2012. More information about the project can be found from the project's website, www.bkcase.org, and from various BKCASE publications (Squires et al. 2009, Squires et al. 2010, Pyster et al. 2010).

The vision of the BKCASE project is defined below:

> "**Systems Engineering competency models, certification programs, textbooks, graduate programs, and related workforce development initiatives around the world align with BKCASE.**"

Content

SEBoK version 0.25 organizes and describes SE Knowledge in four categories:

1. **Introductory Content** system and lifecycle foundations knowledge areas:
   - *Systems Concepts*: what is a system, types of systems and their role, includes a discussion of system-of-interest, system perspectives, and complexity.
   - *Systems Thinking*: describes hard and soft systems thinking, system of systems, system models and languages.
   - *Generic Life Cycle Approaches*: overview of generic life cycle approach. Three types of life cycle are addressed by the SEBoK: Products, Services, and Enterprises.
2. **Organization and Management** knowledge areas:
   - *Enabling Systems Engineering in the Organization:* the incorporation of SE activities within an organization including effective governance, staffing, and resource allocation approaches.
   - *Systems Engineering Management:* focuses on the administration and oversight of SE activities and provides insights on managing the technical aspects of SE.
3. **System Engineering Life Cycle** knowledge areas: based on SE standards (INCOSE, 2010)
   - *System Definition*: early stages of the life cycle, including needs and requirements analysis and architecture development. Stages covered: stakeholder requirements and mission analysis, system requirements, architectural design, and system analysis.
   - *System Realization*: focuses on the construction of the system, including testing to confirm appropriate functionality and use. Stages covered are: implementation, system integration, system verification, and system validation.
   - *System Deployment* and Use: addresses the installation and use of systems in their operating environment, includes insights on how a system can be sustained over time. Stages covered are: operations, maintenance, and logistics.

- *System Life Management*: focuses on the continuation of the system life, including changing and adding functionality to a system in operation, and retiring a system. Stages covered are: service life extension, capability updates, upgrades and modernization, and system disposal and retirement.
- *Systems Engineering Agreement*: provides insight on the contractual aspects of SE.

4. **Specialty Topics**, **Competency**, and **Case Studies**:
   - *Cross-Cutting:* provides a foundation for non-functional characteristics (the "-ilities") of SE discussed throughout the SEBoK including: integration of specialty engineering, affordability/design to cost, human system integration, safety, security, spectrum management, electro-magnetic interference, radiation hardness, reliability and maintainability, manufacturing and production, quality, logistics/supportability, occupational health/work environment, disposal and resilience.
   - *Systems Engineering Competency:* addresses SE competencies at the individual, team, and organization level.
   - *SE Applications/Case Studies:* defines the method and criteria for accepting case studies for a companion guide that will provide domain-dependent examples for the SEBoK.

Review

The review process for SEBoK version 0.25 was primarily focused on validating the scope and structure of and the approach to the SEBoK. Almost 250 volunteer reviewers from across the SE community where invited to review SEBoK 0.25, or these 115 provided comment through a series of questions which focused on the SEBoK purpose, chapter structure and key sources.

Maturity of Systems Engineering

Systems engineering as a discipline is relatively young. Bell Telephone Laboratories is credited with the first use of the term in the early 1940s, although the ideas were already being used. Military applications in World War II and the Cold War accelerated the development of the field, and the first formal military standards for SE were written in 1969 in the United States, followed by civilian standards in 1994 from IEEE and the Electronic Industries Alliance (EIA).

Unlike other engineering disciplines, such as electrical engineering that traces its engineering practices back to the underlying physics of electricity and electromagnetism with their associated mathematical laws, SE has a less well-defined foundation in the physical sciences. Much of the research in SE has been focused on the problems that emerge in the creation of large scale, complex systems.

Thomas S. Kuhn in *The Structure of Scientific Revolutions* describes the state of a science before a commonly agreed framework has been reached:

> In the absence of a [candidate] paradigm, all of the facts that could possibly pertain to the development of a given science are likely to seem equally relevant. As a result, early fact-gathering is a far more nearly random activity [and one restricted to the wealth of data that lie ready to hand] than the one that subsequent scientific development makes familiar… No wonder, then, that in the early stages of the development of any science different men confronting the same range of phenomena, but not usually all the same particular phenomena, describe and interpret them in different ways. (Kuhn, 1970, p. 15)

It is not clear that there is an agreed paradigm (in Kuhn's sense of the word) for SE, and as a result the maturity of the discipline must be assessed as young.

That is not to say that the existing body of knowledge is useless. It is in fact and in practice a useful catalog of techniques that have been applied to promote the successful fielding of systems. If we look at the evolution of these practices we can see new features being added over time. Initial efforts focused on the management processes for developing and fielding large, complex systems; especially the documentation that facilitated communication and coordination across large diverse teams and between suppliers and customers (as defined in the NASA SE Handbook) (NASA 2007). This was followed by the development of more formal life cycle stages to help focus the effort of different engineering and management discipline; and a shift to clear system requirements to allow trade-off and selection between emerging solution technologies (such as those defined in IEEE 1220 or ANSI/EIA 632). Next comes an expansion of SE thinking to encompass a through life cycle approach; with early lifecycle activities focusing on understanding of stakeholder needs and operational effectiveness; and later lifecycle activities bringing system deployment, sustainment and retirement as part of the problem/solution scope (IEC/ISO 15288). More recently we have seen the application of SE lifecycle thinking to System of Systems (SoS) and enterprise problems.

All of these evolutions of SE can be viewed as pragmatic responses to "the next big problem". Can SE continue to be "problem driven" or do we need a more theory driven approach for it to realize its full potential?

The very act of putting together a more formalized SE BoK can be seen as one measure of the growing maturity of SE. The BKCASE project attempts to provide a guide to the SEBoK; not merely cataloguing the practices of SE, but searching for a commonly agreed theory that explains the success and failure of the practices and how these fit together. From a research perspective, we would expect such a SEBoK to also help us identify the potential gaps in SE knowledge; to more clearly formulate the directions for SE research; and to provide a resource for the conduct, management and dissemination of research knowledge. In this paper we will consider the extent to which SEBoK version 0.25 has addressed these goals, and consider what needs to be done to move towards them to contribute to the maturity of SE.

Research Questions

SEBoK and Research

SEBoK version 0.25 defines five specific tasks for which it is intended: *inform practice, inform research, define curriculum, certify professionals, and decide competencies (BKCASE 2009)*. From this a set of primary and secondary users are identified, with a brief outline of what they will get out of the BoK. These users include:

- **Managers, Engineers, Technologist, Researchers or Scientists**: who want to understand SE vocabulary and scope, and understand how SE relates to other disciplines.
- **Systems Engineering Researchers**: who want to identify potential gaps in SE knowledge and to find sources on specific topics.

Thus, while the development of the SEBoK has considered the research community, it would be fair to say that version 0.25 is primarily focused on the SE practice and workforce development outcomes. As a result the majority of the 3251 comments from the reviewers deal with these aspects of the SEBoK.

Research Questions from the SEBoK 0.25 Review

We have looked for comments that identify potential gaps in the BoK itself. In particular 60 comments addressed incomplete or missing knowledge. In addition, the SEBoK authors were asked to consider any knowledge gaps which they encountered in helping to create SEBoK version 0.25. From these comments and reviews we have synthesized a number of questions on SE research.

1. How can SE get better at dealing with complexity; not only the technical complexity caused by multiple system components, but also dynamic and behavioral complexity caused by multiple goals and stakeholders? Can tools like systems dynamics help?
2. How do we do “Brownfield SE” designing around legacy and designing using largely re-used or off the shelf components?
3. How do we make SE more rapid, agile, or tailorable?
4. Can we quantify the effect of SE activities on SE development; and can we apply the ideas of lean processes to SE?
5. How do we do cross discipline tradeoffs – optimizing design across multiple disciplines?
6. How do the ideas of cybernetics and organizational cybernetics apply to SE?
7. How can we help the community learn from previous practice; where do case studies or system patterns fit into this?
8. How can we provide better integration across engineering models, in particular between SE process areas and between levels of the system hierarchy; how does this relate to Model Based Systems Engineering (MBSE)?
9. What is the relationship between enterprise, service and product engineering[1]? Can we define a unified model of “system” that works across all combinations of technical, social and natural systems and that can be used to integrate across the domains?
10. How can we integrate the knowledge and approaches from other system focused activities such as human systems, safety, reliability, etc. with SE?
11. What is the relationship between SE and architecting, SoS engineering, enterprise architecture or capability engineering; and how do these things relate to each other?
12. What is the relationship between SE and other design and management disciplines?
13. What is the relationship between software engineering and SE; is this relationship different to the relationship to other disciplines?
14. How do we integrate knowledge on soft skills and behaviors and their specific application in an SE context, into SE competency frameworks?
15. Most SE competency frameworks are created by examining what experienced systems engineers do. Is there a more rigorous to the identification of SE competencies?
16. Are current research methodologies appropriate to SE and the community’s research needs?

For this short paper we have not shown the traceability between the research questions and SEBoK 0.25 review or author comments. Our intention is to try and inform the research agenda and to consider ways in which future evolutions of the SEBoK can be of more use to the research community.

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[1] SEBoK 0.25 uses these three engineering contexts to organize some of the systems engineering knowledge

Analysis

Research Topics

Given the focus of the early SEBoK on SE practice and education, the research questions produced above are coincidental to the project outcomes, rather than one of its primary foci. Thus, we do not claim that they are in any way a definitive direction for SE research. However, it is informative to look at how gaps in SE knowledge - encountered while trying to define the scope of the SEBoK and define a guide to it useful for all of the purposes above - relate to other work on research strategies.

Figure 1 summarizes the research questions presented above. The questions are presented against two dimensions. The first, between theoretical research to provide the foundations and principles for improving SE and applied research to provide knowledge and products which can be used directly to realize those improvements. The second, between "hard" thinking which looks at system information, artifacts and approaches and "soft" thinking which considers relationships, and behaviors which influence the success of their application to real problems. Two research outputs, shared information models and frameworks and practical examples and case studies, have been placed in the center. These emerge from many of the research questions as ways of packaging and sharing the results of research.

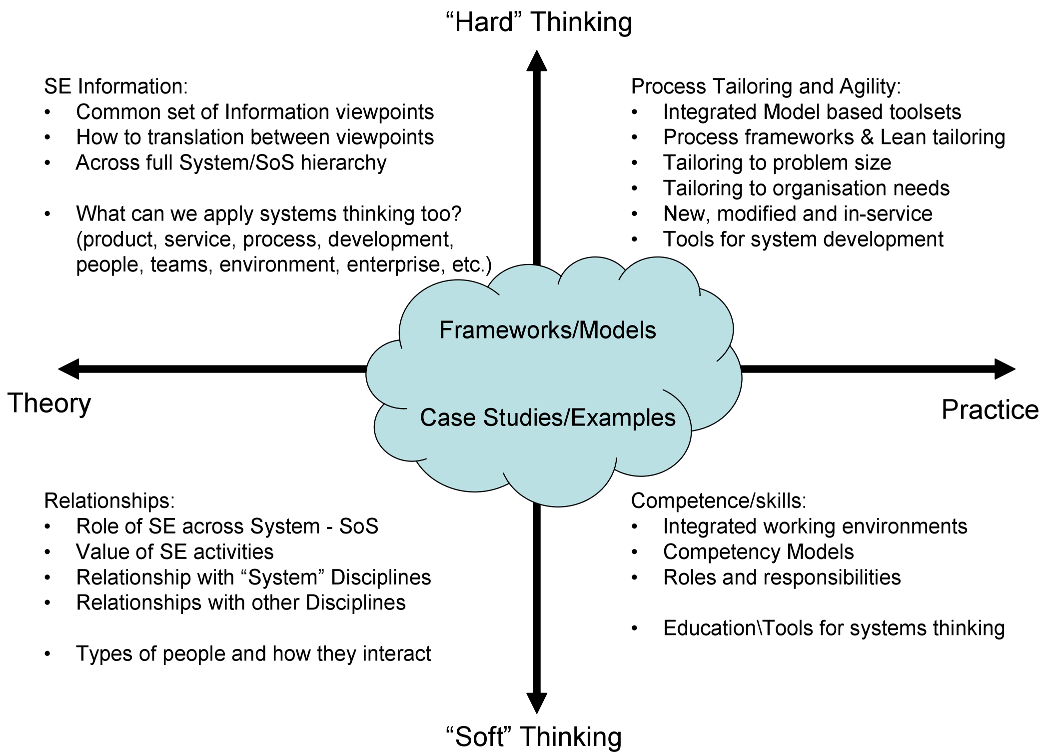

Figure 1, Summary of Research Areas raised by SEBoK version 0.25

How does this scope for SE research compare to published SE research strategies? The INCOSE Vision 2020 document (www.INCOSE.org) identifies a number of future challenges for SE. In particular, MBSE environments, agile process frameworks and SE competencies. Other authors such as (Kawalsky, 2009) and (Sage, 2009) have identified similar sets of research challenges. These published research strategies focus on the practical view of SE: either in improving SE process and models, or in technical competencies. As discussed above, this search to get better at how we do it is typical of a discipline with relatively low maturity. There are those searching for SE unifying models or paradigms, but this is not seen as the main thrust of SE research nor do those looking for improved practices relate them back to a common theoretical base. Others have looked for SE grand challenges. These are real world problems for which society does not have any obvious solutions, e.g. secure energy, provision of clean water, eliminating poverty, etc. This search for the challenges which will energize our research agenda can be seen in other similar efforts such as the America National Academy of Engineering Grand Challenges (http://www.engineeringchallenges.org/).

Research Methodology

The other research issue raised by the SEBoK review is, "do we have adequate research methodologies to tackle SE problems?" Both (Ferris, 2009) and (Brown 2009) consider the nature of SE as a discipline which has much in common with traditional engineering (produce the right solution) and more management intervention style disciplines (identifying the right problem to solve). These authors consider much of the current SE research to be based on traditional engineering research paradigms and look at other ways in which SE research might be organized.

One of the SEBoK reviewers provided feedback from a recent NATO workshop on SE research, run by the Technical Cooperation Program (http://www.dtic.mil/ttcp/)[2] which concluded that ***"The challenge of today's and tomorrow's environment require an investment in SE research because: (a) current SE practice cannot address them, and (b) other disciplines will not solve the highly integrated, socio-technical problem-space"***. Other issues identified at this workshop included: "SE research should be based on sound research principles, and must plan for exploitation of the work"; "All good research ideas in SE are initiated outside Academia"; "SE research should be done in context"; "Industry is only interested in parts of the System of Systems problem space"; "Many researchers are not system thinkers"; "SE education is an important part of SE research". Whether or not one agrees with all of these statements, it is clear that at least a portion of the SE community believes that there are issues with the way we do SE research and that understanding this is part of the SEBoK challenge.

Conclusions

Systems Engineering Knowledge

How should the SEBoK deal with the evolution of knowledge from research into practice? In forming the research questions, we identified three generic kinds of knowledge gaps:

- **Awareness Gaps**: problems in SE for which mature solutions exist (often outside the discipline) which the SE community is not widely aware of.
- **Maturity Gaps**: solutions to known problems which are under development but are not mature enough to be in common usage.
- **Hard problems**: genuine gaps in the SE knowledge for which no current solutions exist.

The SEBoK needs to deal with all of this information. Part of its role is to widen the awareness of practicing systems engineers to the full scope of available system knowledge. This supports the need for research and education to be closely linked. Many of the benefits we seek in improving the practice of SE could be delivered by making all of those involved in system pro-

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[2] These minutes are currently unpublished but can be obtained from the TTCP website o request.

jects fully aware of the underlying principles of a systems approach and the full range of current best practice in SE. It may also be appropriate for SEBoK 0.5 to include a section on "Emerging SE Knowledge". This would allow new ideas on SE practice to be shared and discussed early, before they are fully integrated into the main stream of SE.

One of the outcomes of the BKCASE project is to create a guide to the SEBoK. This will need to include not only a catalogue of the knowledge itself, but also some idea of the underlying paradigm of the systems approach. As the project moves onto version 0.5 of the SEBoK, it is increasingly focusing on this underlying theory of SE and how it informs the organization of the knowledge. Where there are divergent views on SE knowledge it is appropriate for the SEBoK to describe these differences. However, the creation of the SEBoK should also be a catalyst to the SE community to address some of these areas and ensure that the divergence is real and not merely a product of the current immaturity of the discipline of SE. This raises a key question for the BKCASE team and the SE community: ***"does the system paradigm already exist, or do we need more research in this area to complete the SEBoK?"***

Systems Engineering Research

As well as considering the knowledge gaps that drive SE research, the SEBoK reviewers identified knowledge about the research process itself. As a result of these comments it is likely that a new section will be added to SEBoK 0.5 to give a guide to knowledge on the conduct of SE research itself. The issues raised by this paper which the SEBoK must consider include:

- System problems must be tackled in context. It is important that the problem is defined in its wider system context and that relevant stakeholders are involved. This will generally mean that the research will be multi disciplinary, which can be difficult in traditional academic environments. Even if we can overcome the practical issues of doing this, how do we reconcile the engineering, management and social science research approaches?
- Many of the ideas for SE research either come from outside academia or are closely linked to an industrial/government sponsor. This can be a positive as it keeps the research focused and exploitable. However, it can lead to the research sponsors needs being narrower than the full scope of the problem context. A research sponsor will generally not have authority over the full scope of SoS context. In this case how do we gain access to relevant stakeholders and information; and realise all of the potential benefits of our research ideas?
- It would be beneficial to many research projects if the principles of SE were used in the design of the research itself. Many of those involved in SE research do not have a formal research background and may not understand the rigors of the research method. Equally, many of those involved in SE research are not experienced system thinkers and may not naturally look to take a holistic approach. If possible, SE research should include an element of education and knowledge sharing about systems thinking, for both those doing the research and those receiving the solutions.

Systems Engineering Body of Knowledge

The SEBoK has evolved from a more narrow view of SE life cycle processes applied to product development to a broader view of systems (products, services, enterprises), system context (system of interest, system of systems, etc.) and SE related applications (domain dependent, workforce development, etc.). Given the young nature of the discipline, the SEBoK needs to continue to evolve to incorporate results from and to support the direction of new and evolving SE research. The continuing update of the SEBoK, and associated maturing of the SE it describes will continue long past the 2012 release of SEBOK version 1.0, and therefore will fall to the responsibility of the future SEBoK stewards and the members of the SE community to carry forward.

Looking specifically at the research community, additions to the SEBoK of sections on Emerging SE Knowledge and SE Research give researches a clear place to interact with the SEBoK. If we look at the defined uses of the SEBoK by researchers, the SEBoK is intended as a vehicle to identify knowledge gaps and thus set the agenda for future research. The issues raised in this paper have shown how this might be achieved. In particular, two relationships between the SEBoK and research have emerged. Firstly, the creation of an authoritative guide to SE knowledge encourages the investigation of underlying SE theory. Secondly, the SEBoK provides a resource to identify gaps in SE practice.

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Biography

Rick Adcock is a Senior Lecture in Systems Engineering at Cranfield University, and Head of the Centre for Systems Engineering at the Defence Academy of the UK. He has 20 years experience as a practicing Systems Engineer in UK Defence Industry before moving to academia. He is an active member of INCOSE and part of the BKCASE author team.

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