SEBoK GUIDE TO THE SYSTEMS ENGINEERING BODY OF KNOWLEDGE

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

## Part 1

Please note that this is a PDF extraction of the content from www.sebokwiki.org

# Guide to the Systems Engineering Body of Knowledge, Part 1

version 2.1

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# Front Matter

## Letter from the Editor

Hi there! Welcome to the October 2019 instantiation of the Systems Engineering Body of Knowledge. Since version 1.0 appeared in September 2012, that means the SEBoK just celebrated its 7th birthday! This release, version 2.1 is also my third release as Editor in chief. This release brings what I hope are some exciting changes for the readers and authors.

The **first change** I hope you notice is that we have added bylines to those articles for which we can track their origins. As of this release, we are recognizing the contribution of lead authors and the additional contributing authors. It is our hope that these contributions will be beneficial to the authors in their professional lives - being able to prove their contributions to this important knowledge base.

The **next obvious change** should be the way glossary bubbles have been updated. They are more readable now, with a grey background and black text.

Other changes include **new articles** on:

- Digital Engineering
- Mission Engineering
- Set Based Design
- MBSE Adoption Trends 2009-2018

Additionally, we have **updated content** on Resilience, Human Systems Integration, and Capability Engineering. Part 1 also received a wire brushing. We have also begun incorporating video. You will find a short video on the Main page. We are also going to begin to look at existing INCOSE YouTube channel content to look for 1-3 minute clips we can strategically place throughout the SEBoK to add value.

There is a big announcement to be made relative to the SEBoK. The IEEE Computer Society has been one of the three stewards of the SEBoK from the beginning. They have had a seat on the Board of Governors, and have provided invaluable counsel. In January 2020, that stewardship will be transferred from the IEEE Computer Society to the IEEE Systems Council. The Editorial Board looks forward to the continued support and participation of IEEE. Thank you IEEE Computer Society, and in particular to Rich Hilliard and Andy Chen.

Regarding the reach of the SEBoK, there were over 29,000 visitors and 68,781 page views during the the month of July 2019. That brings our total page views to over 3.45M since 2012. Top content pages in July: 1) Stakeholder Needs and Requirements, 2) Types of Models, 3) Types of Systems, 4) Systems Requirements, and 5) Reliability, Availability, and Maintainability. Top countries accessing the SEBoK in July:

1. US
2. India
3. Australia
4. United Kingdom
5. Philippines

Looking forward to the next release, it is my hope that those of you that enjoy working with video will think about creating video content now that we have that capability. Please limit your submissions to no more than 3 minute clips, and the preferred format is mp4.

I am still looking for additional authors and folks interested in taking a leadership role as editors to help manage and grow our content for specific areas. It would be nice to add some more content in Part 6: Related Disciplines, and Part 7: SE Implementation Examples. If you would like to author an article for those sections, please reach our to Nicole Hutchinson (emtnicole@gmail.com) or myself (rcloutier@southalabama.edu).

That is it for now ... I hope to see you at the upcoming International Workshop being held in Torrence, CA in January 2020. If you have ideas for the SEBoK, or would like to get involved, be sure to find me there and we can have some coffee and chat. But, do not feel you have to wait until then to get involved - reach out now! Thanks for your ongoing support.

# 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 Computer Society (IEEE-CS), 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 Computer Society (IEEE CS)**
  - Andy Chen, Rich Hilliard

Past INCOSE governors Bill Miller, Kevin Forsberg, David Newbern, David Walden, Courtney Wright, Dave Olwell, Ken Nidiffer, Richard Fairley, Massood Towhidnejad, and John Keppler. The governors would also like to acknowledge John Keppler, IEEE Computer Society, who has been instrumental in helping the Governors to work within the IEEE CS structure.

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

# Editorial Board

The SEBoK Editorial Board is chaired by an Editor in Chief, supported by a group of Associate Editors.

**SEBoK Editor in Chief**

**Robert J. Cloutier**

*University of South Alabama*

rcloutier@southalabama.edu [1]

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

**SEBoK Managing Editor**

**Nicole Hutchison**

*Stevens Institute of Technology*

nicole.hutchison@stevens.edu [2] or emtnicole@gmail.com [3]

Responsible for the the day-to-day operations of the SEBoK and supports the Editor in Chief.

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

**SEBoK Part 1: SEBoK Introduction**

**Lead Editor: Robert J. Cloutier**

*University of South Alabama*

rcloutier@southalabama.edu [1]

Responsible for Part 1

**SEBoK Part 5: Enabling Systems Engineering**

**Assistant Editor: Emma Sparks**

*Cranfield University*

Jointly responsible for the Enabling IndividualsandEnabling Teams knowledge area

**Assistant Editor: Rick Hefner**

*California Institute of Technology*

Rick.Hefner@ngc.com [18]

**Assistant Editor: Tim Ferris** *Cranfield University*

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**Assistant Editor: Bernardo Delicado**

*MBDA / INCOSE*

bernardo.delicado@mbda-systems.com [20]

**SEBoK Part 6: Related Disciplines**

**Lead Editor: Alice Squires**

*Washington State University (USA)*

alice.squires@wsu.edu [21]

**SEBoK Part 7: Systems Engineering Implementation Examples**

**Lead Author: Clif Baldwin**

*FAA Technical Center*

cliftonbaldwin@gmail.com [22]

Responsible for Part 7: Systems Engineering Implementation Examples, which includes Case Studies and examples.

***Graduate Reference Curriculum for Systems Engineering (GRCSE)***

**David H. Olwell**

*St. Martin's University (USA)*

dolwell@stmartin.edu [23]

Associate Editor for SEBoK.


## Graduate Student Support

With SEBoK v. 2.1, the Governing Board has hired a graduate student to support the Editor in Chief and Managing Editor. Madeline Haas, a master's student at George Mason University, is the current graduate student supporting the SEBoK and we gratefully acknowledge her exemplary efforts.

# 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

If you are interested in being considered for participation on the Editorial Board, please visit the BKCASE website http://www.bkcase.org/join-us/or contact the BKCASE Staff directly at bkcase.incose.ieeecs@gmail.com [24].

**SEBoK v. 2.1, released 31 October 2019**

# 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. 2.1, 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. The stewards have reconfirmed their commitment to making the SEBoK available at no cost to all users, a key principle of BKCASE.

As of the end of July 2019, SEBoK articles have had over 3.4M pageviews from 1.7M unique visits. 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 analysis 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 BKCASE 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 2.1

This version of the SEBoK was released 31 October 2019. 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. 2.1.

## SEBoK Release History

There have been 21 releases of the SEBoK to date, collected into 13 main releases.

### Main Releases

- Version 2.1 - Current version. This is 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 [4] 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.

**SEBoK v. 2.1, released 31 October 2019**

## References

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

# Cite the SEBoK

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

> SEBoK Editorial Board. 2019. *The Guide to the Systems Engineering Body of Knowledge (SEBoK)*, v. 2.1, 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:

> SEBoK Authors. Author name(s). "Article Title." in SEBoK Editorial Board. 2019. *The Guide to the Systems Engineering Body of Knowledge (SEBoK)*, v. 2.1 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 page will include the by line (author names) for the article. If no byline is listed, please use "SEBoK Authors".***

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# Part 1: SEBoK Introduction

## SEBoK Introduction

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. SEBoK Part 1 contains an introduction to both the discipline of SE and an introduction to the SEBoK wiki and how to use it.

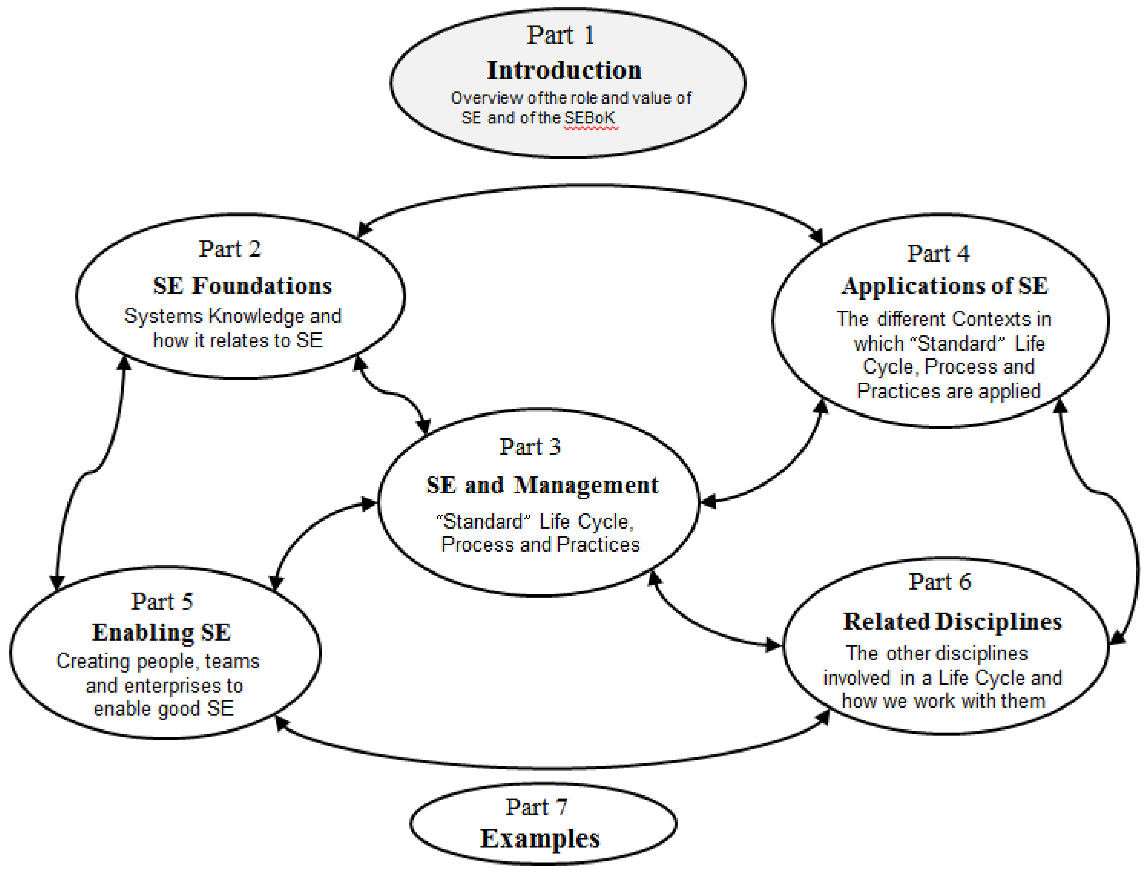


**Figure 1 SEBoK Part 1 in context (SEBoK Original).** For more detail see Structure of the SEBoK

Part 1 also includes an introduction to some of the emerging aspects of systems engineering and a discussion of how these are transforming the discipline. As this knowledge matures it will be migrated into the main body of the SEBoK.

## Part 1 Knowledge Areas

Each part of the SEBoK is divided into knowledge areas (KAs), which are groupings of information with a related theme. Part 1 contains the following KAs:

- Introduction to the SEBoK
- Introduction to Systems Engineering
- Introduction to SE Transformation
- Digital Engineering
- Set Based Design
- SEBoK Users and Uses

## Scope and Context of the SEBoK

While Part 1 introduces Systems Engineering knowledge areas, the remaining SEBoK content (Parts 2 – 6) focuses on domain-independent information—that which is universal to systems engineering regardless of the domain in which it is applied. Part 7 includes examples from real projects. These illustrate the concepts discussed elsewhere in the SEBoK, while detailing considerations relevant to domains such as aerospace, medicine, and transportation.

SE in the context of engineered systems (ES) is the primary scope for the SEBoK, though general systems concepts are also discussed in Part 2. The SEBoK also covers considerations for the disciplines of software engineering and project management, which are strongly intertwined with the practice of SE (see Part 6).

## References

### Works Cited

None

### Primary References

None

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# Introduction to the SEBoK

The SEBoK provides a widely accepted, community-based, and regularly updated baseline of systems engineering (SE) knowledge. Therefore, it is a curated body of knowledge which is updated on a semi-annual basis. This baseline strengthens the mutual understanding across the many disciplines involved in developing and operating systems.

## Topics

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

- Scope of the SEBoK
- Structure of the SEBoK

## References

### Works Cited

None.

### Primary References

INCOSE. 2015. *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*, Fourth Edition. San Diego, CA, USA: International Council on Systems Engineering (INCOSE). INCOSE-TP-2003-002-004.

INCOSE. 2012. *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*, version 3.2.2. San Diego, CA, USA: International Council on Systems Engineering (INCOSE). INCOSE-TP-2003-002-03.2.

Sage, A. and W. Rouse (eds). 2009. *Handbook of Systems Engineering and Management,* 2nd ed. Hoboken, NJ, USA: John Wiley and Sons, Inc.

### Additional References

None.

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# Knowledge Area: Introduction to the SEBoK

## Scope of the SEBoK

The SEBoK is a large, curated compendium of information about systems engineering. It:

- is a guide to the body of SE knowledge which provides references to detailed sources for additional information; it is not a self-contained knowledge resource
- focuses on Engineered Systems contexts, that is socio-technical systems with a recognized SE life cycle,
- while treating social and natural systems as relevant and important environmental considerations (see Part 2)
- describes generic SE life cycle and process knowledge (see Part 3)
- recognizes that SE principles can be applied differently to different types of products, services, enterprises, and systems of systems (SoS) context (see Part 4)
- provides resources for organization support of SE activities (see Part 5)
- explores the interaction between SE and other disciplines, highlighting what systems engineers need to know about these disciplines (see Part 6)
- is domain-independent, with implementation examples to provide domain-specific context (see Part 7)

Each of these considerations depends upon the definition and scope of SE itself, which is the subject of the next section.

### SEBoK Purposes

Ongoing studies of system cost and schedule failures (Gruhl & Stutzke 2005; Johnson 2006, GAO 2016) and safety failures (Leveson 2012) have shown that the failures have mostly come not from their domain disciplines, but from lack of adequate Systems Engineering (NDIA 2003, 2006, 2016). To provide a foundation for the mutual understanding of SE needed to reduce these failure, the SEBoK describes the boundaries, terminology, content, and structure of SE. In so doing, the SEBoK systematically and consistently supports six broad purposes, described in Table 1.

**Table 1. SEBoK Purposes. (SEBoK Original)**

| # | Purpose | Description |
|---|---|---|
| 1 | Inform Practice | Inform systems engineers about the boundaries, terminology, and structure of their discipline and point them to useful information needed to practice SE in any application domain. |
| 2 | Inform Research | Inform researchers about the limitations and gaps in current SE knowledge that should help guide their research agenda. |
| 3 | Inform Interactors | Inform performers in interacting disciplines (system implementation, project and enterprise management, other disciplines) and other stakeholders of the nature and value of SE. |
| 4 | Inform Curriculum Developers | Inform organizations defining the content that should be common in undergraduate and graduate programs in SE. |
| 5 | Inform Certifiers | Inform organizations certifying individuals as qualified to practice systems engineering. |
| 6 | Inform SE Staffing | Inform organizations and managers deciding which competencies that practicing systems engineers should possess in various roles ranging from apprentice to expert. |

The SEBoK is a guide to the body of SE knowledge, not an attempt to capture that knowledge directly. It provides references to more detailed sources of knowledge, all of which are generally available to any interested reader. No proprietary information is referenced, but not all referenced material is free—for example, some books or standards must be purchased from their publishers. The criterion for including a source is simply that the authors & editors believed it offered the best generally available information on a particular subject.

The SEBoK is global in applicability. Although SE is practiced differently from industry to industry and country to country, the SEBoK is written to be useful to systems engineers anywhere. The authors & editors were chosen from diverse locales and industries, and have refined the SEBoK to broaden applicability based on extensive global reviews of several drafts.

The SEBoK aims to inform a wide variety of user communities about essential SE concepts and practices, in ways that can be tailored to different enterprises and activities while retaining greater commonality and consistency than would be possible without the SEBoK. Because the world in which SE is being applied continues to evolve and is dynamic, the SEBoK is designed for easy, continuous updating as new sources of knowledge emerge.

## SEBoK Uses

The communities involved with SE include its various specialists, engineers from disciplines other than systems engineering, managers, researchers, and educators. This diversity means that there is no single best way to use the SEBoK. The SEBoK includes use cases that highlight potential ways that particular communities can draw upon the content of the SEBoK, identify articles of interest to those communities, and discuss primary users (those who use the SEBoK directly), and secondary users (those who use the SEBoK with assistance from a systems engineer). For more on this, see the article SEBoK Users and Uses.

## SEBoK Domain Independent Context

The SEBoK uses language and concepts that are generally accepted for domain-independent SE. For example, the domain-independent conceptual foundations of SE are elaborated in Part 2: Foundations of Systems Engineering. However, each of the numerous domains in which SE is practiced — including telecommunications, finance, medicine, and aerospace — has its own specialized vocabulary and key concepts. Accordingly, the SEBoK is designed to show how its domain-independent material relates to individual domains in two ways.

Firstly, by means of examples that tell stories of how SE is applied in particular domains. Part 7: Systems Engineering Implementation Examples ) consists of examples (case studies and vignettes), each set in a particular domain such as aerospace, medicine, or software, and featuring vocabulary and concepts special to that domain. There are similar vignettes in some of the Use Cases in Part 1. These examples demonstrate the effect of domain on the application of SE and complement the domain-independent information elsewhere in the SEBoK. They show how a concept works in a given domain and provide a fair opportunity for reviewers to reflect on whether there are better ways to capture application-dependent aspects of SE knowledge.

In addition, the SEBoK will contain knowledge areas in Part 4: Applications of Systems Engineering which explicitly describe the domain specific language, approaches, specialized processes and tools, etc. of particular application domains. In this version of the SEBoK there are a limited set of domain knowledge areas.

The SEBoK authors & editors recognize the value of both case studies and domain extensions, both will be expanded in later versions.

# References

## Works Cited

GAO, 2016. *Weapon System Requirements. Detailed Systems Engineering Prior to Product Development Positions Programs for Success*. Government Accounting Office Report to Congressional Committees.

Gruhl, W. and Stutzke, R. 2005. "Werner Gruhl Analysis of SE Investments and NASA Overruns," in R. Stutzke, *Estimating Software-Intensive Systems*. Boston, MA, USA: Addison Wesley, page 290.

Johnson, J. 2006. *My Life Is Failure: 100 Things You Should Know to Be a Better Project Leader*. Boston, MA, USA: Standish Group International.

Leveson, N. 2012. *Engineering a Safer World: Systems Thinking Applied to Safety*. Cambridge, MA, USA: MIT Press.

NDIA (National Defense Industrial Association). 2003. *Top 5 Systems Engineering Issues Top 5 Systems Engineering Issues within DOD and Defense Industry Task Report*. Version 9, dated 1/23/03July. Last accessed 10/25/2019 from https://www.aticourses.com/sampler/TopFiveSystemsEngineeringIssues_In_DefenseIndustry.pdf [1].

NDIA (National Defense Industrial Association). 2006. *Top 5 Systems Engineering Issues Top 5 Systems Engineering Issues within DOD and Defense Industry DOD and Defense Industry: Task Report*. Dated July 26-27, 2006. Last accessed 10/25/2019 from https://ndiastorage.blob.core.usgovcloudapi.net/ndia/2006/systems/Wednesday/rassa5.pdf.

NDIA (National Defense Industrial Association). 2016. *Top Systems Engineering Issues In US Defense Industry 2016*. Version 7c. Last accessed 10/25/2019 from https://www.ndia.org/-/media/sites/ndia/divisions/systems-engineering/studies-and-reports/ndia-top-se-issues-2016-report-v7c.ashx?la=en.

## Primary References

None.

## Additional References

None.

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**SEBoK v. 2.1, released 31 October 2019**

# References

[1] https://ndiastorage.blob.core.usgovcloudapi.net/ndia/2006/systems/Wednesday/rassa5.pdf

# Structure of the SEBoK

The **Guide to the Systems Engineering Body of Knowledge (SEBoK)** is a living authoritative guide that discusses knowledge relevant to Systems Engineering. SEBoK does not contain all of this knowledge itself, but provides a starting point and key resources to allow the reader to navigate the wider body of knowledge that exists in published sources. To do this SEBoK:

- Defines relevant knowledge and structures it to facilitate understanding.
- Provides short discussions of key idea, principles and concepts within that structure.
- Points to reference sources important to the discipline, which explore these ideas in more detail.

In doing this it is inevitable that differences in terminology, alternative approaches and even fundamentally different ways of thinking within the knowledge will appear. SEBoK attempts were possible to provide clarity of similar or overlapping idea, or to highlight real differences and the reasons behind them. In particular the SEBoK Glossary of Terms contains the most used or generally agreed definitions of terms when it can, but may highlight more than one definition if needed to show breadth of current thinking.

## SEBoK Structure

Figure 1, below, gives a summary of the 7 parts of the SEBoK and how they are related.

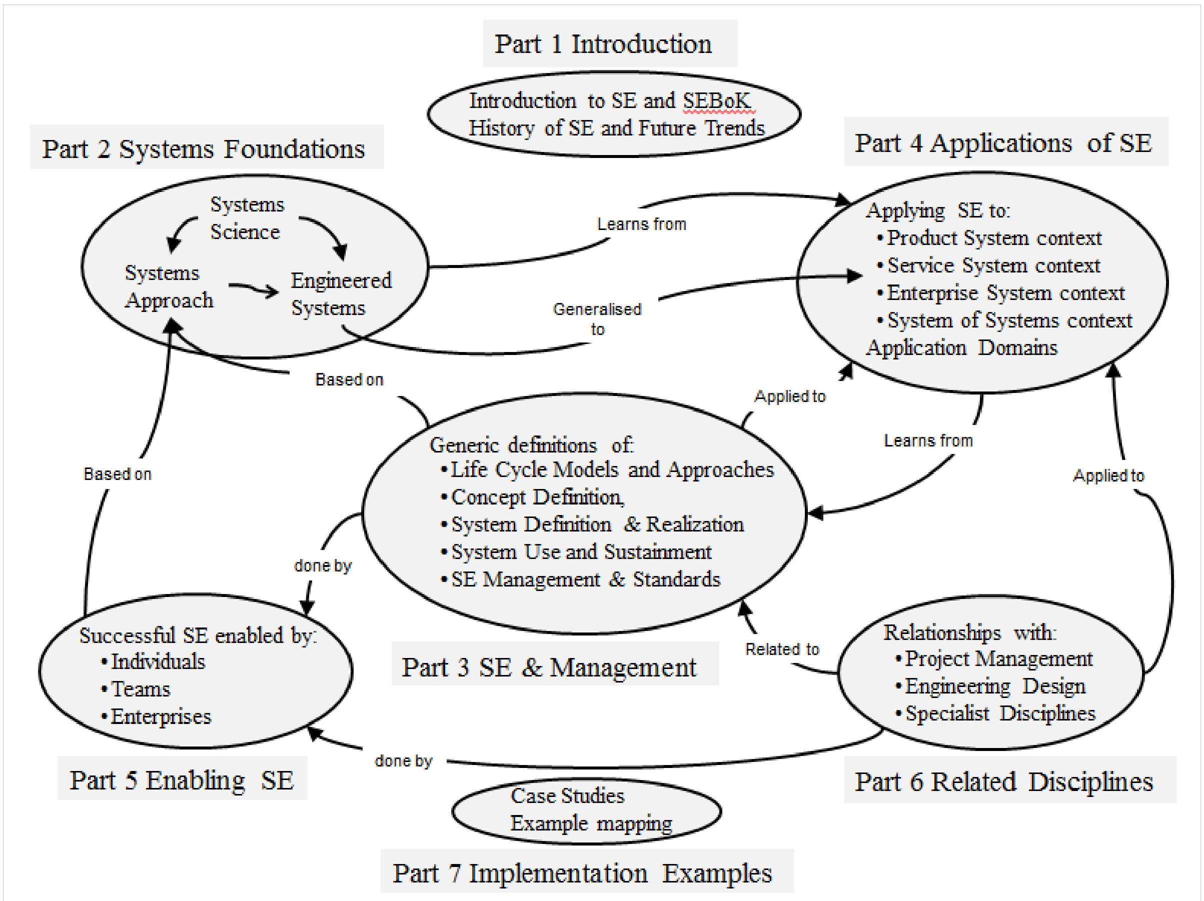


**Figure 1 Relationships between SEBoK Parts (Adcock et al. 2016).**

The scope of each part and the key relationships amongst them is briefly discussed below. For a more detailed discussion of how this structure was evolved see (Adcock et al, 2016).

## Overview of Parts

### Part 1: SEBoK Introduction

This part explains the scope, context, and structure of the SEBoK, and of systems engineering (SE).

An overview of who should use the SEBoK, and for what purpose, is followed by detailed use cases. The economic value, history, and relationship to other disciplines are discussed. Part 1 also contains a section which discussed the future evolution of the SEBoK and allows for new areas of content to be introduced before being transitioned into other SEBoK parts.

### Part 2: Foundations of Systems Engineering

This part provides an introduction and overview of areas of knowledge which provide the foundations of SE.

A discussion of the definitions and basic concepts of system is followed by an overview of the principles, concepts, methods, models and patterns of some of the key foundational areas of systems science. This includes a detailed consideration of the foundational knowledge related to systems models and modelling.

Part 2 looks in more detail at two aspects of this foundational knowledge of particular value to SE. The first is to discuss aspects of systems knowledge related to a systems approach to complex problems and opportunities. This approach provides foundations for how SE is defined and practices (see Parts 3 and 5 below). The second is to describe the different ways in which system concepts are applied to real world concerns. The SEBoK defines an engineered system (ES) as the primary focus for the application of SE (see Part 4 below).

### Part 3: Systems Engineering and Management

This part describes generic knowledge on the practice of SE and related management activities.

Part 3 begins with the life cycle models common in SE and the general principles behind their application. It then moves on to SE management activities. Covering both technical activities such as requirements, architecture, test and evaluation; and management activities such as planning, measurement, risk. Next is product and service life management, a distinct area of SE management that emphasizes the entire life cycle including retirement and disposal. An account of SE standards concludes this part.

Focused on what many think of as the main body of SE, including best practices and common pitfalls, this part constitutes a substantial proportion of the SEBoK. As already discussed, the knowledge in Part 3 is based on the systems approach from Part 2. The links between Part 3 and the other parts of the SEBoK are discussed below.

### Part 4: Applications of Systems Engineering

This part describes how to apply SE principles to different types of system context.

Part 4 focuses on four major engineered system contexts in turn: products, services, enterprises, and systems of systems (SoS). For each one the system abstraction, commercial relationships and application of generic SE is described.

The generalized contexts above should be viewed as overlapping models of how SE can be applied in different kinds of situation. Combinations of one or more of them are fully realized when applied in an application domain. Part 4 currently described this application in a small number of such domains. This will be expanded in later updates. The applications of SE in this part describe the real world practice of SE. The generalized knowledge in both Parts 2 and 3 evolves through what we learn from these applications. Part 2 includes a discussion of this relationship between theory and practice.

### Part 5: Enabling Systems Engineering

This part describes how to organize to enable the success performance of SE activities.

Part 4 covers knowledge at the enterprise, team, or individual level. The range of considerations extends from value proposition, business purpose, and governance, down to competency, personal development as a systems engineer, and ethics.

All of these relate to the baseline definitions of SE in Part 3, further generalized in the levels of application in Part 4. The systems approach in Part 2 should also form a foundation for this part. Since the practice of SE is transdisciplinary, Part 5 also has a link to Part 6 as discussed below.

### Part 6: Related Disciplines

This part describes the relationships between SE and other disciplines.

Part 6 covers the links between SE and software engineering (SwE), project management (PM), industrial engineering and procurement. It also describes how SE is related to specialty engineering, which describes the various system "–ilities" (like reliability, availability, and maintainability) that SE must balance and integrate.

The knowledge in this part provides an interface to other bodies of knowledge, focused on how it is linked to Parts 3, 5 and 5 above.

### Part 7: Systems Engineering Implementation Examples

A set of real-world examples of SE activities forms the natural conclusion of the SEBoK. These come in two forms: case studies, which refer the reader to and summarize published examinations of the successes and challenges of SE programs, and vignettes, which are brief, self-contained wiki articles. This part is a key place to look within the SEBoK for lessons learned, best practices, and patterns. Many links connect material in the examples to the conceptual, methodological, and other content elsewhere in the SEBoK.

### Addenda

The SEBoK contains a Glossary of Terms, which provides authoritatively-referenced definitions of key terms. This information is displayed when the reader hovers the mouse pointer over a glossary term within an article. It also contains a list of Primary References, with additional information about each reference. Quicklinks in the left margin provide additional background information, including a table of contents, a listing of articles by topic [1], and a list of Acronyms.

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### Primary References

None.

### Additional References

None.

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[1] http://sebokwiki.org/1.1.1/index.php?title=Category:Topic

# Knowledge Area: Introduction to Systems Engineering

# Introduction to Systems Engineering

The primary focus of the SEBoK is on the current baseline of knowledge describing the practice of domain independent systems engineering (SE). This Knowledge Area (KA) contains topic articles which provide an overview of SE practice and discuss its economic value, historic evolution and key relationships.

## Topics

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

- Systems Engineering Overview
- Economic Value of Systems Engineering
- Systems Engineering: Historic and Future Challenges
- Systems Engineering and Other Disciplines

## Systems Engineering

SE is a transdisciplinary approach and means to enable the realization of successful systems. Successful systems must satisfy the needs of its customers, users and other stakeholders. Some key elements of systems engineering are highlighted in Figure 1 and include:

- The principles and concepts that characterize a system, where a system is an interacting combination of system elements to accomplish a defined objective(s). The system interacts with its environment, which may include other systems, users, and the natural environment. The system elements that compose the system may include hardware, software, firmware, people, information, techniques, facilities, services, and other support elements.
- A systems engineer is a person or role who supports this transdisciplinary approach. In particular, the systems engineer often serves to elicit and translate customer needs into specifications that can be realized by the system development team.
- In order to help realize successful systems, the systems engineer supports a set of life cycle processes beginning early in conceptual design and continuing throughout the life cycle of the system through its manufacture, deployment, use and disposal. The systems engineer must analyze, specify, design, and verify the system to ensure that its functional, interface, performance, physical, and other quality characteristics, and cost are balanced to meet the needs of the system stakeholders.
- A systems engineer helps ensure the elements of the system fit together to accomplish the objectives of the whole, and ultimately satisfy the needs of the customers and other stakeholders who will acquire and use the system.

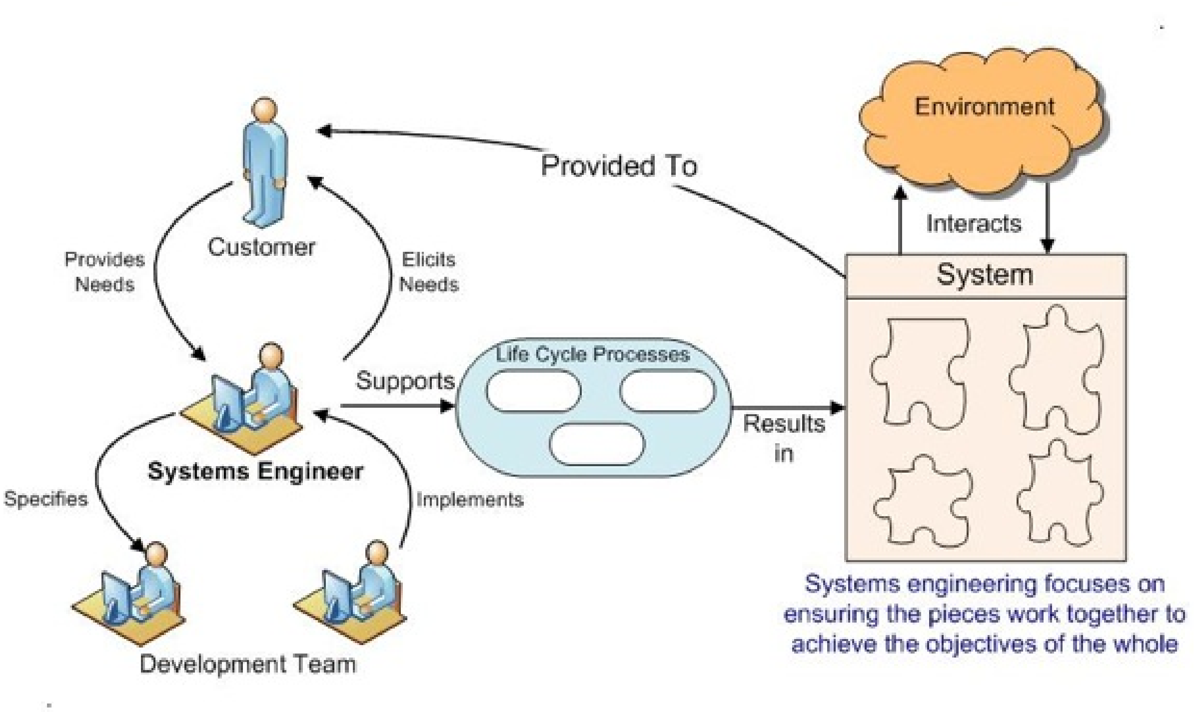


**Figure 1. Key Elements of Systems Engineering.** (SEBoK Original)

## References

None.

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# Systems Engineering Overview

Systems engineering (SE) is a transdisciplinary approach and means to enable the realization of successful systems. Successful systems must satisfy the needs of their customers, users and other stakeholders. This article provides an overview SE as discussed in the SEBoK and the relationship between SE and systems (for additional information on this, please see Part 2).

## Systems and Systems Engineering

In the broad community, the term system "system," may mean a collection of technical, natural or social elements, or a combination of all three. This may produce ambiguities at times: for example, does "management" refer to management of the SE process, or management of the system being engineered? As with many special disciplines, SE uses terms in ways that may be unfamiliar outside the discipline. For example, in systems science and therefore SE, "open" means that a system is able to interact with its environment--as opposed to being "closed" to its environment. But in the broader engineering world we would read "open" to mean "non-proprietary" or "publicly agreed upon." In such cases, the SEBoK tries to avoid misinterpretation by elaborating the alternatives e.g. "system management" or "systems engineering management".

The SEBoK seeks to position SE within the broader scope of knowledge which considers systems as part of its foundations. To do this without attempting to re-define general systems terminology SEBoK introduces two related definitions specific to SE:

- An engineered system, is a technical or socio-technical systems system which is the subject of a SE life cycle
- An engineered system is a system designed or adapted to interact with an anticipated operational environment to achieve one or more intended purposes while complying with applicable constraints.
- An engineered system context centers around an engineered system but also includes its relationships other engineered, social or natural systems in one or more defined environments.

Since the province of SE is an engineered systems, most SE literature assumes this in its terminology. Thus, in an SE discussion, "system architecture" would refer to the architecture of the system being engineered (e.g., a spacecraft) and not the architecture of a natural system outside its boundary (e.g., the solar system). In fact, a spacecraft architecture would cover the wider system context including external factors such as changes in gravity and external air pressure and how these affect the spacecraft's technical and human elements. Thus, the term "system architecture" more properly refers to the engineered system context. The SEBoK tries to be more explicit about this, but may still make these kinds of assumption when referring directly to other SE literature.

An extensive glossary of terms identifies how terms are used in the SEBoK, and shows how their meanings may vary in different contexts. As needed, the glossary includes pointers to articles providing more detail.

For more about the definition of systems, see the article What is a System? in Part 2. The primary focus of SEBoK Part 3: Systems Engineering and Management, and Part 4: Applications of Systems Engineering is on how to create or change an engineered system to fulfill the goals of stakeholders within these wider system contexts. The knowledge in Part 5: Enabling Systems Engineering and Part 6: Systems Engineering and Other Disciplines examines the need for SE itself to be integrated and supported within the human activity systems in which it is performed, and the relationships between SE and other engineering and management disciplines.

# Scope of Systems Engineering within the Engineered Systems Domain

The scope of SE does not include everything involved in the engineer and management of an engineered system. Activities can be part of the SE environment, but other than the specific management of the SE function, not considered to be part of SE. Examples include system construction, manufacturing, funding, and general management. This is reflected in the International Council on Systems Engineering (INCOSE) top-level definition of systems engineering as, “A transdisiplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods.” (Fellows 2019) Although SE can *enable* the realization of a successful system, if an activity that is outside the scope of SE, such as manufacturing, is poorly managed and executed, SE cannot *ensure* a successful realization.

A convenient way to define the scope of SE within engineering and management is to develop a Venn diagram. Figure 3 shows the relationship between SE, system implementation, and project/systems management. Activities, such as analyzing alternative methods for production, testing, and operations, are part of SE planning and analysis functions. Such activities as production line equipment ordering and installation, and its use in manufacturing, while still important SE environment considerations, stand outside the SE boundary. Note that as defined in Figure 3, system implementation engineering also includes the software production aspects of system implementation. Software engineering, then, is not considered a subset of SE.

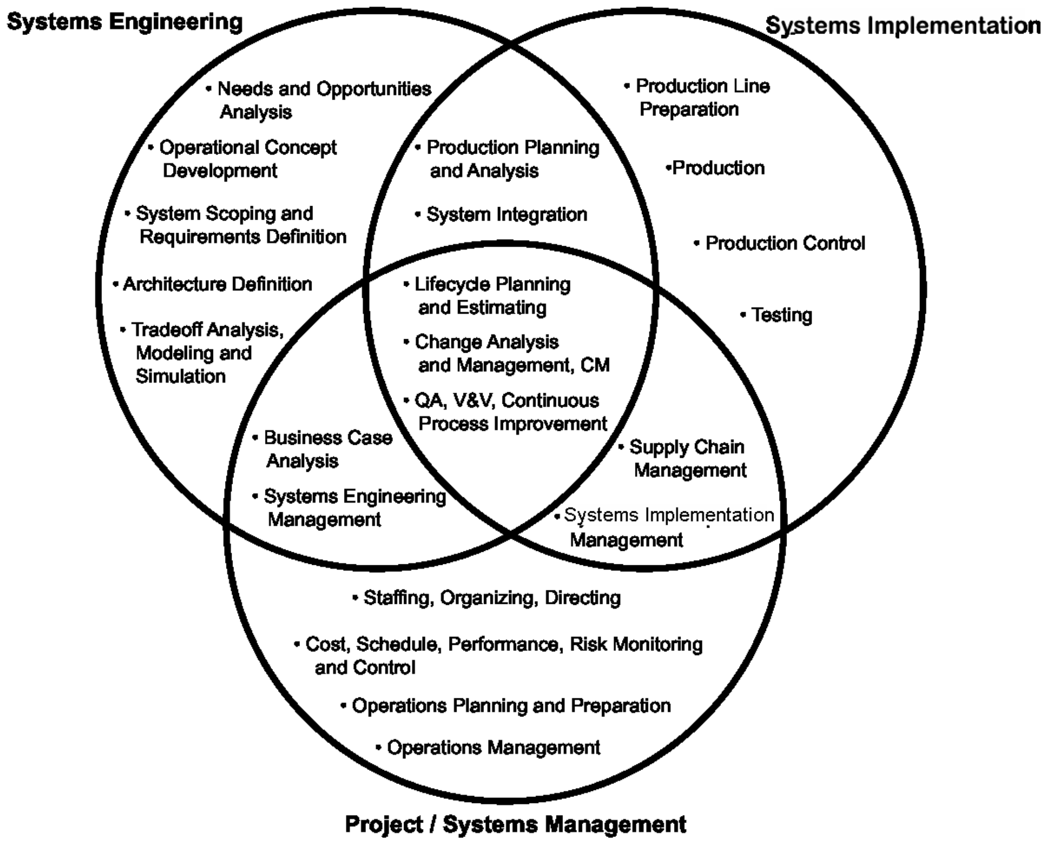


**Figure 3. System Boundaries of Systems Engineering, Systems Implementation, and Project/Systems Management.** (SEBoK Original)

Traditional definitions of SE have emphasized sequential performance of SE activities, e.g., “documenting requirements, then proceeding with design synthesis …”. (INCOSE 2012) Originally, the SEBoK authors & editors departed from tradition to emphasize the inevitable intertwining of system requirements definition and system design in the following revised definition of SE:

*Systems Engineering (SE) is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on holistically and concurrently understanding stakeholder needs; exploring opportunities; documenting requirements; and synthesizing, verifying, validating, and evolving solutions while considering the complete problem, from system concept exploration through system disposal.* (INCOSE 2012, modified)

More recently, the INCOSE Fellows have offered an updated definition of SE that has been adopted as the official INCOSE definition:

*A transdisiplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods.*

Part 3: Systems Engineering and Management, elaborates on the definition above to flesh out the scope of SE more fully.

## Systems Engineering and Engineered Systems Project Life Cycle Context

SE is performed as part of a life cycel approach. Figure 2 summarizes the main agents, activities, and artifacts involved in the life cycle of SE, in the context of a project to create and evolve an engineered system.

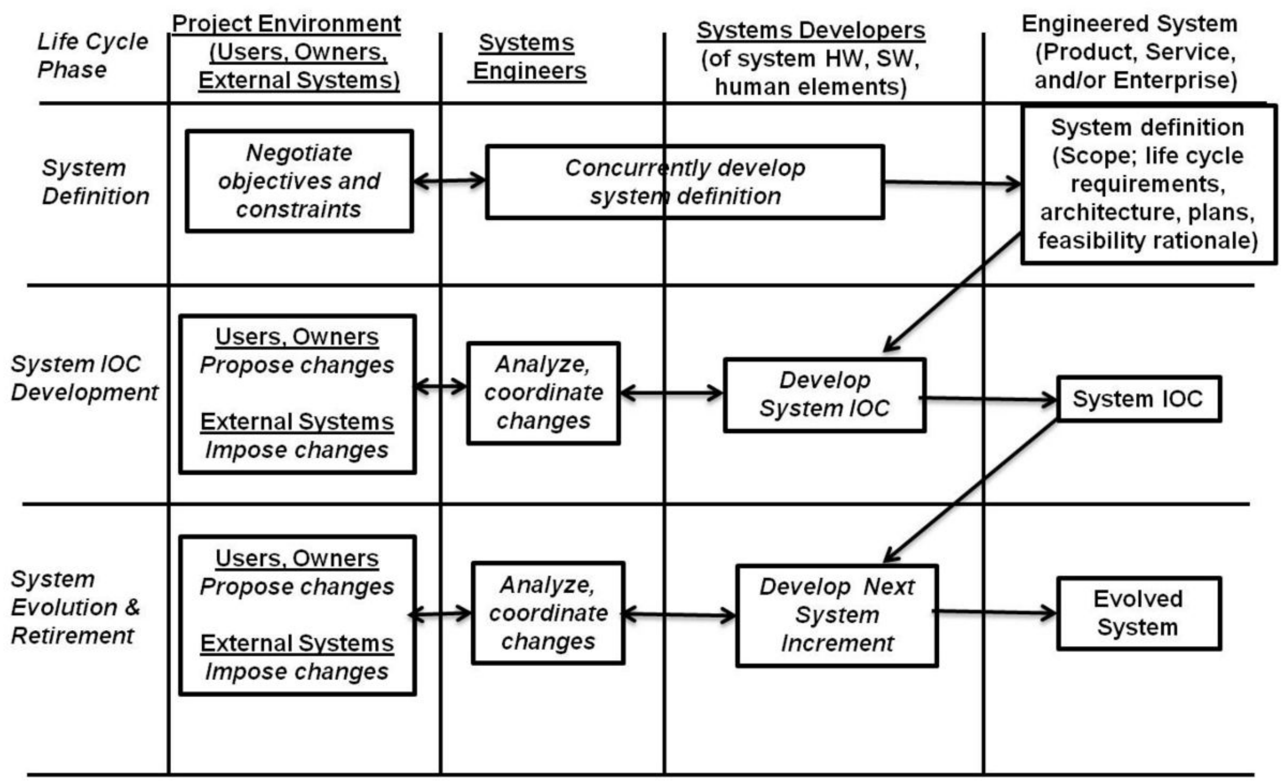


**Figure 2. SE and Engineered System Project Life Cycle Context: Related Agents, Activities, and Artifacts.** (SEBoK Original)

For each primary project life cycle phase, we see activities being performed by primary agents, changing the state of the ES.

- Primary project life cycle phases appear in the leftmost column. They are system definition, system initial operational capability (IOC) development, and system evolution and retirement.
- Primary agents appear in the three inner columns of the top row. They are systems engineers, systems developers, and primary project-external bodies (users, owners, external systems) which constitute the project environment.
- The ES, which appears in the rightmost column, may be a product, a service, and/or an enterprise.

In each row:

- boxes in each inner column show activities being performed by the agent listed in the top row of that column
- the resulting artifacts appears in the rightmost box.

Arrows indicate dependencies: an arrow from box A to box B means that the successful outcome of box B depends on the successful outcome of box A. Two-headed arrows indicate a two-way dependencies: an arrow that points both from box A to box B and from box B to box A means that the successful outcome of each box depends on the successful outcome of the other.

For example, consider how the inevitable changes that arise during system development and evolution are handled:

- One box shows that the system's users and owners may propose changes.
- The changes must be negotiated with the systems developers, who are shown in a second box.
- The negotiations are mediated by systems engineers, who are shown in a third box in between the first two.
- Since the proposed changes run from left to right and the counter-proposals run from right to left, all three boxes are connected by two-headed arrows. This reflects the two-way dependencies of the negotiation.

An agent-activity-artifact diagram like Figure 1 can be used to capture complex interactions. Taking a more detailed view of the present example demonstrates that:

- The system's users and owners (stakeholders) propose changes to respond to competitive threats or opportunities, or to adapt to changes imposed by independently evolving external systems, such as Commercial-off-the-Shelf COTS products, cloud services, or supply chain enablers.
- Negotiation among these stakeholders and the system developers follows, mediated by the SEs.
- The role of the SEs is to analyze the relative costs and benefits of alternative change proposals, and synthesize mutually satisfactory solutions.

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## Additional References

None.

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# Economic Value of Systems Engineering

## The Increasing Value of Systems Engineering

With traditional projects, such as railroads, reservoirs, and refrigerators, a systems engineer faced a self-contained system that typically had relatively stable requirements, a sound scientific base, and numerous previous precedents. As most modern systems become parts within one or more evolving systems of systems (SoS), the performance of effective SE now takes on an ever-higher economic value, as the systems feature a rapidly increasing scale, dynamism, interdependence, human-intensiveness, sources of vulnerability, and novelty.

This is corroborated by the implementation examples in Part 7. Shortfalls in SE lead to either cancellation of already expensive systems or even more expensive systems in terms of total cost of ownership or loss of human life. Part 7 presents the problems in the United States Federal Aviation Administration (FAA) Advanced Automation System (AAS), United States Federal Bureau of Investigation (FBI) Virtual Case File System, the Hubble Space Telescope Case Study, and the Therac-25 medical linear accelerator.

On the other hand, the Global Positioning System (GPS), Miniature Seeker Technology Integration Project (MSTI), and Next Generation Medical Infusion Pump Project all demonstrate that investment in thorough SE results in highly cost-effective systems. Figure 1 summarizes the analyses data by Werner Gruhl, which relates investment levels in SE to cost overruns of the United States National Aeronautics and Space Administration (NASA) projects (Stutzke 2005). The results indicate that there is a general correlation between the amount invested in SE within a program and cost overruns, demonstrating the critical role of properly allocating SE resources.

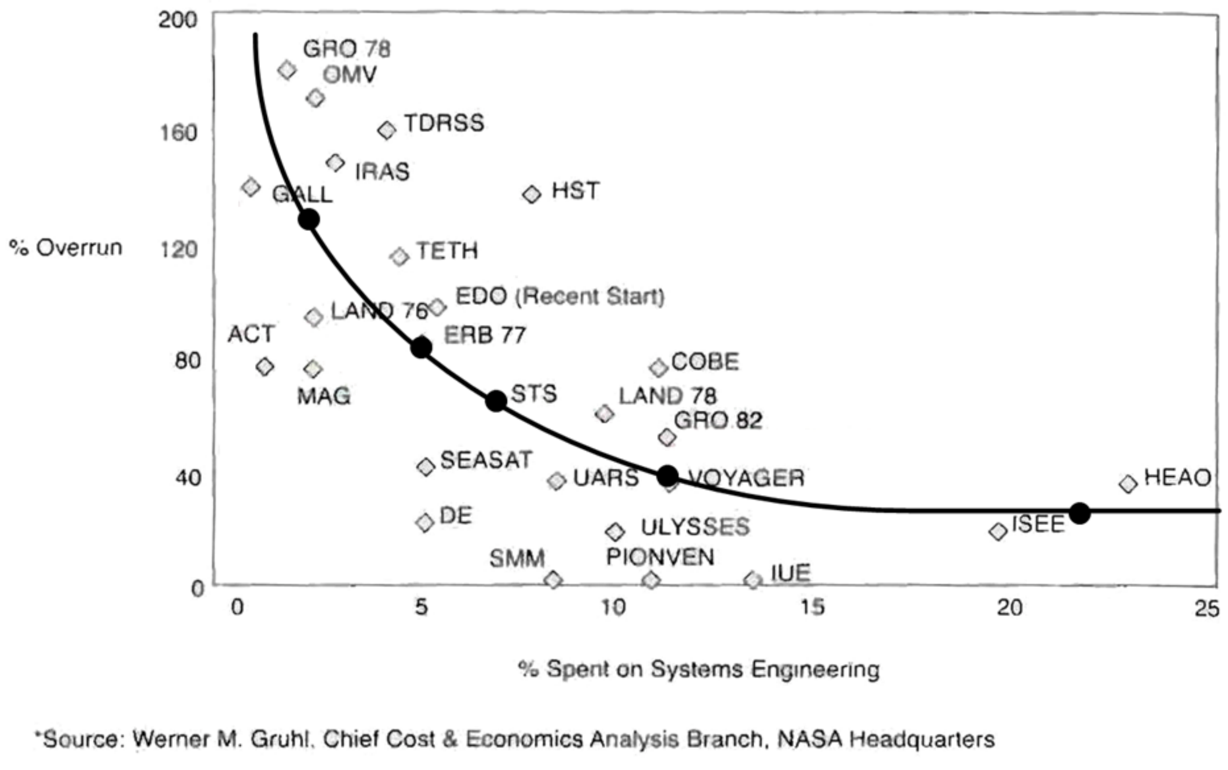


**Figure 1. Relation of SE Investments to NASA Program Cost Overruns (Stutzke 2005).** Released by NASA HDQRT/Gruhl.

## Further Quantitative Evidence of the Value of Systems Engineering

Analysis of the effects of shortfalls in systems architecture and risk resolution (the results of insufficient SE) for software-intensive systems in the 161-project Constructive Cost Model II (COCOMO™ II) database, shows a statistically significant increase in rework costs as a function of project size measured in source lines of code (SLOC): averages of 18% rework for ten-thousand-SLOC projects and 91% rework for ten-million-SLOC projects. This data has influenced many major system projects to reconsider initial underinvestment in SE (e.g., Boehm et al. 2004), and well as to address “how much SE is enough” by balancing the risks of under-investing in SE against those of over-investing (often called “analysis paralysis”), as shown in Figure 2 (Boehm, Valerdi, and Honour 2008).

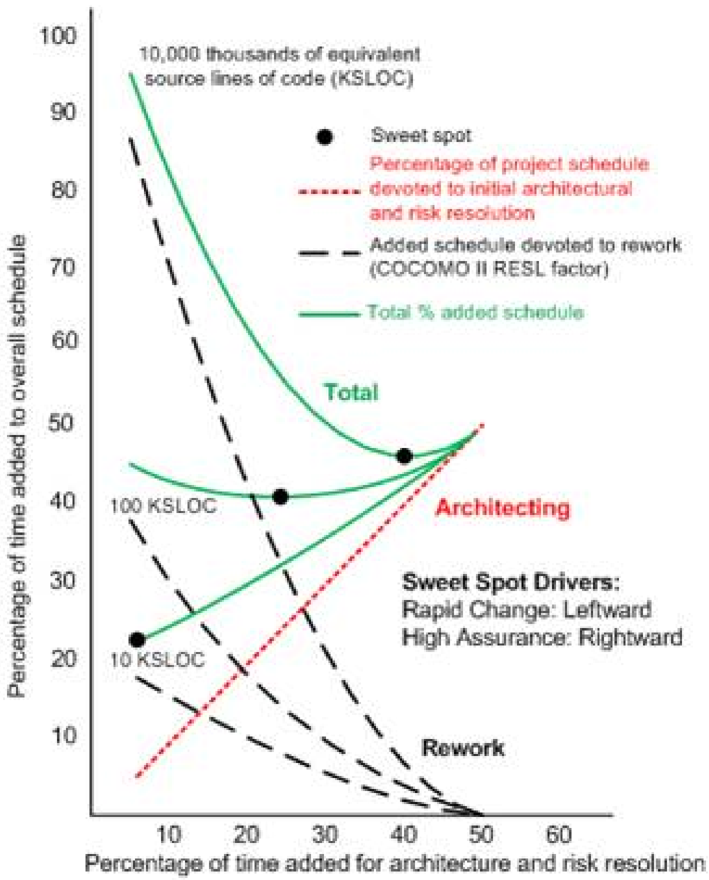


**Figure 2. Risk-Balanced “How Much SE Is Enough” (Boehm, Valerdi, and Honour 2008).** Reprinted with permission of John Wiley & Sons Inc. All other rights are reserved by the copyright owner.

Typically, small projects can quickly compensate for neglected SE interface definition and risk resolution; however, as projects grow larger and have more independently-developed components, the cost of late rework negates any savings in reduced SE effort. Additionally, medium-sized projects have relatively flat operating regions, while very large projects pay extremely large penalties for neglecting thorough SE. Extensive surveys and case study analyses corroborate these results.

Survey data on software cost and schedule overruns in *My Life Is Failure: 100 Things You Should Know to Be a Better Project Leader* (Johnson 2006) indicates that the primary sources of the roughly 50% of the commercial projects with serious “software overruns” are the result of shortfalls in SE (lack of user input, incomplete requirements, unrealistic expectations, unclear objectives, and unrealistic schedules). The extensive survey of 46 government-contracted industry projects conducted by the Software Engineering Institute (SEI)/National Defense Industrial Association (NDIA) illustrated a strong correlation between higher project SE capability and higher project performance (Elm et al. 2007). Ongoing research that combined project data and survey data reported in

“Toward an Understanding of The Value of SE” (Honour 2003) and “Effective Characterization Parameters for Measuring SE” (Honour 2010) has provided additional evidence as to the economic value of SE and further insights on critical factors the affect SE success.

A calibrated model for determining “how much SE is enough”, the Constructive Systems Engineering Cost Model (COSYSMO) has been developed and is discussed in (Valerdi 2008). It estimates the number of person-months that a project needs for SE as a function of system size (i.e., requirements, interfaces, algorithms, and operational scenarios), modified by 14 factors (i.e., requirements understanding, technology risk, personnel experience, etc.), which dictates the amount of SE effort needed. Other economic considerations of SE include the costs and benefits of reuse (Wang, Valerdi and Fortune 2010), the management of SE assets across product lines (Fortune and Valerdi 2013), the impact of SE on project risk (Madachy and Valerdi 2010), and the role of requirements volatility on SE effort (Pena and Valerdi 2010).

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# Systems Engineering: Historic and Future Challenges

Humans have faced increasingly complex challenges and have had to think systematically and holistically in order to produce successful responses to these challenges. From these responses, generalists have developed generic principles and practices for replicating success. Some of these principles and practices have contributed to the evolution of systems engineering as a discipline.

## Historical Perspective

Some of the earliest relevant challenges were in organizing cities. Emerging cities relied on functions such as storing grain and emergency supplies, defending the stores and the city, supporting transportation and trade, providing a water supply, and accommodating palaces, citadels, afterlife preparations, and temples. The considerable holistic planning and organizational skills required to realize these functions were independently developed in the Middle East, Egypt, Asia, and Latin America, as described in Lewis Mumford's *The City in History* (Mumford 1961).

Megacities, and mobile cities for military operations, such as those present in the Roman Empire, emerged next, bringing another wave of challenges and responses. These also spawned generalists and their ideological works, such as Vitruvius and his *Ten Books on Architecture* (Vitruvius: Morgan transl. 1960). "Architecture" in Rome meant not just buildings, but also aqueducts, central heating, surveying, landscaping, and overall planning of cities.

The Industrial Revolution brought another wave of challenges and responses. In the nineteenth century, new holistic thinking and planning went into creating and sustaining transportation systems, including canal, railroad, and metropolitan transit. General treatises, such as *The Economic Theory of the Location of Railroads* (Wellington 1887), appeared in this period. The early twentieth century saw large-scale industrial enterprise engineering, such as the Ford automotive assembly plants, along with treatises like *The Principles of Scientific Management* (Taylor 1911).

The Second World War presented challenges around the complexities of real-time command and control of extremely large multinational land, sea, and air forces and their associated logistics and intelligence functions. The postwar period brought the Cold War and Russian space achievements. The U.S. and its allies responded to these challenges by investing heavily in researching and developing principles, methods, processes, and tools for military defense systems, complemented by initiatives addressing industrial and other governmental systems. Landmark results included the codification of operations research and SE in *Introduction to Operations Research* (Churchman et. al 1957), Warfield (1956), and Goode-Machol (1957) and the Rand Corporation approach as seen in *Efficiency in Government Through Systems Analysis* (McKean 1958). In theories of system behavior and SE, we see cybernetics (Weiner 1948), system dynamics (Forrester 1961), general systems theory (Bertalanffy 1968), and mathematical systems engineering theory (Wymore 1977).

Two further sources of challenge began to emerge in the 1960s, and accelerated in the 1970s through the 1990s: awareness of the criticality of the human element, and the growth of software functionality in engineered systems.

Concerning awareness of the human element, the response was a reorientation from traditional SE toward “soft” SE approaches. Traditional hardware-oriented SE featured sequential processes, pre-specified requirements, functional-hierarchy architectures, mathematics-based solutions, and single-step system development. A Soft Systems approach to SE is characterized by emergent requirements, concurrent definition of requirements and solutions, combinations of layered service-oriented and functional-hierarchy architectures, heuristics-based solutions, and evolutionary system development. Good examples are societal systems (Warfield 1976), soft systems methodology (Checkland 1981), and systems architecting (Rechtin 1991 and Rechtin-Maier 1997). As with Vitruvius, "architecting" in this sense is not confined to producing blueprints from requirements, but instead extends to concurrent work on operational concepts, requirements, structure, and life cycle planning.

The rise of software as a critical element of systems led to the definition of Software Engineering as a closely related discipline to SE. The Systems Engineering and Software Engineering knowledge area in Part 6: Related Disciplines describes how software engineering applies the principles of SE to the life cycle of computational systems (in which any hardware elements form the platform for software functionality) and of the embedded software elements within physical systems.

## Evolution of Systems Engineering Challenges

Since 1990, the rapidly increasing scale, dynamism, and vulnerabilities in the systems being engineered have presented ever-greater challenges. The rapid evolution of communication, computer processing, human interface, mobile power storage and other technologies offers efficient interoperability of net-centric products and services, but brings new sources of system vulnerability and obsolescence as new solutions (clouds, social networks, search engines, geo-location services, recommendation services, and electrical grid and industrial control systems) proliferate and compete with each other.

Similarly, assessing and integrating new technologies with increasing rates of change presents further SE challenges. This is happening in such areas as biotechnology, nanotechnology, and combinations of physical and biological entities, mobile networking, social network technology, cooperative autonomous agent technology, massively parallel data processing, cloud computing, and data mining technology. Ambitious projects to create smart services, smart hospitals, energy grids, and cities are under way. These promise to improve system capabilities and quality of life, but carry risks of reliance on immature technologies or on combinations of technologies with incompatible objectives or assumptions. SE is increasingly needed but increasingly challenged in the quest to make future systems scalable, stable, adaptable, and humane.

It is generally recognized that there is no one-size-fits-all life cycle model that works best for these complex system challenges. Many systems engineering practices have evolved in response to this challenge making use of lean, agile, iterative and evolutionary approaches to provide methods for simultaneously achieving high-effectiveness, high-assurance, resilient, adaptive, and life cycle affordable systems;. The emergence of system of systems (SoS) approaches have also been introduced, in which independent system elements developed and deployed within their own life cycle are brought together to address mission and enterprise needs.

Creating flexible and tailored life cycles and developing solutions using combinations of engineered systems, each with its own life cycle focus, creates its own challenges of life cycle management and control. In response to this enterprise systems engineering (ESE) approaches have been developed, which consider the enterprise itself as a system to be engineered. Thus, many of the ambitious smart system projects discussed above are being delivered as a program of managed life cycles synchronized against a top down understanding of enterprise needs. It is important that within these approaches we create the flexibility to allow for bottom-up solutions developed by combining open, interoperable system elements to emerge and be integrated into the evolving solutions.

More recently, emerging technologies such as artificial intelligence, machine learning, deep learning, mechatronics, cyberphysical systems, cybersecurity, Internet of Things (IoT), additive manufacturing, digital thread, Factory 4.0, etc. are challenging approaches to SE.

Many of the challenges above, and the SE response to them, increase the breadth and complexity of the systems information being considered. This increases the need for up to date, authoritative and shared models to support life cycle decisions. This has led to the development and ongoing evolution of model-based systems engineering (MBSE) approaches.

## Future Challenges

The INCOSE Systems Engineering Vision 2025 (INCOSE 2014) considers the issues discussed above and from this gives an overview of the likely nature of the systems of the future. This forms the context in which SE will be practiced and give a starting point for considering how SE will need to evolve:

- Future systems will need to respond to an ever growing and diverse spectrum of societal needs in order to create value. Individual engineered system life cycles may still need to respond to an identified stakeholder need and customer time and cost constraint. However, they will also form part of a larger synchronized response to strategic enterprise goals and/or societal challenges. System life cycles will need to be aligned with global trends in industry, economy and society, which will, in turn, influence system needs and expectations.
- Future systems will need to harness the ever growing body of technology innovations while protecting against unintended consequences. Engineered system products and services need to become smarter, self-organized, sustainable, resource efficient, robust and safe in order to meet stakeholder demands.
- These future systems will need to be engineered by an evolving, diverse workforce which, with increasingly capable tools, can innovate and respond to competitive pressures.

These future challenges change the role of software and people in engineered systems. The Systems Engineering and Software Engineering knowledge area consider the increasing role of software in engineered systems and its impact on SE. In particular it considers the increasing importance of Cyber-Physical Systems in which technology, software and people play an equally important part in the engineered systems solutions. This requires a SE approach able to understand the impact of different types of technology, and especially the constraints and opportunities of software and human elements, in all aspects of life cycle of an engineered systems.

All of the challenges, and the SE responses to them, make it even more important that SE continues its transition to a model based discipline.

The changes needed to meet these challenges will impact the life cycle processes described in Part 3: Systems Engineering and Management and on the knowledge, skills and attitudes of systems engineers and the ways they are organized to work with other disciplines as discussed in Part 5: Enabling Systems Engineering and Part 6: Related Disciplines. The different ways in which SE is applied to different types of system context, as described in Part 4: Applications of SE, will be a particular focus for further evolution to meet these challenges. The Introduction to SE Transformation knowledge area in SEBoK Part 1 describes how SE is beginning to change to meet these challenges.

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# Systems Engineering and Other Disciplines

As discussed in the Scope of the SEBoK article, there are many touch points and overlaps between systems engineering (SE) and other disciplines. Systems engineers should have a basic understanding of the nature of these other disciplines, and often need to understand aspects of another discipline in detail. This article describes the landscape of disciplines that are intertwined with SE. For a closer view of the individual disciplines, see Part 6.

## Engineering Disciplines Other than Systems Engineering

Engineering disciplines are mostly component-oriented and value-neutral in their intellectual content (Boehm and Jain 2006). Their underlying laws and equations, such as Ohm's Law, Hooke's Law, Newton's Laws, Maxwell's equations, the Navier-Stokes equations, Knuth's compendia of sorting and searching algorithms, and Fitts's Law of human movement, pertain to performance in a system-of-interest. They do not address how that performance contributes to the value propositions of stakeholders.

In contrast, SE is more holistic than component-oriented, and more stakeholder value-oriented than value-neutral, performance-oriented in its intellectual content. Realizing successful systems requires reasoning with stakeholders about the relative value of alternative realizations, and about the organization of components and people into a system that satisfies the often-conflicting value propositions of stakeholders. Stakeholders who are critical to the system's success include funders, owners, users, operators, maintainers, manufacturers, and safety and pollution regulators.

In some disciplines, the engineer evaluates and integrates design elements into a system that satisfies proxies of value. The wider the scope of the SoI, the broader the set of SE skills the engineer needs.

For example, an aeronautical engineer might integrate mechanical, electrical, fluid, combustion-chemical, software, and cockpit design elements into a system that satisfies proxies of value like flight range, payload capacity, fuel consumption, maneuverability, and cost of production and maintenance. In so doing, the engineer operates partly as a systems engineer. The SoI is the aircraft itself and the engineer applies aircraft-domain expertise.

However, the same engineer could participate in the engineering of passenger services, airport configurations, baggage handling, and local surface transportation options. All of these contribute to the value propositions of success-critical stakeholders. The SoIs are wider, and the engineer needs broader SE knowledge, skills, and abilities to operate as a systems engineer. The aircraft-domain expertise remains needed for effective engineering of the wider systems. As discussed in (Guest 1991), most good systems engineers are “T-shaped” people, with both a working knowledge of wider-system considerations, and a deep expertise in a relevant domain, such as aeronautical, manufacturing, software, or human factors engineering.

Engineering disciplines that are intertwined with SE include software engineering (SwE), human factors engineering, and industrial engineering. SwE and SE are not just allied disciplines, they are intimately intertwined (Boehm 1994). Most functionality of commercial and government systems is now implemented in software, and software plays a prominent or dominant role in differentiating competing systems in the marketplace. Software is usually prominent in modern systems architectures and is often the “glue” for integrating complex system components.

The scope of SwE includes both software SE and software construction, but does not include hardware SE. Thus neither SwE nor SE is a subset of the other. See Figure 1 in Scope of the SEBoK. For a definition of the relationship between the SEBoK and the *Guide to the Software Engineering Body of Knowledge (SWEBOK)*, which is published by the Institute of Electrical and Electronics Engineers (IEEE) (Bourque and Fairley 2014.) see Systems Engineering and Software Engineering.

Human factors engineering, from micro-ergonomics to macro-ergonomics, is intertwined with SE (Booher 2003; Pew and Mavor 2007). See Human Systems Integration in Part 6.

Industrial engineering overlaps significantly with SE in the industrial domain, but also includes manufacturing and other implementation activities outside of SE. See Systems Engineering and Industrial Engineering in Part 6.

Finally, to field a successful system, a systems engineer may need to know one or more of the many specialty fields in engineering, e.g., security, safety, reliability, availability, and maintainability engineering. Most of these are considered professional disciplines in their own right and many have their own bodies of knowledge. For explanations of how these disciplines relate to SE, overviews of what most systems engineers need to know about them, and references within their bodies of knowledge, see Systems Engineering and Specialty Engineering in Part 6.

## Non-Engineering Disciplines

SE is intimately intertwined with two non-technical disciplines: technical management (TM), and procurement and acquisition (also known as acquisition and procurement). TM often falls within the purview of a systems engineer. Many SE textbooks, competency models, and university programs include material about TM. TM is a specialization of project management (PM). SE and PM have significant common content in TM, but neither is a subset of the other. See Figure 1 in the article Scope of the SEBoK. For a definition of the relationship between the SEBoK and the *Guide to the Project Management Body of Knowledge (PMBOK)*, which is published by the Project Management Institute (PMI) (PMI 2013), see Systems Engineering and Project Management in Part 6.

Procurement and acquisition practitioners draw upon SE to determine the scope and overall requirements of the system to be procured or acquired. They then prepare requests for proposals and statements of work, determine evaluation criteria, and design source selection processes. Once a leading source is selected, they decide upon contracting options that encompass payments, reviews, audits, incentive fees, acceptance criteria, procedures, and the nature of deliverables. Finally, they monitor progress with respect to plans (including those for SE), and negotiate and execute changes and corrective actions. Many of these activities amount to specialty disciplines within procurement and acquisition. See the article Related Disciplines in Part 6.

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# Knowledge Area: Introduction to Systems Engineering Transformation

# 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 (KA), 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
- 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 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 (in particular 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 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 meet 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.
- Practised 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. Other 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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# 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 a 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, 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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# 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). The reason is 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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# 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 system engineering (MBSE) with an integrated framework can enable the use of SBD tradespace exploration, and 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, characteristics, 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 effected 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.

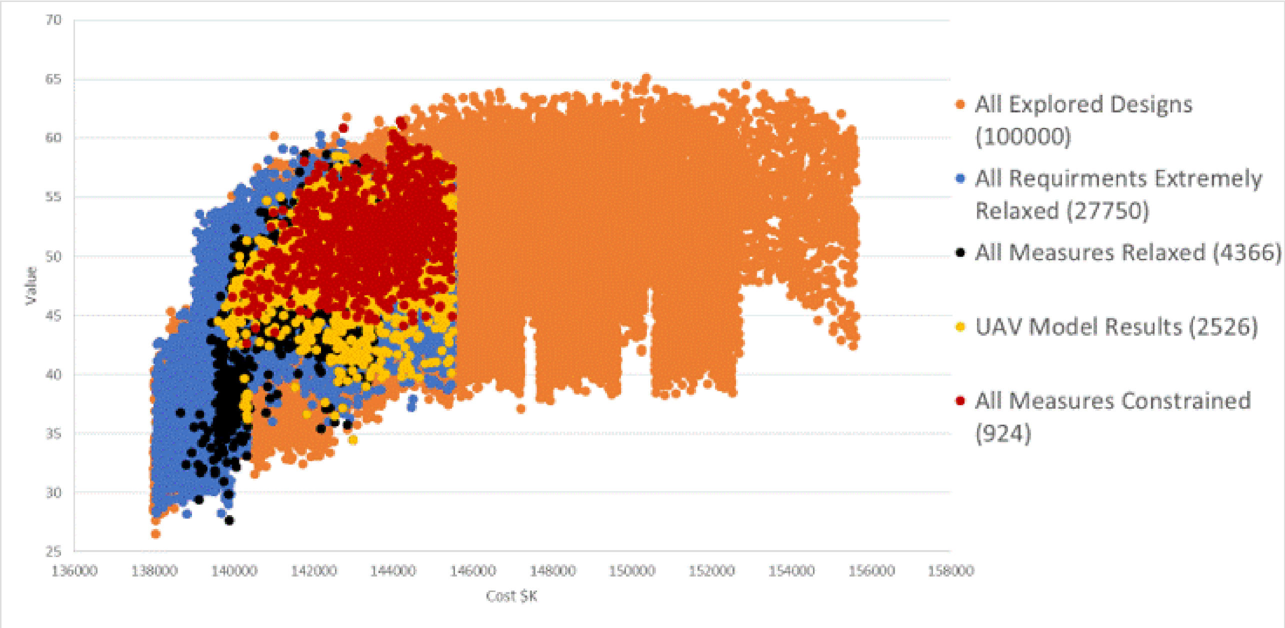


**Figure 1. Effects of Requirements on the UAV's Feasible Tradespace** (Parnell et al. 2019, used with permission)

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 each individual requirement effects 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.

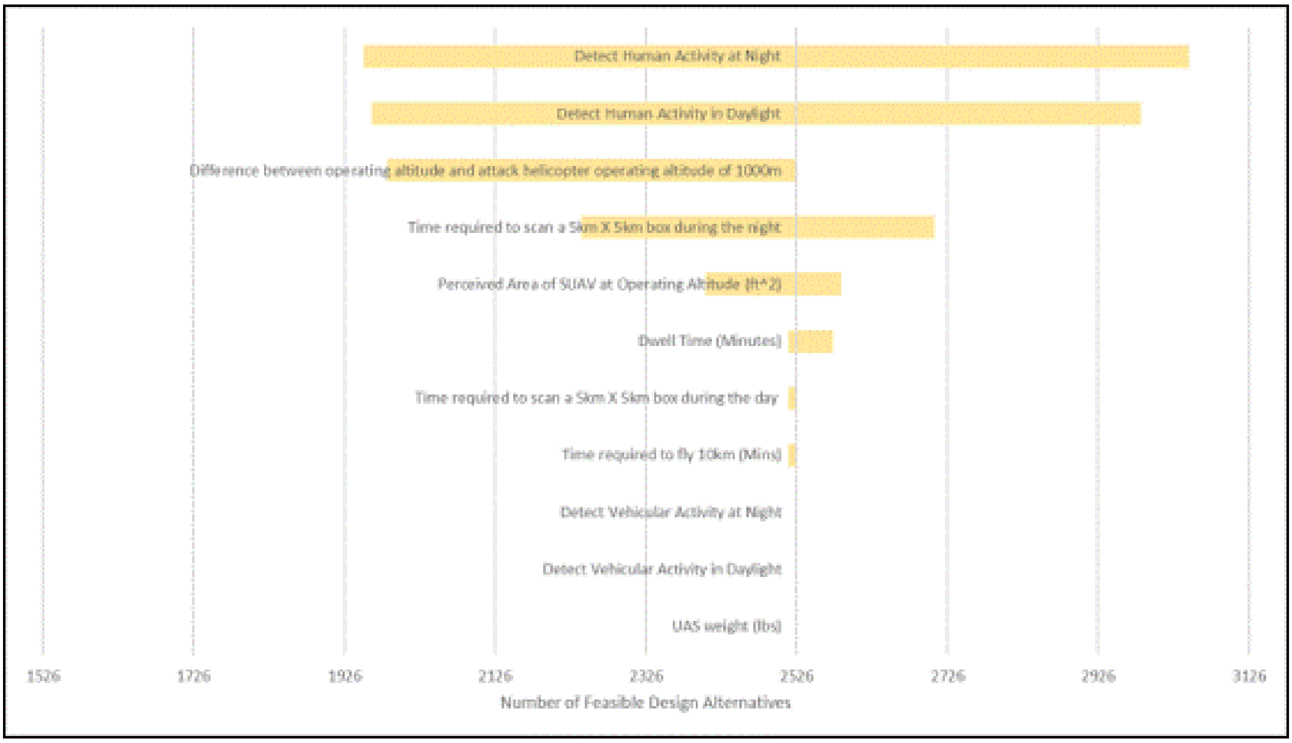


**Figure 2. UAV Case Study Results of One-by-One Requirement Analysis** (Parnell et al. 2019, used with permission)

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 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.

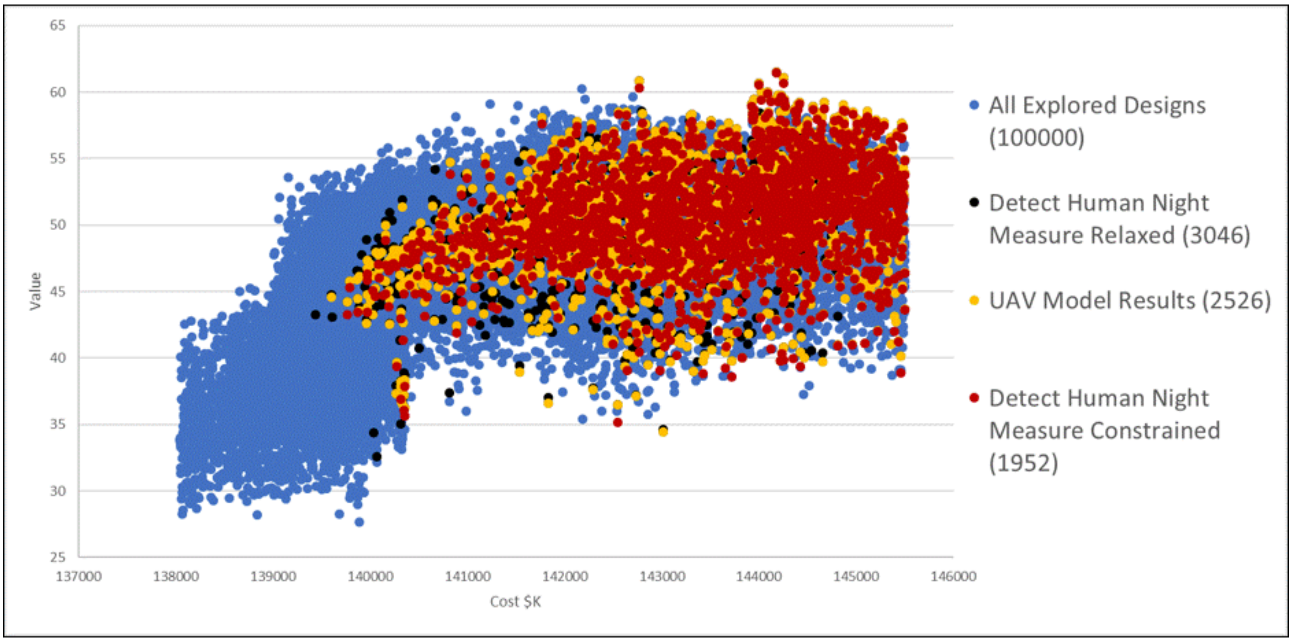


**Figure 3. Effect on Feasible Tradespace by Changing Most Sensitive UAV Requirement** (Specking et al. 2019, used with permission)

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

- enables reliable, efficient communications,
- allows much greater parallelism in the process, with much more effective use of subteams early in the process,
- allows the most critical, early decisions to be based on data, and
- promotes 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)

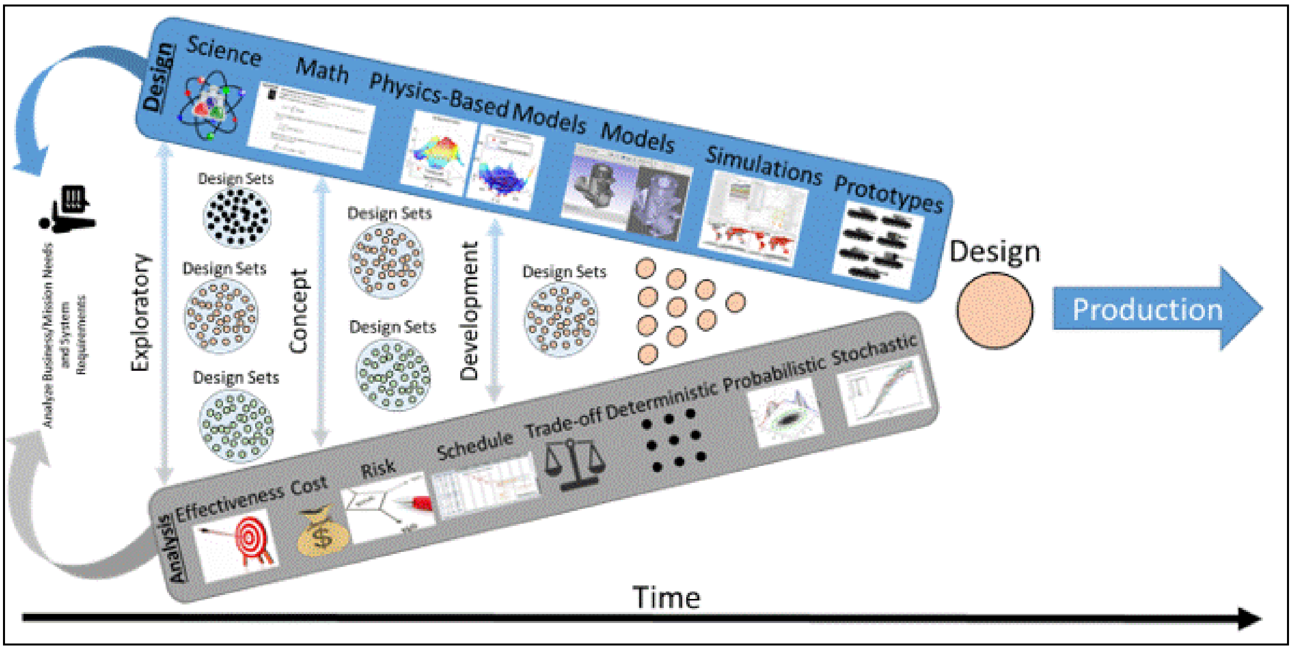


**Figure 4. SBD Conceptual Framework for Systems Design** (Specking et al. 2019, used with permission)

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 process is especially useful to perform early-stage design and is an eight step process (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, system 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.

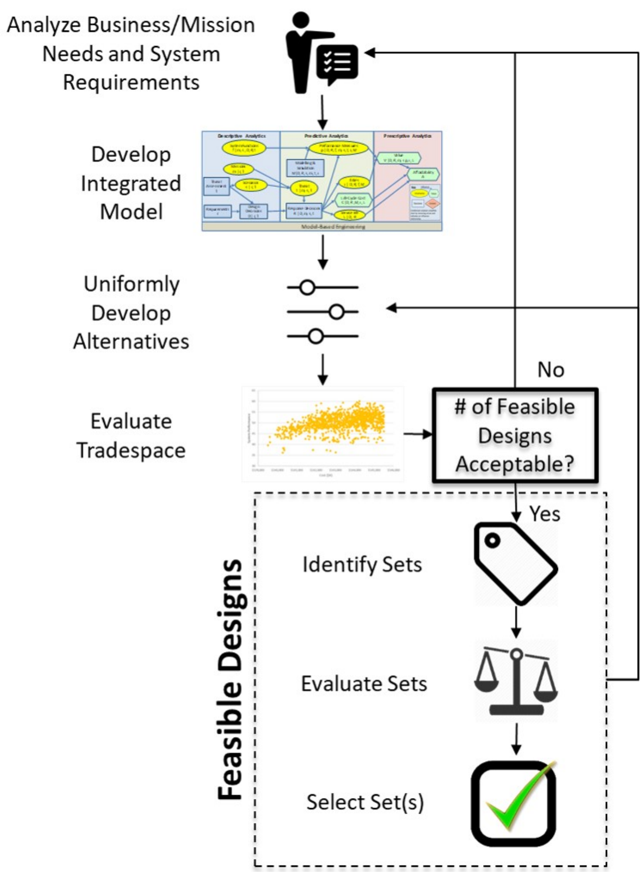


**Figure 5. System Analysts SBD Tradespace Exploration Process**
(Specking et al. 2019, used with permission)

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None.

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None.

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**SEBoK v. 2.1, released 31 October 2019**

# Model-Based Systems Engineering Adoption Trends 2009-2018

***Lead Author:*** *Rob Cloutier*

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

Surveys were conducted in 2009, 2012, 2014, and 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 {{TermModel_(glossary) 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 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.

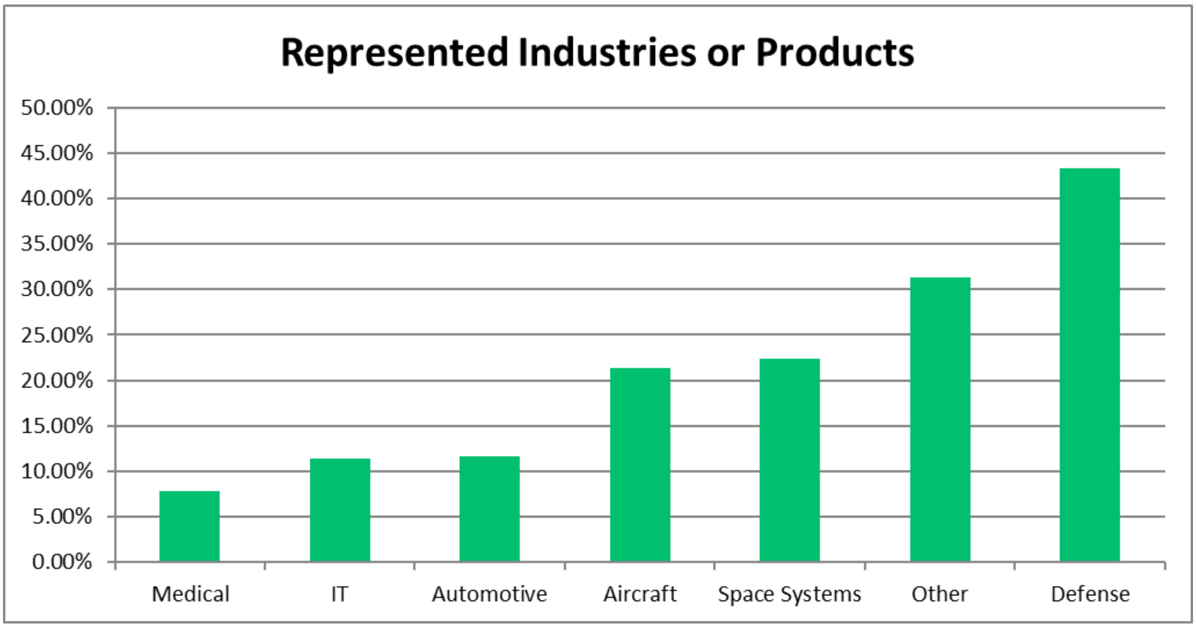


**Figure 1. Industries Represented in the 2018 MBSE Survey.** (Cloutier 2019a, used with permission)

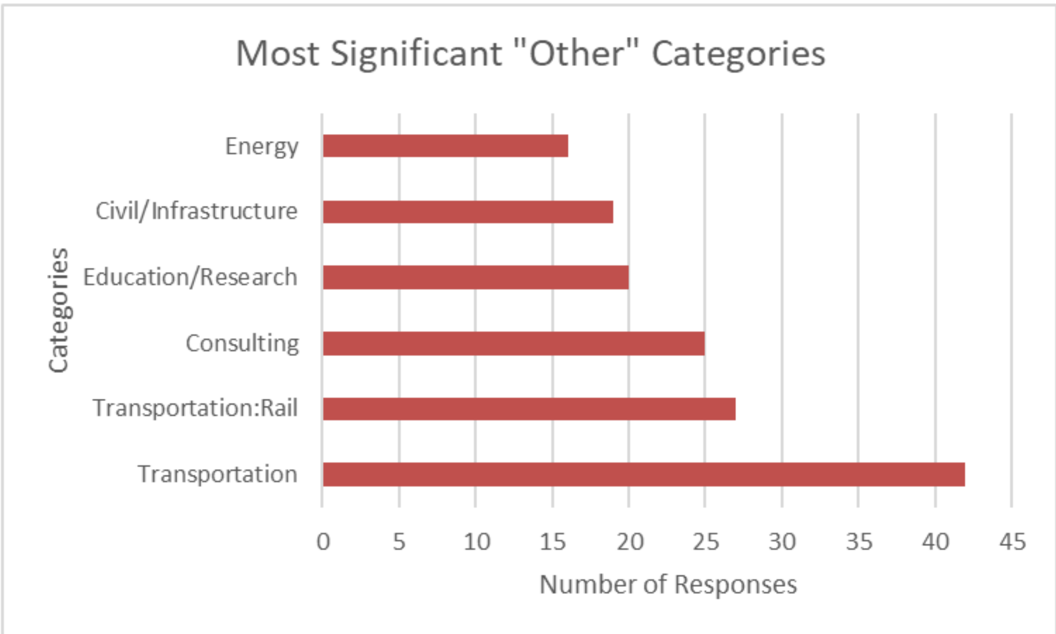


**Figure 2.** "Other" Industries Represented in the 2018 MBSE Survey. (Cloutier 2019a, used with permission)

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.

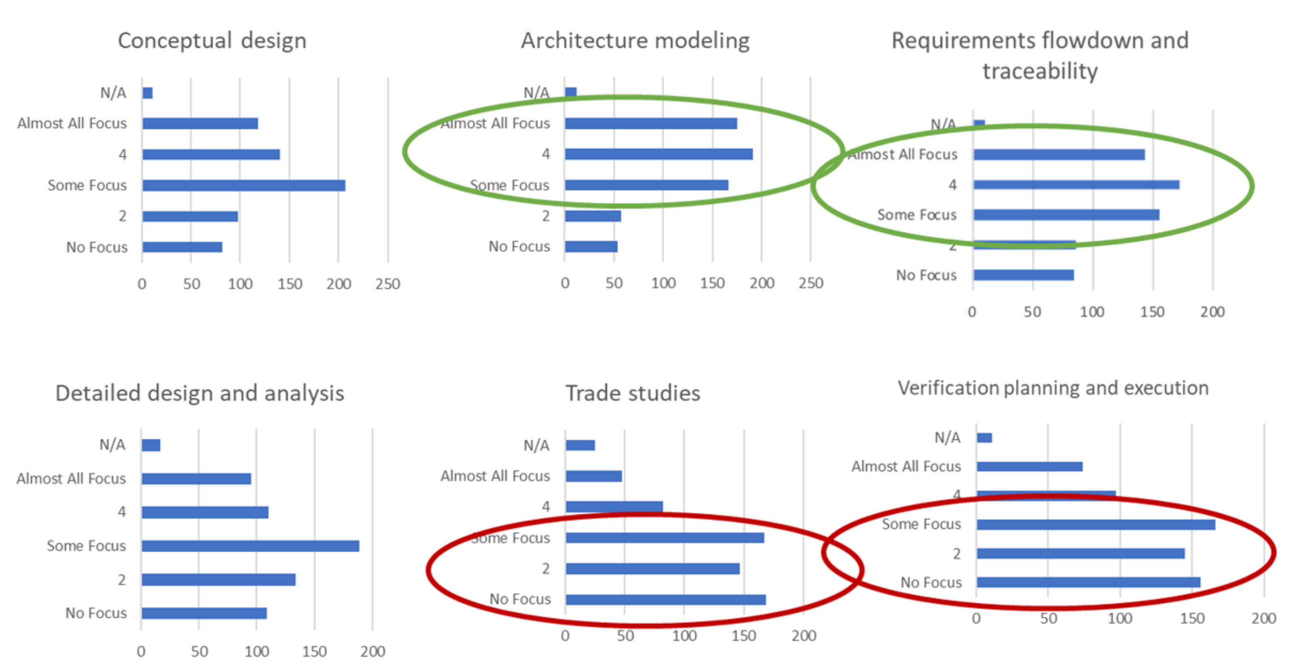


**Figure 3.** MBSE is More Likely to be Used in Early Stages of Systems Engineering (Cloutier 2019a, used with permission)

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).

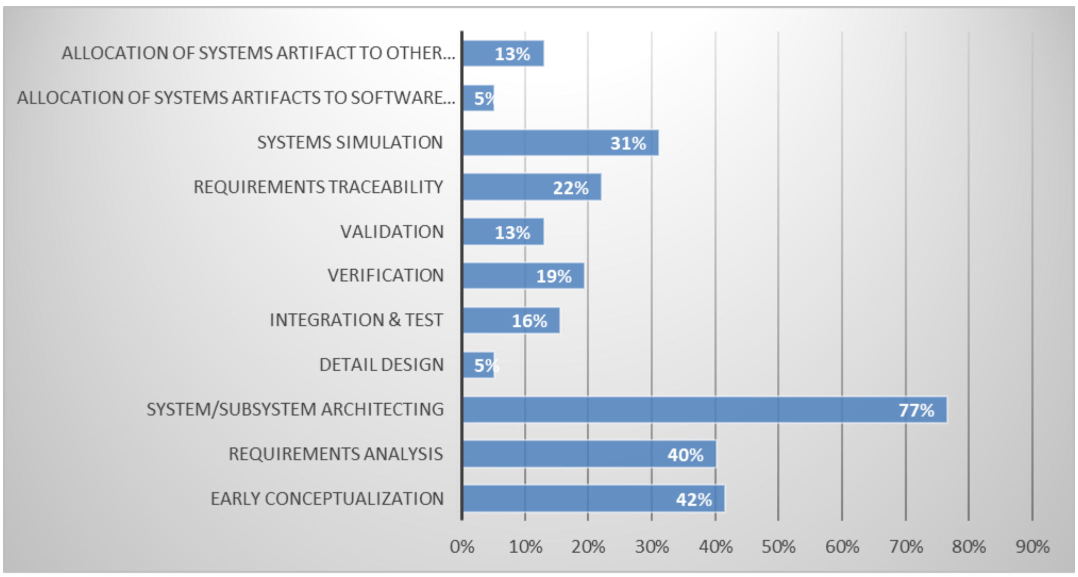


**Figure 4.** JPL Workshop Response Regarding "Where MBSE Holds the Most Promise" (Coutier 2019b, used with permission)

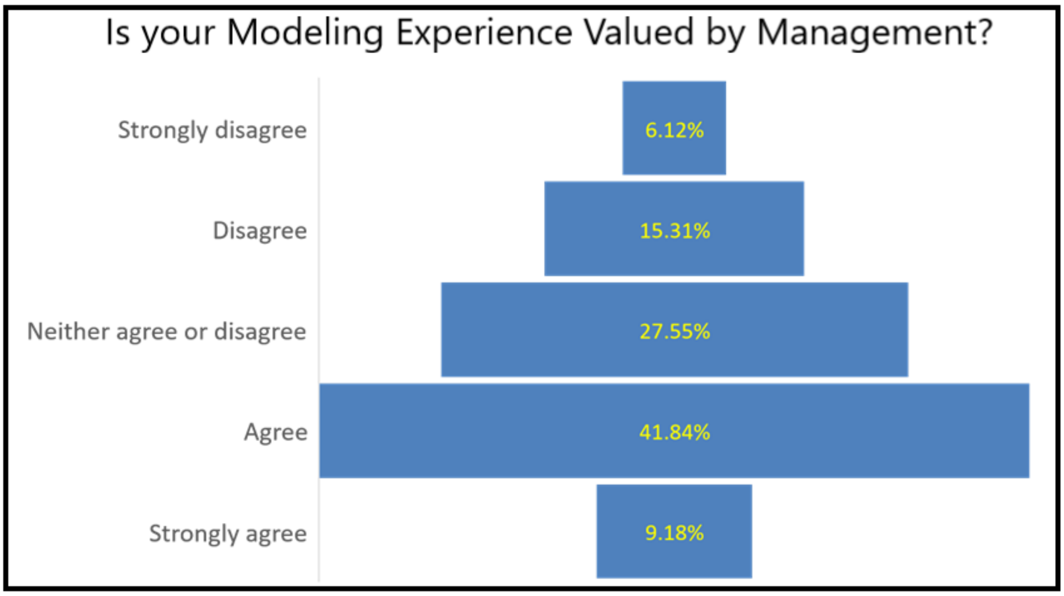


**Figure 5.** JPL Workshop Response Regarding "Is Your Modeling Experience Valued by Management?" (Coutier 2019b, used with permission)

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 my 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 is going to 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.

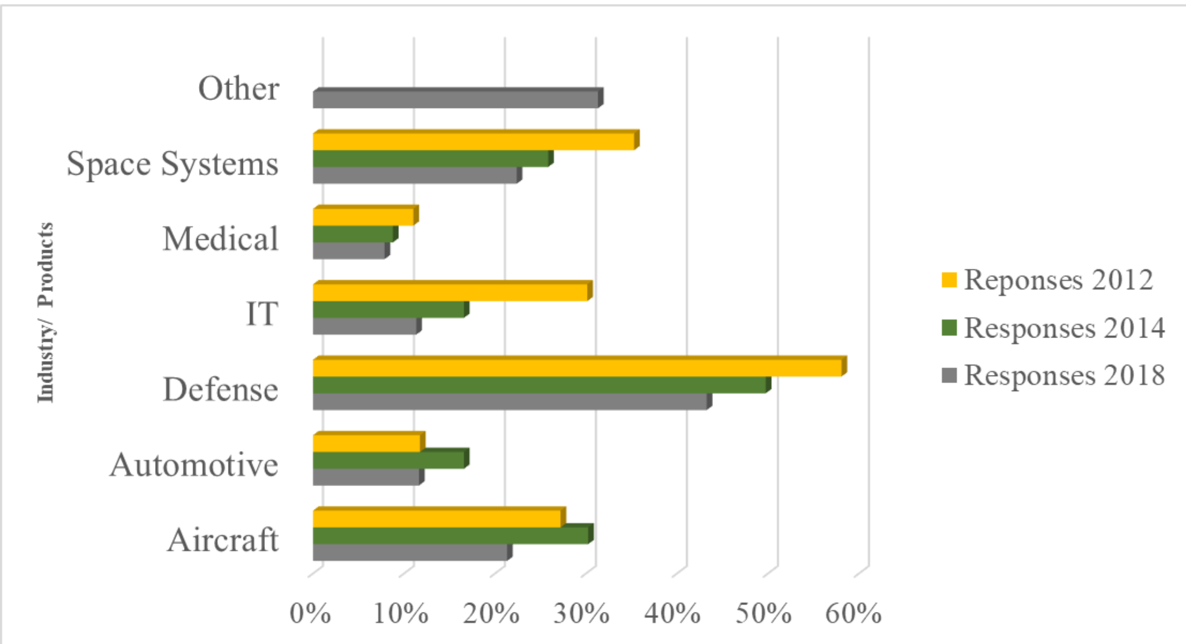


**Figure 6.** Shift of MBSE Adoption in New Industries (Cloutier 2019a, used with permission)

Model-based systems engineering seems to be expanding in influence in that it is not just in the purview of the 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.

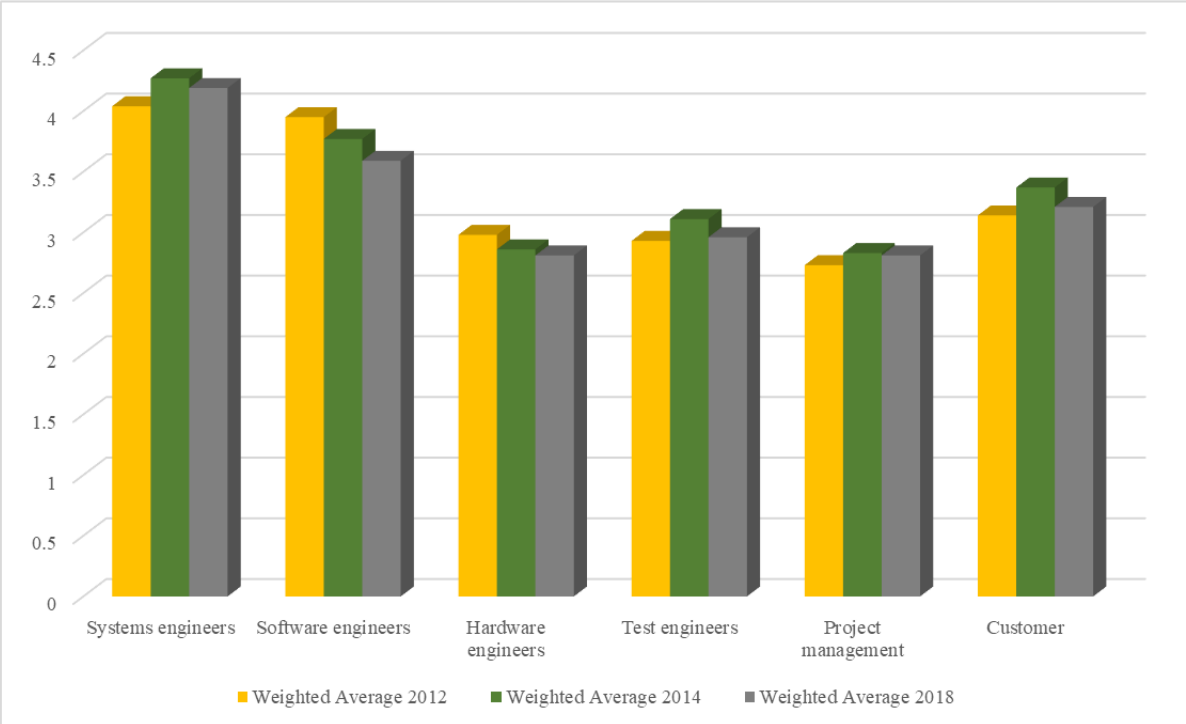


**Figure 7.** Perceived Value of MBSE Practices to Different Project Segments (Cloutier 2019a, used with permission)

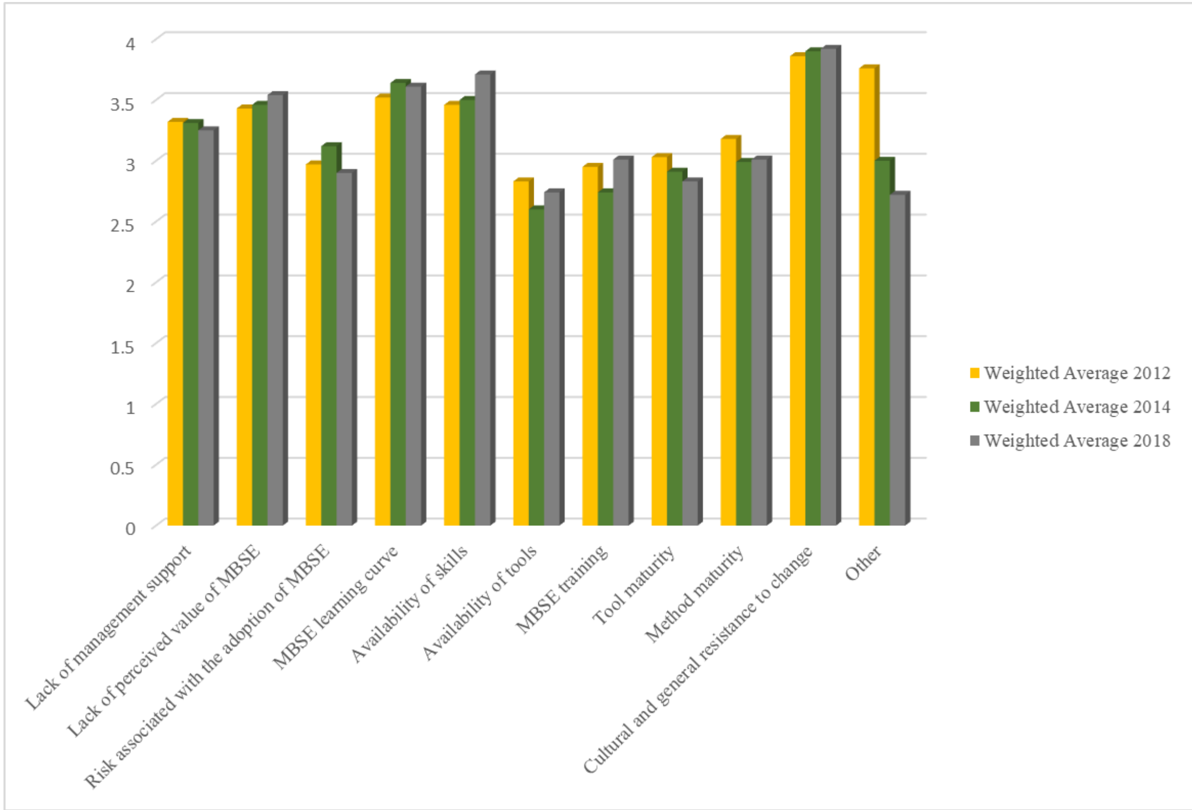


**Figure 8.** Inhibitors to the Successful Adoption of MBSE within an Organization/Company (Cloutier 2019a, used with permission)

Figure 8 demonstrates that availability of MBSE skills, 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 to using models to perform systems engineering.

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# Systems Engineering Core Concepts

## Purpose and Uses of the Systems Engineering Concept Model

The Systems Engineering Concept Model (SECM) captures the concepts that are referred to in the Systems Engineering Body of Knowledge. The SECM provides a means to evaluate the consistency and coverage across the broad set of Systems Engineering concepts, and can facilitate communication to better understand and evolve these concepts. Although the primary reference for the SECM was the SEBoK, the concepts were cross-checked against other industry references including ISO/IEC/IEEE 15288:2015 and the INCOSE Systems Engineering Handbook Version 4, enabling the SECM to be used to evaluate, understand, and evolve the concepts in these references as well. A small team developed the SECM to support the requirements for the next generation of the OMG Systems Modeling Language (OMG SysML™) to ensure SysML is consistent with the three leading industry standards.

## SECM Approach

A concept model, called the Concept Map, was developed by the original SEBoK team prior to release of the SEBoK v1.0 in 2012, and was used to support integration of the initial concepts across the SEBoK topic areas. The Concept Map included a concept model, and a mapping of the concepts to the glossary terms and to the sections of the SEBoK.

The SECM captures the Systems Engineering concepts and their relationship that are contained in today's SEBoK. The small subset of UML constructs and symbols, shown in Figure 1, are used to represent the SECM model. The choice of notations is intended to balance simplicity, understandability, and precision.

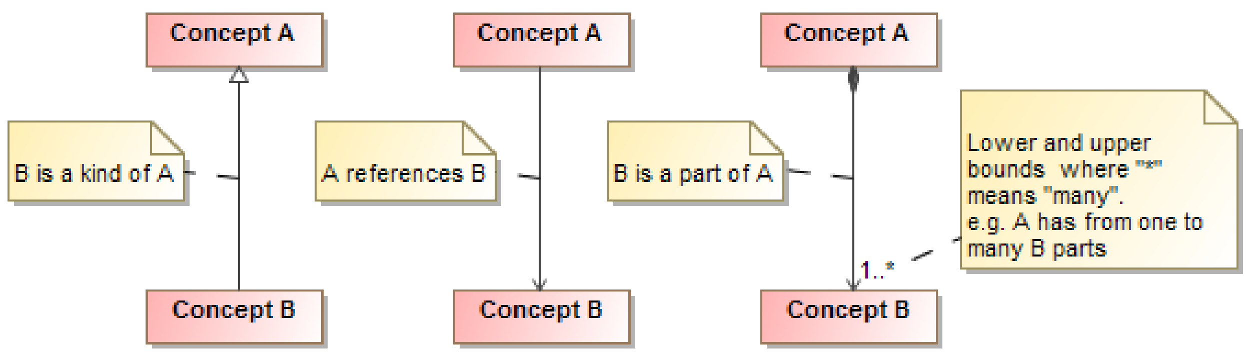



**Figure 1 Concept Relationships used in the SECM**. (SEBoK Original)

Figure 2 below shows a usage of these constructs and symbols when applied to a simple example of a Car. This diagram shows that a Car is kind of a Vehicle, and that the Driver drives the car (a reference relationship), and that there are four wheels that are parts of the Car.

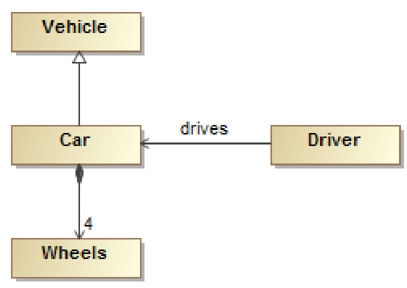



**Figure 2 Example of Relationships between Concepts** (SEBoK Original)

The SECM is presented in a series of diagrams that generally represent concepts for particular knowledge areas and topics in the SEBoK, and also include references to glossary terms in the SEBoK.

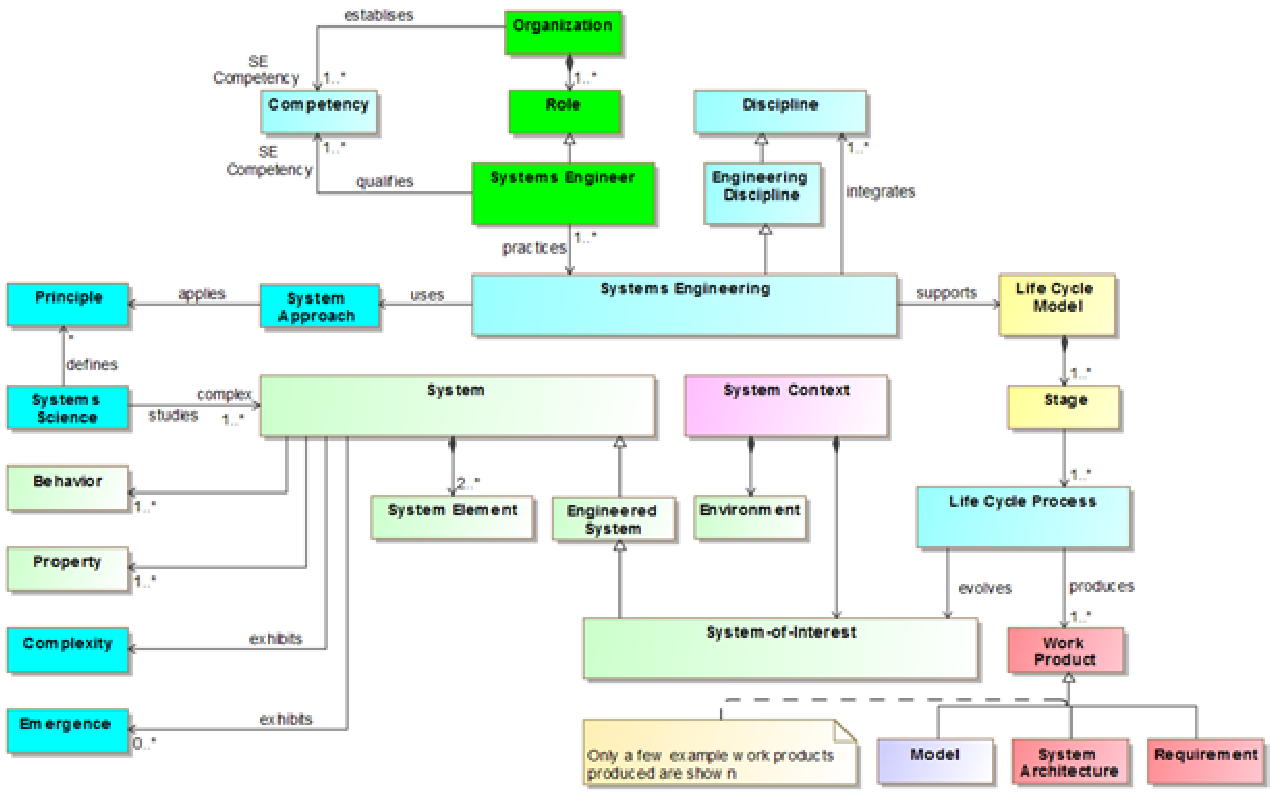
The approach used to capture the SECM content from the SEBoK is described in the following steps:

1. A topic within a SEBoK knowledge area is selected and the text is evaluated to identify key Systems Engineering concepts
2. From the sentences containing the concepts, the subjects, i.e. the concepts, and the predicate, i.e. the relationship between concepts, are identified. The predicate is a statement that says something about the subject
3. A search is conducted for this concept in other areas of the SEBoK, and the accompanying text, is evaluated to further refine the concept and its relationships to other concepts.
4. The definition of the concept in the SEBoK glossary, if available, is evaluated.
5. The use and definition of this concept in the other two industry references is evaluated.
6. The concept and a derived definition from the above evaluation are added to the SECM.
7. The discovered relationships between the concepts are added to the model and to the relevant diagrams. The diagrams group related concepts often associated with a SEBoK Knowledge Area or Topic.
8. As new contributions are made to the SEBoK, this approach can be used to identify new concepts and relationships, and add them to the SECM.

## Introduction to Core Concepts

The SECM was developed independently of the BKCASE project to support the evolution of the SysML standard. These models can be used to identify inconsistencies and/or areas requiring additional coverage within the SEBoK to support future updates.

The Core Concept Diagram shown in Figure 3 provides a high level view of the some of the key concepts presented in the SEBoK. It should be emphasized that this figure is intended to be a representative interpretation of the current SEBoK without modifying or adding concepts, and no claim of the completeness of the SEBoK concepts is made. The colors correspond to logical groupings of concepts.




Core SEBoK Concepts. (SysML Roadmap SECM. Used with permission)

A brief description of the core concepts model is provided below.

A *Systems Engineer* is a role within an *Organization* that practices the *Engineering Discipline of Systems Engineering* (SE), and is qualified by a set of SE *Competencies*. *Systems Engineering* integrates other *Disciplines* to support the *Life Cycle Model*. The Life Cycle Model is composed of life cycle *Stages* that typically include conceptual, realization, production, support, utilization and retirement stages (not shown). Each life cycle *Stage* refers to *Life Cycle Processes* that produce various kinds of *Work Products*. The *Life Cycle Processes* evolve the *System-of-Interest* (SoI).

There are many kinds of systems including natural systems, social systems, and technological systems (not shown). Systems that are created by and for people are referred to as *Engineered Systems*. An *Engineered System* whose life cycle is under consideration is referred to as a System-of-Interest (SoI).

A System-of-Interest is part of a broader *System Context*, which also includes an *Environment*. The Environment consists of other open systems (not shown) that can influence the SoI. Systems are composed of System Elements, and have Behavior and Properties. Systems can exhibit *Emergence* and *Complexity*.

Systems Engineering uses a *System Approach* which applies established system *Principles*. *Systems Science* is an interdisciplinary field of science that studies complex systems and helps define and update the *Principles* that are applied by the *System Approach*, which is used by the discipline of Systems Engineering.

## References

### Works Cited

ISO/IEC/IEEE. 2015. Systems and Software Engineering -- System Life Cycle Processes. Geneva, Switzerland: International Organisation for Standardisation / International Electrotechnical Commissions / Institute of Electrical and Electronics Engineers. ISO/IEC/IEEE 15288:2015.

INCOSE. 2015. Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, version 4.0. Hoboken, NJ, USA: John Wiley and Sons, Inc, ISBN: 978-1-118-99940-0

SysML Roadmap: Systems Engineering Concept Model Workgroup (SECM) [OMG SysML Portal] http://www.omgwiki.org/OMGSysML/doku.php?id=sysml-roadmap%3Asystems_engineering_concept_model_workgroup

### Primary References

ISO/IEC/IEEE. 2015. Systems and Software Engineering -- System Life Cycle Processes. Geneva, Switzerland: International Organisation for Standardisation / International Electrotechnical Commissions / Institute of Electrical and Electronics Engineers. ISO/IEC/IEEE 15288:2015.

INCOSE. 2015. Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, version 4.0. Hoboken, NJ, USA: John Wiley and Sons, Inc, ISBN: 978-1-118-99940-0

### Additional References

None

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# Knowledge Area: SEBoK Users and Uses

# SEBoK Users and Uses

The users and uses described in this article were identified based on the six SEBoK purposes described in the SEBoK Introduction.

Users can either be primary (those who use the SEBoK directly) or secondary (those who use the SEBoK with assistance from a systems engineer). Indicative, but not exhaustive, sets of example uses are shown in Tables 1 and 2 below.

## New to SEBoK or Systems Engineering?

The list of users and use cases below allow someone who has come to the SEBoK with a particular focus to identify quickly where to focus their reading. If you are completely new to systems engineering or have no clear view of how it is covered in the SEBoK you should use Use Case 0 below to orient yourself and learn the basics before looking at the other use cases:

- Use Case 0: Systems Engineering Novices

## Primary Users

Primary users are those who use the SEBoK directly, as shown in Table 1. Hyperlinks in the second column link to the associated use case, where one has been written. The use cases are listed at the end of the topic, and may also be seen here. [1]

**Table 1. Primary SEBoK Users and Common Uses. (SEBoK Original)**

| # | Users | Uses |
|---|---|---|
| 1 | Practicing Systems Engineers ranging from novice through expert | • Taking on a new SE role in a project; preparing by finding references for study<br>• Expanding SE expertise and specialization; preparing by finding references for study<br>• Seeking to understand the principles of SE; seeking the best references to elaborate on those principles<br>• Reviewing a project or mentoring a new SE performer; seeking to understand what best practices to look for<br>• Pursuing professional development through study of SE topics, including new developments in SE |
| 2 | Process engineers responsible for defining or implementing SE processes | • Maintaining a library of SE process assets; seeking to understand which SE process models and standards are most relevant<br>• Tailoring a process for a specific project; seeking to learn how others have tailored processes, or how a specific application domain affects tailoring<br>• Measuring the effectiveness of an organization's SE processes; seeking to learn how others have done that<br>• Defining standards for a professional society or standards organization |
| 3 | Faculty Members | • Developing a new graduate program in SE, and deciding what core knowledge all its students must master; the user should consult the *Graduate Reference Curriculum for Systems Engineering (GRCSE™)* in conjunction with the SEBoK<br>• Developing a new SE course; seeking to identify course objectives, topics, and reading assignments<br>• Incorporate SE concepts in courses or curricula focused on engineering disciplines other than SE |
| 4 | GRCSE authors | • As members of the GRCSE author team, deciding what knowledge to expect from all SE graduate students<br>• See *Graduate Reference Curriculum for Systems Engineering (GRCSE™)* (Pyster et al. 2015) |

| | | |
|---|---|---|
| 5 | Certifiers | • Defining a company's in-house SE certification program; seeking to understand what others have done, how such programs are typically structured, and how to select the knowledge that each person seeking certification should master<br>• Defining certification criteria for a professional society or licensure program |
| 6 | General Managers, Other Engineers, developers, testers, researchers | • Mastering basic vocabulary, boundaries, and structure of SE; seeking a few primary references<br>• Learning what the scope of SE is, relative to the General Manager role<br>• Learning what the role of the systems engineer consists of, relative to others on a project or in an organization<br>• Learning to effectively perform a general manager role on an SE integrated product team |
| 7 | Customers of Systems Engineering | • Providing resources to and receiving artifacts from systems engineers<br>• Seeking to better understand what to ask for, how to request it, how much to pay for it, and how to judge the quality of what is received |
| 8 | SE managers | • Evaluating possible changes in team processes and tools proposed by systems engineers on various teams; seeking independent information with which to evaluate the proposals<br>• Hiring systems engineers, and developing competency-based job descriptions |
| 9 | SE researchers | • Looking for gaps are in SE knowledge to help guide a research agenda<br>• Getting familiarize with a research topic; seeking the most important articles about the topic |

## Secondary Users

Secondary users are those who use the SEBoK with assistance from a systems engineer, as shown in Table 2.

**Table 2. Secondary SEBoK Users and Common Usages. (SEBoK Original)**

| # | Users | Uses |
|---|---|---|
| 1 | Human resource development professionals | • Supporting the hiring and professional development of systems engineers |
| 2 | Non-technical managers | • Augmenting understanding of central concerns with information about relevant SE topics; e.g., a contracting manager might want to better understand SE deliverables being called out in a contract |
| 3 | Attorneys, policy makers | • Defining the impact of SE performance on central concerns; e.g., understanding the liability of a systems engineer for errors in judgment on a project, or the limitations of SE in guaranteeing the success of a project against actions of sponsors, managers, or developers |

## List of Use Cases

At this time not every class of user has a use case developed. To illustrate the major uses, the following use cases are included:

- Use Case 1: Practicing Systems Engineers. This covers the first set of users from Table 1.
- Use Case 2: Other Engineers. This covers the second and sixth sets of users from Table 1.
- Use Case 3: Customers of Systems Engineering. This covers the seventh set of users from Table 1.
- Use Case 4: Educators and Researchers. This covers the third, fourth, and ninth sets of users from Table 1.
- Use Case 5: General Managers. This covers the sixth and eighth sets of users from Table 1.

While not exhaustive, the use cases show the utility of the SEBoK in various applications and contexts.

## References

### Works Cited

None.

### Primary References

None.

### Additional References

None.

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## References

[1] http://sebokwiki.org/draft/Case_Studies

# Use Case 0: Systems Engineering Novices

Some users of the Systems Engineering Body of Knowledge (SEBoK) may be new to the field. This article provides recommended readings for such a user.

## Learn the Basic Terms

As discussed in the Introduction to the SEBoK, there are four key terms that you should first understand when learning about systems engineering (SE):

- A system is “a collection of elements and a collection of inter-relationships amongst the elements such that they can be viewed as a bounded whole relative to the elements around them. Open Systems exists in an environment described by related systems with which they may interact and conditions to which they may respond. While there are many definitions of the word “system,” the SEBoK authors believe that this definition encompasses most of those which are relevant to SE.
- An engineered system is an open system of technical or sociotechnical elements that exhibits emergent properties not exhibited by its individual elements. It is created by and for people; has a purpose, with multiple views; satisfies key stakeholders’ value propositions; has a life cycle and evolution dynamics; has a boundary and an external environment; and is part of a system-of-interest hierarchy.
- Systems engineering is “an interdisciplinary approach and means to enable the realization of successful (engineered) systems”. It focuses on holistically and concurrently understanding stakeholder needs; exploring opportunities; documenting requirements; and synthesizing, verifying, validating, and evolving solutions while considering the complete problem, from system concept exploration through system disposal.
- A systems engineer is “a person who practices systems engineering” as defined above, and whose systems engineering capabilities and experience include sustained practice, specialization, leadership, or authority over SE activities. These activities may be conducted by any competent person regardless of job title or professional affiliation.

## Get an Overview

The next step for someone new to SE is get an overview of the discipline. Part 1: SEBoK Introduction contains four articles particularly helpful to one new to SE.

- The article Systems Engineering Overview frames systems engineering inside the larger topic of ‘Systems Science.’
- The article Economic Value of Systems Engineering makes the business case for investing in systems engineering as a way to reduce total ownership cost.
- The article Systems Engineering and Other Disciplines discusses briefly how systems engineers and other engineers interact as together they develop complex systems.
- Finally, the article Systems Engineering: Historic and Future Challenges gives a quick history of the discipline and discusses what lays ahead.

## Learn about Systems

Engineering is often described as the application of science to develop new products or systems. Part 2: Foundations of Systems Engineering describes some of the underlying systems principles that form the foundation for systems engineering.

- The Knowledge Area on Systems Fundamentals contains five articles. What is a System? is recommended for a new user.
- The Knowledge Area on Systems Science presents two articles on its history and approaches. Both are recommended.
- The Knowledge Area on Systems Thinking has four articles. The first, What is Systems Thinking?, is recommended on a first reading.
- One of the most important current research and practice areas of SE is Model Based Systems Engineering (MBSE). The Knowledge Area Representing Systems with Models provides the foundation for MBSE. The first three of the five articles in the KA are recommended.

## Learn how the Systems Approach is Applied to Engineered Systems

The Knowledge Area Systems Approach Applied to Engineered Systems describes how systems science and systems thinking lead to the practice of systems engineering. All eight articles are recommended.

- Overview of the Systems Approach
- Engineered System Context
- Identifying and Understanding Problems and Opportunities
- Synthesizing Possible Solutions
- Analysis and Selection between Alternative Solutions
- Implementing and Proving a Solution
- Deploying, Using, and Sustaining Systems to Solve Problems
- Stakeholder Responsibility
- Applying the Systems Approach

## Explore the Methods of Systems Engineering

The SEBoK uses a life-cycle framework to describe the processes that comprise systems engineering. Part 3: SE and Management contains the plurality of the content of the SEBoK in eight knowledge areas. A new user should be familiar with the introductions to each of these Knowledge Areas, and should read further in those KAs of interest.

- Life Cycle Models
- Concept Definition
- System Definition
- System Realization
- System Deployment and Use
- Systems Engineering Management
- Product and Service Life Management
- Systems Engineering Standards

## Explore the Applications of Systems Engineering

The SEBoK partitions the body of knowledge between methods and areas of application. Areas of application are classified as:

- Product Systems Engineering
- Service Systems Engineering
- Enterprise Systems Engineering
- Systems of Systems (SoS)

A new user should read the introduction to Part 4: Applications of Systems Engineering and to the four knowledge areas listed above. The reader's interests can then suggest which further reading should be done.

## Read Case Studies

Finally, the new user should scan the case studies and vignettes in Part7: SE Implementation Examples and read a few of those in areas that appeal to the reader. This will help reinforce the fundamentals as well as illustrate the practice of SE.

The following case studies are included:

- Successful Business Transformation within a Russian Information Technology Company
- Federal Aviation Administration Next Generation Air Transportation System
- How Lack of Information Sharing Jeopardized the NASA/ESA Cassini/Huygens Mission to Saturn
- Hubble Space Telescope Case Study
- Global Positioning System Case Study
- Medical Radiation Case Study
- FBI Virtual Case File System Case Study
- MSTI Case Study
- Next Generation Medical Infusion Pump Case Study

## For Later Reading

Part 6: Related Disciplines contains a broad selection of Knowledge Areas and Topics that describe how systems engineers work with other disciplines. The Knowledge area on SE and Software Engineering is particularly important, as modern systems get much of their functionality from software.

Part 5: Enabling Systems Engineering has KAs describing how individuals, teams, and organizations can develop to practice effective systems engineering.

A person new to SE should become familiar with several references that are beyond that SEBoK. They include the INCOSE Handbook, several standards (listed in Relevant Standards), and the main journals of systems engineering (including but not limited to *Systems Engineering*, the *Journal of Enterprise Transformation*, and *Systems, Man, and Cybernetics*).

## References

### Works Cited

None.

### Primary References

None.

### Additional References

None.

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# Use Case 1: Practicing Systems Engineers

Both for the entry-level systems engineer learning the discipline of systems engineering (SE), and the more experienced systems engineer seeking the knowledge required to accomplish a work activity, the SEBoK serves as a primary information source and a quick, comprehensive reference for SE information.

What these system engineers find in the SEBoK includes:

- definitions of terms,
- explanations of basic concepts and principles,
- useful discussions of topics,
- references to articles and textbooks that cover topics in-depth, and
- pointers to additional sources.

## How Systems Engineers Use Topics

Researching SE-related subjects, identifying educational resources, and connecting with individuals or organizations which offer specialized expertise are all part of the job for the practicing systems engineer. The time available to the SE for these activities can be quite limited. The SEBoK is designed to ease the pressure on the systems engineer in this situation, in several ways:

- Because its content is based on research, proven practices, and emerging knowledge, the SEBoK makes high-quality information available to the systems engineer right away.
- Being composed of articles of 2000 words or less in most cases, the SEBoK enables the systems engineer to quickly get an overview of relevant topics.
- By providing primary references, each topic offers a direct route to more detailed information.
- Even greater detail, breadth, and a sense of what's relevant in the SE literature are available through the additional references each topic provides.
- Since the SEBoK sources have been reviewed and vetted by a team of experts, the SEBoK helps the systems engineer avoid less reliable information which can be hard to eliminate within Internet search results.
- The systems engineer who needs to connect with educators and researchers can find relevant names and institutions in SEBoK topics and references.

Systems engineers using the SEBoK may choose one or more of several approaches:

- searching on keywords or article names, using the text field, Search [1] button, and Go [2] button at the top right of each SEBoK page
- scanning the Quick Links, Outline (where the table of contents is located), or Navigation indexes that appear at the left of each SEBoK page, and following links from there to articles that seem likely to be of interest
- searching on keywords using an Internet search engine
- reading through one or more of Parts 1 through 7 in sequence

Reading the SEBoK in sequence is especially suitable for the practicing engineer who is new to SE, or is enrolled in an SE-related training course. For this engineer, SE (or some aspect of it) is a subject to be learned comprehensively. This is made easier by navigation links from each article to the previous, next, and parent articles as found in the Table of Contents.

For practicing systems engineers, having the SEBoK makes it possible to gain knowledge more quickly and reliably than they would otherwise. The goal is to spend less time searching for and compiling new information from disparate sources and more time getting work done.

For a team of practicing engineers, the gap in knowledge between more- and less-experienced engineers can be a major obstacle. The SEBoK serves as a tool for the team to build a framework of agreed-upon definitions and perspectives. The consistency of such a framework enhances communication across the team. New teams, especially, can benefit from bridging the gap between legacy and more-recently-acquired knowledge. For more information, see Enabling Teams in Part 5.

## How Systems Engineers Use Implementation Examples

The SEBoK is written, for the most part, independent of any particular domain of practice. By design, parts 1 though 6 focus on the discipline of SE and not the numerous domains where SE can be applied.

This lack of domain-specific content is partly offset by Part 7, Systems Engineering Implementation Examples, which consists of case studies and examples drawn from a number of domains where SE is applied. Each example demonstrates the impact of a particular application domain upon SE activities. Examples are generally most useful to the systems engineer when they are aligned with the domain in which the he or she is working, but sometimes ideas from an example in one domain can be usefully applied to situations in another.

## Example: Model-Based Systems Engineering Practitioners

For practitioners of model-based systems engineering (MBSE), the Representing Systems with Models knowledge area is of central importance within the SEBoK.

Academic faculty who use the SEBoK to support curriculum development and assessment can refer to the same knowledge area to ensure that their curricula accurately cover the languages and/or methodologies such as System Modeling Language (SysML) and Object-Process Methodology (OPM).

SE researchers, too, can adopt an MBSE approach, making their research products more formal and rigorous by basing them on models.

In MBSE, models of systems support system life cycle activities, including requirements engineering, high-level architecture, detailed design, testing, usage, maintenance, and disposal.

## Vignette: Systems Engineering for Medical Devices

Tara Washington has worked as a engineer for the HealthTech medical device company for seven years. Besides continuing to improve her strong software skills, she has shown an aptitude for systems thinking. To better understand the products that her software supports, Tara has taken courses in electrical engineering, mechanical engineering, and physiology. The coursework has helped her to perform effectively as a software system analyst on the SE teams of her last two projects.

HealthTech's Research Division proposes a new concept for a highly programmable radiation therapy device that monitors the effects of the radiation on various parts of the body and adjusts the parameters of the radiation dosage to maximize its effectiveness, subject to a number of safety constraints. The software-intensiveness of the device leads Tara's project manager to recommend her as the lead systems engineer for the design and development of the product.

Tara welcomes the opportunity, knowing that she possesses enough domain knowledge to take the lead SE role. Even so, she realizes that she has picked up SE skills mainly by intuition and needs to build them up more systematically. Tara begins to consult some of HealthTech's lead systems engineers, and to study the SEBoK.

After reading the SEBoK Introduction, Tara feels that she has a solid overview of the SEBoK. Tara finds that the next topic, Scope and Context of the SEBoK, outlines the key activities that she expects to lead, along with others which will require her to collaborate with systems developers and project and systems management personnel.

The same topic identifies those parts of the SEBoK that Tara needs to study in preparation for her lead systems engineer role:

- SE concepts, principles, and modeling approaches in Part 2 (Representing Systems with Models knowledge area (KA))

- life cycle processes, management, technical practices, in Part 3 (Systems Engineering and Management KA)
- approaches for specifying, architecting, verifying and validating the hardware, software, and human factors aspects of the product, as well as common pitfalls to avoid and risks to manage, also in Systems Engineering and Management
- guidelines for the systems engineering of products, in Part 4: Applications of Systems Engineering, including references
- SE knowledge, skills, abilities, and attitudes (KSAAs) needed for a project in Part 5: Enabling Systems Engineering including references
- specialty engineering disciplines that may be key to the project's success, in Part 6: Related Disciplines

Tara's awareness of the deaths caused by the Therac-25 radiation therapy device motivates her to study not only the Safety Engineering topic in Part 6, but all of its key references as well.

While reading about SE life cycle process models in Systems Engineering and Management in Part 3, Tara notes the reference to the Next Generation Medical Infusion Pump Case Study in Part 7. This case study strikes Tara as highly relevant to her medical-device work, and she observes that it is organized into phases similar to those used at HealthTech. From the case study, Tara gains understanding of how a project such as hers would progress: by concurrently evaluating technology opportunities, by discovering the needs of various device stakeholders such as patients, nurses, doctors, hospital administrators, and regulatory agencies, and by working through increasingly detailed prototypes, specifications, designs, plans, business cases, and product safety analyses.

The case study mentions its source: Human-System Integration in the System Development Process [3] (Pew and Mavor 2007), published by the U.S. National Research Council. Tara obtains this book. In it, she finds numerous good practices for human-systems needs analysis, organizational analysis, operations analysis, prototyping, usability criteria formulation, hardware-software-human factors integration, process decision milestone review criteria, and risk management.

As a result of her SEBoK-based study, Tara feels better-qualified to plan, staff, organize, control, and direct the SE portion of the HealthTech radiation therapy device project and to help bring the project to a successful conclusion.

## Summary

In the SEBoK, practicing engineers have an authoritative knowledge resource that can be accessed quickly to gain essential high-level information, and to identify the best references for in-depth study and research into SE topics when an individual's initial level of understanding is not adequate to get the job done.

The SEBoK is also a resource for practicing engineers who teach, as well as those taking training courses.

## References

### Works Cited

Pew, R. and A. Mavor. 2007. *Human-System Integration in the System Development Process: A New Look.* Washington, DC, USA: The National Academies Press.

### Primary References

None.

### Additional References

None.

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## References

[1] http://www.mediawiki.org/wiki/Help:Searching
[2] http://meta.wikimedia.org/wiki/Help:Go_button
[3] http://www.nap.edu/catalog.php?record_id=11893

# Use Case 2: Other Engineers

The realization of successful complex systems requires experts from many disciplines to work together. This makes the SEBoK useful to engineers with backgrounds in biomedical, civil, electrical, chemical, civil, materials, mechanical, software, and many other engineering disciplines.

Studying the SEBoK enables engineers from disciplines other than systems engineering (SE) to

- see why good systems engineering practice must involve multiple disciplines,
- appreciate a broader view of systems beyond their specialties,
- understand how their contributions fit into the larger systems picture, and
- prepare to solve more difficult and encompassing problems.

In many cases, engineers who study systems engineering as a supplement to their area of specialization find their professional value enhanced when they put the new knowledge into practice.

## Use of Topics

For engineers from non-SE backgrounds, each part of the SEBoK contributes something to the experience of learning about systems engineering.

- Part 1 provides an overview both of systems engineering and of the SEBoK itself
- Part 2 highlights the areas of systems knowledge most relevant to systems engineering, providing a foundation for the theory and practice of systems engineering as explained in Parts 3, 4 and 5
- Part 3 includes the knowledge areas of Life Cycle Models, System Definition, System Realization, and System Deployment and Use, all highly important when approaching study of SE from another discipline.
  - Also in Part 3, Systems Engineering Management includes such relevant topics as risk management, measurement, configuration management, and quality management.
- Part 4 identifies the SE activities for four kinds of engineered systems, namely products, services, enterprises, and systems of systems (SoS).
  - The primary references and glossary terms — not just the content — for a given type of system are essential reading for an engineer developing or modifying a system of that kind.
- Part 5, especially Team Capability, explains how systems engineers and other types of engineers fit into the larger picture of enabling individuals and teams to perform systems engineering activities, and into the larger picture of systems engineering organizational strategies.

- Part 6 is key for engineers from non-SE backgrounds.
  - Within Part 6, Systems Engineering and Project Management should be of interest to almost all readers, while Systems Engineering and Software Engineering and Systems Engineering and Specialty Engineering are naturally most essential for engineers in the respective disciplines.
- Part 7 illustrates how systems engineering practices, principles, and concepts are applied in real settings, and contains much universally-useful insight

Engineers may be tempted to skip over knowledge areas or topics which sound more like management than engineering stories, for example Systems Engineering Management in Part 3 or Part 5. This temptation should be resisted, because these topics are actually about how SE orchestrates the efforts of multiple disciplines, not management in the administrative sense.

Finally, the extensive lists of references throughout the SEBoK provide a basis for further readings.

## Vignette: Software Engineer

Jose Wilks is an entrepreneurial software engineer who wants to learn more about systems engineering principles applied to embedded systems for advanced document identification and verification. He wants to implement best practices in developing highly secure systems for real-time image processing and forensic verification of documents. His company provides a rapid, secure and cost-effective solution for verifying the authenticity of identification, travel, and financial documents, with technology that runs on proprietary tablet computers for portable and fixed locations.

Jose is knowledgeable about computer hardware engineering, low-level interfaces between hardware and software, and the related tradeoffs in embedded devices. His company has developed research prototypes, but without the stringent security requirements for actual field usage linked to government identification databases. The few experimental units which have been sold have fared well in limited testing, but Jose wants to expand into markets for government agencies, law enforcement departments and the private sector. To make headway into those diverse markets, he will need to confront abundant new constraints and challenges.

Jose begins his study of SE by skimming the SEBoK Introduction and the Scope and Context of the SEBoK to get an overview of the SEBoK contents. As he reads, he sometimes refers to the *Software Engineering Body of Knowledge (SWEBoK)* (Bourque and Fairley 2014), which Jose already knows from his many years of experience on software projects. In the SEBoK, Jose is looking for nuggets of knowledge and pointers that can help his enterprise expand. Here are his notes:

- Part 3: Systems Engineering and Management has concepts that are new to us and that may work. Extra system-level verification and validation (V&V) gates identified in Life Cycle Models can be incorporated in company processes, and the references can help with implementation details. There is also material about system-wide procedures beyond software V&V, and about where to find testing and regulation standards used by various government entities. Together with the traditional software testing already in place, these processes could ensure conformity to the regulations and expedite the product's approval for use.
- Though the system concept is proven, the company must still convince potential buyers of the system's financial benefits while demonstrating that all security criteria are satisfied. To do that, we must understand the needs of the stakeholders better. In expressing system requirements and benefits, we need to start using the terminology of users, corporate/government purchasers, and regulatory agencies. Stakeholder Needs and Requirements is relevant here. The company needs to quantify expected return on investment (ROI) for its products.
- System Realization addresses our broader V&V concerns. We need to demonstrate the measures we are taking to boost reliability of system performance. The standard models and measures for system reliability described in the SEBoK are new to us — now staff must develop tests to quantify important attributes. We may want to model reliability and system adherence to regulations using a form of model-based systems engineering (MBSE). We can learn more about this from the references.

- Systems Engineering Management makes it clear that new configuration management (CM) and information management (IM) procedures need to be adopted for federal database controls and integrity. We can use the references in Systems Engineering Standards to learn how to define processes and develop test cases.
- Part 5: Enabling Systems Engineering makes a convincing case that having the right people for a new systems engineering culture is critical. We should probably hire a systems engineer or two to augment our engineering department expertise.
- Our application must deal with private data concerns, and Part 7: Systems Engineering Implementation Examples, the FBI Virtual Case File System Case Study could help us avoid pitfalls that have hurt others in similar situations. We can put this in context based on Security Engineering in Part 6: Related Disciplines, and then follow up with further study based on the references.

Now Jose feels that he is better prepared to adapt his processes for new system lifecycles and environments, and that he can see a clear path through the morass of agencies and regulations. His priorities are to quantify the value proposition for his technology innovations, make inroads into new markets, and strengthen his staff for the long-term enterprise.

## Vignette: Mechanical Engineer

Cindy Glass is a mechanical engineer whose experience in the petroleum industry has focused on large-scale oil extraction equipment in the field. Now Cindy is tasked with helping to manage the development of new offshore oil platforms featuring robotic technology and computer networks. This calls for incorporating SE principles from day one to cope with the systems considerations, which are broader than anything in Cindy's previous experience.

Some of the drilling is to be done with remote-controlled, unmanned underwater vehicles (UUVs). Along with safety, which was always a major concern, cybersecurity now takes center stage. Hostile state actors, “hacktivists,” or others could cause havoc if they succeed in taking control of the remote vehicles or other infrastructure. Unfortunately, software system implementation is completely new to Cindy, who realizes that this entails dealing with many more engineering disciplines and dimensions of system constraints than she previously encountered.

Cindy is accustomed to implementing minor design changes in existing equipment, with automation and safety guidelines already in place. Now she is starting from scratch, with the earliest stages of the platform lifecycle. While Cindy understands tradeoffs involving mechanical sub-systems like rigs and drilling materials, she now must now broaden her system analysis to include new environmental constraints and system security.

Cindy consults the SEBoK and discovers that for her effort to understand system design with many "-ilities," System Realization is a good starting point and its references should provide the in-depth information she needs.

The project lifecycle requires pursuing several major activities concurrently:

- engineering platform sub-components
- evaluating technology opportunities
- understanding the needs of all stakeholders inside and outside the company
- progressing through increasingly detailed prototypes, working slices of software, system specifications, designs, plans, business cases, and, security and safety analyses of the platform architecture and its operations.

To understand how to manage such a project lifecycle, Cindy turns to Part 3: Systems Engineering and Management. The planning section provides detailed advice for starting out. Cindy expects to conduct her management activities on a rigorous basis, to consider the interfaces between the engineering specialties, and to produce a project plan that calls for a broad set of integrated management and technical plans.

Being new to the software development world, Cindy reads The Nature of Software and Key Points a Systems Engineer Needs to Know about Software Engineering, and consults the SWEBoK [1] for references on software engineering.

These readings show Cindy how closely systems engineering and software engineering are intertwined. For example, they remind her to include security specialists at both the software level and the systems level from the beginning.

From her initial plunge into study of the SEBoK, Cindy has gained an appreciation of the wide range of system constraints she must account for, and the many engineering disciplines she must work with as a result. She plans to consult the references in the SEBoK on each unfamiliar subject that she encounters throughout the architecting, design, development and deployment of the new platforms.

# Summary

Engineers from disciplines other than systems engineering benefit from the insights about SE principles that the SEBoK provides. Studying the knowledge areas highlighted in this use case and the sources to which their references point can help such engineers become more interdisciplinary. Ultimately, they can consider broadening their work responsibilities, rendering them more valuable to their employers and society.

# References

## Works Cited

Bourque, P. and R.E. Fairley (eds.). 2014. *Guide to the Software Engineering Body of Knowledge (SWEBOK)*. Los Alamitos, CA, USA: IEEE Computer Society. Available at: http://www.swebok.org

## Primary References

None.

## Additional References

None.

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[1] http://www.computer.org/portal/web/swebok

# Use Case 3: Customers of Systems Engineering

Customers of systems engineering (SE) provide resources to SE organizations and individuals, and receive SE products and services in return. They are among the stakeholders for a system-of-interest (SoI). They and other stakeholders express needs and expectations for results that system engineers provide.

Although their main SE activity is helping to define the system, customers must take account of all life cycle aspects. The better they understand the activities that systems engineers perform, the better customers know what to request, how to request it, how much to pay for it, and how to judge the quality and value of the results of systems engineering. In short, what customers need to grasp is how systems engineers participate in the realization of engineered systems resulting in products, services, enterprises, and systems of systems (SoS).

The SEBoK assists the customers of systems engineering by providing a broad, comprehensive treatment of the concepts, principles, theory, and practice related to systems in general and SE in particular. Its references inform customers about books and articles that provide important perspectives on systems and SE.

Customers of SE include:

- sponsors of internal SE organizations
- organizations that maintain long-term customer-domain relationships with external SE organizations, and
- organizations that outsource SE functions to general-purpose SE organizations.

The two vignettes below show how the SEBoK can assist SE customers. In one, the customer of an internal, corporate SE organization leads the transition to a mobile supply chain management system. In the other, the customer of a mixture of customer-domain and other SE organizations presides over the SE of a catastrophe-response sSoS, which entails integration over multiple domains.

## Use of Topics

For customers of SE, most parts of the SEBoK offer immediately relevant knowledge about SE.

Part 1:

- explains the relationship between SE, system development, and project management,
- summarizes overall trends in the rate of growth of systems interdependency, complexity, assurance levels, and pace of change, and of the evolving nature of integrated hardware-software-human systems, and
- provides pointers to other parts of the SEBoK of interest to customers.

Part 3:

- explains evolving system life cycle models and their elements, indicating which elements are SE-intensive (see Life Cycle Models),
- provides overall perspectives on customer participation in SE activity,
- identifies customer influence points on SE activity, and
- explains how customers can express their concerns in the form of needs, expectations, and requirements (see System Definition).

Part 4:

- explains how the SE function varies by class of system product, service, enterprise, and systems of systems engineering).

Part 6:

- explains how SE relates to project management, procurement and acquisition, and specialty engineering for such customer-intensive specialties as safety, security, maintainability, usability, and affordability.

Part 7:

- provides case studies and examples to illustrate how the parts have been used in similar situations, presenting successes to emulate and failures to avoid.

If there is a central theme here, it is that the quality of customer input is critical. That is because the systems engineer evaluates customer input, then uses it in formulating an approach to defining and realizing the system. Part 3 addresses this, explaining that the customer should expect the systems engineer to provide:

- a well-architected product, service, enterprise, or system of systems that meets customer needs and expectations (again, this depends on high quality input from stakeholders — see System Definition)
- a managed life cycle model from the customer need and requirements to the delivered product, service, enterprise or system of systems (see Life Cycle Models)
- verification that the system-of-interest (SoI) meets the needs and requirements of the stakeholders, and
- validation that the final result, when deployed in an operational environment, provides the value added that was desired are critical to systems engineering (see System Realization and System Deployment and Use).

## Implementation Examples

Good examples provide a basis for deeper understanding. In Part 7, the SEBoK provides summaries of and references to full case studies and examples. These are linked back to the appropriate areas of the SEBoK and a matrix is provided that shows the primary areas of the SEBoK addressed by each example. Readers can use the matrix to find case studies and examples- and through these, references - that relate to their concerns.

### Vignette: Mobile Supply Chain Management

Barbara Bradley is the Director of Supply Chain Management Systems for a large manufacturing company. Her main area of expertise is transportation logistics. She has led the evolution of a highly successful corporate supply chain management system based on desktop and mainframe technology, more by making incremental strategic choices than by applying formal SE.

Now, many of her suppliers and distributors adopt mobile devices and cloud services and Barbara sees that her own company must do the same. The company's status quo approach of incremental, ad hoc choices is clearly inadequate for a technology transition of this magnitude. Not only that, but the company must evolve to the new mode of operation while providing continuity of service to the supply chain stakeholders.

Barbara decides that these challenges require formal SE. As a first step, she plans to put together a Next-Generation Supply Chain Management System integrated product team (IPT). Members of the IPT will include Barbara's supply chain experts, her supply-chain success-critical stakeholders, and the corporate SE organization.

Barbara has never used the corporate SE organization before, and wants to better understand an SE organization’s overall capabilities and modes of operation. She turns to the SEBoK for answers to the questions about SE that are on her mind:

- How do we maintain continuity of service while pursuing incremental development?
  - What choices about life cycle models can make this possible?
- What is the role of the customer in defining systems of interest (SoIs)?
  - How do we provide guidance to the customer in expressing needs, concerns, and requirements?
- What is the role of the customer at early decision milestones?
  - How do we ensure that results of our interaction with the customer include well-architected products and thorough development plans, budgets, and schedules?
- What is the role of the customer in product acceptance, specifically when we verify stakeholder requirements and when we validate the final result?

Barbara seeks the answer to one question in Part 4: Applications of Systems Engineering:

- Given that a supply chain management system combines product, service, enterprise, and SoS views, how do we understand what goes into all those views, and keep the overall picture clear?

Barbara's final question is addressed in Part 6: Systems Engineering and Other Disciplines:

- How do we integrate SE and software engineering (SwE)?

Once in command of the answers to these questions, Barbara is ready to lead the IPT in analyzing, negotiating, and defining an approach that is satisfactory to all of the success-critical stakeholders. By having the IPT members read the portions of the SEBoK that she has found most valuable, Barbara begins to build a shared vision within the IPT. As the IPT defines a Next-Generation Supply Chain Management System and prepares the transition from the old system to the new, the SEBoK is an important tool and resource.

## Vignette: Catastrophe-Response System of Systems

Ahmed Malik is the Information Systems Division General Manager in his country’s Department of Natural Resources. The country suffers frequent wildfires that destroy crops, forests, villages, and parts of cities, and also cause problems with emergency care, crime prevention, and the water supply.

During a recent catastrophic wildfire, personnel responsible for firefighting, crime prevention, traffic control, water supply maintenance, emergency care facilities, and other key capabilities found themselves unable to communicate with each other. As a result, the Minister for Natural Resources has been tasked with improving the country’s catastrophe response capabilities, and has named Ahmed as the SE customer lead for this effort.

The Minister suggests that Ahmed organize a workshop to scope the problem and explore candidate solutions to the communications problems. Ahmed invites the various actors involved in catastrophe response — medical, insurance, and news media organizations from both public and private sectors. He also invites SE organizations with SoS experience.

Ahmed has strong experience in information SE, but none in the development of SoSs. To come up to speed in his role as the SE customer lead, Ahmed turns to the SEBoK Part 3: Systems Engineering and Management. To better understand the challenges of SoS SE, he studies the SoS knowledge area in Part 4, and its references. Ahmed also schedules meetings with the leading SoS SE provider organizations, who are eager to tell him about their capabilities. Overall, Ahmed looks for both guidance and pointers to candidate solution sources in the SEBoK.

Thus prepared, Ahmed structures the workshop to address three key challenges:

- mutual understanding of organization roles, responsibilities, and authority
- summary analyses of previous catastrophe response communication gaps and needs
- candidate solution capabilities in communications, data access, geolocation services, public emergency warning systems, coordinating evacuation procedures, architectural connector approaches for improving interoperability, and sharable models for evaluating alternative solution approaches.

The workshop brings the primary organizations involved in catastrophe responses together with the most capable SoS SE provider organizations. The results of their discussions provide Ahmed and his Minister with sufficient information to prepare a phased plan, budget, and schedule for incremental development of improved catastrophe response capabilities, beginning with simple interoperability aids and analysis of architecture alternatives for performance, scalability, and feasibility of evolution from the initial simple fixes. The plan is then iterated with the key stakeholders, and converged to a common-consensus approach for achieving strong, credible early improvements and a way forward to a much more scalable and cost-effective catastrophe-response SoS.

This vignette is based on the Regional Area Crisis Response SoS (RACRS) in (Lane and Bohn 2010).

## Summary

For the customers of SE, the SEBoK provides both general and specific knowledge that will help users gain important insight in relating to systems engineers. Key to this is learning about life cycles, the definition of SoIs, and how to provide guidance in expressing needs, concerns, and requirements. Further, customers need to know what to expect as a result of SE activities in the form of well-architected products, services, enterprises, or systems of systems and a managed life cycle. The results of verification of stakeholder requirements and the validation of the final result in respect to fulfilling the user needs are vital.

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# Use Case 4: Educators and Researchers

For educators or researchers, the SEBoK should be used together with GRCSE (*Graduate Reference Curriculum for System Engineering*). The SEBoK is a guide to the knowledge that constitutes the system engineering domain, while GRCSE [1] "describes a program for a professional master's degree focused on developing student ability to perform systems engineering tasks and roles" (Pyster et al. 2012).

An educator, for purposes of this use case, is a university faculty member or a professional trainer. Educators use the SEBoK and the GRCSE to develop curricula or courses focused on systems engineering (SE) generally, on domain-centric systems engineering, or on another engineering discipline that touches on SE. The SEBoK and GRCSE are means to assure accuracy, completeness, and effective assessment at all levels, from lessons through objectives.

A researcher, for purposes of this use case, is a person actively contributing to the body of SE knowledge.

## The Use of Topics

Educators can use SEBOK topics and their primary and additional references as:

- assigned readings for courses,
- supplemental references for student research, and
- content for curriculum development.

Educators can also use the concepts, perspectives, and references to develop or refine course objectives and the techniques for assessing them.

Researchers can use SEBoK topics and their primary and additional references to learn about the state of the art in the subject areas of interest, for summaries of the literature, and to look for opportunities to advance those areas by further research.

A good course or research topic should reflect multiple perspectives, which the SEBoK provides. As well, cataloging the wide diversity in accepted practices across SE is an important function of the SEBoK from the researcher's perspective.

For both educators and researchers, the fact that the SEBoK provides both primary and additional references in each topic is useful. So is the fact that the SEBoK is a wiki, which allows frequent updates to keep pace with the dynamic evolution of the systems engineering domain. See Acknowledgements and Release History.

## Implementation Examples

Good examples make for good teaching. The Systems Engineering Implementation Examples in the SEBoK consist of relatively in-depth case studies and shorter examples, which are linked back to appropriate areas of the SEBoK. A matrix shows which SEBoK topics are addressed by each case study or vignette.

Each case study in the SEBoK is actually a summary of an original case found in the SE literature, and is accompanied by a reference to the full, published case study. Case study summaries or examples from the SEBoK may be incorporated in curricula.

## Educator

University faculty may use the SEBoK and GRCSE to develop:

- a complete SE curriculum,
- a single course in systems engineering, either for use in an SE curriculum, or in a curriculum that belongs to some other discipline, or
- assessment criteria for curricula or courses.

Likewise, professional trainers use the SEBoK to develop training material, or to evaluate or update existing training courses.

Both faculty and trainers pursue professional development, in the form of SE study, using the SEBoK.

### Vignette: Curriculum and Course Development

A university designates a faculty team to investigate the feasibility of developing a graduate degree in SE.

Results of preliminary feasibility analysis (including evaluating the market, competing degree programs, and so on) are encouraging. The faculty team then begins to design the program, by identifying:

- program constituents
- potential objectives, outcomes and entrance requirements, based on review of GRCSE
- one half of the of the curriculum content, based on review of the typical curriculum architecture (GRCSE chapter 5) and the core body of knowledge (CorBoK) (chapter 6) of GRCSE and
- the other half of the curriculum content based on review the SEBoK (Parts 2 through 7) .

According to the GRCSE, 50% of the total knowledge conveyed in a graduate program should be based on the CorBoK, to assure a common foundation among programs offered at different institutions. At the same time, restricting the CorBoK to no more than 50% encourages a healthy variety in those programs.

Once these steps are complete, the overall architecture and the content and the scope of the curriculum are defined. Now the faculty designs the courses themselves, defining in turn:

- the prerequisites for each course
- the overall course sequencing for the curriculum, based on the course prerequisites
- the objectives and goals for each course and
- the expected outcomes of each course.

Finally, the faculty is ready to develop the content for each individual course.

Defining course content is done based on topics in the SEBoK that cover the subject of the course.

Using primary and additional references as much as the topics themselves, the faculty responsible for course design define:

- the scope of the course content
- the course coverage, that is, what within the course content scope is actually taught in the course.

Given the scope and coverage, the next and final step is to develop the course material.

A professional trainer designing the training material performs the same kinds of activities. To customize the training course for a specific industry or customers, the trainer may integrate domain-specific content as well.

## Researcher

Researchers use SEBoK topics and their primary and additional references to learn about the state of the art in the subject areas of topics, and to look for opportunities to advance those areas by further research.

### Vignette: Software Engineering Research

William McGregor, a software engineer, wants to learn more about software intensive systems (SIS). Initially, William wants to answer the question: Do the activities and practices used to develop SIS represent special treatments of standard activities and practices?

William has already reviewed the SWEBoK and its primary references extensively for an answer to his question. In the course of his research, William learns about the SEBoK and decides to look there, too.

William finds no specific discussion of the SIS within the SEBoK. As he looks through the SEBoK, though, he realizes that there are activities throughout the system development life cycle which can be adapted or customized for the development of SIS. Accordingly, William decides to replace his original question with two new ones: (a) what best practices are applied throughout the software development life cycle and (b) how can those practices be adapted to SISs?

William now focuses on Part 3 to learn about the system development life cycle, and identify development activities and practices that he can customize for software intensive systems.

## Summary

Educators use the SEBoK as a framework or a resource which helps them:

- determine what subject matter should be included in a new curriculum
- identify gaps in an existing curriculum and craft plans to address those gaps, and
- design individual courses.

The case studies and vignettes in the SEBoK may be used by educators in the classroom.

To develop curricula at the program level, educators should use the SEBoK in tandem with the GRCSE.

Researchers use the SEBoK to learn about the state of the systems engineering discipline, and to look for opportunities to advance that state by further research.

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None.

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[1] http://www.grcse.org

# Use Case 5: General Managers

General managers preside over system development projects, system acquisitions, product lines, systems of systems (SoSs), and commercial and government organizations. For general managers, the SEBoK serves as a primary information source and quick, comprehensive reference for systems engineering information.

In particular, the SEBoK helps the general manager understand:

- the boundaries and synergies among systems engineering (SE), systems development, project management (PM), and life cycle support
- how those boundaries and synergies are likely to evolve with increasing use of evolutionary development, lean and agile methods, and systems that provide purchased services as opposed to salable products
- how to best balance a mix of hardware, software, human factors, domain, and specialty-area systems engineers and
- how an organization can evolve to take advantage of the trend towards cross-discipline systems engineers.

## Use of Topics

For general managers, most parts of the SEBoK offer immediately relevant knowledge about SE.

Part 1:

- explains the relationship between SE, system development, and project management
- summarizes overall trends in the nature of systems interdependency, complexity, assurance levels, and pace of change
- describes the evolving nature of integrated hardware-software-human systems and
- provides pointers to other parts of the SEBoK of interest to general managers.

Part 3:

- explains evolving system life cycle models and their elements, indicating which elements are SE-intensive (see Life Cycle Models) and
- provides overall guidance on the management of SE activity.

Part 4:

- explains how the SE function varies by class of system product, service, enterprise, and systems of systems engineering).

Part 5:

- explains SE governance and competence development.

Part 6:

- explains how SE relates to software engineering, project management, industrial engineering, procurement and acquisition, and specialty engineering for such specialties as safety, security, maintainability, and usability.

Part 7:

- provides case studies and vignettes to illustrate how the parts have been used in similar situations in successes to emulate and failures to avoid.

## Vignette: Emerging Nation Satellite System

Tom Lee is General Manager for Telecommunications in a ministry of a large emerging nation. The government does not have much existing capability for developing capital-intensive infrastructure projects. The government decides to use a major investment in technology as a vehicle to develop national enterprise capabilities.

To accomplish this, the minister assigns Tom to lead a project to develop a national satellite system for telecommunications and earth resources observation. Tom understands that this is a very complex system, and decides to do some background research. During this research, Tom discovers the SEBoK and decides that is may be a useful resource.

Tom first reads:

- Part 1 for an overview and pointers to relevant sections of Parts 3 through 6,
- portions of Part 3, Part 4, Part 5, and Part 6 to learn about the life cycle, nature, scope, and management aspects of enterprise SE,
- the successful satellite system case studies in Part 7 (Global Positioning System, Miniature Seeker Technology Integration spacecraft) for approaches to emulate, and
- the satellite system case study in Part 7 which describes development and integration problems (Hubble Space Telescope) for pitfalls to avoid.

Tom continues by carefully reading Part 5. He realizes that he must develop simultaneously individuals, teams, and the enterprise. The knowledge areas (KAs) from Part 5 give useful background. For this project, Tom enlists both a proven multi-national satellite SE company and some of his brightest aerospace systems engineers. Tom expects his local systems engineers to learn from the SE company, and he plans to use them as the core group of the national satellite system as it ultimately develops and operates.

He realizes that correct problem definition and requirements setting will be critical first steps. He carefully reads the Concept Definition and System Definition KAs. As his team develops the Stakeholder Needs and Requirements and the System Requirements, he makes sure they follow good practices as listed in the SEBoK. Once architectural designs have been proposed and approved, he requires his team to perform cost-benefit tradeoff analyses of alternative solutions.

Thus prepared, Tom is confident that he can formulate and execute a successful approach.

## Vignette: Commercial Safety Equipment Company

Maria Moreno is General Manager at Safety First Equipment Company, specialists in hardware-intensive safety equipment. Maria’s background is in electromechanical systems. Safety First is highly successful, but beginning to lose market share to competitors who offer software-intensive capabilities and user amenities.

Maria is preparing an initiative to make Safety First into a leading software-intensive safety equipment provider. She decides to make the SEBoK a primary resource for gathering concepts and insights for the initiative. She begins by skimming through all of Parts 1 through 6, both to become familiar with the SEBoK itself and to start organizing her thoughts on SE.

Now Maria is ready to focus on subjects of prime importance to her task. Here are those subjects, listed with the places in the SEBoK where she find information about them.

In Systems Engineering and Software Engineering in Part 6:

- the nature of software
- differences between hardware and software architectures and practices and

- key aspects of managing software teams.

In the article Human Systems Integration in the Systems Engineering and Specialty Engineering knowledge area, also in Part 6:

- the SE of user amenities.

In the Next Generation Medical Infusion Pump Case Study in Part 7:

- the software aspects of safety practices, such as software fault tree analysis and failure modes and effects analysis and
- overall approaches for concurrent engineering of the hardware, software, and human factors aspects of safety-critical equipment.

In the Medical Radiation Case Study in Part 7:

- hardware-software pitfalls to avoid in safety-critical equipment.

Maria chose the last two items from among the case studies in Part 7 because being safety-critical, they contain lessons directly applicable to her initiative at Safety First.

With this framework of concepts and practical information in place, Maria begins assembling a core team of Safety First systems engineers, complemented by external experts in software and human factors engineering. Maria wants the team to begin by developing a shared vision. To that end, she asks them to read the portions of the SEBoK that she has found most valuable in assessing the challenges of transitioning Safety First into a leading software-intensive, user-friendly safety equipment provider.

# Summary

For the general manager whose organization includes systems engineers, the relationship between SE, systems development, project management, and life cycle support is a central concern. The SEBoK provides insights and guidance about this and other aspects of SE principle and practice, and explains the role of SE in a variety of management challenge areas and application domains.

The SEBoK complements the general management guidance available in sources such as the *PMBOK® Guide* (PMI 2013).

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