SEBoK GUIDE TO THE SYSTEMS ENGINEERING BODY OF KNOWLEDGE

Guide to the Systems Engineering Body of Knowledge (SEBoK), version 2.2

Part 8

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Guide to the Systems Engineering Body of Knowledge, Part 8

version 2.2

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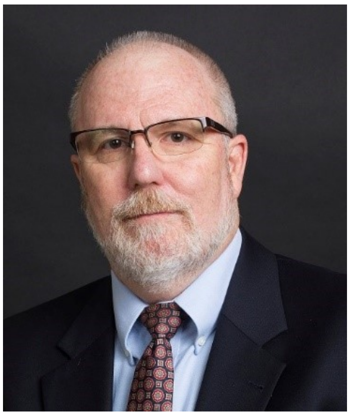


Hi there. Welcome to the May 2020 instantiation of the SEBoK. We are now at version 2.2. If you remember, we celebrated our 7th anniversary last update. Well, this update we are celebrating too. In the month of April 2020, we had our 2 millionth visit since we started. And, we have over 4 million page views since we first rolled out the SEBoK! Month over month usage of the SEBoK continues to grow. That could mean that the editorial staff and authors continue to add value to you our stakeholders and customers or it could mean that Systems Engineering is growing around the world, and we are the "go to" location for that information. I choose to believe it is a bit of both. Thank you for continuing to visit the SEBoK, contribute to its content, and to tell others about this resource.

In case you are wondering, here are the top 10 pages visited in April 2020, in order:

1. Stakeholder Needs and Requirements
2. System Requirements
3. Reliability, Availability, Maintainability
4. Types of Systems
5. Types of Models
6. System Life Cycle Process Models: Vee
7. Systems Architecture
8. Systems Engineering Overview
9. Life Cycle Models
10. Logical Architecture Model Development

So, what is new for Version 2.2?

First update, and this is big - notice the IEEE logo on the top of the page has changed from the IEEE Computer Society to the **IEEE Systems Council**! We are excited to have them onboard and are already coordinating new contributions and participation of IEEE members. Welcome! I'd also like to thank the IEEE Computer Society for all of their guidance and support of the SEBoK since 2013.

Second update – notice that we have updated the organization of Part 7: Implementation Examples. Examples are now aligned with engineering domains. We hope this makes it easier for you to find relevant examples of Systems Engineering in the real world.

Third update – in addition to reorganizing Part 7, we have added an entirely new Part to the SEBoK: Part 8, Emerging Knowledge. Systems Engineering is evolving faster and faster as the world is changing. In Part 8, the SEBoK will endeavor to inform you of trends that are taking root in some of our systems engineering communities. We moved the SE Transformation items from Part 1 to this new part. Additionally, we have added a section for Emerging Research. This is a place to provide pointers to doctoral level systems engineering that has been defended in the recent past.

New articles to check out:

- Systems Engineering Principles
- Apollo 1 Disaster

I would like to point out some changes in the **editorial organization** of the SEBoK. Tom McDermott has agreed to be the Lead Editor for Part 4: Applications of Systems Engineering. Nicole Hutchison, our Managing Editor, will become the Lead Editor for Part 5: Enabling Systems Engineering. Art Pyster is now the Lead Editor for Part 6: Related Disciplines. And finally, Dan DeLaurentis will become the Lead Editor for the new Part 8: Emerging Knowledge. Thank you all for your ongoing commitment to the SEBoK.

OPPORTUNITY: Finally, we continue to look for ways to add some multimedia to the SEBoK. In this update, we have identified some links to relevant YouTube talks that we believe might be of value to you. However, most of that material was intended for something else. I am looking for one or more amateur videographers and hobbyists to produce a number of 3-5 minute videos on systems engineering specifically for the SEBoK. NO AGENDAS. NO PROMOTIONS. NO ADVERTISEMENTS. Just straight talk on a specific topic of systems engineering. Ideally, these will have good quality, good volume, and great content. I am hoping they do not look like they were shot at a conference or in a classroom. If you are up to this challenge, please contact me at: rob@calimar.com [1]. I look forward to your ideas.

THANK YOU for reading this rather lengthy missive. If you would like to contribute an article to the SEBoK, or have an idea for one, please reach out to me – we always need new articles, video, etc. And, I am still in search of a Lead Editor for Part 3: Systems Engineering and Management. Thanks to all for your ongoing support and readership.

References

[1] mailto:rob@calimar.com

BKCASE Governance and Editorial Board

BKCASE Governing Board

The three SEBoK steward organizations – the International Council on Systems Engineering (INCOSE), the Institute of Electrical and Electronics Engineers Systems Council (IEEE-SYSC), and the Systems Engineering Research Center (SERC) provide the funding and resources needed to sustain and evolve the SEBoK and make it available as a free and open resource to all. The stewards appoint the BKCASE Governing Board to be their primary agents to oversee and guide the SEBoK and its companion BKCASE product, GRCSE.

The BKCASE Governing Board includes:

- **The International Council on Systems Engineering (INCOSE)**
  - Art Pyster (Governing Board Chair), Paul Frenz
- **Systems Engineering Research Center (SERC)**
  - Jon Wade, Cihan Dagli
- **IEEE Systems Council (IEEE-SYSC)**
  - Stephanie White, Bob Rassa

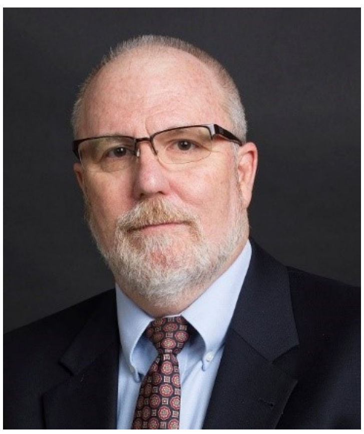
Past INCOSE governors Bill Miller, Kevin Forsberg, David Newbern, David Walden, Courtney Wright, Dave Olwell, Ken Nidiffer, Richard Fairley, Massood Towhidnejad, John Keppler. The governors would also like to acknowledge Andy Chen and Rich Hilliard, IEEE Computer Society, who were instrumental in helping the Governors to work within the IEEE CS structure and who supported the SEBoK transition to the IEEE Systems Council.

The stewards appoint the SEBoK Editor in Chief to manage the SEBoK and oversee the Editorial Board.

SEBoK Editorial Board

The SEBoK Editorial Board is chaired by the Editor in Chief, who provide the strategic vision for the SEBoK. The EIC is supported by a group of Editors, each of whom are responsible for a specific aspect of the SEBoK. The Editorial Board is supported by the Managing Editor, who handles all day-to-day operations. The EIC, Managing Editor, and Editorial Board are supported by a student, Madeline Haas, whose hard work and dedication are greatly appreciated.

SEBoK Editor in Chief



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Responsible for the appointment of SEBoK Editors and for the strategic direction and overall quality and coherence of the SEBoK.

SEBoK Managing Editor

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Systems Engineering Research Center

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Each Editor has his/her area(s) of responsibility, or shared responsibility, highlighted in the table below.

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SEBoK Part 6: Related Disciplines

Student Support

Madeline Haas, a student at George Mason University, is currently supporting the SEBoK and we gratefully acknowledge her exemplary efforts. Ms. Haas has also taken responsibility for managing the Emerging Research knowledge area of the SEBoK. The EIC and Managing Editor are very proud of the work Madeline has done and look forward to continuing to work with her.

Interested in Editing?

The Editor in Chief is looking for additional editors to support the evolution of the SEBoK. Editors are responsible for maintaining and updating one to two knowledge areas, including recruiting and working with authors, ensuring the incorporation of community feedback, and maintaining the quality of SEBoK content. We are specifically interested in support for the following knowledge areas:

- System Deployment and Use
- Product and Service Life Management
- Enabling Businesses and Enterprises
- Systems Engineering and Software Engineering
- Procurement and Acquisition
- Systems Engineering and Specialty Engineering

In addition, the Editor in Chief is looking for a new Lead Editor for Part 3: Systems Engineering and Management.

If you are interested in being considered for participation on the Editorial Board, please contact the SEBoK Staff directly at sebok@incose.org [24].

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References

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Acknowledgements and Release History

This article describes the contributors to the current version of the SEBoK. For information on contributors to past versions of the SEBoK, please follow the links under "SEBoK Release History" below. To learn more about the updates to the SEBoK for v. 2.2, please see the Letter from the Editor.

The BKCASE Project began in the fall of 2009. Its aim was to add to the professional practice of systems engineering by creating two closely related products:

- *Guide to the Systems Engineering Body of Knowledge (SEBoK)*
- *Graduate Reference Curriculum for Systems Engineering (GRCSE)*

BKCASE History, Motivation, and Value

The **Guide to the Systems Engineering Body of Knowledge (SEBoK)** is a living authoritative guide that discusses knowledge relevant to Systems Engineering. It defines how that knowledge should be structured to facilitate understanding, and what reference sources are the most important to the discipline. The curriculum guidance in the **Graduate Reference Curriculum for Systems Engineering (GRCSE)** (Pyster and Olwell et al. 2015) makes reference to sections of the SEBoK to define its core knowledge; it also suggests broader program outcomes and objectives which reflect aspects of the professional practice of systems engineering as discussed across the SEBoK.

Between 2009 and 2012, BKCASE was led by Stevens Institute of Technology and the Naval Postgraduate School in coordination with several professional societies and sponsored by the U.S. Department of Defense (DoD), which provided generous funding. More than 75 authors and many other reviewers and supporters from dozens of companies, universities, and professional societies across 10 countries contributed many thousands of hours writing the SEBoK articles; their organizations provided significant other contributions in-kind.

The SEBoK came into being through recognition that the systems engineering discipline could benefit greatly by having a living authoritative guide closely related to those groups developing guidance on advancing the practice, education, research, work force development, professional certification, standards, etc.

At the beginning of 2013, BKCASE transitioned to a new governance model with shared stewardship between the Systems Engineering Research Center (SERC) [1], the International Council on Systems Engineering (INCOSE) [2], and the Institute of Electrical and Electronics Engineers Computer Society (IEEE-CS) [3]. This governance structure was formalized in a memorandum of understanding between the three stewards that was finalized in spring of 2013 and subsequently updated. In January 2020, the IEEE Systems Council [4] replaced the IEEE-CS in representing IEEE as a steward. The stewards have reconfirmed their commitment to making the SEBoK available at no cost to all users, a key principle of BKCASE.

As of April 2020, SEBoK articles have had over 4.2M pageviews from 1.7M unique visitors. We hope the SEBoK will regularly be used by thousands of systems engineers and others around the world as they undertake technical activities such as eliciting requirements, creating systems architectures, or analyzing system test results; and professional development activities such as developing career paths for systems engineers, deciding new curricula for systems engineering university programs, etc.

Governance

The SEBoK is shaped by the SEBoK Editorial Board and is overseen by the BKCASE Governing Board. A complete list of members for each of these bodies can be found on the BKCASE Governance and Editorial Board page.

Content and Feature Updates for 2.2

This version of the SEBoK was released 15 May 2020. This is a significant release of the SEBoK which includes new articles, new functionality and minor updates throughout. The SEBoK PDF was also updated (see Download SEBoK PDF).

For more information about this release please refer to Development of SEBoK v. 2.2.

SEBoK Release History

There have been 22 releases of the SEBoK to date, collected into 14 main releases.

Main Releases

- Version 2.2 - Current version. This is a significant release, including the first new Part to be added since v. 1.0 - Emerging Knowledge - which is a place to highlight new topics in systems engineering that are important but may not yet have a large body of literature. Recent dissertations around emerging topics are also included. A new case study on Apollo 1 was added to Part 7, which has also been reorganized around topics. Additional minor updates have occurred throughout.
- Version 2.1 - This was a significant release with new articles, new functionality, and minor updates throughout.
- Version 2.0 - This was a major release of the SEBoK which included incorporation of multi-media and a number of changes to the functions of the SEBoK.
- Version 1.9.1 - This was a micro release of the SEBoK which included updates to the editorial board, and a number of updates to the wiki software.
- Version 1.9 - A minor update which included updates to the System Resilience article in Part 6: Related Disciplines, as well as a major restructuring of Part 7: Systems Engineering Implementation Examples. A new example has been added around the use of model based systems engineering for the thirty-meter telescope.
- Version 1.8 - A minor update, including an update of the Systems of Systems (SoS) knowledge area in Part 4: Applications of Systems Engineering where a number of articles were updated on the basis of developments in

the area as well as on comments from the SoS and SE community. Part 6: Related Disciplines included updates to the Manufacturability and Producibility and Reliability, Availability, and Maintainability articles.

- Version 1.7 - A minor update, including a new Healthcare SE Knowledge Area (KA), expansion of the MBSE area with two new articles, Technical Leadership and Reliability, Availability, and Maintainability and a new case study on the Northwest Hydro System.
- Version 1.6 - A minor update, including a reorganization of Part 1 SEBoK Introduction, a new article on the Transition towards Model Based Systems Engineering and a new article giving an overview of Healthcare Systems Engineering, a restructure of the Systems Engineering and Specialty Engineering KA.
- Version 1.5 - A minor update, including a restructure and extension of the Software Engineering Knowledge Area, two new case studies, and a number of corrections of typographical errors and updates of outdated references throughout the SEBoK.
- Version 1.4 - A minor update, including changes related to ISO/IEC/IEEE 15288:2015 standard, three new case studies and updates to a number of articles.
- Version 1.3 - A minor update, including three new case studies, a new use case, updates to several existing articles, and updates to references.
- Version 1.2 - A minor update, including two new articles and revision of several existing articles.
- Version 1.1 - A minor update that made modest content improvements.
- Version 1.0 - The first version intended for broad use.

Click on the links above to read more information about each release.

Wiki Team

In January 2011, the authors agreed to move from a document-based SEBoK to a wiki-based SEBoK, and beginning with v. 0.5, the SEBoK has been available at www.sebokwiki.org [5] Making the transition to a wiki provided three benefits:

1. easy worldwide access to the SEBoK;
2. more methods for search and navigation; and
3. a forum for community feedback alongside content that remains stable between versions.

The Managing Editor is responsible for maintenance of the wiki infrastructure as well as technical review of all materials prior to publication. Contact the managing editor at emtnicole@gmail.com [3]

The wiki is currently supported by Ike Hecht from WikiWorks.

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References

[1] http://www.sercuarc.org
[2] http://www.incose.org
[3] http://www.computer.org
[4] https://ieeesystemscouncil.org/
[5] http://www.sebokwiki.org

Cite the SEBoK

When **citing the SEBoK in general**, users must cite in the following manner:

> SEBoK Editorial Board. 2020. *The Guide to the Systems Engineering Body of Knowledge (SEBoK)*, v. 2.2, R.J. Cloutier (Editor in Chief). Hoboken, NJ: The Trustees of the Stevens Institute of Technology. Accessed [DATE]. www.sebokwiki.org. BKCASE is managed and maintained by the Stevens Institute of Technology Systems Engineering Research Center, the International Council on Systems Engineering, and the Institute of Electrical and Electronics Engineers Computer Society.

To **cite a specific article** within the SEBoK, please use:

> Author name(s). "Article Title." in SEBoK Editorial Board. 2020. *The Guide to the Systems Engineering Body of Knowledge (SEBoK)*, v. 2.2 R.J. Cloutier (Editor in Chief). Hoboken, NJ: The Trustees of the Stevens Institute of Technology. Accessed [DATE]. www.sebokwiki.org. BKCASE is managed and maintained by the Stevens Institute of Technology Systems Engineering Research Center, the International Council on Systems Engineering, and the Institute of Electrical and Electronics Engineers Computer Society.

Note that each many pages include the by line (author names) for the article. If no byline is listed, please use "SEBoK Authors".

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When **citing the SEBoK in general**, please refer to the format described on the Cite the SEBoK page.

When **using images, figures, or tables from the SEBoK**, please note the following intellectual property (IP) classifications:

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Part 8: Emerging Knowledge

Emerging Knowledge

Lead Author: *Robert Cloutier*

Like other portions of the SEBoK, the notion and content of a Part is evolving. Part 8 will have 2 Knowledge Areas or Sections. They are:

- Emerging Topics
- Emerging Research

Scope and Purpose

While the practice and need for systems engineering began appearing in journals from 1950 onward, the practice currently seems to be gaining momentum in most engineering and even non-engineering circles.

The classically trained systems engineers of the 1970s and even 1980s are faced with a C note shift in thinking brought on by the rapid advance of the software centricity of our systems, cybersecurity, agent-based, object-oriented, and model-based practices. These emerging practices bring their own methods and tools. Hall (1962, p. 5) may have been prescient when he wrote “It is hard to say whether increasing complexity is the cause or the effect of man's effort to cope with his expanding environment. In either case a central feature of the trend has been the development of large and very complex systems which tie together modern society. These systems include abstract or non-physical systems, such as government and the economic system.”

These changes and the rate of change are causing systems engineering to evolve. Some of the practices may not even be recognizable to classically trained systems engineers. This Part of the SEBoK is intended to introduce some of the more significant emerging changes to systems engineering. As topics discussed in this Part evolve and become mainstream, they will be moved into the appropriate Part of the SEBoK

Emerging Topics

The Emerging Topics section will evolve over time as it is meant to inform the reader on the more significant and emerging changes to the practice of systems engineering. Examples of these emerging topics include:

- What is the potential to change systems engineering processes or the ways in which we perform systems engineering?
- How will the development of artificial intelligence impact systems engineering?
  - Will AI change the way we think of systems architecture?
  - How will we perform V&V of an AI system?
- How will the push towards vertically integrated digital engineering influence systems engineering?

Emerging Research

As these emerging topics gain visibility, researchers will begin to investigate them. Corporate R&D may do early work, but academia and government will formalize this research. The emerging research section is a place to gather the references to this disparate work into a single repository to better inform systems engineers working on related topics.

References

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Additional References

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Goode, H. Herbert., Machol, R. Engel. (1957). *System Engineering: An Introduction to the Design of Large-Scale Systems.* New York, NY, USA: McGraw-Hill.

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Emerging Topics

Emerging Topics

Lead Author: *Robert Cloutier*

The emerging topics knowledge area is intended to introduce and inform the reader on significant and rapidly emerging methods, processes and tools within the systems engineering community. It is not intended to be all-inclusive. Instead, those topics that have a high probability of significantly impacting the practice of systems engineering, as determined by the SEBoK editorial board, will be covered. If the reader has recommendations of emerging topics that should be covered, please send an email to SEBoK@incose.org, or leave a comment in the comment feature at the bottom of this page.

Topics in Part 8

- Introduction to SE Transformation
- Transitioning Systems Engineering to a Model-based Discipline
- Model-Based Systems Engineering Adoption Trends 2009-2018
- Digital Engineering
- Set-Based Design

References

Works Cited

None.

Additional References

None.

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Introduction to SE Transformation

While the primary focus of the SEBoK is on the current practice of domain independent systems engineering, it is also concerned with the future evolution of the discipline.

The topics in this Knowledge Area (KA) summarize SE knowledge which is emerging and transitioning to become part of the practice of systems engineering, such as Model-Based Systems Engineering (MBSE). In general, topics will be introduced here and then expanded into other SEBoK KA's over time.

The knowledge covered in this KA reflects the transformation and continued evolution of SE. For a summary of the current and future challenges that contribute to this evolution, see Systems Engineering: Historic and Future Challenges. This notion of SE transformation and the other areas of knowledge which it includes are discussed briefly below.

Topics

Each part of the SEBoK is divided into Knowledge Areas (KAs), which are groupings of information with a related theme. The KAs, in turn, are divided into topics. This KA contains the following topics:

- Transitioning Systems Engineering to a Model-based Discipline
- Digital Engineering
- Set-Based Design
- Model-Based Systems Engineering Adoption Trends 2009-2018
- Systems Engineering Core Concepts

Systems Engineering Transformation

The INCOSE Systems Engineering Vision 2025 (INCOSE 2014) describes the global context for SE, the current state of SE practice and the possible future state of SE. It describes a number of ways in which SE continues to evolve to meet modern system challenges. These are summarized briefly below.

Systems engineering has evolved from a combination of practices used in a number of related industries (particularly aerospace and defense). These have been used as the basis for a standardized approach to the life cycle of any complex system (see Systems Engineering and Management). Hence, SE practices are still largely based on heuristics. Efforts are under-way to evolve a theoretical foundation for systems engineering (see Foundations of Systems Engineering) considering foundational knowledge from a variety of sources.

Systems engineering continues to evolve in response to a long history of increasing system complexity. Much of this evolution is in the models and tools focused on specific aspects of SE, such as understanding stakeholder needs, representing system architectures or modeling specific system properties. The integration across disciplines, phases of development, and projects continues to represent a key systems engineering challenge.

Systems engineering is gaining recognition across industries, academia and governments. However, SE practice varies across industries, organizations, and system types. Cross fertilization of systems engineering practices across industries has begun slowly but surely; however, the global need for systems capabilities has outpaced the progress in systems engineering.

INCOSE Vision 2025 concludes that SE is poised to play a major role in some of the global challenges of the 21st century, that it has already begun to change to meet these challenges and that it needs to undergo a more significant **transformation** to fully meet these challenges. The following bullet points are taken from the summary section of Vision 2025 and define the attributes of a transformed SE discipline in the future:

- Relevant to a broad range of application domains, well beyond its traditional roots in aerospace and defense, to meeting society’s growing quest for sustainable system solutions to providing fundamental needs, in the globally competitive environment.

- Applied more widely to assessments of socio-physical systems in support of policy decisions and other forms of remediation.
- Comprehensively integrating multiple market, social and environmental stakeholder demands against "end-to-end" life-cycle considerations and long-term risks.
- A key integrating role to support collaboration that spans diverse organizational and regional boundaries, and a broad range of disciplines.
- Supported by a more encompassing foundation of theory and sophisticated model-based methods and tools allowing a better understanding of increasingly complex systems and decisions in the face of uncertainty.
- Enhanced by an educational infrastructure that stresses systems thinking and systems analysis at all learning phases.
- Practiced by a growing cadre of professionals who possess not only technical acumen in their domain of application, but who also have mastery of the next generation of tools and methods necessary for the systems and integration challenges of the times.

Some of these future directions of SE are covered in the SEBoK. Others need to be introduced and fully integrated into the SE knowledge areas as they evolve. This KA will be used to provide an overview of these transforming aspects of SE as they emerge. This transformational knowledge will be integrated into all aspects of the SEBoK as it matures.

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Relevant Videos

- Leading the Transformation of Model-Based Engineering [1]

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References

[1] https://www.youtube.com/watch?v=VRnNun2EH-o

Transitioning Systems Engineering to a Model-based Discipline

Systems engineers have always leveraged many kinds of models, including functional models to support requirements development, simulation models to analyze the behavior of systems, and other analytical models to analyze various aspects of the system such as reliability, safety, mass properties, power consumption, and cost. However, the discipline still relies heavily on document-based artifacts to capture much of the system specification and design information, such as requirements, interface control documentation, and system architecture design descriptions. This information is often spread across many different documents including text, informal drawings, and spreadsheets. This document-based approach to systems engineering suffers from a lack of precision, inconsistencies from one artifact to another, and difficulties in maintaining and reusing the information.

Model-Based Systems Engineering

Model-based systems engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing through development and later life cycle phases (INCOSE 2007). A distinguishing characteristic of an MBSE approach is that the model constitutes a primary artifact of the systems engineering process. The focus on developing, managing and controlling a model of the system is a shift from the traditional document-based approach to systems engineering, where the emphasis is on producing and controlling documentation about the system. By leveraging the system model as a primary artifact, MBSE offers the potential to enhance product quality, enhance reuse of the system modeling artifacts, and improve communications among the systems development team. This, in turn, offers the potential to reduce the time and cost to integrate and test the system, and significantly reduce cost, schedule, and risks in fielding a system.

MBSE includes a diverse set of descriptive and analytical models that can be applied throughout the life cycle, and from system of systems (SoS) modeling down to component modeling. Typical models may include descriptive models of the system architecture that are used to specify and design the system, and analytical models to analyze system performance, physical characteristics, and other quality characteristics such as reliability, maintainability, safety, and cost.

MBSE has been evolving for many years. The term MBSE was used by Wayne Wymore in his book by this name (Wymore 1993), that provided a state-based formalism for analyzing systems in terms of their input/output characteristics, and value functions for assessing utility of technology independent and technology dependent systems. Simulations have been extensively used across industry to provide high fidelity performance analysis of complex systems. The Standard for Integration Definition for Function Modeling (IDEF0 1993) was introduced in the 1990’s to support basic functional modeling. A modeling formalism called the enhanced functional flow block diagram (Long 2000) has been used to model many different types of systems. The Object Management Group (OMG) introduced the concept of a Model Driven Architecture (MDA®) (OMG 2003) that leverages a standards-based approach to modeling. The Systems Modeling Language (OMG SysML™) (OMG 2015) was adopted by the OMG in 2006 as a general-purpose systems modeling language. In addition, the Unified Profile for DoDAF and MODAF (UPDM) (OMG 2013) was adopted by the OMG in 2008 to support enterprise modeling. Several other domain specific modeling languages have been introduced as well.

MBSE Transition

The INCOSE Systems Engineering Vision 2025 (INCOSE 2014, pg 38) describes the current state of MBSE as follows: "Model-based systems engineering has grown in popularity as a way to deal with the limitations of document-based approaches, but is still in an early stage of maturity similar to the early days of CAD/CAE."

SE Vision 2025 also describes a continuing transition of SE to a model-based discipline in which: "Formal systems modeling is standard practice for specifying, analyzing, designing, and verifying systems, and is fully integrated with other engineering models. System models are adapted to the application domain, and include a broad spectrum of models for representing all aspects of systems. The use of internet driven knowledge representation and immersive technologies enable highly efficient and shared human understanding of systems in a virtual environment that span the full life cycle from concept through development, manufacturing, operations, and support." The transition to a more model-based discipline is not without its challenges. This requires both advancements in the practice, and the need to achieve more widespread adoption of MBSE within organizations across industry sectors.

Advancing the practice requires improvements in the modeling languages, methods, and tools. The modeling languages must continue to improve in terms of their expressiveness, precision, and usability. MBSE methods, such as those highlighted in A Survey of Model-Based Systems Engineering (MBSE) Methodologies (Estefan 2008), have continued to evolve, but require further advancements to provide a rigorous approach to modeling a system across the full system lifecycle, while being more adaptable to a diverse range of application domains. The modeling tools must also continue to evolve to support the modeling languages and methods, and to integrate with other multi-disciplinary engineering models and tools in support of the broader model-based engineering effort. The movement towards increased use of modeling standards, that are more widely available in commercial tools, and rigorous model-based methodologies, increase the promise of MBSE.

Many organizations are adopting aspects of MBSE to improve their systems engineering practice, particularly since MBSE was introduced in the INCOSE Systems Engineering Vision 2020 in 2007. However, as indicated in the SE Vision 2025, MBSE is still being applied in pockets within organizations and unevenly across industry sectors. Similar to the evolution of model-based approaches in other disciplines such as mechanical and electrical engineering, the transition occurs incrementally as the methods and tools mature.

The adoption of MBSE requires a workforce that is skilled in the application of MBSE. This requires organizations to provide an infrastructure that includes MBSE methods, tools, and training, and a commitment to deploy this capability to their programs. As with any organizational change, this must be approached strategically to grow this capability and learn from their experiences.

Like other engineering disciplines, the transition of systems engineering to a model-based discipline is broadly recognized as essential to meet the challenges associated with increasing system complexity and achieving the productivity and quality improvements. The SEBoK will continue to reflect the growing body of knowledge to facilitate this transition.

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SEBoK v. 2.2, released 15 May 2020

Model-Based Systems Engineering Adoption Trends 2009-2018

Lead Author: *Rob Cloutier*, ***Contributing Author:*** *Ifezue Obiako*

The MBSE Initiative was kicked off at the INCOSE International Workshop (IW) in 2007 at the Albuquerque, NM, USA Embassy Suites. There were approximately 45 INCOSE members for this first meeting, held during the two days preceding IW.

Surveys were conducted in 2009, 2012, 2014, 2018, and 2019 to better understand the adoption trends of model-based systems engineering.

Introduction

Model-based systems engineering (MBSE) is not a new concept. Wymore (1993) published the seminal work on the topic. This book presents the mathematical theory behind MBSE. Since that time, engineering has made significant movement from text-based approaches using office-based tools (e.g. Harvard Graphics, Microsoft PowerPoint, Microsoft Visio, etc.) to an interconnected set of graphical diagrams. These diagrams are generally created in a tool with a specialized graphical user interface.

Today aerospace engineers no longer use drafting boards to create their drawings – they use computer aided design (CAD) tools. Likewise, software engineers seldom use EMACS or Vi (text editors), instead, they use software GUIs that allow them to code, check syntax, compile, link, and run their software all in a single environment.

Broadly speaking, a model_ can be thought of as a facsimile or abstraction of reality. To this end, even a requirements document can be considered a model – it represents what a real system should do in performing its mission or role. While systems engineering has used models for a very long time, MBSE is the systems engineering migration to computer-based graphical user interfaces to perform our analysis and design tasks just as our other engineering brethren have moved to computer-based graphical user interfaces.

A discussion of available tools is beyond the scope of this article, and it is not the practice of the SEBoK to review or promote specific tool offerings. However, it is fair to state that current MBSE tools fall into three broad categories: 1) Functional decomposition tools that use IDEF0 (also called IPO) diagrams, N2 diagrams, functional flow block diagrams, etc., 2) Object-oriented tools that implement the Object Management Group's Systems Modeling Language (SysML), and 3) Mathematical modeling tools.

This migration for systems engineering might have begun in the late 90's. The INCOSE INSIGHT publication proclaimed that MBSE was a new paradigm (INSIGHT 1998). Cloutier (2004) addressed the migration from a waterfall systems engineering approach to an object-oriented approach on the Navy Open Architecture project. At that time, SysML did not exist, and the teams were using the Unified Modeling Language (UML) that was predominately a software modeling tool. Zdanis & Cloutier (2007a, 2007b) addressed the use of activity diagrams instead of sequence diagrams for systems engineering based on the newly released SysML. In 2009, the INCOSE INSIGHT publication proclaimed MBSE was THE new paradigm (INSIGHT 2009).

Approach

In 2009, a survey was commissioned by the Object Management Group (OMG) with the intent of informing the SysML Working Group on necessary changes to SysML since its first release (Cloutier & Bone 2010). That survey focused on process more than adoption. Beginning in 2012, INCOSE has commissioned three more surveys to understand adoption trends and obstacles. The survey instrument remained relatively unchanged for 2012, 2014, and 2018 (Cloutier 2015, Cloutier 2019a). In January of 2019, the Jet Propulsion Lab (JPL) conducted an MBSE

Workshop (Cloutier 2019b). A survey of those participants was conducted, and the intent of the questions was to augment knowledge gained from the 2018 survey. The table below shows the number of respondents in each of the surveys.

Table 1. MBSE Survey Purposes and Responses (SEBoK Original)

Year	Survey Purpose	Responses
2012	INCOSE MBSE Initiative	134
2014	INCOSE MBSE Initiative	205
2018	INCOSE MBSE Initiative	661
2019	JPL MBSE Workshop	98

Responses and Response Demographics

Each survey was sent to a diverse group of MBSE practitioners. Table 2 shows that of the 661 responses for the 2018 survey, 410 indicated their country of origin. This international representation is similar to all surveys conducted.

Table 1. MBSE Survey Purposes and Responses (Cloutier 2019, used with permission)

Country	Responses	Country	Responses
USA	197	Israel	4
United Kingdom	52	Singapore	3
France	30	China	2
Germany	28	New Zealand	2
Australia	20	Poland	2
Netherlands	19	Russia	1
Japan	8	Romania	1
Canada	6	Turkey	1
Italy	6	Columbia	1
Sweden	6	Norway	1
South Africa	5	South Korea	1
Switzerland	4	UAE	1
Brazil	4	Belarus	1
India	4		

As part of the demographics, Figure 1 shows the represented industries. Because the “Other” category was so large, the data was analyzed to better understand Figure 2.

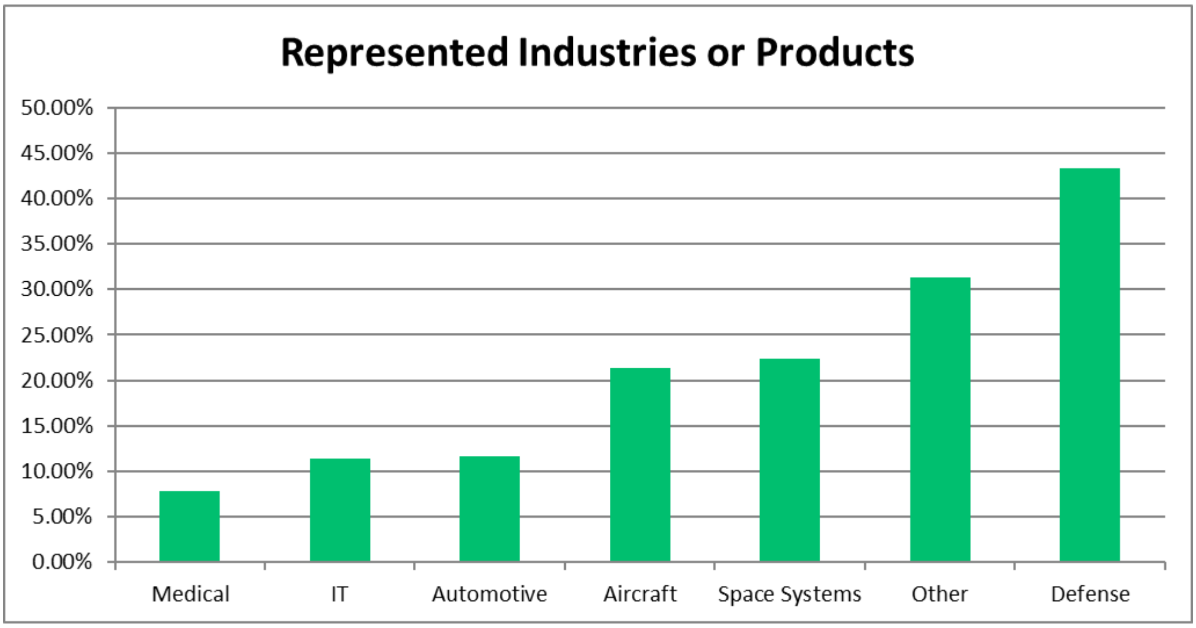

Figure 1. Industries Represented in the 2018 MBSE Survey. (Cloutier 2019a, used with permission)

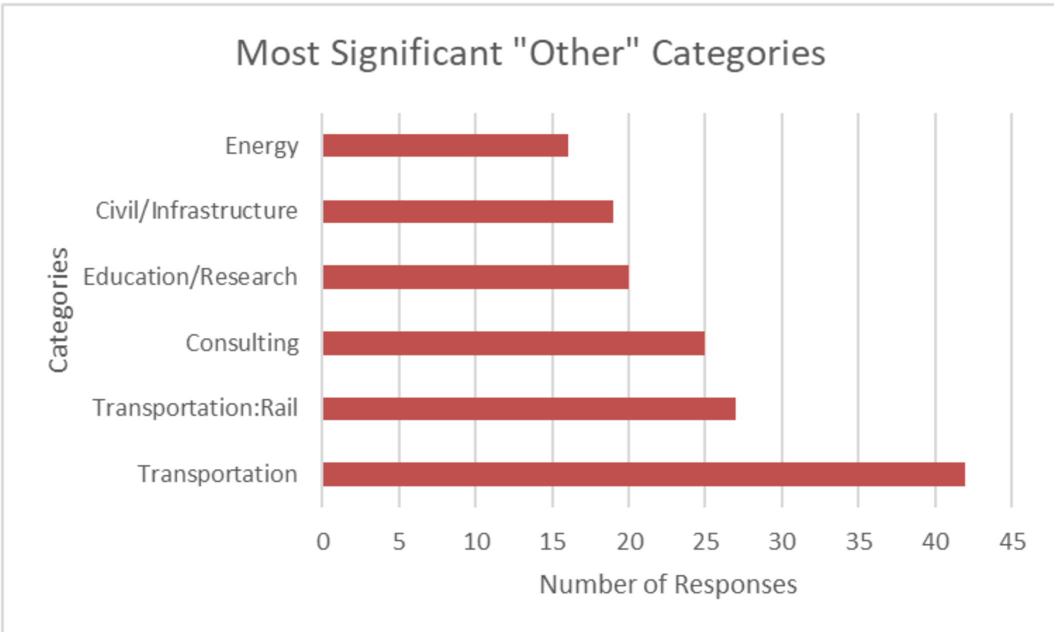

Figure 2. "Other" Industries Represented in the 2018 MBSE Survey. (Cloutier 2019a, used with permission)

The 2018 survey indicated that there seems to be an increased application of MBSE in traditionally civil engineering industries – specifically energy, infrastructure, and transportation (Figure 2) One of the most interesting aspects of the 2018 survey is the finding that MBSE is being applied in the early phases of systems engineering, and less so in the later phases as shown in Figure 3.

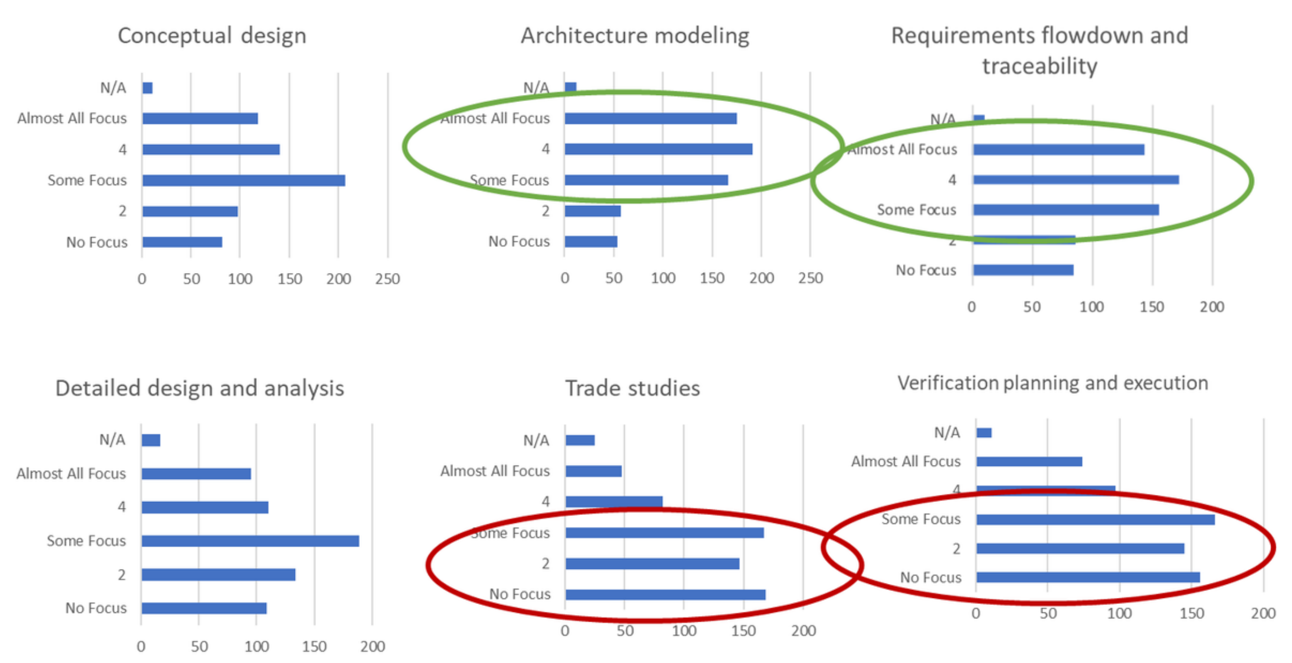

Figure 3. MBSE is More Likely to be Used in Early Stages of Systems Engineering. (Cloutier 2019a, used with permission)

This was confirmed by the JPL question "Where do we believe MBSE holds the most promise?" Figure 4 shows that 76% of the responses indicated system/subsystem architecting, 42% thought requirements analysis, and 39% believed early conceptualization (note: the question allowed for multiple answers).

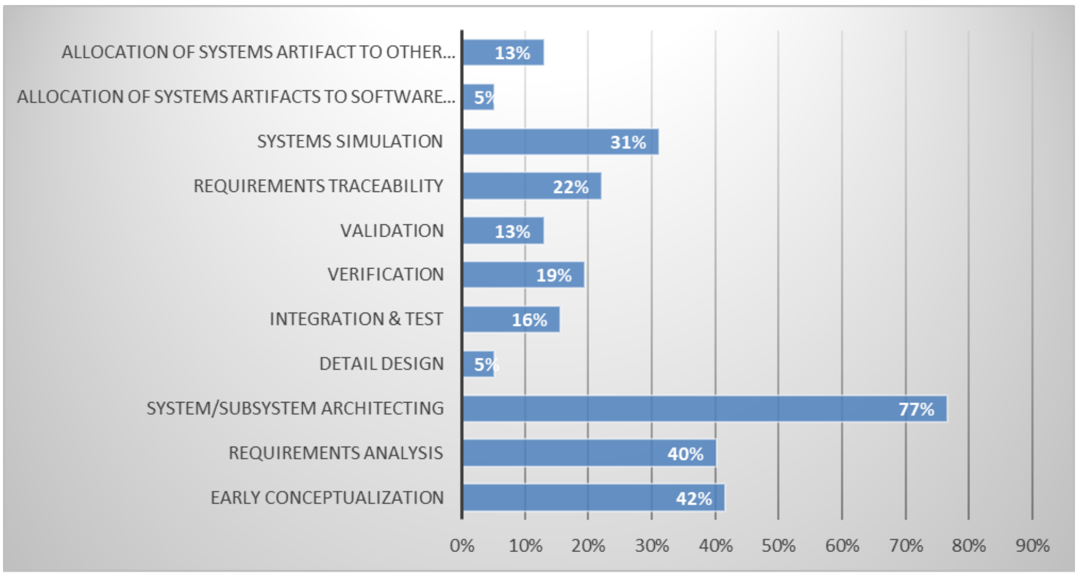

Figure 4. JPL Workshop Response Regarding "Where MBSE Holds the Most Promise." (Cloutier 2019b, used with permission)

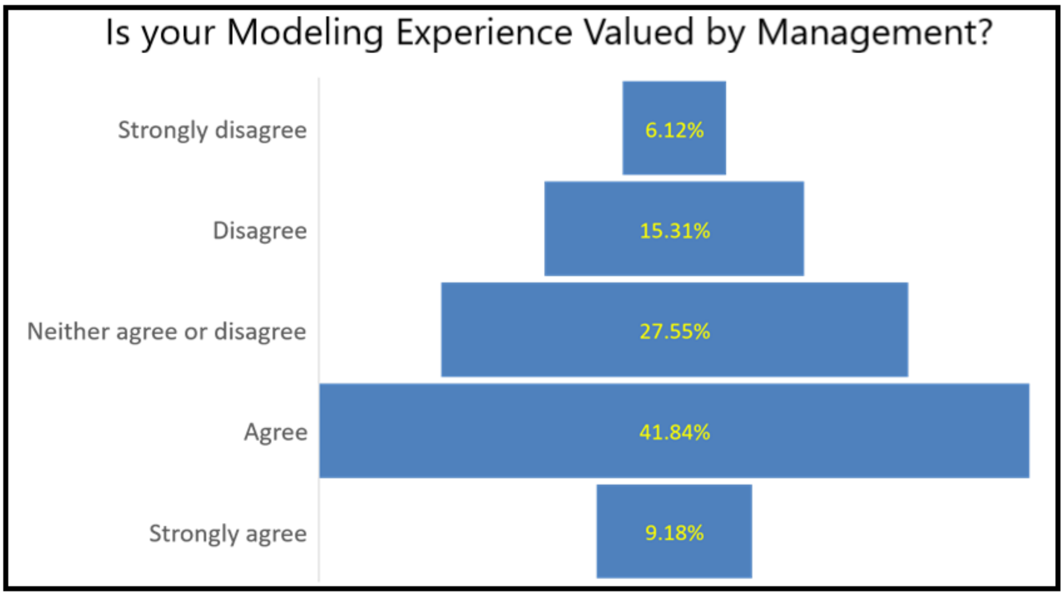

Figure 5. JPL Workshop Response Regarding "Is Your Modeling Experience Valued by Management?"(Cloutier 2019b, used with permission)

When asked whether the JPL survey respondents believed that their systems modeling experience is recognized as a valued skill supporting career growth of systems engineers in their organization, just over 50% believed management valued their experience. A smaller number, 21%, believed their modeling experience was not valued (Figure 5).

Key Adoption Trends

The remainder of this article will look at some of the trends identified across the surveys, from 2009 to 2018. Figure 6 shows that MBSE is moving from a defense and space dominated practice into other industries as discussed in Figure 4.

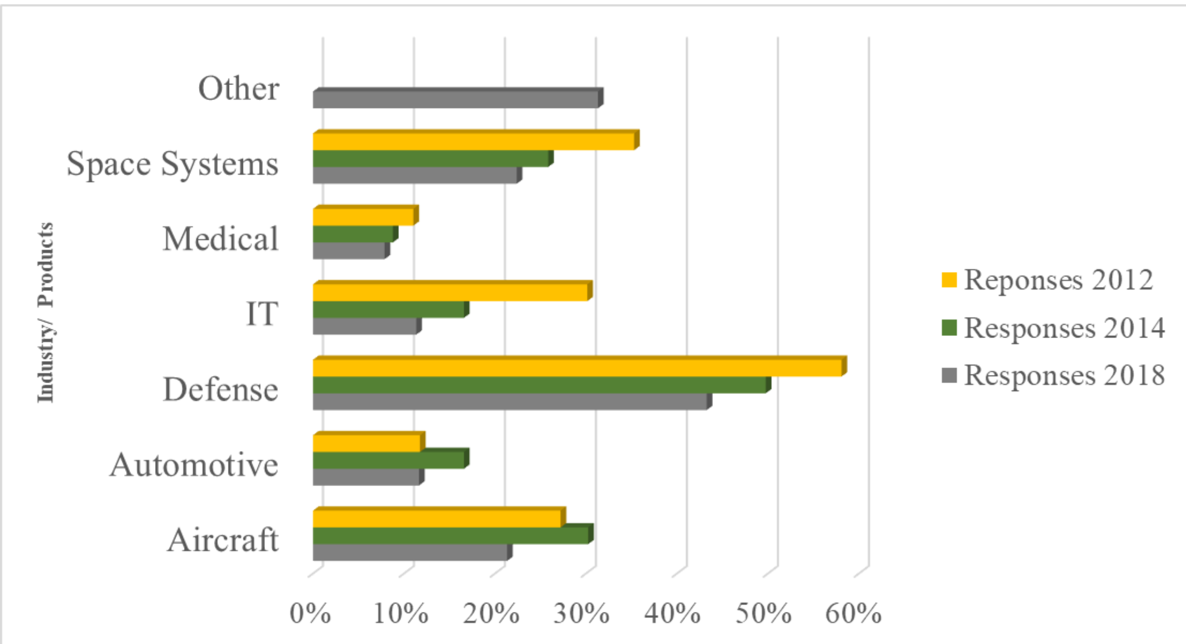

Figure 6. Shift of MBSE Adoption in New Industries. (Cloutier 2019a, used with permission)

Model-based systems engineering seems to be expanding in influence in that it is not just in the purview of systems engineers. While systems and software engineers find value in MBSE practices, Figure 6 demonstrates that the customer is finding value in MBSE practices. It is also interesting that software engineers' perceived value of MBSE is declining from survey to survey.

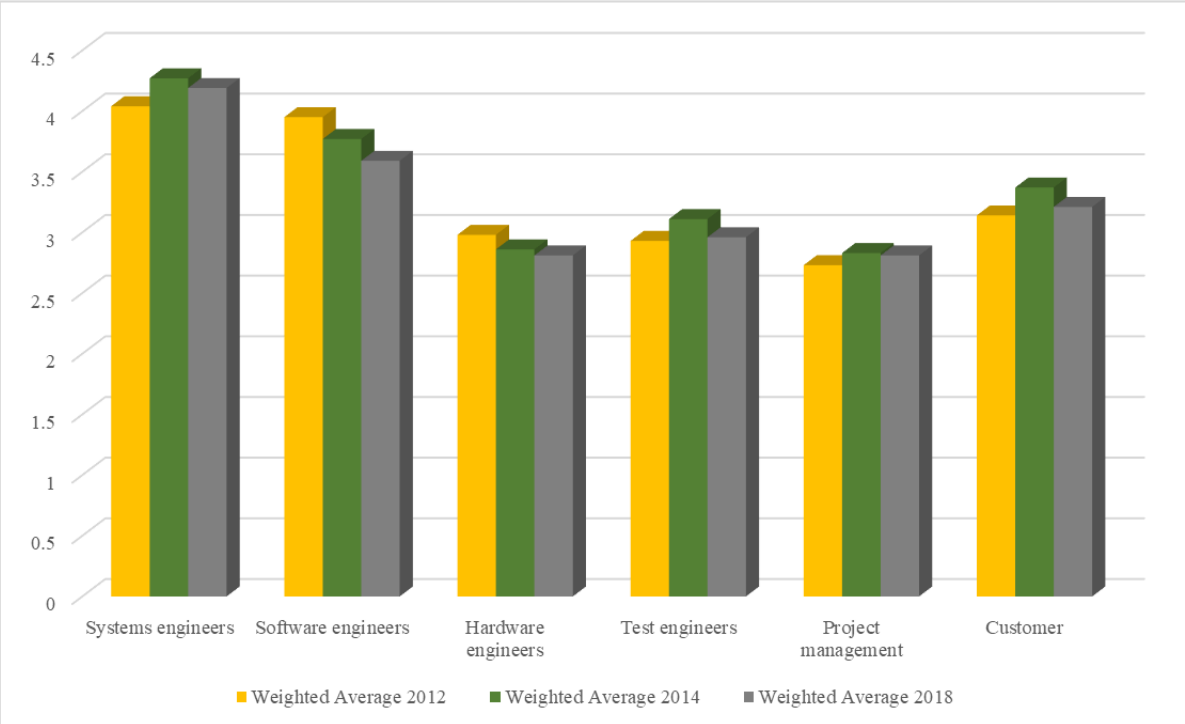

Figure 7. Perceived Value of MBSE Practices to Different Project Segments. (Cloutier 2019a, used with permission)

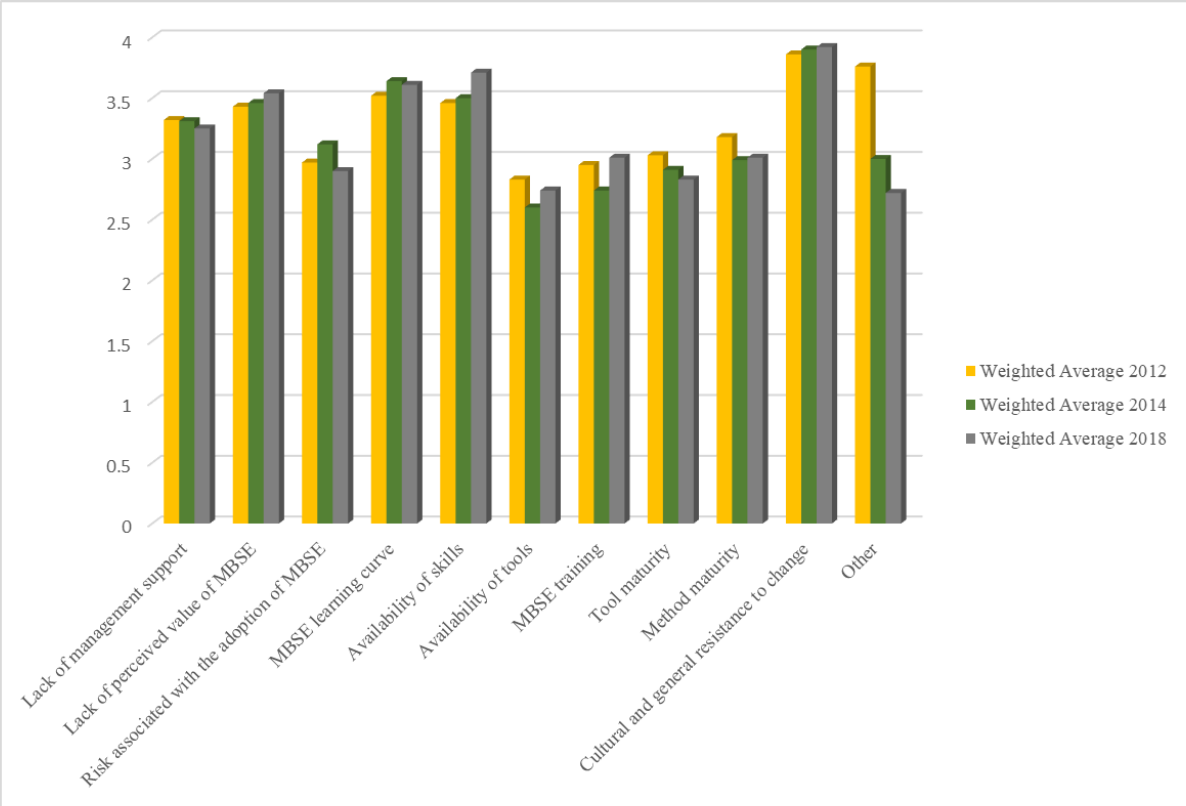

Figure 8. Inhibitors to the Successful Adoption of MBSE within an Organization/Company. (Cloutier 2019a, used with permission)

Figure 8 demonstrates that availability of MBSE skills and cultural and general resistance to change have continued to increase. Lack of perceived value reflects the findings in Figure 6 – software and hardware engineers are not seeing the value of MBSE.

Conclusions

Surveys conducted between 2012 and 2018 demonstrate that MBSE practices are spreading beyond traditional Defense and Space domains. Most MBSE practitioners are finding MBSE is most useful in the early project phases of conceptualization, requirements analysis, and systems architecting. There continues to be a skills shortage, yet companies/organizations are providing less training to improve MBSE skills. Both systems engineers, systems engineering management, and the systems engineering customer are finding value in using models to perform systems engineering.

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Digital Engineering

Lead Author: *Ron Giachetti*

The US Under Secretary of Defense for Research and Development released the US Department of Defense (DoD) Digital Engineering Strategy in June 2018 describing five goals to streamline the DoD acquisition process through the creation of a digital thread enabling the conception, design, and development of complex weapon systems (DoD 2018; Zimmerman 2017). The crux of digital engineering is the creation of computer readable models to represent all aspects of the system and to support all the activities for the design, development, manufacture, and operation of the system throughout its lifecycle. These computer models would have to be based on shared data schemata so that in effect a digital thread integrates all the diverse stakeholders involved in the acquisition of new weapon systems. The Digital Engineering Strategy anticipates digital engineering will lead to greater efficiency and improved quality of all the acquisition activities.

Relationship with MBSE

Model-based systems engineering (MBSE) is a subset of digital engineering. MBSE supports the systems engineering activities of requirements, architecture, design, verification, and validation. These models would have to be connected to the physics-based models used by other engineering disciplines such as mechanical and electrical engineering. One challenge remaining for digital engineering is the integration of MBSE with physics-based models.

Foundation to digital engineering is the representation of the system data in a format sharable between all stakeholders (Giachetti et al. 2015; Vaneman 2018). SysML 2.0 is one of several future developments promising to provide a representation sufficient to support digital engineering. An ontology defining the entities and relationships between them can be used to define the concepts relevant to systems engineering. Such a representation is necessary to create the digital thread linking all the models together in a cohesive and useful manner.

Digital Engineering as a Transformation

For many organizations, digital engineering represents a transformation of how they normally conduct systems engineering (e.g., see Bone et al. 2018) since most organizations conduct a document-intensive systems engineering process. The adoption of digital engineering requires concomitant changes to how organizations perform system engineering activities. Everything from documenting requirements, technical reviews, architecture design, and so forth would be based on the models in a digital engineering environment (Vaneman and Carlson, 2019). The digital thread would be the authoritative source of truth concerning the system data.

Digital Twin

A digital twin is a related yet distinct concept to digital engineering. The digital twin is a high-fidelity model of the system which can be used to emulate the actual system. An organization would be able to use a digital twin to analyze design changes prior to incorporating them into the actual system.

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Additional References

None.

Relevant Videos

- Digital Engineering: MBSE Approach for DoD [1]

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SEBoK v. 2.2, released 15 May 2020

Set-Based Design

Lead Authors: *Eric Specking, Gregory S. Parnell, and Ed Pohl*

Set-based design (SBD) is a complex design method that enables robust system design by 1) considering a large number of alternatives, 2) establishing feasibility before making decisions, and 3) using experts who design from their own perspectives and use the intersection between their individual sets to optimize a design (Singer, Doerry, and Buckley 2009). Model-based engineering (MBE)/model-based systems engineering (MBSE) with an integrated framework can enable the use of SBD tradespace exploration, for some situations (i.e. early-design stage with low fidelity models), in near-real time (Specking et al. 2018a). This article provides insights on using model-based design to create and assess alternatives with set-based design.

Introduction

SBD analyzes sets of alternatives instead of single solutions. Sets are "two or more design points that have at least one design option in common" (Specking et al. 2018b) or "the range of options for a design factor" (Singer et al. 2017). A design factor is a "solution parameter, characteristic, or relationship that influences the design at the system level" (Singer et al. 2017). Systems engineers should develop sets determining the design factors and separating the design factors into set drivers or set modifiers. Set drivers are "fundamental design decisions that define the system characteristics that enable current and future missions," while set modifiers are "design decisions that are 'added on' to the system and can be modified to adapt for new missions and scenarios" (Specking et al. 2018b).

SBD is not the best design method for every situation. SBD is particularly useful in early-stage design and if the project contains the following attributes:

- A large number of design variables,
- Tight coupling among design variables,
- Conflicting requirements,
- Flexibility in requirements allowing for trades, or
- Technologies and design problems not well understood – learning required for a solution (Singer et al. 2017)

In early-stage design, SBD helps inform requirements analysis and assess design decisions (Parnell et al. 2019). Quantitative SBD requires an integrated MBE environment to assess the effects of constraining and relaxing requirements on the feasible tradespace. For example, Figure 2 demonstrates the effects of constraining or relaxing requirements of an unmanned aerial vehicle case study with all of the explored designs in orange, the tradespace affected by non-requirement constraints (e.g. physics with requirements relaxed to not affect the tradespace) in blue, the original UAV feasible tradespace in yellow, and the relaxed (black)/constrained (red) tradespaces.

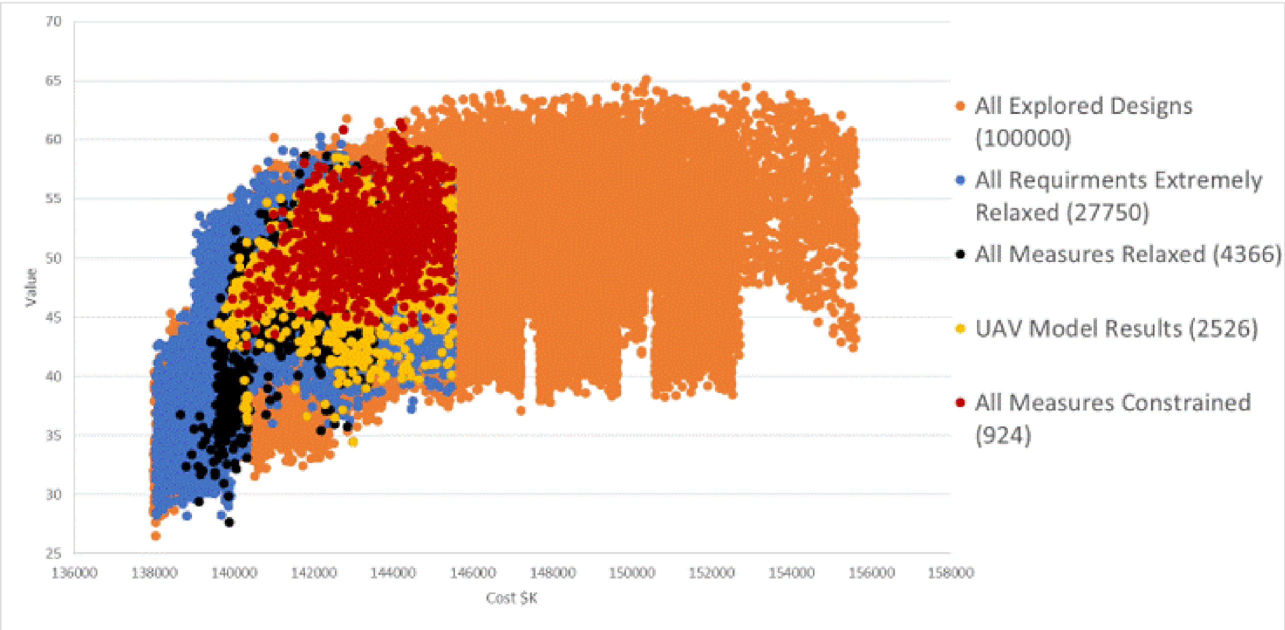

Figure 1. Effects of Requirements on the UAV's Feasible Tradespace (Parnell et al. 2019, used with permission)

The tornado diagram seen in Figure 3 shows results of a one requirement at a time analysis. This makes it easy to see how the constraining/relaxing of each individual requirement affects the feasible tradespace. Figure 3 shows that the requirements “Detect Human Activity at Night” and “Detect Human Activity in Daylight” have the greatest impact on the feasible tradespace.

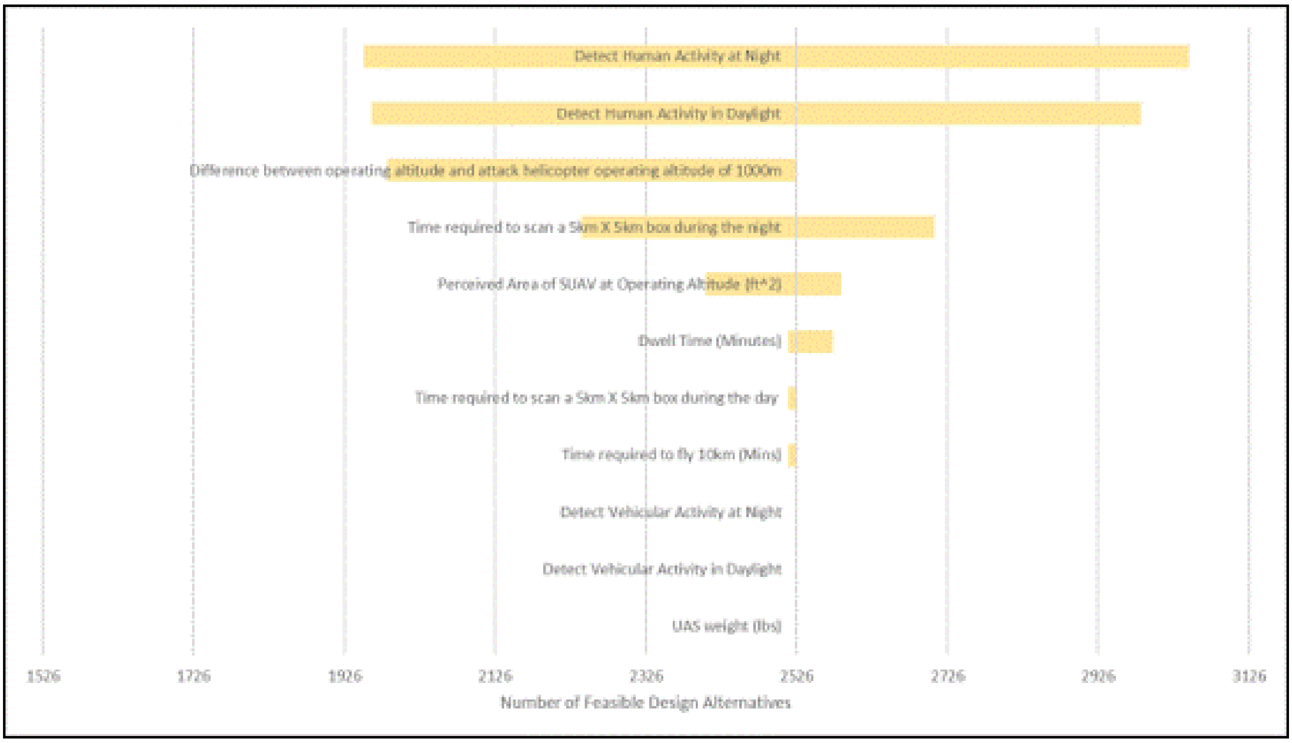

Figure 2. UAV Case Study Results of One-by-One Requirement Analysis (Parnell et al. 2019, used with permission)

Changing the requirements does not always translate to finding improved designs. The individual one requirement at a time analysis scatterplot provides important information, as seen in an example illustration in Figure 4. It is important to carefully analyze the Pareto Frontier created by each change (represented by a different color) and compare it to the Pareto Frontier of the original analysis. If the original requirement level produces better alternatives, then it does not make sense to change (constrain or relax) the requirement.

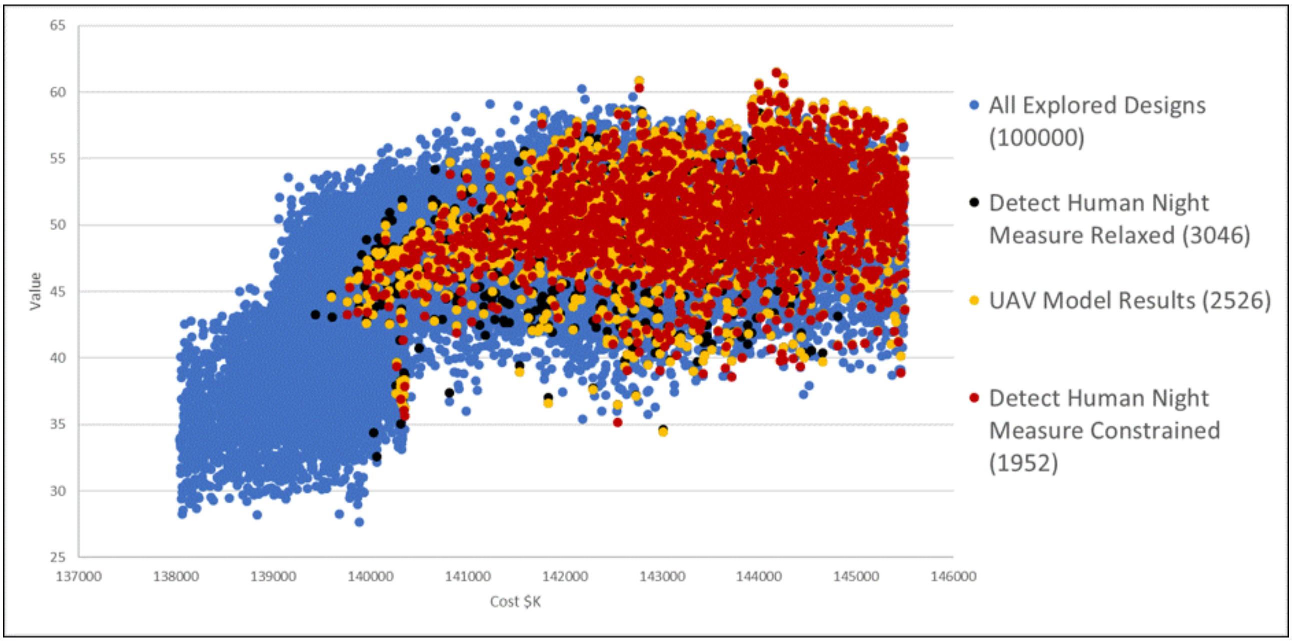

Figure 3. Effect on Feasible Tradespace by Changing Most Sensitive UAV Requirement (Specking et al. 2019, used with permission)

Additionally, using SBD can add value to the overall project and team. Some of the advantages include:

- enabling reliable, efficient communications,
- allowing much greater parallelism in the process, with much more effective use of subteams early in the process,
- allowing the most critical, early decisions to be based on data, and
- promoting institutional learning (Ward et al. 1995).

System Analyst Set-Based Design Tradespace Exploration Process

Figure 4 illustrates SBD as a concept for system design and analysis. This SBD illustration contains 5 distinct characteristics:

1. start by determining the business/mission needs and system requirements;
2. use the business/mission needs and system requirements to perform design and analysis techniques throughout time in the exploratory, concept, and development stages of the system's life cycle;
3. perform design and analysis concurrently as much as possible;
4. inform requirement analysis by using feasibility, performance, and cost data; and
5. consider a large number of alternatives through the use of sets and slowly converge to a single point solution (Specking et al. 2019).

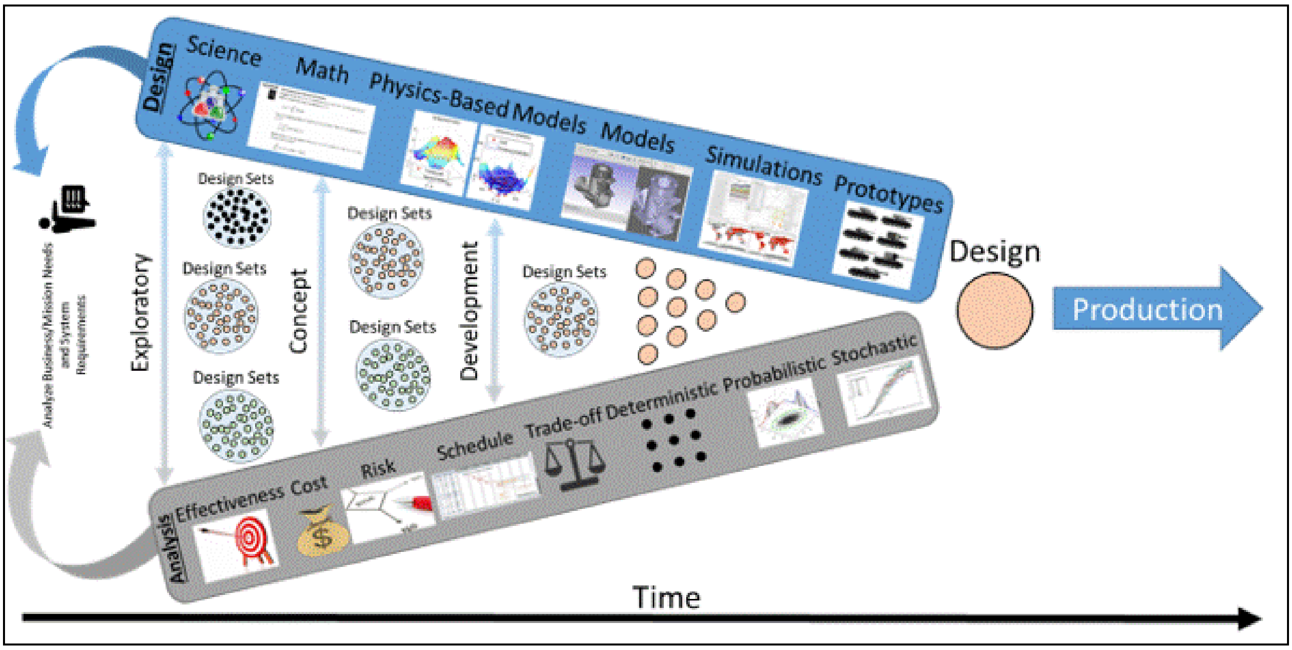

Figure 4. SBD Conceptual Framework for Systems Design (Specking et al. 2019, used with permission)

SBD is a social-technical process and should involve input and interactions from several teams, but Figure 6 provides a SBD tradespace exploration process for system analysts (Specking et al. 2019). This eight-step process is especially useful to perform early-stage design (Specking et al. 2018b). The system analyst starts by analyzing the business/mission needs and system requirements. Systems engineers use this information, along with models and simulations developed by themselves or provided by systems and subsystem teams, to develop an integrated model. Systems engineers include requirements to assess feasible and infeasible alternatives using this integrated model. They explore the tradespace by treating each design decision as a uniform (discrete or continuous) random variable. An alternative consists of an option from every design decision. Systems engineers then use the integrated model to evaluate each alternative and to create the feasible tradespace. Monte Carlo simulation is one method that enables a timely alternative creation and evaluation process. The created tradespace will consist of infeasible and feasible alternatives based upon the requirements and any physics-based performance models and simulations. Systems engineers should work with the appropriate stakeholders to inform requirements when the tradespace produces a significantly small number of or no feasible alternatives. In addition to feasibility, systems engineers should also analyze each design decision by using descriptive statistics and other analyses and data analytics techniques. This information provides insights into how each design factor influences the feasible tradespace. Once the tradespace contains an acceptable number of alternatives, it is then classified by sets. This is an essential part of SBD. If the set drivers or design factors are not known, systems engineers should view the tradespace by each design decision for insights. Systems engineers should use dominance analysis and other optimization methods to find optimal or near optimal alternatives based upon the measures of effectiveness. Systems engineers should explore the remaining sets for additional insights on the feasible tradespace and the requirements. The final part of this process is to select one or more sets to move to the next design-stage. It should be noted that this process contains cycles. At any part of this process, systems engineers should use the available information, such as from tradespace exploration or set evaluation, to inform requirement analysis or update the integrated model. Additionally, the systems engineer should update the integrated model with higher fidelity models and simulations as they become available. The key is to have the "right" information from the "right" people at the "right" time.

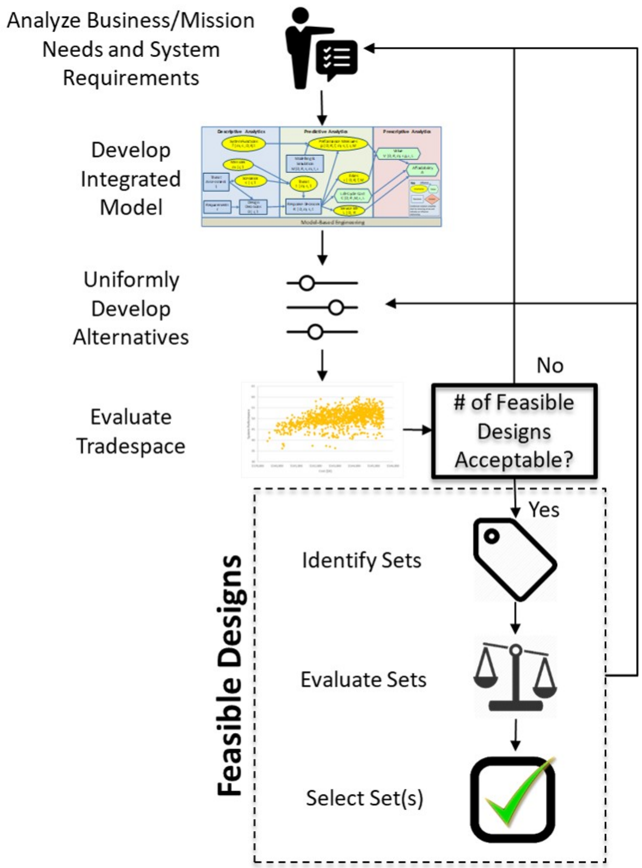

Figure 5. System Analysts SBD Tradespace Exploration Process
(Specking et al. 2019, used with permission)

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SEBoK v. 2.2, released 15 May 2020

Emerging Research

Emerging Research

Lead Authors: *Robert Cloutier, Arthur Pyster*

Doctoral level systems engineering research has taken root over the last two decades. Many programs that have either an Industrial Engineering and/or Systems Engineering Master’s program also have a doctoral program. This has enabled new and interesting research to be conducted. The problem arises, however, of finding this research. Some of this research is found in national or international repositories that can be searched. Some is resident in university libraries. Some can be found on the researcher’s webpage. And sadly, some does not see the light of day once it is successfully defended. The SEBoK Board of Governors has approved the creation of a new section where this research may be found. The first article in the SEBoK states “The purpose of the Guide to the Systems Engineering Body of Knowledge (SEBoK) is to provide a widely accepted, community-based, and regularly updated baseline of systems engineering (SE) knowledge.” The Emerging Research topic under the SEBoK Emerging Topics will be a place to showcase some of the systems engineering research published in the past 3-5 years. Here you will find bibliographic citations and summaries for recently defended research. Bibliographic information will contain the **Author** of the research, the **Title** of the research, the **Institution** in which the research was performed, the **Year** the research was defended, and either a **Link** to the repository where the dissertation can be located (preferred) or an email link to the researcher.

To be considered for inclusion in the SEBoK, the dissertation must contribute to the field of systems engineering. It may focus on systems engineering principles, processes, methodologies, etc. Submitted dissertations must have been published within the last 3-5 years unless a compelling reason is presented. If the SEBoK already has an established Part, Knowledge Area, or article addressing the content of a dissertation, it will not be accepted into the Emerging Research portion of the SEBoK.

Submissions must contain the name of the author, the title of the dissertation, the date of publication, the university at which the work was completed, and a direct link to the dissertation itself. If you are comfortable summarizing the dissertation in one paragraph, that would be appreciated. If not, the SEBoK team will do so if the abstract is provided to them. If there are published conference papers, journal papers, books, or book chapters based on the dissertation, we welcome full citation information for them as well. Dissertation submissions can be directed to mhaas5@masonlive.gmu.edu.

Dissertations

Towards Early Lifecycle Prediction of System Reliability

Salter, C. “Towards early lifecycle prediction of system reliability,” Ph.D. dissertation University of South Alabama, Mobile, Alabama, July 2018. Available: ProQuest Store [1]

Reliability is traditionally defined as “the probability that an item will perform a required function without failure under stated conditions for a stated period of time” (O'Connor, 2012). This definition is applicable to all levels of a system, from the smallest part to the system as a whole. Predicting reliability requires extensive knowledge of the system of interest, thus making prediction difficult and complex. This problem is further complicated by the desire to predict system reliability early in the acquisition lifecycle. This work set out to develop a model for the prediction of system reliability early in the system lifecycle. The model utilizes eight factors: number of system requirements, number of major interfaces, number of operational environments, requirements understanding, technology maturity, manufacturability, company experience, and performance convergence. These factors come together to form a model much like the software engineering and systems engineering models COCOMO and COSYSMO. This work provides the United States Department of Defense a capability that previously did not exist: the estimation of system reliability early in the system lifecycle. The research demonstrates that information available during early system development may be used to predict system reliability. Through testing, the author found that a model of this type could provide reliability predictions for military ground vehicles within 25% of their actual recorded reliability values.

Toward the Evolution of Information Digital Ecosystems

Lippert, K. “Toward the evolution of information digital ecosystems,” Ph.D dissertation, University of South Alabama, Mobile, Alabama, May 2018. Available: ProQuest Store [2].

Digital ecosystems are the next generation of Internet and network applications, promising a whole new world of distributed and open systems that can interact, self-organize, evolve, and adapt. These ecosystems transcend traditional collaborative environments, such as client-server, peer-to-peer, or hybrid models (e.g., web services) to become a self-organized, interactive environment. The complexity of these digital ecosystems will encourage evolution through adaptive processes and selective pressures of one member on another to satisfy interaction, adaptive organization, and, incidentally, human curiosity. This work addresses one of the essential parts of the digital ecosystem – the information architecture. The research, inspired by systems thinking influenced by both biological models and science fiction, applies the TRIZ method to the contradictions raised by evolving data. This inspired the application of patterns and metaphor as a means for coping with the evolution of the ecosystem. The metaphor is explored as a model of representation of rapidly changing information through a demonstration of an adaptive digital ecosystem. The combination of this type of data representation with dynamic programming and adaptive interfaces will enable the development of the various components required by a true digital ecosystem.

Cybersecurity Decision Patterns as Adaptive Knowledge Encoding in Cybersecurity Operations

Willett, K. “Cybersecurity decision patterns as adaptive knowledge encoding in cybersecurity operations”, Ph.D. dissertation, Stevens Institute of Technology, Hoboken, NJ, July 2016. Available: https://pqdtopen.proquest.com/doc/1875237837.html?FMT=ABS.

Cyberspace adversaries perform successful exploits using automated adaptable tools. Cyberspace defense is too slow because existing response solutions require humans in-the-loop across sensing, sense-making, decision-making, acting, command, and control of security operations (Dōne et al. 2016). Security automation is necessary to provide for cyber defense dynamic adaptability in response to an agile adversary with intelligence and intent who adapts quickly to exploit new vulnerabilities and new safeguards. The rules for machine-encoding security automation must come from people; from their knowledge validated through their real-world experience. Cybersecurity Decision Patterns as Adaptive Knowledge Encoding in Cybersecurity Operations introduces cybersecurity decision patterns (CDPs) as formal knowledge representation to capture, codify, and share knowledge to introduce and enhance security automation with the intent to improve cybersecurity operations efficiency for processing anomalies.

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