

DISSERTATION

CHARACTERIZING AND IMPROVING THE ADOPTION RATE OF MODEL-BASED
SYSTEMS ENGINEERING THROUGH AN APPLICATION OF THE DIFFUSION OF
INNOVATIONS THEORY

Submitted by

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ABSTRACT

CHARACTERIZING AND IMPROVING THE ADOPTION RATE OF MODEL-BASED SYSTEMS ENGINEERING THROUGH AN APPLICATION OF THE DIFFUSION OF INNOVATIONS THEORY

As the environment and operational context of new systems continue to evolve and become increasingly complex, the practice of [Systems Engineering \(SE\)](#) must adapt accordingly. A great deal of research and development has gone and continues to go into formulating and maturing a model-based approach to SE that addresses many of the shortcomings of a conventional, document-based SE approach. In spite of the work that has been done to advance the practice of [Model-Based Systems Engineering \(MBSE\)](#), it has not yet been adopted to a level that would be expected based on its demonstrated benefits. While research continues into even more effective MBSE approaches, there is a need to ascertain why extant MBSE innovations are not being adopted more widely, and if possible, determine a way to accelerate its adoption. This outcome is particularly important as MBSE is a key enabler to an [Agile Systems Engineering \(ASE\)](#) approach that satisfies the desire of many stakeholders to apply agile principles to SE processes.

The [Diffusion of Innovations \(DoI\)](#) theory provides a useful framework for understanding the factors that affect the adoption rate of innovations in many fields. This theory has not only been effective at explaining why innovations *are* adopted but has also been able to explain why objectively superior innovations are *not* adopted. The DoI theory is likely to provide insight into the factors that are depressing the adoption rate of MBSE.

Despite prior efforts in the SE community to promote MBSE, the DoI theory has not been directly and deliberately applied to understand what is preventing widespread MBSE adoption. Some elements of the theory appear in the literature addressing MBSE adoption challenges without any recognition of awareness of the theory and its implications. The expectation is that harnessing

the insights offered by this theory will lead to MBSE presentation and implementation strategies that will increase its use. This would allow its benefits to be more widely realized in the SE community and improve the practice of SE generally to address modern, complex environments.

The DoI theory has shown that the most significant driver of adoption rate variability is the perceived attributes of the innovation in question. A survey is a useful tool to discover the perceptions of potential adopters of an innovation. The primary contribution of this research is the development of a survey to capture and assess a participant's perceptions of specified attributes of MBSE, their current use of MBSE, and some limited demographic information. This survey was widely distributed to gather data on current perceptions of MBSE in the SE community.

Survey results highlighted that respondents recognize the relative advantage of MBSE in improving data quality and traceability, but perceived complexity and compatibility with existing practices still present barriers to adoption. Subpopulation analysis reveals that those who are not already involved in MBSE efforts face the additional adoption obstacles of limited trial opportunities and tool access (chi-squared test of independence between these populations resulted in $p = 0.00$). The survey underscores the potential for closer alignment between MBSE and existing SE methodologies to improve the perceived compatibility of MBSE.

Targeted actions are proposed to address these barriers to adoption. These targeted actions include improving the availability and use of reusable model elements to expedite system model development, improved tailoring of MBSE approaches to better suit organizational needs, an increased emphasis on ASE, refining MBSE approaches to reduce the perceived mental effort required, a lowering of the barrier to entry for MBSE by improving access to the resources (tool, time, and training) required to experiment with MBSE, and increased efforts to identify and execute relevant MBSE pilot projects. The lessons and principles from the DoI theory should be applied to take advantage of the opportunity afforded by the release of SysML v2 to reframe perceptions of MBSE. Future studies would benefit from examining additional variables identified by the DoI theory, incorporating control questions to differentiate between perceptions of SE gener-

ally and MBSE specifically, identifying better methods to assess current MBSE use by participants, and measures to broaden the participant scope.

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DEDICATION

To Katie,

Claire,

Sophie,

John,

Luke,

and Joseph.

With all of my love.

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ACRONYMS

AADL Architecture Analysis and Design Language *on page(s): 19*

API Application Programming Interface *on page(s): 83*

ASE Agile Systems Engineering *on page(s): ii, 6, 11, 88*

ASoT Authoritative Source of Truth *on page(s): 17, 20, 39, 49*

BPMN Business Process Model and Notation *on page(s): 19*

CSU Colorado State University *on page(s): 45, 49*

DE Digital Engineering *on page(s): 46, 84*

DoD Department of Defense *on page(s): 46, 49*

DoI Diffusion of Innovations *on page(s): ii, 3*

FE Fisher Exact *on page(s): 55*

INCOSE International Council on Systems Engineering *on page(s): 4, 22, 46, 49, 77*

IRB Institutional Review Board *on page(s): 7, 45, 114*

ISO International Organization for Standardization *on page(s): 19*

IT Information Technology *on page(s): 49*

KerML Kernel Modeling Language *on page(s): 82*

LLMs Large Language Models *on page(s): 84*

MBCM Model-Based Capability Matrix *on page(s): 49, 77*

MBSE Model-Based Systems Engineering *on page(s): ii, 4*

NAS Net Agreement Score *on page(s): 54*

OMG Object Management Group *on page(s): 18*

OOSEM Object-Oriented Systems Engineering Method *on page(s): 19*

OPL Object-Process Language *on page(s): 19*

OPM Object-Process Methodology *on page(s): 19*

OR Odds Ratio *on page(s): 132*

SDL Specification and Description Language *on page(s): 19*

SE Systems Engineering *on page(s): ii, 1, 3*

SoS System of Systems *on page(s): 25*

SysML Systems Modeling Language *on page(s): 7, 18, 40*

T&E Test and Evaluation *on page(s): 21*

UML Unified Modeling Language *on page(s): 18*

V&V Verification and Validation *on page(s): 19*

XM Qualtrics Experience Management *on page(s): 45*

Chapter 1

Introduction

1.1 Overview

The objective of [Systems Engineering \(SE\)](#) is to employ a holistic, methodical, top-down approach to facilitate the specification, development, operation, sustainment, and disposal of systems through completion of a set of technical and management processes to meet specific stakeholder needs or requirements [8]. Systems are characterized by the exhibition of the property of emergence, or the idea that a collection of components (which can be systems themselves) interact to provide a function that is not possible by any of the components individually [9]. There are no limitations as to the type of components that can be included in engineered systems (mechanical, electrical, software, biological, social, technological, etc.), and as such, SE is necessarily a transdisciplinary¹ field [14].

While [SE](#) has roots that reach back even further, it emerged as a distinct discipline in the 1950s as a means to manage the complexity of large systems, like spacecraft and weapon systems, that began to be developed around that time [15]. During the subsequent decades, the discipline matured as it became a field of research and study, standards emerged, and practitioners accumulated experience. While it is not the purpose of this work to recount the full history and purpose of SE as a discipline, it is important to recognize and appreciate its purpose and origins. While there is still room to improve to meet current and emerging challenges, SE is a mature discipline that has evolved over decades of use and refinement, and its principles are not obsolete.

Despite its mature foundation and past successes, SE has experienced significant growing pains in the information age [16, 17]. As a discipline that concerns itself with the specification and man-

¹Systems engineering has also been referred to as an interdisciplinary or multidisciplinary field [10, 11]. I prefer the term transdisciplinary to emphasize the fact that an SE approach does not simply incorporate principles and practitioners from various disciplines. Rather, a transdisciplinary SE approach integrates disparate disciplines and fields to produce a holistic approach to facilitate the development of new systems [12, 13].

agement of the components that constitute a system and their relationships, its work has increased exponentially with the central role of software in modern systems. Figure 1.1 shows the exponential growth of software size in various domains. With this exponential growth, the legacy processes used to manage these systems through manually generated artifacts (documents, diagrams, spreadsheets, etc.) have quickly become untenable, and SE outcomes are suffering [18].

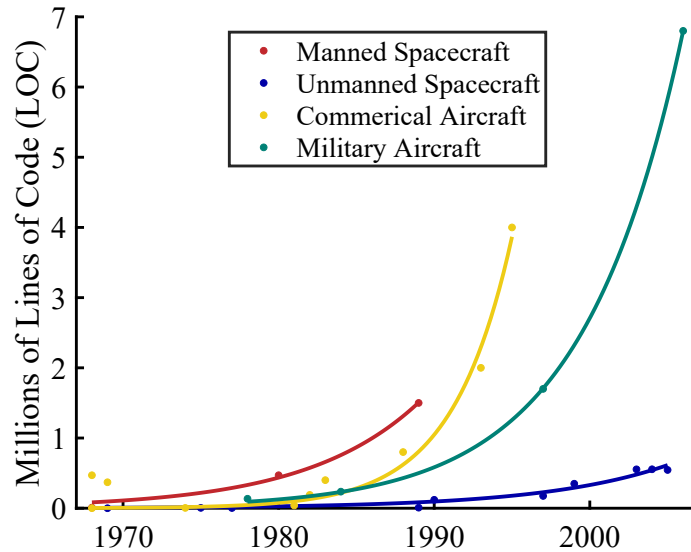


Figure 1.1: Historical trends in lines of code in various domains (data from [2–5]) [6].

The transdisciplinary nature of SE is evident in the Graduate Reference Curriculum for Systems Engineering (GRCSE®), as developed by the Body of Knowledge and Curriculum to Advance Systems Engineering (BKCASE) project that, as its name suggests, is meant to codify a curriculum that will prepare SE students for the challenges they will face in engineering the complex systems being developed today. It references a diverse set of disciplines in identifying that “[systems engineering] incorporates skill sets from many disciplines; including traditional engineering disciplines (electrical, mechanical, civil, etc.) as well as more management-focused disciplines (project management, program management, industrial engineering, etc.)” [19]. These management-focused disciplines arise from the fact that every system created by a systems engineer has a human element, as SE encompasses the organizations and processes that manage the entire life cycle of the system-of-interest.

When considering the challenges facing the SE community, it is also important to remember that many authors and practitioners recognize that while there are many technical processes associated with SE, there is an art to the discipline that may not exist in other engineering fields [20–24]. Considering the artistic nature of SE and the impact of the human element, there is almost certainly a benefit to looking beyond the traditional fields in educating systems engineers and improving the SE practice [25]. Former NASA administrator, undersecretary of defense for research and engineering, and SE educator, Michael Griffin, while specifically addressing some of the shortcomings in the field of SE, observed that “until and unless we begin to delve into the social and cognitive aspects of how engineers work together and how system engineering is performed. . . possible contributions from fields far apart from engineering will continue to go unrecognized. . . The study of human interactions, cognitive psychology, social choice theory, and other disciplines *must be included* in the development of effective theories of system engineering” [11] (emphasis added).

Application of “fields apart from engineering” offer benefits in their own right, but they can also serve as a “force multiplier”, enabling research and development within the SE discipline to be applied in more effective ways [26]. There are many opportunities to investigate how these disparate fields can be incorporated into the practice of SE. One such field that offers promise is the study of the usage and adoption of innovations. In the field of innovation research, Everett Rogers’ [Diffusion of Innovations \(DoI\)](#) theory has come to the forefront, offering a useful framework for understanding adoption patterns and trends [1]². This theory provides a framework for understanding the adoption patterns of innovations. It also identifies variables that contribute to the variability in adoption rate amongst innovations.

The DoI theory seeks to explain the variation in adoption rate and breadth of innovations [1]. This is relevant to SE as it is an active field with a constant flow of new research and innovations [27]. Some of these innovations have not been adopted to a degree commensurate with the apparent benefits they offer SE practitioners. One such innovation, developed to address the short-

²Innovation in this context means “an idea, practice, or object that is perceived as new by an individual or other unit of adoption” [1].

comings inherent to the traditional SE approach described above and to leverage digital tools that are now available, is the practice of [Model-Based Systems Engineering \(MBSE\)](#) [28–30]. The [International Council on Systems Engineering \(INCOSE\)](#) defines MBSE as “the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases” [9]. MBSE can be characterized as both a process and a behavioral innovation as it introduces new methods, modeling languages, and tools to existing SE activities that often require changes in organizational culture to adopt [31]. It is possible that an understanding and application of the DoI theory can accelerate the adoption rate of MBSE and allow its benefits to be realized more widely in the SE community.

In a model-based SE approach, the primary artifact of SE activity is a system model. MBSE effectively addresses the challenge of managing complexity by facilitating the development of various systems and subsystems through distinct, authoritative, and interconnected models. Through interconnected relationships, these models maintain consistency, enabling a synchronized representation across the entire system architecture. This approach enhances clarity and facilitates a streamlined process for handling intricate relationships within a complex engineering project.

Despite its suitability to address the challenges facing systems engineers of modern, complex systems, MBSE has thus far failed to achieve widespread adoption. A great deal of research has addressed challenges encountered during MBSE adoption efforts [32–42]. For the most part, efforts to identify and address these adoption challenges have approached the problem directly by identifying specific issues SE practitioners have encountered in their efforts to adopt MBSE. These efforts have resulted in a valuable corpus of literature and training that has facilitated an increase in the adoption and use of MBSE in the SE community. However, we still refer to a model-based approach to SE as MBSE, as the SE community has not established a consensus regarding MBSE as the SE standard practice.

A study of MBSE adoption patterns through the lens of the DoI theory may provide new and valuable insights into factors that may be negatively impacting the adoption rate of MBSE [43].

With an understanding of these factors, we can devise targeted actions to accelerate the adoption rate of MBSE so that its benefits can be more broadly realized in the SE community.

1.2 Research Objectives

The purpose of this research is to determine the relevance of the DoI theory to MBSE adoption in an effort to accelerate the adoption rate of MBSE. The study of innovation adoption is a mature field, and the DoI theory has been shown to explain variation in the adoption rates of many innovations in a variety of fields. This theory identifies factors, over and above the objective benefits of the innovation, that can influence the rate and breadth of its adoption. Within the SE field, MBSE is an innovation that has yet to be widely adopted, despite its demonstrated and potential benefits. There are potential benefits that have yet to be achieved by organizations that have not adopted a model-based approach to their SE efforts. So that the benefits of MBSE may be more widely realized, the primary research question that this dissertation will address is: **how can the DoI theory be applied to understand and improve the adoption rate of MBSE?**

The three research objectives that will address this question are:

Research objective 1: Perform a thorough literature review of extant publications relating to MBSE benefits, adoption trends, and adoption challenges to support the case that efforts to improve the adoption rate of MBSE are warranted and should be encouraged.

Research objective 2: Conduct a survey of the SE community to assess the applicability of the DoI theory to MBSE adoption by assessing the perception of attributes of MBSE and conducting statistical analyses to determine underlying factors that are predictive of an individual's use of MBSE.

Research objective 3: Develop recommendations for targeted actions, based on the DoI theory and survey results, that can be introduced to the practice and presentation of MBSE to accelerate its adoption.

1.3 Dissertation Overview

The objective of this dissertation is to build a case as to why (through a literature review) and how (by application of the DoI theory) the use of MBSE can be expanded within the SE community. To this end, this dissertation will be organized as follows:

Chapter 2 presents a historical perspective of MBSE, its core principles, and identifies some of the challenges facing the SE community in managing the complexity inherent in the centrality of software in modern systems³. It makes an argument for the continued relevance of SE even as many organizations are looking for broader application of processes based on agile principles [44] that evolved from the software development field, and to reduce the overhead associated with traditional SE processes. This chapter also shows how MBSE is a key enabler to [Agile Systems Engineering \(ASE\)](#) as a means of bridging the gap between SE rigor and agile methods.

Chapter 3 provides an overview of the DoI theory as developed by Everett Rogers⁴. It explains the variables identified by this theory that affect the adoption rate of an innovation. Examples are presented of how the theory may apply to MBSE and includes an example of a successful MBSE adoption effort that exhibits factors described by the theory.

Chapter 4 outlines the motivation for and goals of a survey to discover current perceptions of MBSE and how those perceptions are related to the use of MBSE. This is in an effort to demonstrate the relevance of the DoI theory to MBSE adoption patterns and to determine if any of the five perceived attributes of the innovation have a greater impact on the adoption rate than the others. The chapter then goes on to explain each section of the survey and contains a rationale for the questions included in the survey.

³The contents of this chapter are based on a paper published in the proceedings of the INCOSE International Symposium in July 2023 as *A Case for Model-Based Systems Engineering in an Agile World and Principles for Growth* [6]

⁴The contents of this chapter are based on the paper *Applicability of the Diffusion of Innovation Theory to Accelerate Model-Based Systems Engineering Adoption* published in *Systems Engineering* [43]

Chapter 5 presents the findings of the survey, including results tied to sub-populations identified by the demographic questions in the survey⁵. This chapter also includes a discussion of the survey analysis methods.

Chapter 6 contains a discussion of the survey results and targeted actions, informed by the survey results with supporting literature, to improve MBSE adoption. This chapter also presents ways in which the upcoming release of version 2 of the SysML presents a prime opportunity to re-frame perceptions of MBSE generally with a goal of increased adoption and use.

Finally, Chapter 7 will summarize the conclusions of this dissertation, including a summary of recommendations. This chapter will also identify the limitations of this research and propose follow-on work that is outside the present scope of this dissertation.

Appendix A contains the complete survey as it will be presented to participants and as it was submitted to the Institutional Review Board (IRB) (without the annotations and explanations included in Chapter 4), including the informed consent letter and instructions to participants. Appendix C contains additional figures of survey results not included in Chapter 5.

⁵The contents of this chapter are based on the paper *The Effects of the Assessed Perceptions of MBSE on Adoption* to be published in proceedings of the INCOSE International Symposium in July 2024 as well as an expanded version to be submitted for publication in *Systems Engineering*

Chapter 2

A Case for Model-Based Systems Engineering⁶

2.1 Introduction

The challenges to effective SE accompanying the increase in system complexity outlined in Chapter 1 have had significant effects on organizational SE efforts. To illustrate these effects, consider a hypothetical yet representative scenario of the modernization efforts of a large, operational weapon system. With the increasing complexity of subsystems and components, traditional, document-based SE approaches became too cumbersome to complete effectively and did not support required system development timelines within the organization [45]. In addition to schedule and budget pressure, the challenges associated with this project's scope made it impossible to adequately manage SE efforts and artifacts, which compromised SE rigor, resulting in a lower-quality product [46, 47]. The chief engineer and program manager recognized the need for a dramatic SE paradigm shift. Agile methods have revolutionized software development, and because of the software-centric nature of the system of interest, it was proposed that agile methods be adopted at the system level and adapted for SE [44]. Because agile methods were developed for software development based on the agile manifesto, there was no direct application of specific agile methods or processes to SE [48]. Instead, agile coaches taught the four key statements and accompanying 12 principles from the agile manifesto, as well as some techniques for scaling agile methods to a large enterprise [49].

These concepts were applied in the SE context where practical. The most obvious change was a move away from a waterfall development model where new product deliveries occurred every 3-5 years with many fully-formed capabilities and major development stages were completed for the entire system prior to moving on to the next step. Work was broken into increments with

⁶The contents of this chapter are based on the paper *A case for model-based systems engineering in an agile world and principles for growth* published in *The Proceedings of the 33rd INCOSE International Symposium* [6]

the understanding that capability would be delivered on a set cadence and partial capabilities that could deliver value to the user would be delivered before the full functionality of the capability was available. Cross-functional agile teams were formed, and development work commenced. Unfortunately, most of the changes were to the software development work within the organization, and there was no accompanying change in how the SE work was done to fit this agile approach. Systems engineers were forced to reduce the rigor of their processes to move faster and meet the new release cadence, to the point that they were often only reacting to work that was already in process. SE technical processes were pared down to the point that there was no one in the organization with the title or role of “Systems Engineer”. In this particular organization, SE died a slow, quiet death.

In an effort to address a legitimate problem, the inability of traditional SE methods to scale to the scope of modern systems, stakeholders are too quick to abandon the valuable aspects of SE in an effort to remove its undesirable qualities. The practice of SE will continue to be critical in the development of modern systems and should not be abandoned, but continue to evolve [50]. This chapter will highlight some ideas that are particularly important to this evolution, including the role of MBSE in supporting an agile SE approach.

2.2 The Language of Systems Engineering

The linguistic relativity hypothesis posits that the language an individual or culture speaks shapes the way they think and perceive the world [51]. While there is still debate in the linguistic world about the strength and scope of this hypothesis, there is a great deal of supporting evidence and many examples of its application. An example that is particularly relevant to this discussion has to do with the Pormpuraaw, an aboriginal group in Australia. In their language, Kuuk Thaayorre, there are no words for relative positions equivalent to “left” or “right” in English. Instead, all references to the positions of objects are based on the cardinal directions (north, east, south, and west). As a result, even young children of the Pormpuraaw exhibit exceptional ability to know what direction they are facing at all times, to a degree that some experts did not think was possible

for humans. This phenomenon is not unique to sense of direction as similar language-based effects have been observed with color perception and math skills, among others. Cognitive psychologist Lera Boroditsky has shown that this phenomenon is strong evidence that language not only affects how an individual thinks and perceives the world but that individuals can develop cognitive ability based on the language they use [52].

Much like the difference between the natural language of individuals or cultures, different fields of study, professions, and other social groups have developed their own “languages” in the form of ontologies, which are “a collection of standardized, defined terms and relationships between the terms” [53]. Using a domain-specific ontology allows group members to communicate with each other in a more direct and precise manner using a more meaningful vocabulary. Based on Boroditsky’s research on the connection between language and cognitive ability, there is reason to believe that the adoption and understanding of a domain-specific ontology may improve the cognitive ability of an individual within that domain.

There have been efforts within the SE community to codify an SE ontology [53–56]. The purpose of this chapter is not to argue for or against a single SE ontology or what should or should not be contained in such an ontology. The reality is that, even in the absence of an authoritative ontology, SE does have its own “language” based on decades of experience and research. Individuals who “speak” the language of SE may develop cognitive abilities specific to doing the work of a systems engineer and shape the way they perceive and approach problems.

Abandoning the language of SE introduces the risk of sacrificing its associated cognitive ability. Notably, the cognitive ability associated with language seems to be tied to the language itself, not specific practices or processes. Innovations and improvements to the application of SE can, and should, continue while preserving its language. The language of SE will continue to evolve, as all languages do, but as it does, it should be built on the existing body of knowledge and experience. This is not to say that a system will be doomed to failure without this language, but the advantage of proven principles of SE will be lost without it. Instead of abandoning SE, there is a need to strengthen the way that SE and its accompanying language are documented, communicated, and

taught to harness the power of the linguistic relativism hypothesis, thereby enhancing the cognitive ability of individual systems engineers.

2.3 Agile Systems Engineering

The introductory section of this chapter introduced a hypothetical organization that abandoned SE rigor in an effort to realize benefits offered by agile principles and methods. However, this choice between SE rigor and agile methodology is a false dichotomy [57, 58]. There is no reason why a robust SE approach cannot include agile principles [59]. While most established agile methods apply specifically to software development, agile principles are generally related to being adaptive to change, iterative and incremental development, and being people-oriented [60].

The desire and need to apply agile methods to SE processes has given rise to the concept of agile systems engineering. When referring to agile systems engineering, it is important to make a distinction between *agile systems* engineering and *agile systems engineering*. The former refers to the engineering of systems that could be described as agile in their ability to adapt and respond to change, while the latter refers to a systems engineering approach that incorporates agile principles used to engineer systems that themselves may or may not be agile [61, 62]. While development of agile systems is important in many instances, the focus of this dissertation is on SE approaches, and all future references in the dissertation to [Agile Systems Engineering \(ASE\)](#) are in reference to an *agile systems engineering* approach. A generic ASE approach that uses incremental and iterative development to respond to change is depicted in Figure 2.1. Note that this figure explicitly depicts SE activities as cycles that provide inputs to and receives feedback from preceding and subsequent events, as opposed to discrete events seen in the traditional SE “vee” model.

ASE does not refer to a specific approach as there is no single, commonly accepted definition of or process that can be authoritatively referred to as agile systems engineering. In fact, Kemp et al. have identified four distinct ways that the term agile SE is used [63]:

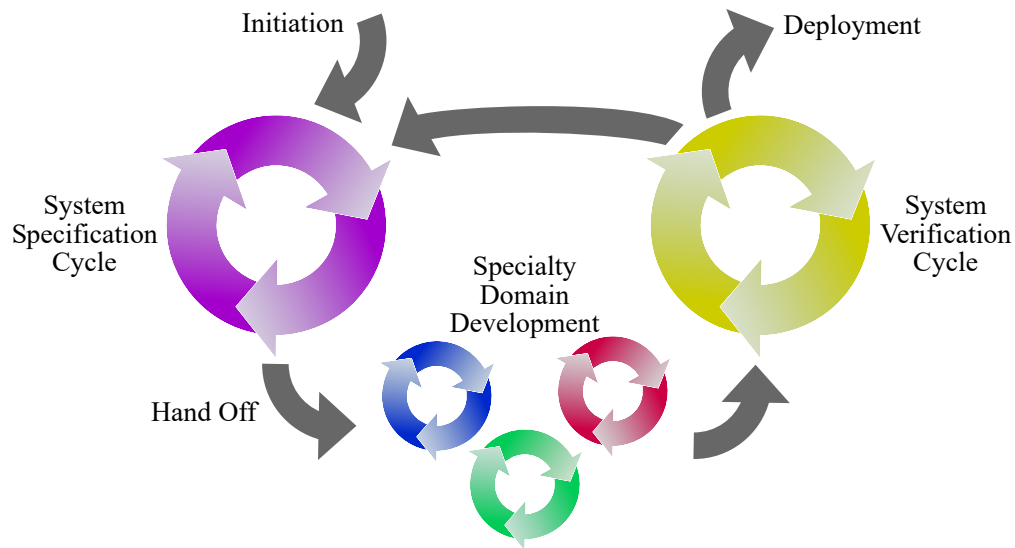


Figure 2.1: An agile systems engineering approach (adapted from [7]).

1. Agile System Development- Closest to an agile approach as understood in a software development context as it is focused on using operational feedback to carry out SE processes in response to rapid environmental and requirement changes.
2. Higher Tempo Conventional SE- Tailoring of conventional SE processes and tools to reduce the overall amount of time spent on SE in support of compressed system delivery timelines where there is a desire to employ agile methods, but the SE process must be clearly defined (for example, safety-critical and/or highly regulated systems).
3. Agile SE Document/Model Development- An approach where users are engaged early on and agile principles are applied primarily to the development of the system specification (document or model) for hand off to other engineering disciplines.
4. Snake Oil- This is not really an agile approach at all, but an instance where agile principles are presented as an excuse to avoid SE rigor or “adopted” to comply with an expectation or mandate with no understanding of how to do so or evidence of likely success. This is the approach utilized by the hypothetical organization from the introduction and is, unfortunately, applied far too often.

The concept of ASE is a natural and necessary progression for SE in a world where software is a dominant driver of modern systems. Because software is responsible for the implementation of high-level specifications that are the output of SE processes and the relative ease of producing software compared to physical components, software size and complexity has necessarily outpaced the number of components and/or subsystems that contribute to SE complexity. Because of this, the software development community has been addressing the challenges of managing this size and complexity for decades. However, as systems have continued to become more complex and software-centric, the SE community is now facing many of the same problems associated with the level of complexity that the software development community encountered that led to the conception and formalization of agile software development key statements, principles, and processes. Systems engineers have the benefit of leveraging and adapting research on and development of agile methods that have been developed by software developers over the last 25+ years.

The development and maintenance of document-based SE artifacts presents challenges in an ASE approach due to the pace and scope of required changes to those artifacts. However, MBSE and ASE are very complementary and not only can but *should* coexist [7]. Though they share many attributes, ASE and MBSE are not synonymous and are distinct specializations of a more generalized SE approach. An SE approach for an organization could include both ASE and MBSE elements, ASE or MBSE elements, or contain neither ASE nor MBSE elements as illustrated in Figure 2.2.

ASE is not new and an ASE approach has been thoroughly elaborated by Douglass [7], among others [61,64–66]. While the agile manifesto [44] was written for software development, Douglass has mapped its key statements and principles to SE. While his approach is focused on the development of a system specification, some agile best practices that are particularly suited for an ASE approach utilizing MBSE are: [7]:

- Incremental development of work products
- Continued verification of work products

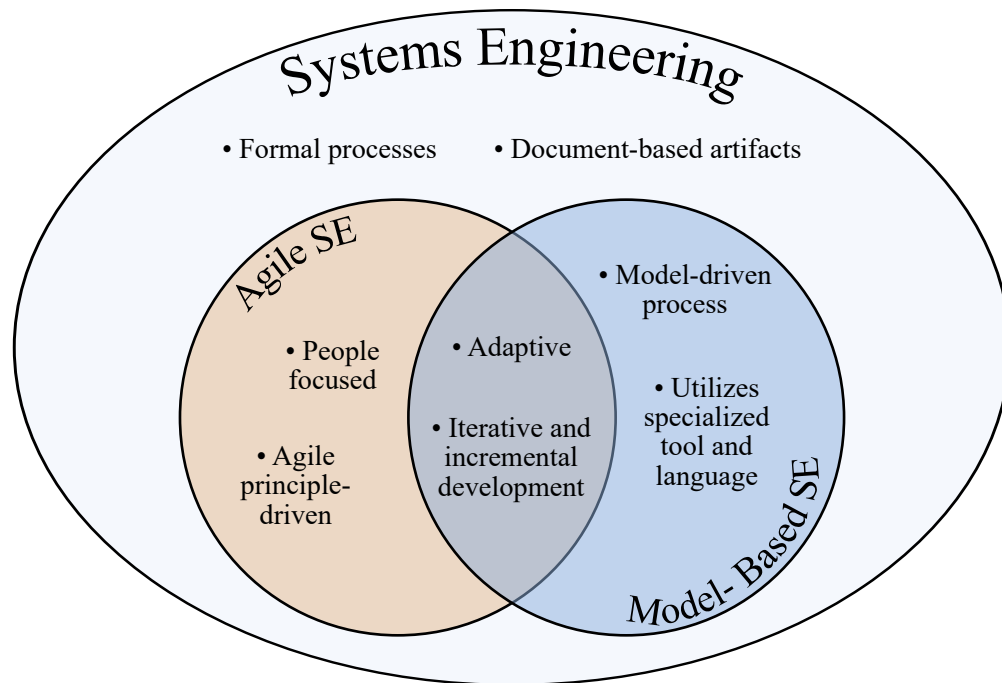


Figure 2.2: Relationship between systems engineering generally, agile SE, and MBSE

- Executable requirements models
- Model-based specification linked to textual specification
- Model-based hand off to downstream engineering
- Dynamic planning

Incremental development of work products — When SE activities are strictly carried out serially, that is subsequent activities are not begun until the preceding activity is completed, then critical decisions may be made on incomplete information. The alternative, agile approach would be to begin subsequent SE activities as soon as “just enough” of the preceding activity is completed. By working incrementally, lessons learned from subsequent activities can be fed back to preceding activities and changes made before additional, incorrect work is completed. An MBSE approach, with its strength in managing change, is well suited for this situation.

Continued verification of work products — The primary means of verifying work products in a document-based SE approach is through the use of reviews. This is not because there is not

a desire for a more robust verification process, but largely due to the absence of any other option. When SE work products are model-based, validation rules can be built into the modeling tool to ensure product quality, compliance with standards, and internal consistency. Component and subsystem behaviors specified in the model can be simulated to verify they yield the desired system behavior. This allows for identification and resolution of potential defects during the design phase, before they are introduced into the realized system necessitating expensive rework to correct.

Model-based specification linked to textual specification — There are benefits (and sometimes requirements) to being able to demonstrate traceability from textual requirements to the system behaviors that satisfy those requirements and the structural elements to which those behaviors are allocated. With this traceability stakeholders can be assured that all of the requirements are accounted for in the design and allow for system design trade space exploration before development costs are incurred. An MBSE approach affords this traceability in a way that is prohibitively difficult in a document-based approach. Using any number of commercially available modeling tools, the process of creating, maintaining, and reporting on these traceability links can be somewhat trivial.

Model-based hand off to downstream engineering — Text-based requirements and specifications written in a natural language are often ambiguous which can lead to misunderstanding when they are to be implemented. Use of a modeling language, like SysML, that has at least semi-formal semantics can help to eliminate some of this ambiguity. If downstream engineering is versed in the modeling language and organizational modeling standards and conventions, then communication can be more precise and the verified designs generated by the SE team can be implemented more effectively. Again, when changes are required based on development work by downstream engineering, those changes are propagated throughout the specification more effectively and consistently using a model-based approach.

Dynamic planning- The ability to plan dynamically is one of the most powerful agile principles that can be applied to SE. Dynamic planning is in contrast to static, or as Douglass refers to it “ballistic planning”, where a plan is made from the start of a project [7]. With a dynamic planning

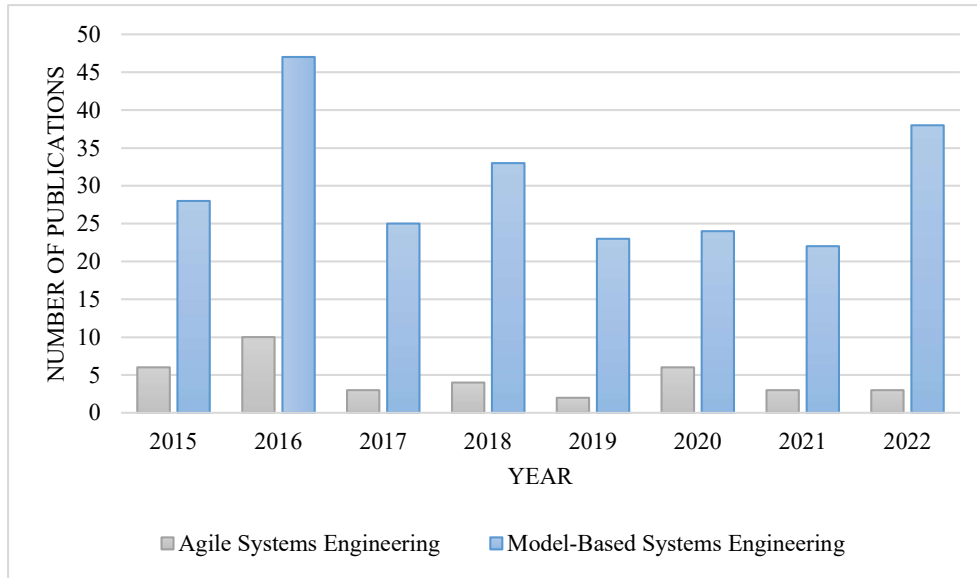


Figure 2.3: Comparison of publications about ASE compared to MBSE in INCOSE IS proceedings

paradigm there is an acknowledgement by all the project stakeholders of the many unknowns at the beginning of a project. Any plans based on the information known at the outset of the project are almost certain to be flawed. General road maps and milestones are appropriate, but detailed planning should be conducted as incrementally as possible, as more is learned about the system and its context through the SE processes. MBSE is a key enabler of dynamic planning when it comes to SE work because this planning will result in iterations of SE artifacts at a pace that cannot be effectively managed using a document-based approach.

It would appear that ASE, especially when it is paired with MBSE, may be able to effectively bridge the gap between the need to respond faster to changing environments and the benefits of robust SE. In spite of this, ASE has not received the same level of attention as MBSE. A cursory search through the proceedings of the INCOSE International Symposium from 2015 to 2022 shows there was an average of 4.6 papers published per year that included the term “agile systems engineering” in the abstract compared to 30 papers per year for “model-based systems engineering” (See Figure 2.3). Many MBSE publications address many of the same problems that ASE can address, but an approach to these problems would likely benefit from more research into expanding the application of agile principles and ASE along with MBSE.

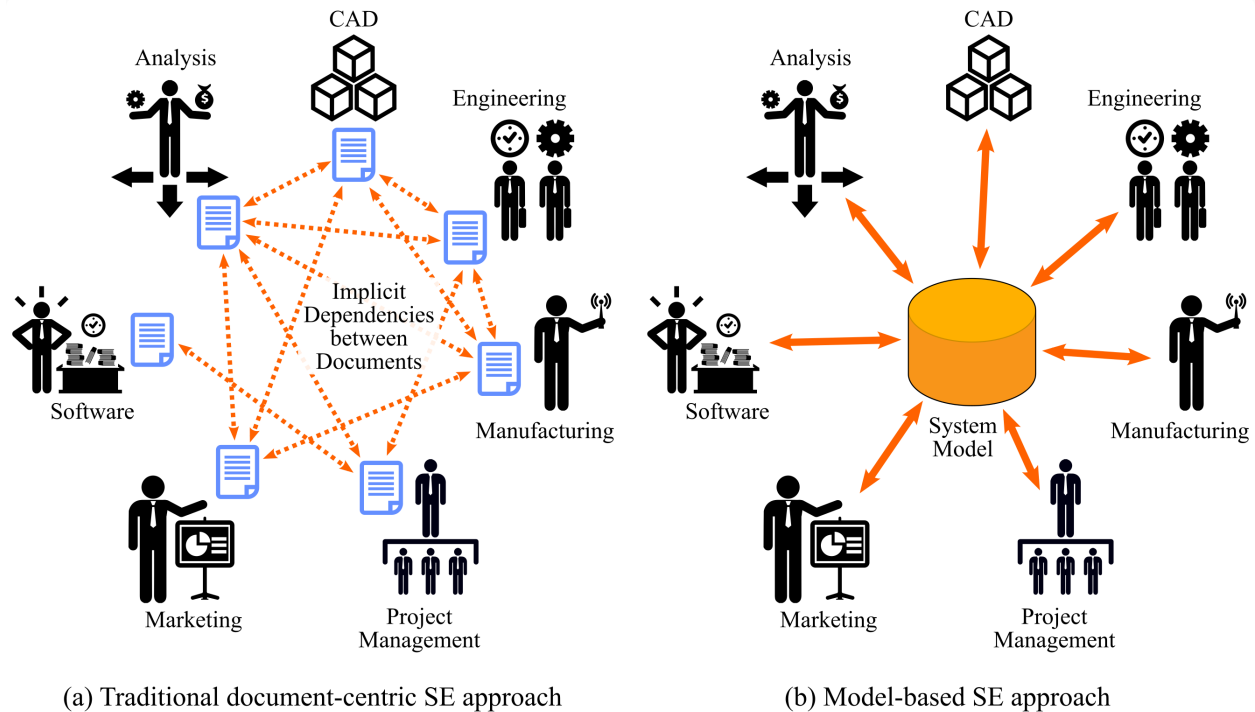


Figure 2.4: Illustration of (a) traditional document-centric systems engineering and (b) model-based systems engineering.

2.4 Demand for Effective MBSE Implementation

MBSE has emerged as an approach to SE that specifically addresses the challenges associated with large, complex systems [67], managing rapid change inherent to compressed delivery timelines, and is a key enabler of effective ASE [68–71]. It is important to recognize that MBSE is still fundamentally systems engineering and traditional SE processes are integral to an effective MBSE approach. The primary difference from the traditional approach is that in an MBSE approach, these processes are model-driven, and the outputs are captured in a system model that can function as a single [Authoritative Source of Truth \(ASoT\)](#) for SE data as all stakeholders are able to deliver and access SE data in the model directly [41]. This shift significantly reduces the exponential interactions typical of document-centric approaches, enhancing the clarity and traceability of system information.

2.4.1 Origins and Principles of MBSE

The history of MBSE can be traced back to the early use of models in SE. Initially, models were employed to facilitate specific aspects of engineering projects, such as simulations and structural analyses [72]. However, the concept of using models as the central artifacts in the engineering process began to gain traction in the 1990s and early 2000s [73]. This period saw the development of various modeling languages and frameworks (many adopted from fields such as software engineering, operations research, electrical engineering, manufacturing, etc. [72]), which laid the groundwork for what would come to be known as MBSE. Early pioneers of MBSE recognized the limitations of traditional document-centric SE and sought to leverage digital tools to manage the increasing complexity of modern systems.

The formal recognition and promotion of MBSE as a distinct discipline within SE emerged in the mid-2000s. Organizations such as INCOSE and the [Object Management Group \(OMG\)](#) played an important role in advocating for MBSE by providing definitions, standards, and best practices that helped shape the field [74]. A significant milestone in the history of MBSE was the development and adoption of the [Systems Modeling Language \(SysML\)](#) [75]. SysML, first introduced in 2006, provided a standardized modeling language tailored specifically for SE. It extended the [Unified Modeling Language \(UML\)](#) to include concepts, elements, and diagrams to support the needs of systems engineers, providing an important tool for the specification of complex system models.

Delligatti identifies three “pillars” associated with MBSE — a modeling language, a modeling tool, and a modeling methodology [31]. A system modeling language is used to capture and express information about the system using formal syntax and semantics that allows for creating precise and unambiguous models of complex systems. It enables engineers to represent the various aspects of a system, including its structure, behavior, and interactions, in a standardized and comprehensible manner. The common vocabulary of a modeling language facilitates clear communication among diverse stakeholders, ensuring consistency and understanding throughout the system development process. By defining a set of notations and rules, the modeling language ensures

that models are consistent, interoperable, and scalable. While SysML has emerged as the most prevalent systems modeling language, it is not the only one. Some of the other systems modeling languages in use are UML [76], the [Architecture Analysis and Design Language \(AADL\)](#) [77], the [Business Process Model and Notation \(BPMN\)](#) [78], the [Specification and Description Language \(SDL\)](#) [79], and the [Object-Process Language \(OPL\)](#) [80].

A systems modeling tool serves as the platform that enables engineers to apply the chosen modeling language and methodology effectively. It provides the environment to create, visualize, analyze, and manage complex system models. By integrating the syntax and semantics of the modeling language with the structured processes of the modeling methodology, the tool facilitates a cohesive and comprehensive approach to SE. These systems modeling tools facilitate collaboration among stakeholders, ensuring consistency and traceability across different phases of the system lifecycle. They support a wide range of SE activities and processes such as requirement capture, functional and architectural decomposition, performance simulation, and [Verification and Validation \(V&V\)](#).

A systems modeling methodology, like the INCOSE [Object-Oriented Systems Engineering Method \(OOSEM\)](#) [9], IBM's Harmony [81], and the ISO standardized [Object-Process Methodology \(OPM\)](#) developed by Dori [80], provides the structured processes and best practices that guide the application of modeling techniques throughout SE process. A methodology defines or provides guidelines for the sequence of MBSE activities while ensuring that modeling efforts are systematic, repeatable, and aligned with organizational standards and goals [82]. By integrating the principles of a modeling language and leveraging the capabilities of modeling tools, a methodology facilitates the coherent and consistent development of system models [83]. It also supports effective communication and collaboration among multidisciplinary teams, enabling stakeholders to understand, evaluate, and contribute to the system design. The use of a well-defined modeling methodology enhances the ability to manage complexity and ensure that the final system meets its intended functions and performance criteria.

Though specific approaches vary, all of the processes and actions that have been done in SE traditionally should still be accounted for in an MBSE approach. The selection of a language, tool, and methodology is non-trivial and should be given appropriate analysis and consideration by all stakeholders to the MBSE effort [84]. Utilizing a properly tailored MBSE approach will improve the chances of realizing the benefits of MBSE [85].

2.4.2 The Benefits of MBSE

In addition to the benefits inherent to an MBSE approach identified in the previous section, many additional benefits of MBSE have been identified through the course of experience over the past two decades. Not only does a system model serve as an *ASoT*, it also improves communication and collaboration by enhancing the ability of all stakeholders to understand and visualize the system through the use of diagrams and tables, which in turn can enhance stakeholder engagement and improve system knowledge management [40, 74, 86–88]. The ease with which changes can be made and propagated throughout a system model improves the flexibility and adaptability of the SE process [89]. A system model supports requirements management and traceability to structural and behavioral elements that satisfy requirements, which can improve the alignment of system performance with operational requirements [41, 90]. The analysis capabilities supported by an MBSE approach aid in decision making in complex systems, further enhancing the predictability and control of capability development [18, 84, 91, 92]. This traceability can lead to streamlined integration and testing as well as improved life cycle management [42, 93]. As an MBSE approach matures, it is able to increase SE efficiency by automating some tasks and leveraging the reuse of model elements, resulting in cost and time savings [94–97]. A novel benefit of MBSE is the emergent capability to identify for removal unnecessary or obsolete technological components in a system that has a long development timeline [98]. The use of interoperable system modeling tools in an MBSE approach can also support digital transformation efforts (including the development of digital twins [99, 100] and digital threads [101]) within organizations, allowing the realization of benefits associated with digital transformation more generally [85]. In a direct comparison to

traditional SE, MBSE has demonstrated a more comprehensive and effective way of capturing and managing architectural knowledge, thereby enhancing accuracy, efficiency, and overall project outcomes in complex SE tasks [102]. All of these benefits work together to reduce overall project risks [103].

MBSE has also demonstrated value in many different specific SE processes including, but not limited to, requirements engineering [104], system architecting [91], mission engineering [105], system/conceptual design [106, 107], interface definition/specification [108, 109], risk management [110], system V&V [95, 111–113], and **Test and Evaluation (T&E)** [86, 114]. It has been used in the development of cybersecurity [115] and safety-critical [116] systems and in highly regulated environments [117]. MBSE has been successfully applied in a variety of sectors, including aerospace, automotive, medical, construction equipment, embedded systems, vehicular systems, and even nuclear energy [118–123]. MBSE can even be used (and the argument is made that it *should* be used) in the development of the MBSE system itself [124].

2.4.3 MBSE Adoption Challenges

While the description and benefits of MBSE in the previous two sections paint a glowing picture of MBSE, in practice, there are challenges associated with MBSE adoption that have prevented it from being adopted to the degree that would be expected based on these documented benefits [29, 32, 38, 125]. Past studies have sought to understand the challenges associated with MBSE adoption and the misalignment between how MBSE is presented on paper and how it is practiced [126]. The learning curve associated with learning a new language, tool, and methodology was one of the earliest identified and understood challenges to MBSE adoption [118]. Furthermore, the extensive time and resource investment required for developing system models has proven to be challenging, especially in existing DoD programs with a significant amount of document-based SE data [39]. Some of the MBSE adoption challenges stem from the immaturity of MBSE approaches as the three pillars of MBSE are not adequately integrated [127]. In a 2018 study, Chami and Bruehl identified a set of MBSE adoption challenges based on their own research and experience,

then conducted an online survey to determine opinions on the challenges, what life cycle phase they occur in, and dependencies between them [32]. Henderson identified organizational factors that contribute to and affect MBSE adoption [34]. Gregory et al. focused on the identification of the problems encountered with traditional SE that MBSE is particularly suited to address in their study of MBSE adoption challenges [37].

From a tool vendor perspective, Blott and Buchholz group adoption challenges into five categories: organization, benefits, implementation, process, and user feedback [33]. Through a series of interviews, Vogelsang et al. concluded that immaturity of tools, uncertainty about the return on the substantial investment required, and fears of changing current processes are major impediments to MBSE adoption [36]. Just as in a document-centric MBSE approach, configuration management of SE artifacts (in this case, SE models) remains a challenge in an MBSE approach [128,129]. Frequent use of the acronym “MBSE” may be obscuring the fact that MBSE is fundamentally systems engineering, slowing adoption by those with established SE plans and processes [43]. Outside of the technical challenges to adoption, Weilkens explicitly identifies the human tendency to resist change as the most significant challenge to MBSE adoption [35, 130].

A significant factor that may be affecting MBSE adoption and success is that there is still no widespread understanding of what exactly constitutes “MBSE” throughout the SE community, leading to ineffective MBSE implementations. The INCOSE definition of MBSE introduced in Chapter 1, is “the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases” [9]. Without an understanding of exactly what a “formalized application of modeling” entails or what it means to “support” SE activities throughout the system life cycle, the scope as to what can be considered MBSE is not immediately clear.

The result of this ambiguity can be illustrated using the same hypothetical organization referenced in the introduction of this chapter. Because of the atrophied SE activity, as already described, integration challenges arise, and system quality suffers. MBSE is a popular topic and receives a

lot of attention, so the chief engineer and program manager decided that they will “do MBSE”. Expensive tool licenses are purchased, several engineers are trained on a modeling language and tool, and these newly trained engineers are assigned to a development team with the role of “modelers”. Development work continues much as it has before, with the system modelers capturing architecture and design decisions as they are made or implemented in a system model. There are occasional times that a potential problem is identified through the use of the model, but the model is used primarily as a way to document decisions that have already been made, not as a design tool. Over time modeling efforts wane as no one is really using the model, and it slows work down more than it helps. The model never delivers value to the organization, and everyone involved eventually accepts the fact that MBSE is a fad and begins looking for another path forward to solve their integration and quality challenges.

This hypothetical organization may be somewhat caricatured, but it raises the question of what constitutes an MBSE approach that has a likely chance of providing value to an organization? The three pillars associated with MBSE identified by Delligatti introduced in Section 2.4.1 — a modeling language, a modeling tool, and a modeling methodology — provide insight into the challenges that were encountered in this MBSE adoption effort. The example organization clearly had a modeling language and tool, but no methodology was specified. A modeling methodology establishes the purpose of the modeling effort and identifies specific tasks and standards that will be used in the creation of the model. The importance of a modeling methodology suggests that the mere existence of a system model is not what provides value to an organization and does not constitute a true MBSE approach [131]. Rather, it is the SE processes that are used and the act of developing the model where the value is generated.

Vaneman supports the argument against the INCOSE definition of MBSE, making the point that it does not go far enough. His expanded definition addresses the ambiguity of the term “support” in the INCOSE definition. He defines MBSE as “the formalized application of modeling (static and dynamic) to support system design and analysis, throughout all phases of the system lifecycle, through the collection of modeling languages, structures, model-based processes, and presentation

frameworks used to support the discipline of SE in a model-based or model-driven context” [53]. This extension of the INCOSE definition specifies what is included in an MBSE approach. To describe how useful models are produced, this definition stipulates the use of a modeling language (as opposed to plain English), defined structures, model-based processes (that is, processes that are centered on the modeling efforts with results that are captured in the model), and the frameworks by which the modeling artifacts will be presented.

Some other additions that are worth highlighting are that this definition includes both static and dynamic models. Even if we consider traditional SE artifacts to be models since they are abstract representations of the system of interest, they are still only static models. The dynamic models that are enabled by MBSE yield significant value to the SE process. Finally, the inclusion of SE activities being model-driven adds further emphasis to the central role of models in an MBSE approach. Models are not created to capture decisions made using arbitrary processes. Instead, the models drive and inform new, modified SE processes that are employed in an MBSE approach. This definition of MBSE is a valuable contribution to the understanding of what exactly MBSE entails, and its application could lead to improved MBSE outcomes.

2.4.4 MBSE Adoption Case Studies

There are many case studies published in the SE literature that detail efforts to adopt MBSE. Presented here is a selection of representative case studies from various sectors and industries, illustrating the diverse experiences and outcomes organizations have encountered in their MBSE adoption journeys. These examples highlight both the challenges faced and the significant benefits realized through the implementation of MBSE, providing valuable insights for other organizations considering similar transitions.

The adoption of MBSE in the Submarine Warfare Federated Tactical Systems (SWFTS) program demonstrated significant improvements over traditional document-centric approaches [89, 132]. The transition to MBSE resulted in higher quality SE products, more effective management of baselines and complexity, and reduced costs per change. This shift led to measurable benefits,

including reduced defect rates and earlier detection of issues, ultimately enhancing the efficiency and effectiveness of SE processes within this complex [System of Systems \(SoS\)](#) for the U.S. Navy.

The case study of Saab's adoption of MBSE, as detailed by Hallqvist and Larsson, highlights the challenges and lessons learned during the transition [92]. Initially, the implementation faced significant hurdles due to a lack of clear vision and stakeholder engagement, which necessitated a reevaluation of the strategy. By adopting a more structured approach with systematic process analysis, incremental steps, and comprehensive risk analyses, Saab was able to realign their MBSE implementation with organizational goals and operational needs, ultimately emphasizing the importance of leadership and clear communication for successful adoption.

Amorim et al. provide a detailed study on the challenges and strategies for adopting MBSE in the embedded systems industry [121]. Through interviews with experts from various companies, the research identified 18 best practices, emphasizing the importance of starting with new projects and small pilot initiatives to build experience and demonstrate value. Critical to successful adoption is ensuring sufficient budget and time for these pilot projects, allowing for the learning curve and overhead associated with MBSE. The study underscores that a strategic, phased approach, supported by raising awareness and real-world piloting, is essential for effective MBSE implementation in complex engineering environments.

A case study in the vehicular systems industry identified key drivers and obstacles encountered during MBSE adoption [122]. The study, based on semi-structured interviews with professionals, highlights that active engagement from all participants and strong management support are crucial for successful MBSE adoption. However, a significant barrier is the lack of MBSE knowledge among stakeholders, which can impede effective implementation. The case study concludes that while MBSE adoption is complex and requires a structured approach, the long-term benefits, including improved efficiency and product quality, justify the initial investment, making it a valuable strategy for managing complex engineering tasks and enhancing team collaboration.

The adoption of MBSE by Volvo Construction Equipment was driven by the increasing complexity due to electromobility and automation, necessitating a shift from traditional methods [120].

Key challenges included the steep learning curve, resistance to change, and integration with existing project management frameworks. Despite these obstacles, the implementation resulted in improved communication, enhanced traceability from requirements to system architectures, and better management of system complexity, demonstrating the potential of MBSE to enhance the efficiency and effectiveness of complex system development.

A case study by Vasenev et al. outlines a structured approach to adopting MBSE in organizations focused on managing interfaces within software-intensive healthcare equipment production [119]. The study makes a case for a step-wise implementation, starting with interface management to address integration challenges in SoS. This approach, guided by a Process-People-Technology (PPT) framework, ensures alignment and integration of processes, people, and technology. By beginning with interface control, the strategy facilitates independent innovation among teams and reduces integration risks, gradually expanding to other aspects like document generation and simulations as trust in MBSE processes grows. This careful, incremental method allows organizations to manage the complexities of SE, aligning MBSE adoption with organizational capabilities and needs.

The purpose of a project in the Australian defense sector was to enhance ground-based air and missile defense capabilities by shifting from traditional document-centric methods to a more integrated MBSE approach [133]. The application of MBSE to the preliminary phases of Project LAND 19-7, such as developing Preliminary Capability Definition Documentation (PCDD), improved robustness, traceability, and project knowledge retention. Despite challenges like cultural shifts and the need for ongoing stakeholder engagement, MBSE provided significant benefits, including enhanced communication, better decision-making support, and improved alignment with operational needs, suggesting its broader application throughout the project lifecycle for maintaining consistency and integrity.

Major challenges identified while implementing MBSE at NASA Johnson Space Center (JSC) include organizational inertia, significant initial costs and effort, and the difficulty of getting started without clear best practices [134]. To address these, the authors recommend educating stakeholders

on MBSE benefits, providing institutional support, and developing specific guidelines and tools. Successful application of these strategies in projects like the Habitat Demonstration Unit (HDU) demonstrated how MBSE facilitated better integration and coordination, highlighting the importance of strategic support and clear methodologies for enhancing system modeling and analysis in complex environments like space exploration.

2.5 Conclusion

The needs of modern complex systems require an evolution of the practice of SE. There is value in the “language” of SE that should be preserved in the face of pressure to adopt Agile principles to develop systems in place of traditional SE processes. Agile SE is well suited to meet the demand for faster, more iterative deliveries of SE products without sacrificing SE rigor. While not synonymous, ASE and MBSE are complementary, and MBSE is a key enabler of ASE. The development of a model-based approach to SE is a natural progression given the demands of modern, complex systems and the availability of digital resources. MBSE offers a host of significant benefits over a document-based approach, but is not without its challenges. Many organizations have experienced significant challenges in their efforts to adopt MBSE. However, many organizations *have* been successful in adopting MBSE and have shared lessons learned in case studies available to the SE community. Based on lessons learned from a review of the extant SE literature, efforts to improve the adoption rate of MBSE are warranted and should be encouraged.

Chapter 3

The Diffusion of Innovations Theory⁷

3.1 Introduction

The most significant innovations in any field do not provide value to an organization until they are adopted or put into practice. The study of the diffusion of innovations is a well-established field pioneered and popularized by the rural sociologist Everett Rogers. Rogers first captured this theory in his book “Diffusion of Innovations” in 1962. Since then, he continued his research and published the fifth edition in 2003. Innovation became a field of study because technologists wanted to understand why some innovations gained rapid, widespread acceptance while others with comparable advantages took much longer or were never adopted at all [1]. This idea ran contrary to the intuition that if a genuinely improved product or process were introduced, it would be adopted on its own merits. Within the context of this theory, Rogers defines diffusion as “the process in which an innovation is communicated through certain channels over time among the members of a social system.” [1] This theory has been applied to understand the adoption patterns of innovations in a range of products and processes ranging from new agricultural technology in the United States [135] to sanitation efforts in Peru [136] and contraception in Korea [137]. It has also been shown to apply to the adoption of innovations commonly associated with and referred to as digital transformation [138].

As noted in Chapter 1, an innovation is “an idea, practice, or object that is perceived as new by an individual or other unit of adoption [1]. A key element of this definition is that the idea, practice, or object is *perceived* as new and does not actually have to be new. As will be shown, perception is an important part of the DoI theory and comes into play in several areas. In the physical sciences, diffusion is the intermingling and mixing of substances. This mixing requires that the particles be

⁷The contents of this chapter are based on the paper *Applicability of the Diffusion of Innovation Theory to Accelerate Model-Based Systems Engineering Adoption* published in *Systems Engineering* [43]

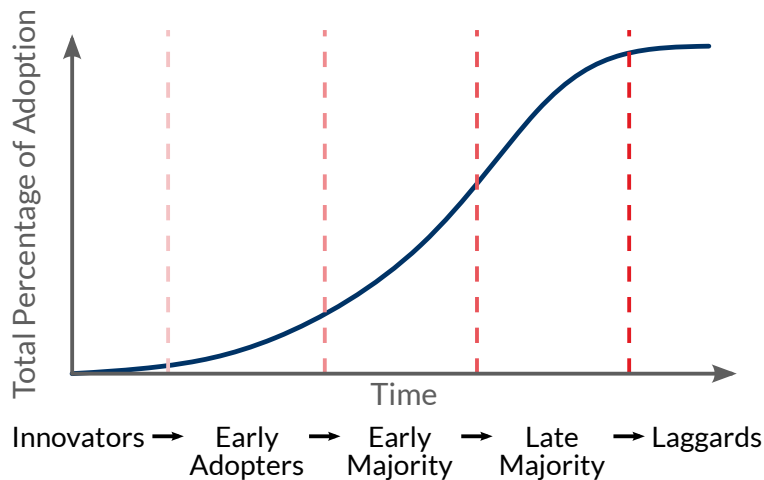


Figure 3.1: Adoption s-curve

suspended in some medium in which they can move freely. The diffusion of innovations requires a medium through which the innovation, or at least awareness of it, can move. Communication channels are the medium through which innovations move and diffuse.

Even the most popular innovations are not adopted in a population instantaneously. Most innovations follow an adoption s-curve as depicted in Figure 3.1 where the percentage of a population that has adopted an innovation increases with time. Adoption typically starts off slowly as a small group of innovators and early adopters learn about, refine, and choose to adopt an innovation. Once knowledge and appreciation of the innovation increases, the adoption of the innovation accelerates with adoption by the early majority of adopters. As an innovation is more widely adopted, its pool of potential adopters shrinks, and the adoption rate slows down as the late adopters embrace the innovation. Finally, the adoption curve levels out as the last of the potential adopters that will eventually adopt the innovation, the laggards, adopt it. Figure 3.1 is a generalized adoption s-curve, and the adoption curves for specific innovations vary significantly. Some innovations reach their maximum adoption percentage in a matter of weeks or months, while others may take years or decades. Also, not every innovation is adopted by the same percentage of potential adopters. Some innovations may reach maximum adoption at 20% of the population of potential adopters, while another may diffuse to 80%.

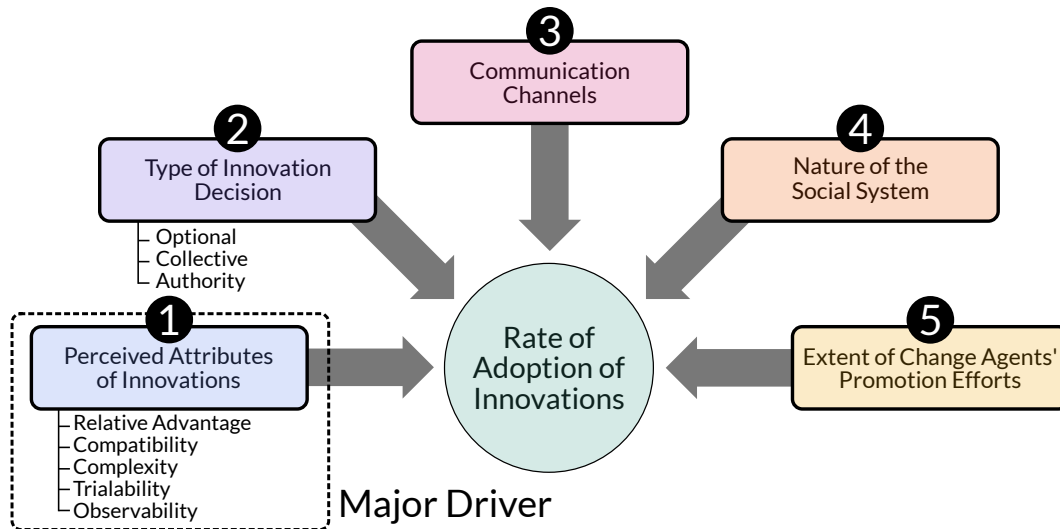


Figure 3.2: Variables that affect the rate of adoption of innovations

The DoI theory identifies five variables that affect the rate of adoption of innovations (shown in Figure 3.2):

- **Perceived attributes of the innovation-** how the innovation is perceived by those who may consider adopting it.
- **Type of innovation-decision-** how the decision is made to adopt the innovation. Some innovation decisions are made by a single individual (CEO making a decision for an entire company or an individual consumer purchasing a product), while other decisions require consensus by a group to make the innovation-decision.
- **Communication channels used to spread knowledge of the innovation-** mass communications through the use of commercials or internet ads that are widely viewed, or interpersonal that relies on word of mouth and one-on-one interaction. While mass communication channels can reach a broader audience, interpersonal communication channels lend more credibility to the message as people are more likely to trust the opinion of someone they know when making an innovation-decision over a generic advertisement.
- **Nature of the social system of the potential adopters-** whether the social system (community, ethnic group, professional sector, etc.) is open or closed. Some social systems are open

and readily accept change and innovation, while others are naturally more reserved and risk averse and may require more time to adopt. Innovations are generally adopted more quickly in open social systems [139].

- **Extent of change agents' promotion efforts**- the degree to which a change agent (or champion) promotes the adoption of the innovation. If a change agent is actively promoting and facilitating the adoption of an innovation, it is more likely to be adopted than if potential adopters are left to their own devices to learn about the innovation themselves. Change agents play a big role in the adoption of an innovation.

Of these five variables, the perceived attributes of innovations have been shown to account for 49% to 87% of the variance in the rate of adoption and will be the primary focus of this research [1].

In addition to these variables and attributes, the DoI theory introduces some specific terms that will be used in this description. *Potential adopters* refer to the population that could possibly adopt an innovation. Depending on the innovation, this population could be small (e.g., potential adopters of a specialized piece of scientific equipment) or large (e.g., potential adopters of smartphones). It is important to appreciate that the extent to which an innovation has diffused is measured within its pool of potential adopters, not the general population. A *change agent*, as introduced above, is one who promotes and facilitates the adoption of an innovation. Change agents can be internal or external to an organization or population of potential adopters. An internal change agent could be a member of the organization that has become familiar with an innovation and becomes a “champion” for its adoption. Oftentimes, professional organizations or tool vendors act as external change agents.

3.2 Perceived Attributes of Innovations

It is worth noting that the DoI theory does not identify the attributes of innovations themselves as a key variable in their rate of adoption; rather, it makes the distinction that it is how those attributes are perceived by potential adopters that often causes variability in adoption rates. This is because “if [people] perceive situations as real, they are real in their consequences” [140]. Fur-

Table 3.1: Definitions of the attributes of innovations as defined by “Diffusion of Innovations” [1]

Attribute	Definition
Relative Advantage	The degree to which an innovation is perceived as being better than the idea it supersedes
Compatibility	The degree to which an innovation is perceived as consistent with the existing values, past experiences, and needs of potential adopters
Complexity	The degree to which an innovation is perceived as relatively difficult to understand and use
Trialability	The degree to which an innovation may be experimented with on a limited basis
Observability	The degree to which the results of an innovation are visible to others

thermore, while efforts have been made to quantify these attributes as they apply to innovations, there are no generally accepted, quantifiable ways to measure these attributes in all domains; they are inherently subjective. The importance of the perception of these attributes presents challenges and opportunities. The challenge is that perception is not always accurate, and the adoption of a beneficial innovation can be delayed by the inaccurate perception of its actual attributes. The opportunity is a result of the ability of perceptions to be shaped through various means, including education, without having to change the innovation itself. Table 3.1 contains a brief explanation of the attributes of innovations as defined in “Diffusion of Innovations”.

The **relative advantage** of an innovation is simply the benefit of the innovation relative to the idea or technology the innovation supersedes. Relative advantage can be measured in many ways (economic, performance, prestige, and so forth) depending on the innovation and adopting group. This is perhaps the most intuitively understood attribute of innovations. Innovations that are perceived as offering an advantage over the status quo are more likely to be adopted. Perceived relative advantage has been shown to be one of the strongest predictors of the adoption rate of an innovation [1]. This attribute also explains why preventative innovations, that is innovations intended to prevent a potentially negative outcome from occurring (like wearing a seat belt to minimize injury in the event of a car accident), typically take longer to diffuse than incremental innovations that offer more immediate and observable benefits. Because the relative advantage of a preventative innovation is a nonevent that may never be directly observed, its perceived relative

advantage is lower. Relative advantage may also lead to over adoption of innovations, which is when an innovation is adopted where it is not warranted (e.g., purchasing a high-end computer to be used primarily for word processing).

Compatibility refers to the degree to which an innovation aligns with the existing practices and norms of potential adopters. The key idea with compatibility is that most potential adopters do not make an adoption decision based on scientific research; instead, they evaluate an innovation using their own mental models formed by what they are familiar with. The more compatible an innovation is with their current understanding, the more likely they will adopt it. Whether they are individuals or organizations, potential adopters are not blank slates that will evaluate an innovation independent of any prior knowledge, experience, or understanding. Rather, when an innovation is introduced, its promoters need to be cognizant of the “indigenous knowledge systems” (the current knowledge and understanding from which they form their mental models) that exist amongst the potential adopters. If an innovation is not compatible with this indigenous knowledge system, then it is unlikely to be adopted. Finally, an innovation is more likely to be adopted if it is compatible with a need; that is, the innovation corresponds to a problem or shortcoming confronting a potential adopter.

The **complexity** of an innovation is characterized by the perceived difficulty of its use. Complexity is the only attribute that, as defined, is negatively correlated with the rate of adoption of an innovation. The more complex an innovation is perceived to be by its potential adopters, the less likely it is to be adopted. High complexity can be a significant hurdle to the diffusion of innovations that would likely be adopted based upon their relative advantage and compatibility alone. As subsequent iterations or releases of the innovation become less complex and more user-friendly, the rate of adoption will often accelerate even if no new features are added.

High **trialability**, or the ability to experiment with an innovation before large-scale adoption, is positively correlated with the adoption rate. When faced with a decision to adopt an innovation, like any decision, one of the primary goals of the decision-making process is to reduce the level of uncertainty about the innovation [141]. Personal experimentation with an innovation prior to

making the decision is a prime way to reduce uncertainty. Innovations with a lower cost of entry to experimentation and that can be initially implemented on a limited scale have faster rates of adoption than those that require a significant investment of resources to experiment with and require large-scale implementation before any benefits are generated. If the innovation has already been adopted by a significant population of similar organizations or individuals, their experience can serve the purpose of a trial for late adopters.

An innovation has high **observability** if potential adopters can directly observe the effects of the innovation. If potential adopters can see the positive effects of an innovation, they are more likely to adopt the innovation themselves. A significant factor that affects observability is whether the innovation consists of a tangible product or is more information or process-oriented. Tangible products typically generate effects that are directly observable and widely understood. The effects of innovations that consist primarily of information or a process usually require more time and special methods to measure their benefits and typically call for a higher degree of domain knowledge to comprehend. Innovations characterized by tangible products generally have faster adoption rates than information and process-based innovations.

3.3 The Dvorak Keyboard

The Dvorak keyboard is a classic example of how the application of the DoI theory can aid in understanding why an innovation that is an improvement over the product it was created to replace has failed to achieve widespread adoption. The Dvorak keyboard was created by Professor August Dvorak of the University of Washington in 1932. Dvorak recognized that the QWERTY keyboard in use on typewriters of his time, and still in use today, was not the most efficient design. The first typewriters would jam if a typist did not allow enough time for the hammer from a key to reset (via gravity) before pressing an adjacent key. The QWERTY keyboard was designed to space out the most commonly used letters to minimize the occurrence of adjacent keys being pressed in order [1]. As typewriter technology improved, the QWERTY layout was no longer necessary to prevent jamming, yet it persisted as the standard layout.

8 most common alphabetical keys pressed are highlighted

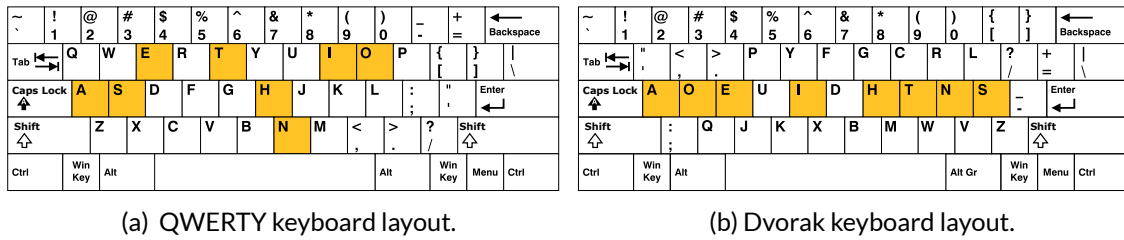


Figure 3.3: Comparisons between the 8 most common alphabetical keys pressed using the QWERTY keyboard layout (a) compared to the Dvorak keyboard layout (b)

Dvorak spent more than a decade studying what slows people down as they type, identifying such things as how often keys on different rows are used, the balance of typing between right and left hands, and how much typing each finger is responsible for relative to its dexterity. Informed by these observations, he produced a layout to mitigate these typing inefficiencies (see Figure 3.3). For example, on a QWERTY keyboard, only 32% of typing is done on the most efficient home row, compared to 70% on the Dvorak. By minimizing the distance that fingers must travel, the Dvorak layout has also been shown to reduce strain and repetitive use injuries in typists and measurable improvements in typing speed [142]. Despite these advantages over a QWERTY keyboard, the Dvorak keyboard has never gained any degree of widespread adoption.

With an understanding of the DoI theory and the effect of the attributes of an innovation on adoption rate, it becomes clear why the Dvorak keyboard is only used by a minority of the potential population. The perceived relative advantage of the Dvorak keyboard is low since most people know and have observed someone who can type very fast on a QWERTY keyboard. There is a general sense that typing speed is a function of the amount of time spent practicing typing, not the keyboard layout being used, and adequate performance can be attained by additional training with a QWERTY keyboard. The perceived compatibility of the Dvorak keyboard is low because if someone invested the time to learn how to use a Dvorak keyboard, they would likely find themselves frustrated when using a computer with a standard QWERTY keyboard. Also, the Dvorak keyboard is not compatible with a relevant need of potential adopters.

While the Dvorak is objectively no more complex than a QWERTY keyboard, to a population that has only ever seen QWERTY keyboards, a new keyboard layout and typing method is foreign and perceived as very complex. There are no real opportunities to experience the advantages of the Dvorak without dedicating significant time to acquire specialized skills, so its trialability is limited. The Dvorak keyboard has low observability as most people have never heard of a Dvorak keyboard, let alone seen one used or used one themselves. Additionally, a skilled Dvorak keyboard user would be recognized as a proficient typist, and there would be no readily observable benefit to the keyboard for someone not trained in the physiology of typing.

When viewed through the lens of the DoI theory, it would actually be more surprising if the Dvorak keyboard had been widely adopted than the fact that after nearly a century of availability, it has been relegated to a minuscule community of niche users. This example demonstrates the value of the DoI theory in explaining how the adoption rate of an innovation *cannot* be predicted by the objective, quantifiable benefits of the innovation alone.

3.4 Application to Model-Based Systems Engineering

While there has been an increase in the use of MBSE over the last decade, the fact that it is still referred to as *model-based* systems engineering instead of simply *systems engineering* is evidence that MBSE has not reached a level of general acceptance⁸. MBSE as an approach to SE offers benefits to the practice of SE that other disciplines have achieved through their use of digital and model-based methods. An understanding of the DoI theory and how the perceived attributes of an innovation affect rate of adoption can be applied within organizations practicing SE to accelerate the adoption rate of MBSE.

3.4.1 Relative Advantage

An oft-cited barrier to MBSE adoption is the “lack of perceived value of MBSE” [143]. While there is wide consensus amongst those familiar with MBSE that it provides a relative advantage

⁸Lenny Delligatti, personal communication

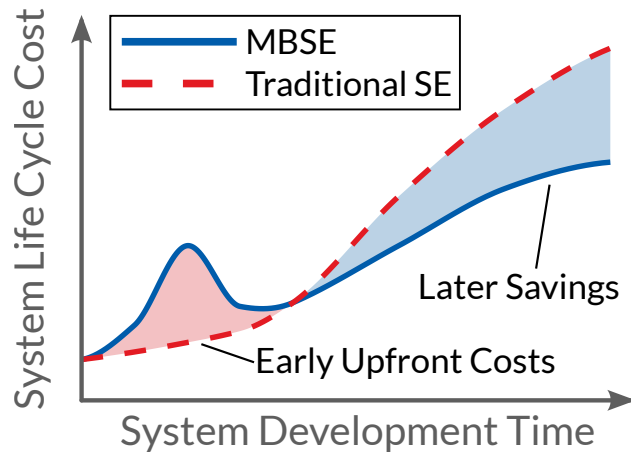


Figure 3.4: Systems Engineering cost over time for an MBSE approach compared to a traditional approach

over traditional methods [7, 10, 31, 40], the perception of that advantage is lagging in the SE community generally. This disparity can likely be attributed to several factors.

The first is because the advantages of MBSE are not realized early in a system life cycle when using MBSE. In fact, the up-front SE cost and effort are typically significantly higher during the early phases of a systems life cycle than those of a traditional approach due to the costs associated with defining an MBSE process, standing up a modeling environment, training staff, configuration management, and doing the actual modeling work and reviews [144] (see Figure 3.4). It takes a significant amount of patience and commitment to make this investment over and above what a traditional approach requires.

The second factor depressing the perceived relative advantage is that MBSE is, in many ways, a preventative innovation [45]. This is to say that many of the advantages of MBSE are not due to the production of measurable benefits but from the elimination of undesirable consequences. When MBSE is done effectively, many of these undesirable consequences are eliminated, but it is difficult to quantify or appreciate problems that are never realized.

Finally, a literature review has shown that much of the published work on the benefits of MBSE [145] do not contain empirical proof but are instead based on anecdotal accounts [146]. There has not been an argument made to refute the idea that MBSE is beneficial, just that the quantitative evidence of those benefits is lacking.

To increase the perceived relative advantage of MBSE, more studies should be conducted to provide that empirical evidence to support the benefit claims of MBSE. These studies and charts like Figure 3.4 will demonstrate to potential adopters that the benefits are real, but will not begin to be realized until after considerable investment has been made. The initial investment in MBSE is significant but will be recouped over time. Additionally, design quality metrics should be captured for projects done using a traditional approach and MBSE to show the undesirable effects (defects, problem reports, etc.) were reduced using MBSE.

3.4.2 Compatibility

In Chapter 2 the idea was introduced that the acronym “MBSE” may be working against its adoption. To those unfamiliar with MBSE, the use of the acronym can obscure its true meaning. The fact that the “SE” in “MBSE” stands for systems engineering can be overlooked. MBSE should not be presented as a new SE process but an approach that augments and improves current SE work within the organization. To improve the perceived compatibility of MBSE, the current SE methodology of an organization should be studied and understood, and an appropriate MBSE methodology selected and/or tailored to complement that methodology [147]⁹. Artifacts produced by the modeling tool can be tailored to present information that is managed in the model in a format that is familiar to the stakeholders. In this way, potential adopters can transfer their existing SE experience to MBSE.

Perhaps the most important factor in increasing the perceived compatibility of MBSE is to emphasize its compatibility with the pressing needs of systems engineers. A need that MBSE is particularly suited to address is the difficulty in maintaining the consistency of SE artifacts in the presence of requirement, constraint, and design changes that are inevitable in modern, complex systems. The difficulty in maintaining consistency in a document-based approach is because there is no mechanism to propagate changes made to a system element to all other references of that

⁹This assumes the organization already has a sound SE methodology in place [148]. If an organization is new to SE generally, then the organizational perception of the attributes of SE should be assessed and addressed. The DoI theory likely applies to the diffusion of SE generally, but application of the theory to SE is beyond the scope of this paper.

element wherever they may be found dispersed amongst text, figures, tables, and matrices in multiple documents. When a change is made, it must be made manually and repeatedly. With this manual process, there is a possibility for error in inputting the information incorrectly in one of the locations or missing some of the references that should be updated [31]. These errors can be very costly to a program as engineering work in other domains (for example, electrical, mechanical, and software) use the specifications generated by systems engineers, and any errors or inconsistencies in the specifications will be introduced to their designs. Using a well-designed MBSE approach, any change made to the product information contained in the model as a model element is immediately and automatically implemented wherever that element is used. MBSE also offers the possibility of integrating other repositories of product information, such as product life cycle management tools or requirements databases, with the system model. The need to manage change and enforce consistency is a compelling need with which MBSE is highly compatible.

Another need of potential adopters with which MBSE is compatible is the need for an organization to have an [Authoritative Source of Truth](#) for a system. When SE data are captured in documents that are exchanged between project stakeholders, it is often difficult to determine and track: 1) which document contains the desired information, 2) which version or revision of the document contains the most current information, and 3) traceability between stakeholder concerns, requirements, structural and behavioral design decisions, and verification methods. These difficulties are alleviated through the use of a configuration-managed system model that encompasses all SE data and the relationships between system and model elements. The value of a system model as an authoritative source of truth is enhanced as MBSE tools, methods, and processes improve their integration with domain-specific models and simulations [149].

3.4.3 Complexity

For systems engineers that are accustomed to working with textual specifications and creating standalone tables and figures in productivity tools, the idea of creating and working from a model repository in a new tool can result in a high perceived complexity for MBSE. Systems engineers are

familiar with managing complexity in the systems they develop, but adopting a new methodology, tool, and language along with new roles and information standards associated with MBSE adds an additional dimension of complexity. To facilitate adoption, organizations should take proactive measures to minimize the perceived complexity of MBSE.

One of the ways that the perceived complexity can be reduced is to establish a clear purpose for the modeling effort from its beginning and communicate that purpose to everyone that is involved. This purpose should identify a set of questions that the model is designed to answer [31,38]. Without this purpose, the various diagrams, processes, and other artifacts may appear as a disjointed and foreign collection. Conversely, if stakeholders understand the purpose of the model and what questions it has been developed to answer, they will gain valuable context that reduces the perceived complexity of MBSE. Reference models and architectures can be helpful in aligning the understanding of stakeholders [150].

Another way that complexity can be lowered is to define roles for those who are involved in the SE work of the organization and provide training on elements of MBSE that are appropriate for specific roles [66, 151]. For example, a model user role could be defined for those who need to be able to interpret design decisions that are captured in a model diagram. Model users would not need extensive training in the chosen methodology or tool but would need to be trained on the selected modeling language. With this training, the diagrams they are reviewing would no longer appear foreign and would be perceived as less complex. There may be a role defined for designers who need to understand and received tailored training on the methodology and modeling language but are not responsible for creating models and do not need expertise in the modeling tool. Finally, there may be only a small group of modeling experts who are proficient with the tool and are responsible for capturing decisions made by the SE team in the system model. As it contributes to the language pillar of MBSE, SysML is perceived positively by the SE community, suggesting it is not prohibitively complex to those who have received adequate training [152]. With an effective training strategy and clearly defined roles, the perceived complexity of MBSE to all specific users and stakeholders can be significantly reduced.

3.4.4 Trialability

If an organization is considering adopting MBSE, efforts should be made to identify a specific, limited application where a trial or pilot project can be completed [121, 151]. A key point of MBSE to understand in this context is that an entire system does not need to be modeled to yield a benefit and that a model can (and should) be recursively modified to include additional detail as needed to provide additional value to stakeholders. For example, an organization may experiment with MBSE by modeling only the structural and behavioral elements of a system that are required to deliver a single capability or mission thread. If the limited modeling efforts provide benefits to the organization, the modeling effort can be expanded to other capabilities, and over time a complete system model (a model that accounts for all the elements of its intended purpose) will be developed.

For this attribute, what should be done is straightforward, while the how is more difficult as there are obstacles to overcome to experiment with MBSE. To conduct even a limited experiment using MBSE, at least a portion of the spike in initial SE effort shown previously in Figure 3.4 will need to be invested. Stakeholders must also be willing to accept a certain level of (initial) redundancy as models are developed to capture data that is already contained in other sources (documents, databases, etc.). Developing the expertise within the organization to conduct this experiment takes time. This can be accelerated using commercially available training and consultants, though the cost may be prohibitive for some organizations. While these challenges are significant, the DoI theory reveals their importance so that proactive plans can be made to address them.

3.4.5 Observability

As noted in the discussion on relative advantage, MBSE is partially a preventative innovation that inherently leads to poor observability of its benefits. The low observability of MBSE is also closely tied to its high complexity. If the perceived complexity of MBSE can be reduced by implementing some of the actions from the complexity section (such as clearly defined roles and

an effective training plan), then the observability of its benefits can be improved as stakeholders are exposed to MBSE tools, artifacts, and processes. With adequate training, design reviews and working groups can be conducted from the modeling tool, and stakeholders will be able to directly observe how elements of MBSE, like reuse of model elements and object-oriented principles (modularity, encapsulation, inheritance, and so forth), help to enforce consistency, provide traceability, and improve design quality [153]. Conducting meetings and briefings from the modeling tool will allow the stakeholders to see when design ambiguities are discovered and clarified or when conflicting requirements and design decisions are prevented by the tool.

Observability can also be improved by developing metrics that focus on improvements due to an MBSE approach [146]. Compared to document-based SE, MBSE has been shown to reduce project development costs, improve on-time delivery [154], reduce system defect density [155], and improve the probability of success of the project [156]. However, as no two development projects are identical, comparing them to demonstrate an observable improvement that can be attributed to MBSE is an ongoing challenge.

3.4.6 An MBSE Adoption Success Story

The NASA MBSE pathfinder projects and follow-on MBSE infusion and modernization initiative (MIAMI) are compelling examples of how elements of the DoI theory can explain the rate of adoption of MBSE within an organization [157]. Though the team did not report any awareness of the theory or a deliberate effort to apply its principles, their approach was very much in line with what the theory advocates and would predict successful adoption. For example:

- They increased the perceived relative advantage by identifying quantitative and qualitative benefits of MBSE from their earliest efforts
- They increased the perceived compatibility by integrating their MBSE efforts with existing SE and domain engineering processes

- The perceived complexity was decreased by identifying specific purposes for each of the pathfinder projects and MIAMI and all the stakeholders knew how MBSE contributed to those purposes
- Each of these projects and initiatives represent limited trials of MBSE that demonstrated the trialability of MBSE, and each resulted in an expansion of the scope of MBSE work within the organization leading to plans for enterprise-wide implementation of MBSE
- They increased observability by publishing the results of the effort

The experience at NASA suggests that the DoI theory is applicable to MBSE and warrants further attention.

3.5 Conclusion

As the SE field continues to evolve and develop to accommodate the ever-increasing complexity of modern systems, it will benefit from consideration and inclusion of an even more broad set of disciplines than it currently encompasses. The human element of SE organizations and the man-made systems they develop make social sciences particularly relevant [25]. The social sciences should be studied by systems engineers to determine pertinent developments and theories that could be applied to enhance the practice of SE.

The study of innovation is a mature field with a well-established and research-supported DoI theory. This theory provides a framework to understand variability in the adoption rate of innovations in a broad range of domains and potential adopter populations. Of the variables that affect the rate of adoption, the perceived characteristics of an innovation (relative advantage, compatibility, complexity, trialability, and observability) have the most significant impact. The concepts offered by the DoI theory can be applied to innovations in SE research and practice that have demonstrated benefits on a limited scale to speed their adoption in the broader SE community.

While the use of MBSE has increased in recent years, it has yet to become standard practice for SE. The DoI theory offers valuable insights as to why adoption of MBSE is occurring slower

than what may otherwise be expected based on its benefits. The applicability to MBSE of all the variables offered by the DoI theory, including further consideration of the perceived attributes of innovations, warrants additional research.

Chapter 4

Perceived Attributes of MBSE Survey

4.1 Survey Goals

The major contributions of this research are the data, analysis, and conclusions of a survey to determine the SE community's perceptions of MBSE [158]. The goal of this survey is to validate and quantify the applicability of the DoI theory to MBSE. This survey is the instrument used to collect data on potential adopters' perceptions of MBSE in support of this goal. The survey is considered human subject research and is therefore subject to [Institutional Review Board \(IRB\)](#) oversight. However, because there are no identified risks to the participants and no participant personal information will be collected, the protocol was determined to be exempt from approval by the IRB (Protocol #4247).

The survey was built in [Qualtrics Experience Management \(XM\)](#), an online survey tool with access provided by [CSU](#). [XM](#) allowed the survey to be distributed to potential participants using a hyperlink and QR code. The survey was distributed through the INCOSE and MBSE groups on LinkedIn, to digital transformation working groups within the Department of Defense (DoD), and through in-person contact at various conferences and symposia, most notably the 33rd Annual INCOSE International Symposium (IS) in July 2023. [XM](#) provides some basic data analysis capability, and also allows data from survey responses to be downloaded in several file formats. [XM](#) provides some basic data analysis capability, and also allows data from survey responses to be downloaded in several file formats.

4.2 Survey Introduction

The survey begins with an introduction and instruction page, found in [Appendix A](#). This page is built from the [CSU IRB](#) template for the consent form for an anonymous survey. It is meant to inform participants about the purpose of the survey and receive consent to participate.

The first section of the survey is meant to orient the participants to a common understanding of [Digital Engineering \(DE\)](#) (as defined by the [DoD DE strategy](#)) and MBSE (as defined by [INCOSE](#)). The definitions of these terms are given, followed by questions about the participant's familiarity with the terms and involvement in work related to these terms. These questions will help to determine the reliability of any outlier responses as outlier responses where the participant indicated that they are not familiar with these terms may be excluded.

- In the 2018 Department of Defense Digital Engineering Strategy, digital engineering is defined as: “an integrated digital approach that uses authoritative sources of system data and models as a continuum across disciplines to support lifecycle activities from concept through disposal” [[159](#)]
 - Are you familiar with digital engineering as defined above? (Yes /Somewhat / No)
 - Does your organization practice digital engineering? (Yes / Somewhat / No)
 - Are you involved in digital engineering efforts within your organization? (Yes / Somewhat / No)

- The INCOSE SE handbook defines model-based systems engineering (MBSE) as: “the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases” [[9](#)]
 - Are you familiar with MBSE as defined above? (Yes / Somewhat / No)
 - Does your organization utilize a model-based systems engineering approach? (Yes / Somewhat / No)
 - Are you involved with MBSE as part of your normal responsibilities? (Yes / Somewhat / No)

4.3 Perceived Attributes of MBSE

The next section of the survey contains questions related to each of the perceived attributes of MBSE. For each attribute there are several statements about MBSE and participants are asked to rate their agreement with each statement on a 5-point Likert scale (Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree). Most of the questions are positively coded, meaning that a response of “Strongly Agree” results in a high score for that attribute. Questions that are negatively coded (“Strongly Agree” results in a low attribute score) are indicated with a (-) below. There is no indication to the participant about the coding of questions. The questions are grouped by attribute below, but when they are presented to survey participants they are randomized.

The first set of questions address the relative advantage of MBSE. The first four statements are positively coded as they are about the reported benefits of MBSE. The last statement is negatively coded as it relates to the potential for additional work required in an MBSE approach.

- An MBSE approach can improve the quality of systems engineering data in my organization.
- An MBSE approach provides traceability amongst systems engineering artifacts.
- An MBSE approach enforces consistency amongst systems engineering artifacts.
- Using MBSE can reduce errors in my organization’s systems engineering data.
- An MBSE approach increases the overall amount of systems engineering work in my organization. (-)

The next set of questions are about the compatibility of MBSE with existing SE approach, personal work style and an organizational need. They are all positively coded.

- MBSE is compatible with all aspects of my organization’s systems engineering approach.
- An MBSE approach fits my work style.
- MBSE addresses a relevant need of my organization.

As stated in the introduction to the DoI theory above, complexity is the one attribute of an innovation that is negatively correlated with the adoption rate. As such, the statements in the survey that present MBSE in a negative light are positively coded. Statements that indicate lower complexity are negatively coded.

- MBSE is cumbersome.
- MBSE requires significant mental effort.
- It is easy to remember how to perform tasks using an MBSE approach. (-)
- I am familiar with a system modeling language. (-)
- I have experience with a system modeling tool. (-)

These questions on trialability assess the participant's opportunities to experiment with MBSE as well as their opinion on if MBSE is suited to experimentation.

- I have opportunities to experiment with MBSE.
- I have access to a tool to experiment with MBSE.
- An MBSE approach is suited to small scale, pilot projects.

The questions on observability seek to assess the degree to which the participant has been exposed to the use of MBSE and if they have been able to see benefits from its use.

- The benefits of an MBSE approach are apparent to me.
- I have observed an MBSE approach being used by others.

4.4 Level of MBSE Adoption

The next section contains questions that assess the degree to which the participant is using MBSE. It will be the dependent variable in the regression analysis assessing the correlation between the perceptions of MBSE and the level of its adoption. These questions were adapted from

the [INCOSE Model-Based Capability Matrix \(MBCM\)](#) [160]. The [MBCM](#) is used to assess the current model-based capabilities of an organization, determine the model-based capabilities the organization needs in the future, and to develop a road map to develop the needed model-based capabilities. The rows of the matrix represent specific model-based capabilities with a capability description. The columns represent the stage of that capability, ranging from Stage 0 (no capability) to Stage 4 (enterprise-wide capability).

There are a total of 42 model-based capabilities identified in the [MBCM](#) that can be sorted by eight different role-based areas (workforce/culture, SE processes/methodology, program/project processes methodology, model-based effectiveness, [Information Technology \(IT\)](#) infrastructure, modeling tool construction, model use, and modeling policy) or by the five goals of the [DoD DE](#) strategy (formalize development, integration, and use of models, provide an [Authoritative Source of Truth \(ASoT\)](#), incorporate technical innovation, establish infrastructure and environments, and transform culture/workforce) [159]. Two questions were included for each of the role-based areas except for model use which has one question and [IT](#) infrastructure and modeling policy which do not have any questions. Questions were not included for those two areas to manage the length of the survey.

The first draft of the survey that was pre-tested on a pilot group of [CSU](#) MBSE graduate students and colleagues that are familiar with MBSE presented the model-based capability description and all five stages of the capability. There are very few organizations that have achieved stage 5 capability in any of these model-based capabilities and this resulted in artificially low scores for MBSE use in the organizations. Instead, each question in this section was presented with a statement based on the stage 3 level of each model-based capability with a five point Likert scale for the participant to indicate their agreement with the statement as it pertains to their organization (Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree). The scores of the model use questions are aggregated for a single model use score for the response.

These statements are included in the survey for each of the included role-based areas:

- Workforce and culture

- My organization has an MBSE use strategy that is documented as part of the organization’s overall strategy at the system level. Modeling results are used to inform systems engineers across system engineering phases and for all disciplines
- Modeling or model users within my organization have experience on specific tools with respect to their role as a user or modeler
- MBSE process and methodology
 - Modeling is the basis for the technical processes of my organization with digital threads covering some of the processes. Digital artifacts are used to make systems engineering decisions
 - Verification and validation (V&V) plans in my organization rely on model contents and analysis via requirements analysis
- Project management process methodology
 - The systems engineering plan of my organization calls for full system/enterprise models to be developed and applied across the product life cycle and across systems engineering organizations
 - Metrics, beyond those available from the tool configuration, are reported to address model development, quality, and effectiveness needs within my organization
- Model-based effectiveness
 - My organization uses digital artifacts to make program/project level decisions
 - Systems models for projects/programs in my organization are integrated and use the same structured approach. A library of reusable SysML blocks has been created and used
- Modeling tool construction

- Modeling methods are planned for efforts within a portfolio and are as consistent as possible for each project/program in my organization. Best practices are evolving; structuring patterns are emerging
- Inter-database/tool data item associations are defined, captured, and managed in my organization
- Model use
 - An MBSE approach is being adopted across programs/projects within my organization with the intent to apply enterprise and system models

4.5 Organization Information

The final section of the survey contains questions about the participants' organization. There are two primary purposes for this section. The first is to be able to characterize the participant's breadth of experiences. Any insights gained from the collected data will be stronger if it can be shown that a broad spectrum of organizations were considered. Likewise, if the majority of responses come from the same type of organization then the conclusions will be limited to those types of organizations. The second purpose of this section is to look for any correlation between organization types and their perceptions and/or use of MBSE. For example, it could provide insight into if a particular sector has more favorable perceptions of MBSE and/or is already employing an MBSE approach.

The list of sectors and industries for the first question was compiled by Madni and Purohit [144], with the addition of academia/education for completeness.

- To what industry/sector does your organization belong?
 - Aerospace/defense
 - Transportation and mobility
 - Industrial equipment

- Energy, processes and utilities
 - Architecture and construction
 - Life Science
 - High-Tech
 - Marine and offshore
 - Financial and business services
 - Consumer and retail
 - Natural resources
 - Consumer packaged goods and retail
 - Academia/education
- If aerospace/defense is selected — With which branch/service is your organization most closely associated?
 - Air Force
 - Army
 - Marine Corps
 - Navy
 - Foreign military/other

A question on the life cycle stages the organization is involved with is included as MBSE may be more appropriate for some systems life cycle stages than others.

- In which life cycle stage(s) is your organization involved? (select all that apply)
 - Concept
 - Development
 - Production

- Operations/support
- Retirement

Most of the questions in this survey relate to the participant's organization. This leaves a lot of room for interpretation by the participant as to what they consider their "organization" to be. They could consider their immediate team as their organization, or they could refer to a higher-level body. To gauge the context of the participant's response, a question about organization size is included. While smaller organizations may be more flexible and able to adopt a new technology faster, larger organizations may have more resources for experimentation.

- Approximately how many people are part of your organization?
 - < 20
 - 21-100
 - 100-500
 - 500-2000
 - 2000+

For some organizations, an attempt to adopt MBSE may be their first foray into SE generally. Established SE practices in an organization may make it more difficult to adopt MBSE as there is resistance to changing established processes, or it could make it easier as current SE practices are tailored to model-based approaches. This simple (yes/no) question may provide insight into any correlation between established SE practices in an organization and their use of MBSE.

- Does your organization have a formal, written systems engineering plan (model-based or otherwise)? (Yes/No)

Some organizations received guidance or mandates from their leadership directing them to adopt a certain approach. This is referred to in the DoI theory as an authority innovation-decision [1]. This simple (yes/no) question may provide insight into the relevance of the type of innovation-decision on MBSE adoption for future research.

- Is your organization subject to any mandates to adopt and/or use digital engineering? (Yes/No)

Organizations vary in their tolerance and capacity to experiment and innovate. The purpose of this question is to determine if the use of MBSE within the organization is tied to the type of organization or the innovation itself. This is also related to the nature of the social system adoption rate variable identified by the DoI theory [1].

- Does your organization encourage innovation and experimentation? (Yes/Somewhat/No)

The purpose of this final question is to investigate if there is any correlation between a participant's SE experience level and their use of MBSE. Less experienced engineers may be more likely to adopt MBSE as they are not as established in traditional document-based methods, and more experienced engineers may have more success in adopting MBSE as they have a better understanding of SE principles generally.

- How long have you worked in a systems engineering role?
 - Less than 3 years
 - 3-10 years
 - 10+ years
 - I do not work in a systems engineering role

4.6 Analysis Methods

Results for questions about the perception of attributes of MBSE and model use questions (the questions in the survey that utilize a Likert scale) are presented using bar charts showing the percentage of responses in each of the Likert categories along with a [Net Agreement Score \(NAS\)](#) for each response (see [Figure 5.4](#)). The NAS for each response was calculated:

$$\text{NAS} = (\% \text{ Strongly Agree} + \% \text{ Agree}) - (\% \text{ Strongly Disagree} + \% \text{ Disagree})$$

The bar charts are constructed with the extreme scores (“Strongly Agree” and “Strongly Disagree”) in the center of the chart, with the moderate scores on the edges to provide a visual indication of the strength of the agreement or disagreement. “Neutral” scores are not included in the calculation of the NAS and are displayed in a separate subplot. Responses to multiple questions or from multiple subpopulations are included on a single chart to allow for a clear visual comparison of responses.

The analysis of the survey data can be grouped into two types. The first type of analysis can be categorized as exploratory data analysis. The purpose of this exploratory data analysis was to characterize the responses to the survey questions to draw conclusions directly from the responses. The second type of analysis was intended to look for relationships between different categories of data using chi-squared (χ^2) tests, [Fisher Exact \(FE\)](#) tests, and Cronbach’s alpha to determine correlation and significance factors. While correlations between responses do not in and of themselves prove a causal effect between them, it does provide a starting point for investigation as to whether or not there is an effect present [161]. These analyses were carried out using custom scripts written and executed in Python 3.12.2. All survey data and analysis scripts will be made publicly available on GitHub.

Chapter 5

Survey Analysis and Results¹⁰

The survey was open for responses from June 15, 2023 to September 15, 2023. During the time that it was open it received 270 responses, of which 197 were complete responses and 33 did not answer any questions. Figure 5.1 shows the number of responses to each question of incomplete survey submissions. There was a notable drop off between the warming up questions and the perceived attribute questions, and again between the perceived attribute questions and model use questions.

The median time spent on the survey was 6.7 minutes. The responses to the warming-up questions (see Figure 5.2) indicated that the survey reached its intended audience of individuals familiar with digital engineering and MBSE. Furthermore, most participants in the survey are involved with digital engineering (64%) and MBSE (58%) efforts within their organizations, while still allowing for a pool of responses from potential adopters (those not already involved with MBSE efforts).

While efforts were made to distribute the survey to as broad of an audience as possible, the majority of the responses were from the aerospace and defense sector (see Figure 5.3). Within the aerospace and defense sector, most of the responses came from participants most closely aligned with the Air Force. There is no reason to believe that the results of this survey do not apply more broadly than to the aerospace and defense sector and the Air Force as a chi-squared independence test failed to reject the null hypothesis ($p < 0.05$) that the response to any question was independent of association with the Air Force [163] (see Table C.7).

Other demographic results of note were the very even split of responses between participants whose organizations have a formal SE plan (model-based or otherwise) and those that do not (106 and 78, respectively). There was a fairly similar split in the responses to the question regarding

¹⁰The contents of this chapter are based on the paper *The effects of the assessed perceptions of MBSE on adoption to be published in The Proceedings of the 34th INCOSE International Symposium* [162]

Count of Answered Questions in Incomplete Survey Submissions (n = 73)

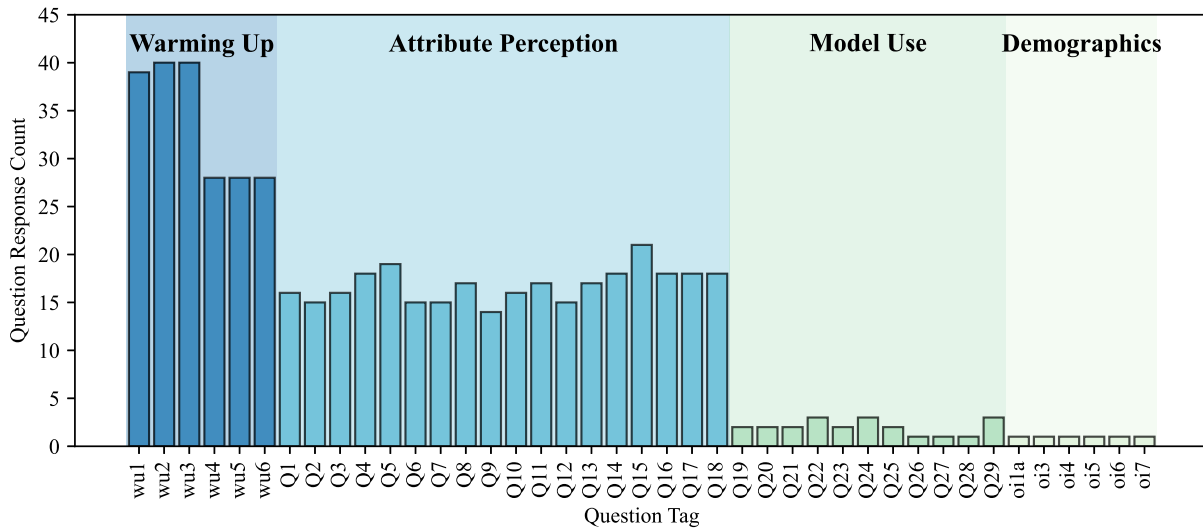


Figure 5.1: Plot of the number of responses to each question within the 73 incomplete survey submissions received. The questions within the “attribute perception” and “model use” sections were presented to survey participants in a randomized order.

the organization being subject to mandates to use DE (108) and those that do not (73). While the numbers of these two subpopulations are very similar, there was very little correlation between responses to these two questions (Cronbach’s alpha = 0.35), indicating that this similarity is coincidental [164]. A complete set of figures with the results to demographic questions is contained in Appendix B.

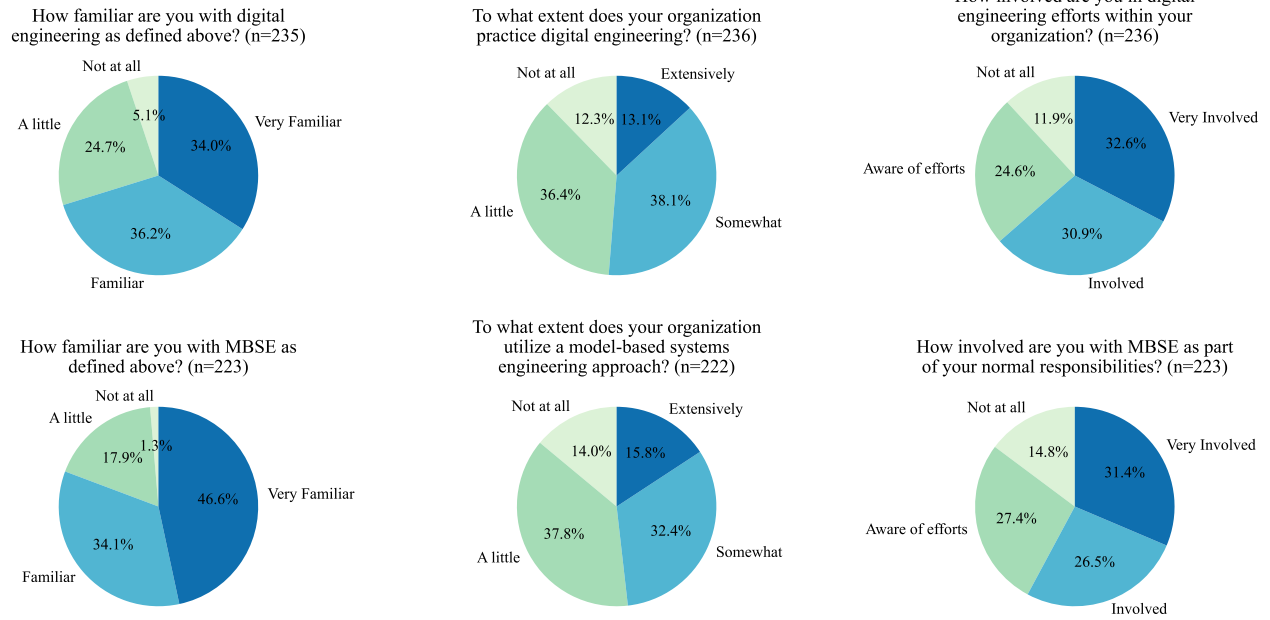


Figure 5.2: Warming up survey questions results.

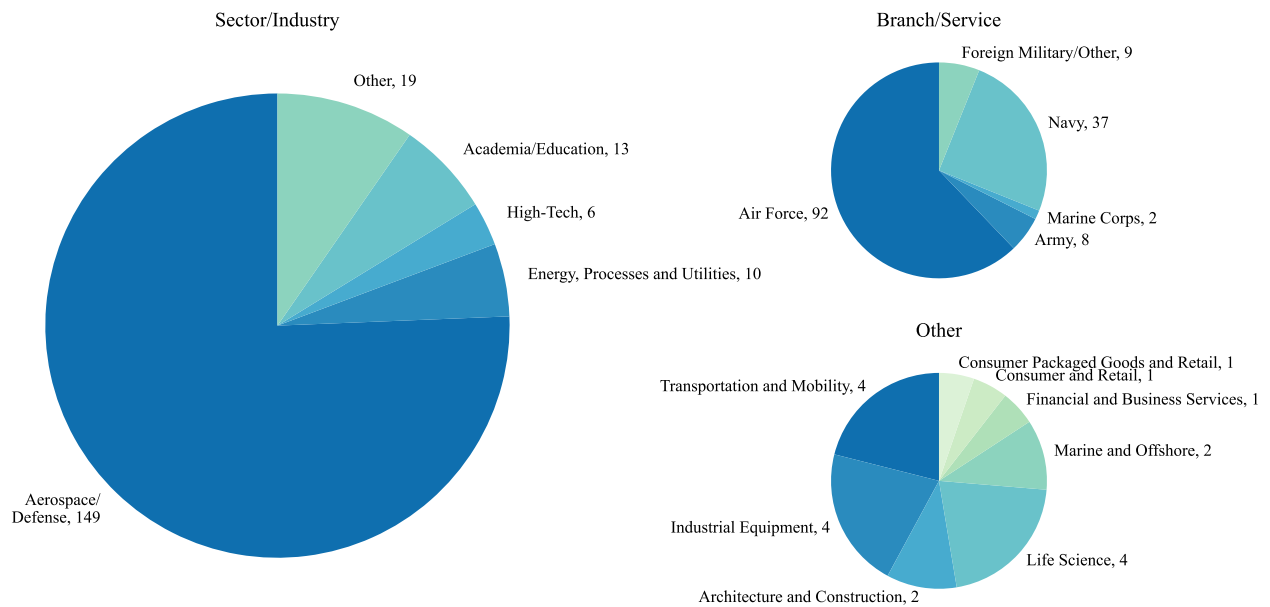


Figure 5.3: Sector/industry of survey participants.

5.1 Perception of Attributes of MBSE

An exploratory data analysis of the results regarding perceptions of MBSE attributes reveals novel insights into how the SE community perceives MBSE. Figure 5.4 - Figure 5.8 contain the results for the questions related to the perceptions of specific attributes of MBSE. The statements presented on the survey are listed along the y-axis of each figure, and the percentage of each response is presented by the stacked bars to the right of each statement. An asterisk next to a statement in these figures indicates that the statement is reverse coded. This reverse coding means that a response of “Strongly Agree” would reflect a poor perception and “Strongly Disagree” a positive perception of MBSE with respect to the attribute in question.

Figure 5.4 displays the results for the survey questions related to the attribute of the relative advantage of MBSE and shows that there is broad agreement on the relative advantage of an MBSE approach. Participants generally agreed that MBSE can improve the quality of and reduce errors in SE data and provides traceability amongst and enforces consistency of SE artifacts. There was one negatively coded question regarding an MBSE approach increasing the overall amount of SE work in an organization (Q5). While 33% of respondents expressed a neutral opinion of this statement, only 20% outright disagreed with it (strongly disagree or disagree), resulting in a NAS of 26%. The perception that an MBSE approach increases the overall amount of SE work to be done likely negatively impacts its perceived relative advantage and contributes to the slow adoption of MBSE.

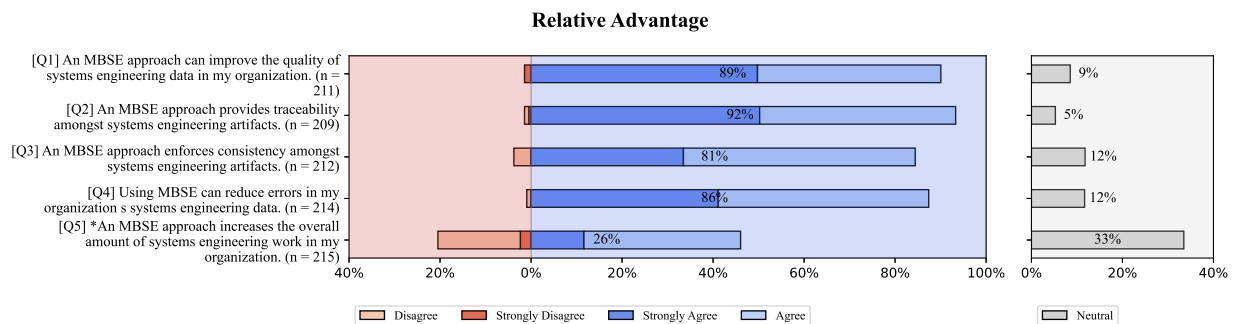


Figure 5.4: Survey results for each statement (y-axis) regarding perceptions of the **Relative Advantage** of MBSE with net agreement score (NAS) for each statement.

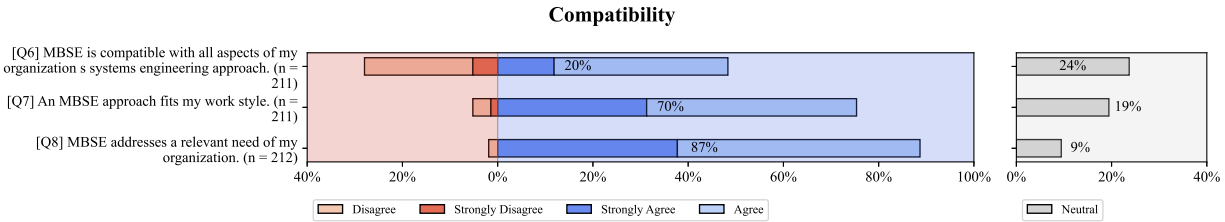


Figure 5.5: Survey results for each statement (y-axis) regarding perceptions of the **Compatibility** of MBSE with net agreement score (NAS) for each statement.

The results to questions about the perceived compatibility of MBSE are shown in Figure 5.5. The statement Q8 showed a NAS of 87% that MBSE addresses a relevant need within their organization. This is a very encouraging result that supports the overall sentiment within the SE community that MBSE is a reasonable approach to the challenges of the SE of modern, complex systems. Most responses (NAS 70%) also agreed that an MBSE approach was compatible with their work style. An area where the perceived compatibility appears to be lacking is in its compatibility with an organization's SE approach, where the NAS of responses to the statement "MBSE is compatible with all aspects of my organization's systems engineering approach" (Q6) was only 20%. This question and its responses alone are not adequate to determine if this incompatibility can be attributed to weakness in the MBSE approaches being applied or to issues with the existing SE approach to which MBSE is being compared. Either way, the responses suggest that the adoption rate would likely be improved by improving the compatibility between MBSE and organizational SE approaches by better tailoring MBSE approaches or by general improvements to existing SE approaches to be more in line with MBSE best practices.

As defined by the DoI theory, complexity is the only attribute that is negatively correlated with the adoption rate of an innovation. Because of this, the questions that reflect poorly on MBSE are positively coded (Q9 and Q10), and the questions that are related to positive aspects of MBSE are negatively coded. The results to questions about the perceived complexity of MBSE are shown in Figure 5.6. While there were many neutral responses (40%), the fact that Q9 about the perception of MBSE as cumbersome had a NAS of -7% is regarded as a favorable result. Conversely, Q10 about the significant mental effort required for MBSE and its NAS of 58%, suggests a higher per-

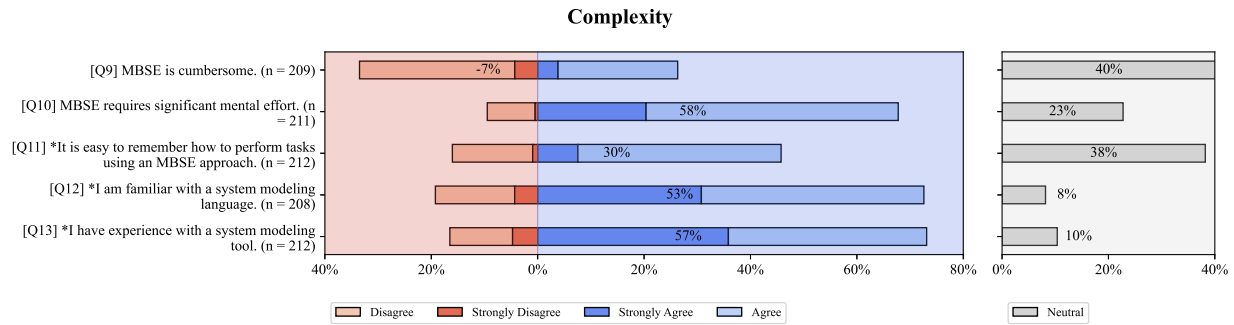


Figure 5.6: Survey results for each statement (y-axis) regarding perceptions of the **Complexity** of MBSE with net agreement score (NAS) for each statement.

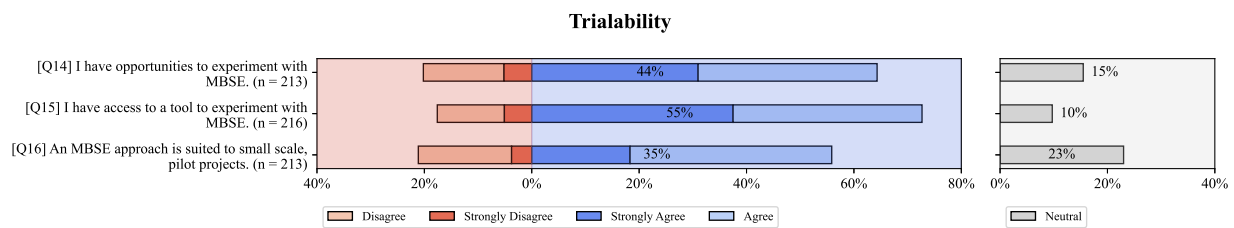


Figure 5.7: Survey results for each statement (y-axis) regarding perceptions of the **Trialability** of MBSE with net agreement score (NAS) for each statement.

ceived complexity that would have a negative impact on adoption. Statements about familiarity and experience with a modeling language and tool (Q12 and Q13) had NASs of over 50%, but there were no additional questions to probe if those experiences were positive or negative. However, it is likely that any level of experience with a modeling language and tool could reduce the perceived complexity of MBSE. From a process or methodology perspective, Q11 about the ease of remembering how to perform tasks in an MBSE approach had a relatively low, 30% NAS.

The statement about trialability with the lowest NAS (35%) was related to the suitability of an MBSE approach to small-scale pilot projects (Q16) (see Figure 5.7). This is a notable result because if MBSE adoption is perceived as an “all or nothing” proposition, it is likely that potential adopters will be more measured and deliberate in their adoption decisions. This result opens the possibility for additional research, publication, and training on how the perceived trialability of MBSE can be improved by first adopting it in a limited approach before being expanded and used more widely. While the responses to questions about opportunities to experiment with MBSE

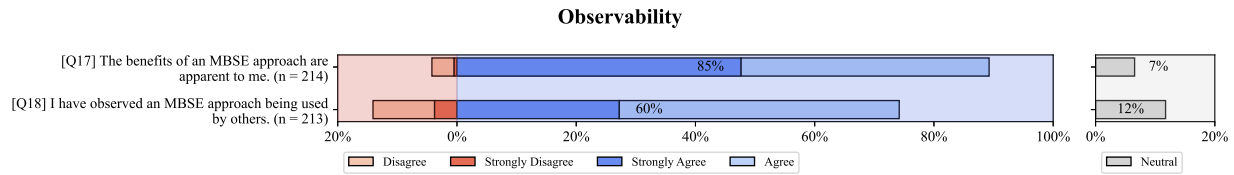


Figure 5.8: Survey results for each statement (y-axis) regarding perceptions of the **Observability** of MBSE with net agreement score (NAS) for each statement.

and access to MBSE tools were widely agreed on (44% and 55%, respectively), their percentages were lower than scores for statements about relative advantage and compatibility, indicating that trialability is more likely to be hindering adoption of MBSE.

Responses to the statements about the perceived observability of MBSE (Q17 and Q18), as shown in Figure 5.8, indicate that its observability has likely had a positive impact on the adoption rate of MBSE. The statement about the observability of the benefits of MBSE (Q17- “The benefits of an MBSE approach are apparent to me”) achieved a NAS of 85%. The responses to the statement that the participant has “observed an MBSE approach being used by others” (Q18) resulted in an NAS of 60%.

5.2 Model Use Results

The percentage of agreement of responses to questions relating to model use was overall fairly low (see Figure 5.9). The statements with the highest NAS were Q20, “Modeling or model users within my organization have experience on specific tools with respect to their role as a user or modeler” and Q29, “an MBSE approach is being adopted across programs/projects within my organization with the intent to apply enterprise and system models” (NAS of only 21% and 15%, respectively). The statement with the lowest score was Q26, “systems models for projects/programs in my organization are integrated and use the same structured approach. A library of reusable SysML blocks has been created and used” (-46% NAS). While the original purpose of the questions in this section was to assess the degree to which MBSE is being used by survey participants, the poor responses to this question provide insight into the perceived relative advantage of MBSE.

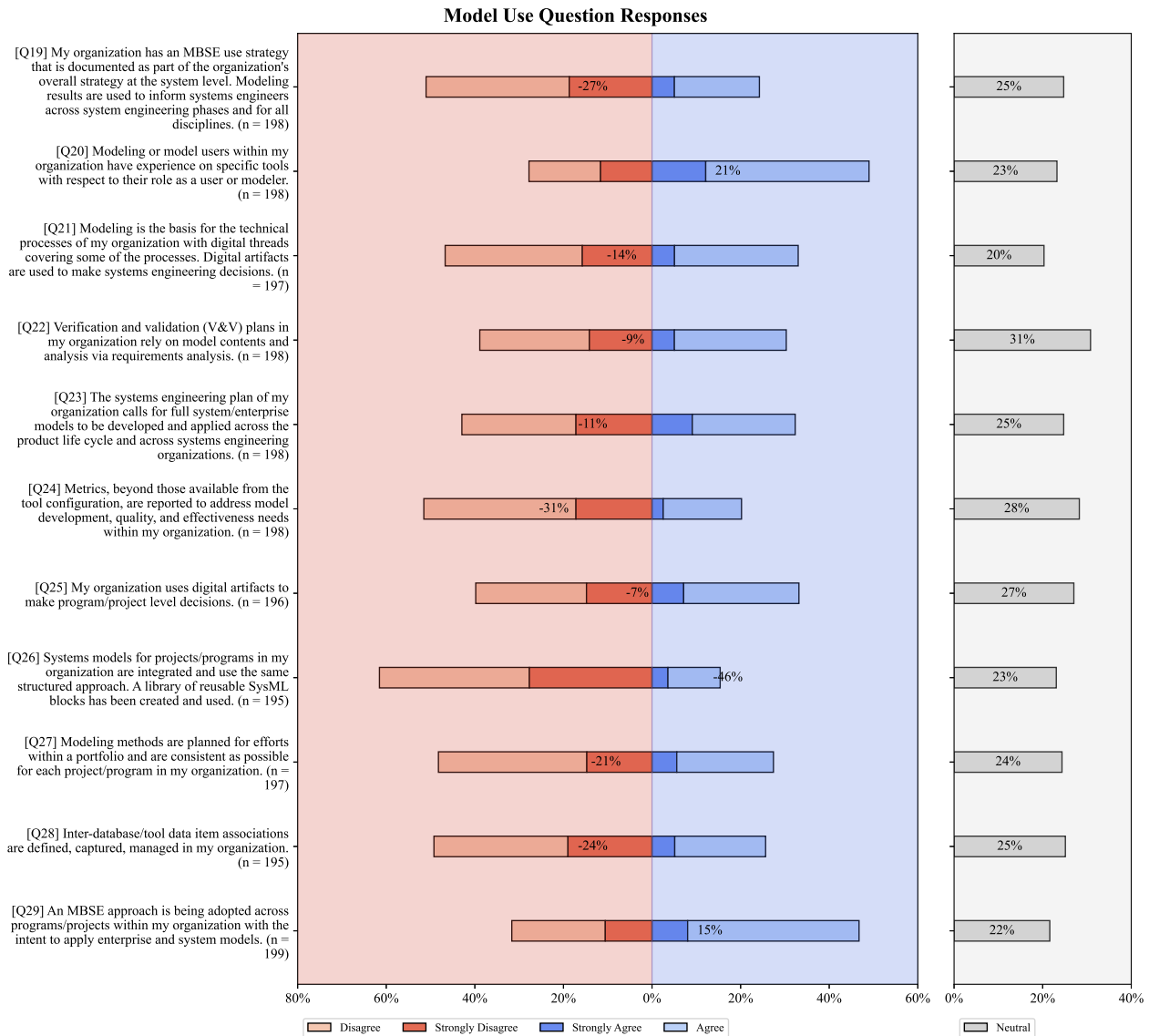


Figure 5.9: Survey results for model use questions

If potential adopters do not have a consistent approach to MBSE and do not have reusable libraries of model components across projects then some of the key benefits of MBSE will not have been realized.

The overall low scores are likely due to the amount of detail listed in these statements as opposed to the very simple statements included in statements about MBSE. This led to a neutral selection on 24% of responses for these questions (compared to 17% neutral responses to the statements relating to the perceived attributes of MBSE). Basing questions on items from the INCOSE

MBCM did not provide the insight desired into the extent of MBSE adoption thus far. In any similar studies conducted in the future, these statements should be simplified to focus on a single attribute of MBSE use, and other metrics should be considered to assess MBSE use in the SE community. The poor scores on these questions negatively impacted the planned regression analyses to investigate correlations between perceptions of MBSE and the use of MBSE.

5.3 Subpopulation Analyses

The warming up, demographic, and model use questions allow for the identification of subpopulations within the total population of survey participants. Chi-squared tests of independence were used to compare the collection of responses from the subpopulations to determine if the responses to the questions were independent of the subpopulation they came from [165]. The chi-squared test of independence is well suited for this data as it is meant to determine if two variables (population and response in this case) are independent from each other. The application of the chi-squared test of independence depends on the assumption that the populations are independent of each other and that the data is categorical, both of which are met for the survey data. For a chi-squared independence test to be valid, there must not be more than 20% of the entries with an expected count of less than 5. In cases where the chi-squared test was not valid, a Fisher Exact test was used to determine significance [166]. A Fisher Exact test is most often used for data with two levels from two populations (i.e., effect vs. no effect and treatment vs. placebo). To reduce the data to two categories, a similar approach was taken as was used to create a NAS for each question, that is “strongly disagree” and “disagree” were combined to form a disagreement score and “strongly agree” and “agree” were combined to form an agreement score. Neutral responses were not included in the Fisher Exact tests. The Fisher Exact test is more conservative than the chi-squared test so, as noted above, it is only used when the chi-squared test is not valid.

For both of these tests, the null hypothesis is that the responses are independent of the population from which they are received. Similarly, the alternative hypothesis is that the response is dependent on the population from which it was received. *p*-values reported in this section represent

the probability that the null hypothesis is true. In cases where the p -value is less than 0.05, we will reject the null hypothesis and fail to reject the hypothesis that the responses are dependent on the population from which they were received. As with any statistical test, a p -value does not prove that the null hypothesis is true, simply that we fail to reject it based on the present evidence. For the purposes of this paper, these population analyses will allow us to draw a connection between certain subpopulations and their responses, though we will not make any claims as to the strength of that connection.

One interesting subpopulation is the participants who indicated that they are not involved with MBSE efforts within their organization ($n = 70$) and those who reported they are either involved or very involved in those efforts ($n = 111$, see Figure 5.2). The chi-squared tests of independence revealed that there was a statistically significant difference ($p < 0.05$) in the way these two populations answered 8 of the 9 questions for which the test was valid. Furthermore, the Fisher Exact test showed that the responses to two additional statements revealed a significant difference (see Table 5.1). While some of the statistically significant differences were unremarkable, some results revealed valuable insights. Particular areas of divergence were in questions related to compatibility and trialability.

The single biggest difference was in the responses to Q14, the statement “I have opportunities to experiment with MBSE” ($p = 0.00$, see Figure 5.10) where the difference between the NAS of the two populations was 93.0 (80.2% for those involved with MBSE compared to -12.9% for those who are not). It is expected that those involved with MBSE would express agreement with this question as opportunities to experiment with MBSE are typically required to be involved with MBSE. However, it is worth noting that those who are not already involved with MBSE generally do not have the opportunity to experiment. This outcome likely has a negative impact on the perceived trialability of MBSE, leading to a slower adoption rate. Notably, this statement on the survey did not delve into the specific factors that would influence one’s perception that they have “opportunities to experiment with MBSE.” These factors could include resources and opportunities to experiment on a relevant project or education and training that would support such experimen-

Table 5.1: Significant results ($p < 0.05$) of the comparison of the subpopulations “Involved with organizational MBSE efforts” and “NOT involved with organizational MBSE efforts” (sorted by the delta between the net agreement score (NAS) of the populations, largest to smallest).

Question Tag	“Involved with organizational MBSE efforts” NAS	“NOT involved with organizational MBSE efforts” NAS	Delta NAS	Test	p-Value
Q14	81.2%	-11.4%	92.6%	χ^2	0.000
Q15	84.6%	8.9%	75.8%	χ^2	0.000
Q13	87.2%	12.7%	74.5%	χ^2	0.000
Q12	82.9%	11.4%	71.5%	χ^2	0.000
Q18	80.3%	30.4%	50.0%	χ^2	0.000
Q6	35.9%	- 5.1%	41.0%	χ^2	0.000
Q7	84.6%	46.8%	37.8%	FE	0.003
Q11	39.3%	12.7%	26.7%	χ^2	0.001
Q17	93.2%	70.9%	22.3%	FE	0.028
Q16	41.9%	21.5%	20.4%	χ^2	0.011
Q8	93.2%	77.2%	15.9%	FE	0.021

[Q14] I have opportunities to experiment with MBSE.

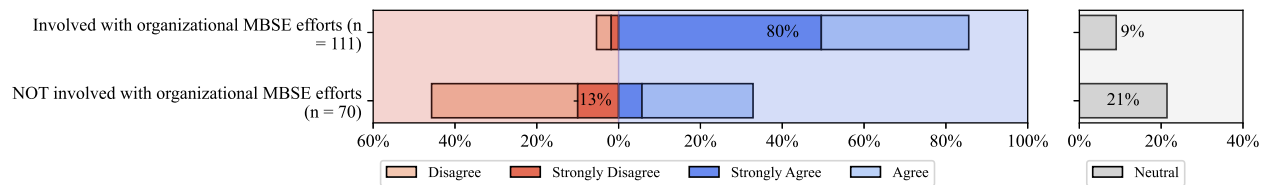


Figure 5.10: Agreement with the statement “I have opportunities to experiment with MBSE” (Q14) by those who are involved with MBSE efforts in their organization compared to those who are not.

tation. When the entire population of responses is examined, access to a tool to experiment with MBSE does outpace the opportunity to experiment (55% to 44%, see Figure 5.7).

A subpopulation analysis based on participants’ experience in an SE role revealed that individuals with more than ten years of SE experience tended to rate their perceptions of MBSE more favorably than their less experienced peers. Notably, this group rated their actual use of MBSE *lower* than those with less experience. In every statistically significant case ($p < 0.05$), the participants with ten or more years of experience perceived MBSE more favorably and rated their model use lower than less experienced participants. This phenomenon may be indicative of the Dunning-Kruger effect, a cognitive bias in which individuals with limited expertise in a particular domain tend to overestimate their abilities, while more experienced individuals may underestimate their

competence [167]. In the context of the survey, it suggests that SE professionals with extensive experience may possess a deeper awareness of the complexities of MBSE, leading to more critical self-assessments regarding their utilization of this methodology, as opposed to less experienced engineers who may perceive their proficiency in MBSE more optimistically. This is further evidence that the use of questions based on the INCOSE MBCM was not well suited to assess the level of MBSE use.

As noted above, the responses to questions based on model use were low and did not support the planned regression analysis with model use as the independent variable. However, the responses to the model use questions did allow for the identification of a population of model users (those who agreed with more of the model use statements than they disagreed with) and non-model users (those who disagreed with more than they agreed with). Much like the comparison between those who are involved with MBSE compared to those who are not, the question that showed the biggest difference between the populations was Q14, about opportunities to experiment with MBSE (see Table 5.2). The statement that had the next biggest difference in NAS was Q6, “MBSE is compatible with all aspects of my organization’s systems engineering approach”, with a difference in NAS of 49.6 ($p = 0.002$, see Figure 5.11). For the non-model users (who represent the potential adopters of MBSE) there were 25% neutral responses and a NAS of only 5%. This outcome is notable as it reveals that among the potential adopters, there is essentially a neutral view (just as many in agreement as disagreement) that MBSE is compatible with existing SE approaches. This outcome suggests that the idea that the “SE” in MBSE is systems engineering is not being effectively conveyed to potential adopters and amplifies the need identified in Section 5.1 to better tailor MBSE approaches to emphasize the importance of effective SE generally.

These model user subpopulations also revealed an interesting result with how they responded to the demographic question “Does your organization encourage innovation and experimentation?”. While very few responses from these two subpopulations answered “No” to this question (7 out of 193), there was a significant difference between these populations in those who answered “Somewhat” and “Yes” (see Figure 5.12). This significance was determined through the use of a chi-

Table 5.2: Significant results ($p < 0.05$) of the comparison of the subpopulations “Model User” and “NON-model User” (sorted by the delta between the net agreement score (NAS) of the populations, largest to smallest).

Question Tag	“Model User” NAS	“NON-model User” NAS	Delta NAS	Test	p-Value
Q14	83.9%	24.4%	59.5%	χ^2	0.000
Q6	54.8%	4.2%	50.6%	χ^2	0.001
Q18	90.3%	45.4%	44.9%	χ^2	0.000
Q11	58.1%	15.1%	42.9%	FE	0.010
Q15	75.8%	42.9%	32.9%	χ^2	0.009

[Q6] MBSE is compatible with all aspects of my organization’s systems engineering approach.

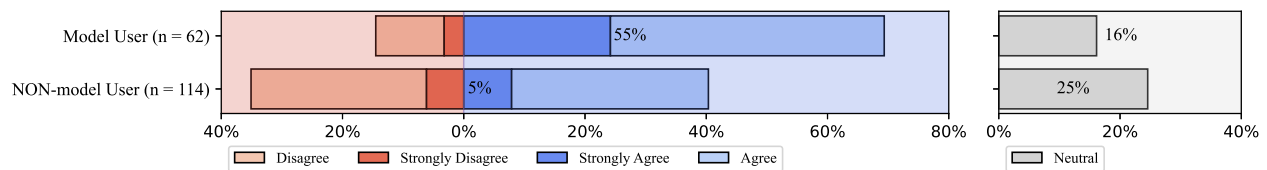


Figure 5.11: Agreement with the statement “MBSE is compatible with all aspects of my organization’s systems engineering approach.” (Q6) by model users compared to non-model users.

squared test ($p = 0.00$) with the “No” responses omitted as the expected value of “No” for each population was less than 5. Again, where the NAS of all responses to Q8 “MBSE addresses a relevant need of my organization” was 87% (see Figure 5.5), organizations can provide a more receptive environment for innovations such as MBSE if their members perceive the organization as encouraging of innovation and experimentation. This also suggests that another variable identified by the DoI theory, the nature of the social system, is affecting MBSE adoption.

Does your organization encourage innovation and experimentation?

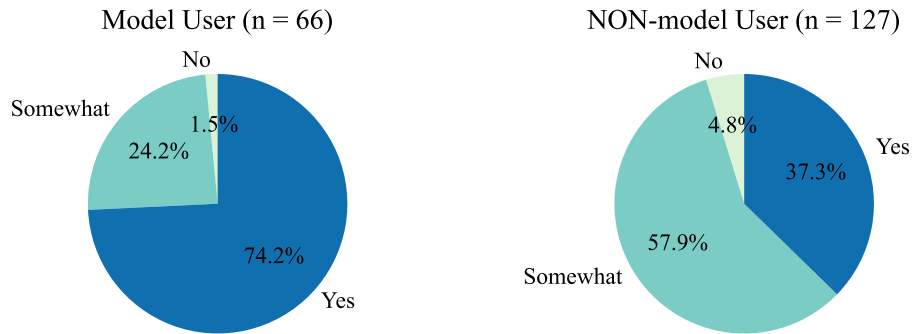


Figure 5.12: Responses to the question “Does your organization encourage innovation and experimentation?” by those who are identified as model users compared to non-model users.

5.4 Additional Thoughts

At the end of the survey, participants were given the opportunity to respond to a single open-ended question: “Do you have any additional thoughts you would like to share?” This question was optional, and the survey could be completed without providing a response. A total of 28 responses were received. Of these, seven indicated that the participant had no additional comments to share. Four responses contained feedback on the survey itself, either offering compliments or suggesting improvements for specific sections or questions. Two responses were categorized as qualifying remarks, where participants clarified their answers in relation to specific domains or languages. The remaining responses were grouped into four categories: adoption-specific (6), general SE (4), comments on MBSE (3), and MBSE limitations (2).

The following subsections will discuss these comments in more detail. It is important to note, however, that due to the limited number of responses and the absence of a formal coding scheme, these comments do not hold statistical significance. They do offer anecdotal insights and provide a glimpse into the perspectives of members of the SE community that are worthy of consideration. These comments could inform the development of questions for future surveys to determine whether these views are supported by any statistical significance.

Table 5.3: Adoption specific comments to free response survey question for additional thoughts.

Identifier	Response (Adoption Specific)
AS1	A game-changer would be dramatically increasing «tool availability» to ALL stakeholders, including those without technical knowledge or interest to install anything on any system. Currently, even the best tools on the market are not easily accessible to fellow Systems Engineers, which gives them a barrier to entry into a capability that depends on accessing a single source-of-truth.
AS2	Adopting is one metric and how well it works is another. Defining the effectiveness of modeling is critical to sustained adoption.
AS3	MBSE curricula is still lacking in many programs, development of this for academia would be incredibly helpful for new Systems Engineers and for overall organizational efficiency gains.
AS4	Programs here are resisting MBSE because they are set in their ways. New programs will be the adopters.
AS5	MBSE must buy its way in and is only a part of Digital engineering.
AS6	My organization is slowly adopting MBSE as a digital engineering tool for mission development.

5.4.1 Adoption Specific

Table 5.3 contains responses characterized as “adoption specific”. These responses touch on issues and experiences associated with the adoption of MBSE, offering insight into both challenges and opportunities.

AS1 underscores the transformative potential of enhancing the accessibility of MBSE tools and models to all stakeholders, identifying it as a potential “game-changer.” By improving access to these tools, organizations could overcome barriers that currently affect the broader adoption of an MBSE approach. Improved tool access not only addresses technical challenges but also facilitates collaboration across diverse functional areas that do not traditionally interface with SE tools. Along with proper training and support, making these tools intuitive and accessible for those without technical expertise or direct involvement in SE could improve the perceived benefits of MBSE, enhancing its relative advantage and organizational value.

The critical distinction between merely adopting MBSE and effectively implementing it is highlighted by AS2. Clear standards are important for evaluating the success of modeling efforts,

extending beyond their mere implementation. This distinction is vital, as the *sustained* adoption of MBSE depends on its proven benefits in improving SE outcomes. Thus, establishing robust metrics for modeling effectiveness is vital to ensure a meaningful, results-driven adoption of MBSE across various projects and organizations.

Response AS3 addresses the challenge associated with MBSE education, specifically the perception of insufficient MBSE courses in academic settings. Although many academic programs *do* offer MBSE courses, practicing engineers are not always inclined or able to enroll in university classes to develop new professional skills [42, 168]. When recent graduates have received MBSE training as part of their academic program, they usually lack the required experience to apply this knowledge in a professional environment effectively. Alternative educational pathways, such as training provided by consultants and the use of onsite consultants to support new MBSE efforts, are viable options for organizations that are attempting to develop new MBSE capabilities. These alternative approaches complement academic education and support the development of practical experience that is used to employ academic MBSE knowledge effectively, which can bridge the gap between theoretical education and practical, real-world application.

Collectively, responses AS4, AS5, and AS6 reveal various perspectives on the adoption of MBSE within different organizational contexts. AS4 explains that established programs resist MBSE adoption due to entrenched practices, suggesting that newer programs are more likely to embrace an MBSE approach. AS5 emphasizes that MBSE must establish value within the broader digital engineering context to be accepted. Finally, AS6 relates that MBSE is being accepted slowly in their organization where it is being used specifically as a digital engineering tool for mission development. These insights highlight the diverse adoption landscape for MBSE, influenced by organizational culture, perceived value, and the integration with existing digital engineering efforts.

Table 5.4: Comments about SE generally in response to free response survey question for additional thoughts.

Identifier	Response (General SE)
GS1	Systems Engineering is the easiest place to use MBSE/DE tools. The long pole continues to be the supporting functions which don't have the relevant mandates to change (i.e., Contracting, Financial Management, Safety, Test&Eval, Cybersecurity...). It's easier to give the bureaucrat the piece of paper he wants than to explain why he doesn't need it. Until the supporting functions are aligned with SE/PM, the benefits of MBSE/DE will be outdone by the burdens.
GS2	I work for [masked], we have a commercial and defense side. I work commercial. Systems engineering is used more on the defense side because the air force mandates it. It's trying to be adopted on the commercial side. The commercial side is at the stage where the initiative has started, it's been attempted/piloted in very small scale areas, but has not successfully been used on a program yet. SE is more in development, but digital and systems engineering groups are set up and supported by management as [masked]'s future vision. ¹
GS3	The hardest part of systems engineering in my role is collaboration with Software Engineers/teams who seem to develop on their own basis agnostic towards developed models and then the models change around them
GS4	MBSE is valuable, but does have limits given the need to evaluate some capabilities in real world situations. Therefore, it can be challenging to know where the lines must be drawn between what is modeled and what must be built.

¹The original GS2 response included the name of the company, but it has been masked here for anonymity.

5.4.2 General Systems Engineering

The comments identified as “general SE” in Table 5.4 are comments that are not unique to MBSE, but apply to SE more generally. These comments can provide some insight into potential challenges to be addressed by the wider SE community.

While this survey is primarily focused on the perceptions of the challenges in MBSE adoption within the SE community, it is important to acknowledge that SE is only a part of a broader product development ecosystem. An effective SE approach should involve external stakeholders from this ecosystem, but these stakeholders are often beyond the direct influence or control of the SE team. As highlighted by GS1, the SE community is prepared to adopt MBSE and other DE practices, but the lack of relevant mandates for change in supporting functions—such as contracting, financial management, safety, test and evaluation, and cybersecurity—is hindering the realization of the full

benefits of a model-based approach, which reduces the perceived relative advantage of and negatively impacts the adoption rate of MBSE [169]. This observation suggests that while MBSE may be compatible with SE, as defined by the DoI theory and demonstrated by the results in Section 5.1, it may not be compatible with all elements of the larger product development ecosystem. Investigating how this ecosystem can be optimized to fully benefit from MBSE adoption could provide valuable insights.

The anecdote from GS2, where an organization is newly introduced to MBSE without prior use of SE, highlights a common scenario [170, 171]. In many organizations, the decision often lies not between a traditional, document-based SE approach and MBSE but between adopting MBSE or having no formal SE at all. Thus, as noted in the previous paragraph, the compatibility question is not just between MBSE and SE, but also between SE and the organization's existing product development or acquisition practices. These scenarios may present a steeper barrier to MBSE adoption due to the absence of an SE foundation, yet they also offer the potential for even greater performance improvements if MBSE is successfully integrated. As an SE community, efforts to promote general SE should advocate for a model-based approach where appropriate, aiming to tailor the selected MBSE approach with existing practices.

GS3 highlights an issue that is exacerbated by a traditional, document-based SE approach but not completely removed in an MBSE approach. This issue arises when a domain engineering team works independently from SE specifications or bases its work on incomplete, incorrect, or outdated SE artifacts. One of MBSE's objectives is to ensure that SE artifacts are not only complete, correct, and consistent but also widely accessible. While MBSE facilitates the enhanced sharing of SE artifacts among various disciplines within an organization, it does not inherently solve the organizational issues regarding how or if those artifacts are utilized. Organizations must proactively address these challenges to harness the potential of MBSE fully.

Finally, GS4 suggests that determining which SE decisions can rely on modeling and simulation versus those requiring physical prototyping presents a challenge in an MBSE approach. This issue exists across all SE approaches, whether model-based or otherwise, and is neither worsened

nor fully mitigated by MBSE alone. SE processes demand sound engineering judgment. When developing an MBSE approach, it is essential to use this judgment to specify which decisions can be supported by a system model and which will necessitate physical prototypes. If physical prototyping is deemed necessary, the MBSE framework can facilitate this by providing detailed specifications for prototypes and test cases, and by integrating the results with the overall system architecture and design. Ultimately, MBSE can offer real value, particularly when physical prototyping is required.

5.4.3 Comments on MBSE

Table 5.5: Comments on MBSE generally in response to free response survey question for additional thoughts.

Identifier	Response (Comments on MBSE)
CM1	Currently MBSE is a niche skill that actually makes it better for small projects than large. A small team can be trained and collaborate effectively where a large team disperse team will be unable to maintain consistent modeling practices and will therefore be ineffective
CM2	MBSE is the Systems Engineering solution that digitally connects engineering artifacts, establishes traceability, and minimizes rework due to having to manually update engineering artifacts after each change of a requirement, design spec, or use case. Once an engineering document is generated, it is already out-of-date, necessitating the use of MBSE to eliminate rework and wasted engineering efforts, being particularly beneficial for large projects due to the enhanced scale of impact that MBSE can have on the project/program.
CM3	Modeling languages and tools are heavy on problem and solution artifacts but light on the thinking (e.g., decision analysis) that transforms the problem into a solution

The comments in Table 5.5 are categorized as “comments on MBSE”, and they shed light on the utility and adaptability of MBSE across varying project scales. They are representative of the complex interplay between the theoretical foundation of MBSE and its practical implementation challenges.

CM1 suggests that MBSE is particularly advantageous in smaller projects due to its reliance on specialized skills that may be easier for a small team to adopt quickly. The agility and close

collaboration of smaller teams facilitate a more uniform application of MBSE practices, helping to avoid the inconsistency that can plague dispersed, larger groups. This observation underscores the potential for MBSE to improve efficiency and communication within a tightly-knit project team, and emphasizes a targeted approach where the strengths of MBSE can be maximized.

In contrast, CM2 highlights the benefits that MBSE offers to large-scale projects, particularly in its ability to integrate and update engineering artifacts dynamically. The scale of large projects often exacerbates the complexity and frequency of updates required, making the capacity of MBSE to reduce rework and streamline processes especially valuable. While the adoption of MBSE may present challenges in larger teams, as noted in CM1, the potential impact and efficiencies gained can justify the initial efforts to standardize MBSE practices across wider, more diverse teams. Together, these perspectives suggest that while the scale of implementation may differ, core benefits of MBSE—enhanced collaboration and consistency—are universally applicable but require tailored strategies for different organizational sizes.

The critique in CM3 that modeling languages and tools focus more on artifact generation than on fostering deep analytical thinking aligns with the discussions in Section 5.4.2 about the inherent limitations of MBSE, which are reflective of broader SE challenges. They highlight that while MBSE provides a structured framework for creating and managing SE artifacts, it does not inherently fulfill the need for seasoned engineering judgment in decision-making processes. This connection emphasizes that an effective MBSE approach should enhance rather than replace the nuanced engineering judgment critical in SE processes and decisions.

5.4.4 MBSE Limitations

The comments in Table 5.6 are related to limitations of MBSE, or better stated *perceived* limitations of MBSE. The perceived limitations are not tied to fundamental MBSE principles, but appear to be more related to ineffective MBSE implementations.

For example, the comment ML1 states that their system model does not contain the level of detail that teams were used to getting in a PDF document. However, by their own admission

Table 5.6: Responses about MBSE Limitations to free response survey question for additional thoughts.

Identifier	Response (MBSE Limitation)
ML1	My thought is about the SysML model. The model cannot replace the paper (pdf, docx,..) documentation because it lacks of documentation. We only focused on design model elements, captured their relationship and behaviors. However, we didn't document about the elements. Therefore; the model turns out a presentation of system on diagrams. It does not explain or describe about the model elements. In the end, engineers find out that the model does not describe the system well like pdf document.
ML2	The biggest problem I see with MBSE is its forced use for activities other than system design, i.e., system performance requirements.

they report that “we only focused on design model elements, captured their relationship and behaviors...we didn't document about the elements” in the model. There is no reason why any documentation that was included in a PDF document could not be included in the model¹¹. No MBSE approach should be adopted without tailoring to meet the specific needs of the organization. Adopting MBSE requires a comprehensive review of existing documentation practices and a commitment to enriching the system model so it fully encapsulates all necessary information, ensuring that the transition to MBSE adds value across all engineering processes.

ML2 unveils another common misconception regarding MBSE. The comment suggests that their organization “forces” the use of MBSE for purposes it deems inappropriate, such as the analysis of system performance requirements. Contrary to this viewpoint, many studies demonstrate that MBSE is indeed well-suited for system performance requirements analysis [172–174], indicating that the issue may stem from an ineffective application of MBSE in this context. However, this observation does underscore a crucial point: MBSE is not a one-size-fits-all solution. If MBSE does not generate value in a particular process within an organization, there are two courses of action available: either tailor the MBSE application to ensure it delivers value, or consider an alternative, non-MBSE approach. In most instances, proper tailoring of MBSE to specific organizational pro-

¹¹If the modeling tool, language, or methodology does not provide support for the required documentation, it should be tailored or replaced with one that does meet this need.

cesses will result in an effective and value-adding strategy. However, the SE community should be cautious to avoid portraying MBSE as a universal remedy for all engineering challenges.

5.5 Survey Limitations

During the course of the data collection and analysis of this survey, several limitations were identified which bear acknowledgement to contextualize the survey results. Any follow on research should address these limitations.

The survey responses were predominantly from the aerospace and defense sector, with a significant representation from participants associated with the Air Force. While no effect was detected during the analysis of the survey data, this sector-specific concentration may bias (or result in a perception of bias) the survey results and limit their applicability to other industries. The unique characteristics of the aerospace and defense sector might influence the adoption and perception of MBSE differently compared to other sectors. Therefore, the results may not be fully representative of the broader SE community's views on MBSE adoption.

The survey did not attempt to categorize participants into the different adopter categories identified by the DoI theory (innovators, early adopters, early majority, late majority, and laggards, see Figure 3.1) [1]. Different categories of adopters typically have different adoption approaches, which could influence their responses. The absence of this characterization means that the analysis did not account for the potential diversity in views and attitudes towards MBSE, which could have provided a richer understanding of adoption patterns.

Because the model use questions were derived directly from the [INCOSE MBCM](#), some questions encompassed multiple concepts. The conflation of ideas within single questions likely led to ambiguous responses, thereby affecting the reliability of the data collected by the model use questions. This limitation obscured insights into specific factors associated with model use and their relation to the perception of MBSE attributes, preventing the planned regression analysis with model use data as the dependent variable.

Finally, no thematic analysis was planned or conducted for the single open-ended question included in the survey. Open-ended questions can yield valuable qualitative data, providing deeper insights into the respondents' perceptions and experiences. The lack of a structured approach to analyze this qualitative data means that potentially important themes and patterns were not systematically explored, limiting the depth of the analysis of this question.

While the survey provides valuable insights into the perceived attributes of MBSE and its adoption, these limitations highlight the need for additional research to capture additional insight into MBSE adoption within the SE community.

Chapter 6

Discussion and Targeted Actions to Improve MBSE

Adoption

This chapter will connect a discussion of the survey results with targeted actions, informed by the DoI theory, to improve the adoption rate of MBSE.

6.1 Discussion of Survey Results

The survey outcomes shed light on important factors affecting the perception and subsequent adoption of MBSE among potential adopters. One notable aspect involves the perceived amount of mental effort associated with an MBSE approach, which potentially diminishes its perceived relative advantage. This outcome presents a considerable challenge, acting to slow the adoption of MBSE practices. Furthermore, respondents identified the need for better compatibility between MBSE and existing SE approaches within their organizations. Tailoring MBSE methodologies to align more closely with established SE practices or enhancing existing SE approaches to encompass MBSE principles are potential strategies to overcome this compatibility gap.

Another notable revelation from the survey is the correlation between access to modeling tools and the adoption rate of MBSE. Limited access to modeling tools (especially for those who are not already involved with MBSE efforts in their organization) and opportunities to experiment with MBSE remain barriers to its widespread adoption. This limitation not only limits trial opportunities but also contributes to the perception that MBSE necessitates substantial mental effort, potentially dissuading potential adopters. Lowering the barrier to entry for MBSE experimentation could be a catalyst for encouraging wider involvement and adoption among potential adopters.

The survey findings underscore the necessity for the SE community to delve deeper into the practical application of MBSE, especially in the context of smaller-scale pilot projects. Addressing this gap in understanding would not only facilitate smoother integration but also bolster confidence

in employing MBSE methodologies. Additionally, by enhancing trial opportunities—by providing wider access to tools, allowing more time for experimentation, and offering comprehensive MBSE education—the transition of a larger proportion of the potential adopter population into the “involved with MBSE” category seems plausible, potentially accelerating the adoption rate of MBSE within organizations.

The critical role of perception in advancing MBSE is further illustrated by the INCOSE Systems Engineering Competency Framework, where the indicators for various competencies often hinge on perceptions [175]. Terms like “best practice”, “suitability”, and “coaching” in the context of system architecting and systems modeling and analysis reflect subjective assessments rather than strictly measurable criteria. Recognizing that these *perceptions* drive key areas of SE underscores the need to consider both organizational/application-specific needs and broader community insights. This awareness helps address compatibility challenges and shapes the development of MBSE strategies that resonate with current and future systems engineers.

6.2 Targeted Actions to Improve MBSE Adoption

The targeted actions outlined in this section represent a foundation for accelerating the adoption rate of MBSE through the application of the DoI theory. These specific actions are intended to start a meaningful conversation within the SE community to generate strategic direction that will foster innovation and change, emphasizing that no single entity can drive this change alone [176]. The collective effort of the SE community (the “we” in these statements) is crucial, and these steps are proposed to encourage collaboration and shared commitment to improving MBSE practices.

The only question indicating that the perceived relative advantage of MBSE may be hindering its adoption was Q5: “An MBSE approach increases the overall amount of systems engineering work in my organization,” which had a NAS of 26% (this was a negatively coded statement, so a negative score is preferable). The positive aspect is the significant number of neutral responses (33%), suggesting that efforts to change this perception can effectively target those who are undecided. To alter the perception that MBSE increases the overall amount of SE work, we should

enhance the availability and use of reference models, reference architectures, and model libraries to expedite system model development [177]. Additionally, we need to emphasize and appreciate the importance of selecting and tailoring the MBSE approach to fit the unique needs of an adopting organization that will ensure that the right amount of SE work is done [45, 178, 179].

The response to the compatibility question Q6: “MBSE is compatible with all aspects of my organization’s systems engineering approach,” had a net agreement score of only 20%, indicating a potential barrier to MBSE adoption. Unfortunately, it is unclear whether this perception is due to shortcomings in MBSE or deficiencies in the existing SE approach. Tailoring MBSE to fit specific organizational needs is important, but so is a strong foundation in SE practices. Therefore, we must enhance our overall commitment to and practice of SE and collaboratively develop MBSE approaches (to include ASE approaches) that support effective SE [117]. With 24% of respondents remaining neutral on this question, there is significant potential to influence those undecided and improve the perceived compatibility of MBSE.

With a NAS of 58%, Q10, “MBSE requires significant mental effort,” reflects poorly on the perceived complexity of MBSE [180]. To address this, we need to refine our entire MBSE approach—encompassing language, tools, and methodology—to reduce its perceived complexity. While SE will always necessitate critical thinking and a reasonable amount of mental effort, if MBSE continues to be viewed as requiring *significant* mental effort, it will hinder its adoption.

Given that the “opportunity” to experiment with MBSE (Q14) is lagging behind “access to a tool” (Q15) (44% to 55%, respectively), we need to identify additional requirements for providing opportunities to experiment with MBSE beyond mere tool access, such as training and allocated time [181]. The barrier to entry for MBSE remains too high for effective experimentation [182]. Adopting ASE methodologies can enhance the perceived trialability of MBSE, as these methodologies emphasize incremental improvement through iterative cycles [183]. Lastly, we must develop strategies to formulate pilot projects that deliver both value and practical experience with MBSE [124, 184].

6.2.1 SysML v2 Specific Opportunities

While significant work has been dedicated to improving the practice of MBSE, the release of SysML v2 provides a valuable opportunity to reframe the perceptions of many attributes of MBSE in a way that can lead to more robust adoption of MBSE moving forward. This opportunity is afforded due to the excitement and anticipation associated with the release of this new language. Potential adopters who may have tried and failed in the past to adopt MBSE may be willing to try again with the hope that the new language represents that the practice of MBSE has made significant advances and is worth another try. The reputation of MBSE has been harmed when it has been promoted in contexts and ways that might not yield optimal results and with inadequate support to optimize the chances of successful adoption. Introducing SysML v2 with an understanding of the DoI theory is perhaps the most powerful targeted action available to improve MBSE adoption.

The modeling language used in an MBSE approach has an impact on all five of the perceived attributes of MBSE. The purpose of this section is to present a path forward for the introduction of SysML v2 based on lessons learned from the DoI theory to aid in its adoption in the furtherance of improving MBSE use generally. While SysML v2 will continue to be revised (as was SysML v1), the opportunity presented by special attention garnered by the initial release of SysML v2 should be seized to improve the use of MBSE more generally.

While not the only systems modeling language, SysML has become the most widely used modeling language in support of MBSE. SysML is a profile of UML 2 that extends UML 2 with model constructs more appropriate for systems engineering than the software engineering for which UML was developed [76]. The first version of SysML was released in 2007 [185]. Since then, there have been periodic updates, up until the most recent version 1.6, released in 2019¹².

Unlike SysML v1, SysML v2 is not an extension of UML, but utilizes the [Kernel Modeling Language \(KerML\)](#) as its metamodel [187]. SysML v2 is a major revision that is not backward-compatible with SysML v1, as it was designed from scratch to improve expressiveness, precision,

¹²SysML v1.7 beta 1 was released in 2022, though this specification was never adopted as a formal version and has been superseded by SysML version 2.0 beta 2 [186]

interoperability, and consistency [88]. The evolution from SysML v1 to v2 was driven by over a decade of industry feedback, highlighting the strengths and weaknesses of SysML v1 and leading to comprehensive enhancements in SysML v2 [188]. SysML v2 specifies a textual notation in addition to a graphical notation that will facilitate more flexible and comprehensive modeling capabilities [189]. The specification of SysML v2 is accompanied by a specification for an [Application Programming Interface \(API\)](#) and services that are to be incorporated with language-compliant tools. This API and services will improve the extensibility of modeling tools and integration of model data with other tools used in the life cycle of a system. This will in turn enhance the opportunities and ease of collaboration for users of the model [190].

The clarity and precision with which it can capture ideas affect the perceived relative advantage of MBSE. An aspect of the perceived relative advantage of MBSE that can be addressed by SysML v2 is the perception that an MBSE approach increases the amount of SE work in an organization (see Figure 5.4). While new methodologies are not required with the advent of SysML v2, attributes of SysML v2 should be used to tailor further and streamline MBSE methodologies to maximize the amount of automation enabled by the API as supported by the language and tool. Perceived relative advantage can also be improved by taking advantage of language features that provide native support for variability modeling [191].

Q6 of the survey, “MBSE is compatible with all aspects of my organization’s systems engineering approach” only earned a NAS of 20%. SysML v2 can improve the compatibility between MBSE and existing SE approaches as it was developed specifically for the SE community (as opposed to an extension of the software-centric UML). SysML v2 was deliberately designed to address the limitations and incompatibilities associated with SysML v1 with the way systems engineers think, work, and approach problems. The origins and purposes of the language should be emphasized to improve the perceived compatibility of MBSE.

Questions about the perceived complexity of MBSE revealed that complexity is likely a major driver hindering the adoption rate of MBSE. While for some, the introduction of a textual notation in addition to a graphical notation is a welcome addition, for others it could increase the perceived

complexity of MBSE when utilizing SysML v2. This perception may also be further exacerbated by the inclusion of an API and services specification and the misconception that these new features (textual notation and API) *must* be used when using SysML v2. Care should be taken when promoting SysML v2 to highlight the fact that these new features are part of the language for those who find value in them, but that they are not required to use the graphical notation of SysML v2 in similar ways to how v1 was used.

There are many ways that SysML v2 can improve (reduce) the perceived complexity of an MBSE approach. In SysML v1, there was a disconnect between elements of usage and the elements of definition used to type those elements of usage. For example, one would need to remember that part properties are elements of usage that are typed by the block element of definition. In SysML v2 elements of usage and elements of definition are more closely aligned. A part (element of usage) is now typed by a part definition (element of definition) and this pattern is consistent amongst all model elements.

The survey showed that MBSE is not broadly viewed as suitable for pilot projects or limited adoption. This is a real detriment to the adoption of MBSE as potential adopters are unwilling to make the investment required to adopt MBSE without a means to decrease the uncertainty accompanying a new SE approach. In promoting SysML v2, change agents should emphasize the opportunities to experiment with the language. These opportunities include improved access to tools for exploring SysML v2 and the enhanced compatibility of SysML v2 with SE. If SysML v2 can improve the perceived trialability of MBSE, this can lead to improved adoption and wider realization of its associated benefits.

While the survey did not identify observability as an impediment to MBSE adoption, an improvement in the perceived observability of MBSE can still improve its adoption rate. SysML v2 can serve as a foundation for [DE](#) by providing a persistent framework that integrates discipline-specific models of a system [192]. The textual notation of SysML v2 facilitates closer integration with [Large Language Models \(LLMs\)](#) to generate models from natural language. This capability should be emphasized and demonstrated to improve the observability of MBSE in use.

6.3 Conclusion

The targeted actions proposed in this section are designed to accelerate the adoption of MBSE by leveraging the principles of the DoI theory. These actions are intended to initiate a collaborative dialogue within the SE community, emphasizing that the collective effort of all stakeholders is essential for fostering innovation and driving effective change in MBSE practices. SysML v2 presents a significant opportunity to enhance MBSE adoption by addressing previous shortcomings and improving key aspects such as expressiveness, precision, and interoperability. The release and introduction of SysML v2 to the SE community, supported by the principles from the DoI theory, seeks to overcome barriers to MBSE adoption by emphasizing tailored methodologies and streamlined processes. With enhanced features like a unified API and services, SysML v2 can reduce the perceived complexity and increase the compatibility of MBSE with existing SE practices, fostering broader acceptance and adoption within the SE community.

Chapter 7

Conclusions and Future Work

7.1 Summary

Through the course of this research and dissertation, all three research objectives were achieved.

Research objective 1: *Perform a thorough literature review of extant publications relating to MBSE benefits, adoption trends, and adoption challenges to support the case that efforts to improve the adoption rate of MBSE are warranted and should be encouraged.* Chapter 2 contains a thorough literature review that shows that MBSE is well suited to address the challenges facing the SE community in the practice of SE of modern, complex systems, and MBSE adoption should be encouraged. This was confirmed during the course of the survey where the questions “An MBSE approach can improve the quality of systems engineering data in my organization” and “MBSE addresses a relevant need of my organization” achieved NAS scores of 89% and 87%, respectively.

Research objective 2: *Conduct a survey of the SE community to assess the applicability of the DoI theory to MBSE adoption by assessing the perception of attributes of MBSE and conducting statistical analyses to determine underlying factors that are predictive of an individual’s use of MBSE.* Chapter 4 outlines the survey, and Chapter 5 contains the results of the survey of the SE community to assess the perception of attributes of MBSE by the SE community. Chapter 5 also contains the results of statistical analyses applied to the survey data to determine relationships between responses to questions. The results of the survey show that based on the perceptions of MBSE by the SE community, the DoI theory predicts barriers to adoption of MBSE. The analysis identifies specific areas where perceptions can be shaped in ways that the DoI theory suggests would improve MBSE adoption.

Research objective 3: *Develop recommendations for targeted actions, based on the DoI theory and survey results, that can be introduced to the practice and presentation of MBSE to accelerate*

its adoption. Chapter 6 contains targeted actions to shape the perceptions of MBSE to accelerate MBSE adoption. These targeted actions include:

- Enhance the availability and use of reference models, reference architectures, and model libraries to expedite system model development.
- Improve the process to tailor an MBSE approach to better suit organizational needs.
- Increase the emphasis on ASE to support SE rigor in the presence of rapid change and software-centric systems.
- Refine MBSE approaches to reduce the perceived mental effort required.
- Lower the barrier to entry for MBSE by improving access to modeling tools, time, and education to provide opportunities to experiment with MBSE.
- Increase efforts to identify and execute MBSE pilot projects that provide real value to organizations and MBSE experience to SEs.
- Use lessons and principles from the DoI theory to take advantage of the opportunity afforded by the release of SysML v2 to reframe perceptions of MBSE.

These research objectives were developed to address the research question: *how can the DoI theory be applied to understand and improve the adoption rate of MBSE?* This research has shown that the DoI theory can be effectively applied to understand and improve the adoption rate of MBSE by assessing the perception of attributes defined within the theory: relative advantage, compatibility, complexity, trialability, and observability. Survey results indicate that addressing the perceived complexity and the significant mental effort required for MBSE is likely to improve MBSE adoption. Enhancing compatibility with existing SE practices and providing better opportunities for trialability, such as pilot projects and accessible tools, can also reduce adoption barriers. The relative advantage of MBSE can be improved as the development of reference models, reference architectures, and model libraries amplifies its benefits.

7.2 Contributions

The primary contribution of this dissertation is an analysis of the factors influencing the adoption of MBSE through the lens of the DoI theory. The research identifies key barriers to MBSE adoption, such as perceived complexity and compatibility issues, and offers targeted actions to mitigate these challenges. By integrating survey data with DoI theory, this work presents actionable insights for improving MBSE methodologies, developing reusable model artifacts, and promoting trialability by increasing opportunities to experiment with MBSE and executing relevant pilot projects. The development and proposal of tailored strategies for MBSE adoption underscore the importance of community-wide collaboration and commitment to evolving SE practices. Additionally, the work highlights the critical role of SysML v2 in addressing previous shortcomings and advancing MBSE capabilities. This dissertation provides a framework for understanding and accelerating the adoption of MBSE within the SE community.

7.3 Future Work

There are some areas of research and future work that, while outside the scope of this current effort, would provide additional value to the SE community.

As noted in Section 2.3, [Agile Systems Engineering \(ASE\)](#), especially when supported by an MBSE approach, is an important bridge that allows organizations that would like to adopt agile principles to maintain SE rigor. However, over the last seven years, there have been approximately 20% as many publications on ASE as there have been on MBSE. While recognizing the overlap between ASE and MBSE research, there are almost certainly areas and topics within ASE that would benefit from additional research to develop SE processes that are more responsive to a rapidly changing world.

While some of the organization information questions in the survey relate to the other variables identified by the diffusion of innovations theory that affect the adoption rate (type of the innovation decision and nature of the social system), the survey was focused primarily on how the perceived attributes of MBSE affect its adoption rate. There is a likely benefit in investigating the

other variables further, especially the ones that were not addressed at all in this survey (type of communication channels used and extent of a change agents' promotion efforts).

Any future surveys should identify a means to better assess the actual MBSE use of participants to investigate correlations between individual perceptions of MBSE attributes (or other variables identified by the DoI theory) and their actual MBSE use. Including control questions about SE in general would help determine if certain perceptions are applicable to SE broadly and not exclusively to MBSE. Additionally, efforts should be made to increase the breadth of survey participants to obtain a more comprehensive cross-section of the SE community.

Finally, this dissertation proposed targeted actions to improve MBSE adoption, but details on how to execute those actions are beyond the scope of this dissertation. For example, though developing better processes for tailoring MBSE methodologies to organizational needs would likely have a positive effect on the adoption rate of MBSE, it is not a trivial task and presents an opportunity for future work. In fact, each of the targeted actions elaborated in Chapter 6 and summarized in Section 7.1 present opportunities for future work.

7.4 Conclusion

The insights gained during the course of this research underscore the critical role of perceptions in the adoption of MBSE. The application of the DoI theory has revealed specific areas where targeted efforts can accelerate the adoption rate of MBSE within the SE community. By assessing the perception of the SE community of key factors such as relative advantage, compatibility, complexity, trialability, and observability, this research provides a framework for addressing the barriers to MBSE adoption. The collective effort of the SE community, informed by these findings, is essential to continuous improvement in MBSE practices.

The potential of SysML v2 to reframe the perception of MBSE cannot be overstated. Its enhancements in expressiveness, precision, and interoperability, coupled with its unified API and services, offer a notable opportunity to streamline and improve MBSE methodologies. However, realizing this potential requires a concerted effort to apply lessons from the DoI theory as it is

introduced to the SE community. Tailoring MBSE approaches to align more closely with established SE practices and enhancing the overall commitment to robust SE principles are important steps in the promotion and success of MBSE. Ultimately, the goal is to arrive at a point where SE and MBSE are seen as synonymous, resulting in the documented benefits (and benefits yet to be recognized) of MBSE being *fully* realized throughout the broader SE discipline.

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Appendix A

Full Survey PDF

The survey as it was submitted to the [IRB](#) is displayed over the next 12 pages. The survey began with the IRB informed consent notice, followed by six warming up questions. The next four pages contain 18 questions about the perceived attributes of MBSE, followed by two pages with 11 model use questions as described in Chapter 4. The last three pages contain organizational demographic information, followed by an end-of-survey message.

Model-Based Systems Engineering (MBSE) Attribute Assessment

Informed Consent

Dear Participant,

My name is Daniel Call, and I am a researcher from Colorado State University (CSU) in the Systems Engineering department. We are conducting a research study on perceptions of attributes of model-based systems engineering (MBSE). The title of our project is MBSE Attribute Perception Assessment. The Principal Investigator is Daniel Herber, also from the CSU Systems Engineering department, and I am the Co-Principal Investigator.

We would like you to take an anonymous online survey. Participation will take approximately 15 minutes. Your participation in this research is voluntary. If you decide to participate in the study, you may withdraw your consent and stop participation at any time without penalty. There are no known risks associated with this study.

We will not collect your name or personal identifiers. Anonymous data collected as a part of this survey may be used in future research studies or distributed to another investigator without additional consent. When we report and share the data to others, we will combine the data from all participants. While there are no direct benefits to you, we hope to gain more knowledge on the factors that affect the adoption rate of MBSE.

To indicate your consent to participate in this research and to continue to the survey, please click "Next Page" button below.

If you have any questions about the research, please contact Daniel Call at daniel.call@colostate.edu. If you have any questions about your rights as a volunteer in this research, contact the CSU IRB at: CSU_IRB@colostate.edu; 970-491-1553.

Thank you for your participation in this research-- your help is greatly appreciated!

Daniel Call

Co-Principal Investigator

Daniel Herber

Principal Investigator

Warming Up Questions

In the 2018 Department of Defense Digital Engineering Strategy, digital engineering is defined as:

"an integrated digital approach that uses authoritative sources of system data and models as a continuum across disciplines to support lifecycle activities from concept through disposal"

wu1- defamiliarity¹- Are you familiar with digital engineering as defined above?

- No
- Somewhat
- Yes

wu2- deuse- Does your organization practice digital engineering?

- No
- Somewhat
- Yes

wu3- deinvolvement- Are you involved in digital engineering efforts within your organization?

- No
- Somewhat
- Yes

{Page Break}

¹ These question identifiers and tags will not be displayed to the survey participant but are included here for reference as they are the tags used in the survey design and analysis

The INCOSE systems engineering handbook defines model-based systems engineering (MBSE) as:

“the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases”

wu4- mbsefamiliarity- Are you familiar with MBSE as defined above?

- No
- Somewhat
- Yes

wu5- mbseuse- Does your organization utilize a model-based systems engineering approach?

- No
- Somewhat
- Yes

wu6- mbseinvolvement- Are you involved with MBSE as part of your normal responsibilities?

- No
- Somewhat
- Yes

Perceived Attributes of MBSE²

This section of the survey contains statements about the use and potential benefits of MBSE. Please indicate the level to which you agree or disagree with each statement.

Q1- relativeadvantage1- An MBSE approach can improve the quality of systems engineering data in my organization.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q2- relativeadvantage2- An MBSE approach provides traceability amongst systems engineering artifacts.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q3- relativeadvantage3- An MBSE approach enforces consistency amongst systems engineering artifacts.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q4- relativeadvantage4- Using MBSE can reduce errors in my organization's systems engineering data.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q5- relativeadvantage5- An MBSE approach increases the overall amount of systems engineering work in my organization.

Strongly Disagree Disagree Neutral Agree Strongly Agree

² The order of the questions in the "Perceived Attributes of MBSE" and "Level of MBSE" sections will be randomized when presented to survey participants.

Q6- compatibility1- MBSE is compatible with all aspects of my organization's systems engineering approach.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q7- compatibility2- An MBSE approach fits my work style.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q8- compatibility3- MBSE addresses a relevant need of my organization.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q9- complexity1- MBSE is cumbersome.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q10- complexity2- MBSE requires significant mental effort.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q11- complexity3- It is easy to remember how to perform tasks using an MBSE approach.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q12- complexity4- I am familiar with a system modeling language.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q13- complexity5- I have experience with a system modeling tool.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q14- trialability1- I have opportunities to experiment with MBSE.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q15- trialability2- I have access to a tool to experiment with MBSE.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q16- trialability3- An MBSE approach is suited to small scale, pilot projects.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q17- observability1- The benefits of an MBSE approach are apparent to me.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q18- observability2- I have observed an MBSE approach being used by others.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Level of MBSE Adoption

This section of the survey contains statements about how MBSE is used in your organization. Please indicate the level to which you agree or disagree with each statement.

Q19- workforce/culture1- My organization has an MBSE use strategy that is documented as part of the organization's overall strategy at the system level. Modeling results are used to inform systems engineers across system engineering phases and for all disciplines.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q20- workforce/culture2- Modeling or model users within my organization have experience on specific tools with respect to their role as a user or modeler.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q21- systemsengineeringprocesses/methodology1- Modeling is the basis for the technical processes of my organization with digital threads covering some of the processes. Digital artifacts are used to make systems engineering decisions.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q22- systemsengineeringprocesses/methodology2- Verification and validation (V&V) plans in my organization rely on model contents and analysis via requirements analysis.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q23- project/programprocess/methodology1- The systems engineering plan of my organization calls for full system/enterprise models to be developed and applied across the product life cycle and across systems engineering organizations.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q24- project/programprocess/methodology2- Metrics, beyond those available from the tool configuration, are reported to address model development, quality, and effectiveness needs within my organization.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q25- model-basedeffectiveness1- My organization uses digital artifacts to make program/project level decisions.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q26- model-basedeffectiveness2- Systems models for projects/programs in my organization are integrated and use the same structured approach. A library of reusable SysML blocks has been created and used.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q27- modelingtoolconstruction1- Modeling methods are planned for efforts within a portfolio and are consistent as possible for each project/program in my organization. Best practices are evolving; structuring patterns are emerging.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q28- modelingtoolconstruction2- Inter-database/tool data item associations are defined, captured, managed in my organization.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Q29- modeluse1- An MBSE approach is being adopted across programs/projects within my organization with the intent to apply enterprise and system models.

Strongly Disagree Disagree Neutral Agree Strongly Agree

Organization Information

oi1- industry/sector- To what industry/sector does your organization belong?

- Aerospace/Defense
- Transportation and Mobility
- Industrial Equipment
- Energy, Processes and Utilities
- Architecture and Construction
- Life Science
- High-Tech
- Marine and Offshore
- Financial and Business Services
- Consumer and Retail
- Natural Resources
- Consumer Packaged Goods and Retail
- Academia/Education

{If the participant selects "Aerospace/Defense, question oi1a is presented}

oi1a- branch/service- With which branch/service is your organization most closely associated?

- Air Force
- Army
- Marine Corps
- Navy
- Foreign Military/Other

oi2- life cycle stage- In which life cycle stage(s) is your organization involved?
(select all that apply)

- Concept
- Development
- Production
- Operations/Support
- Retirement

oi3- organization size- Approximately how many people are part of your organization?

- < 20
- 21-100
- 100-500
- 500-2000
- 2000+

oi4- systems engineering plan- Does your organization have a formal, written systems engineering plan (model-based or otherwise)?

- No
- Yes

oi5- DE mandates- Is your organization subject to any mandates to adopt and/or use digital engineering?

- No
- Yes

oi6- innovation and experimentation- Does your organization encourage innovation and experimentation?

- No
- Somewhat
- Yes

oi7- se experience- How long have you worked in a systems engineering role?

- Less than 3 years
- 3-10 years
- 10+ years
- I do not work in a systems engineering role

End of Survey

We thank you for your time spent taking this survey.

Your response has been recorded.

Appendix B

Survey Participant Demographic Figures

This section contains figures showing the responses to the demographic questions of the survey.

To what industry/sector does your organization belong?

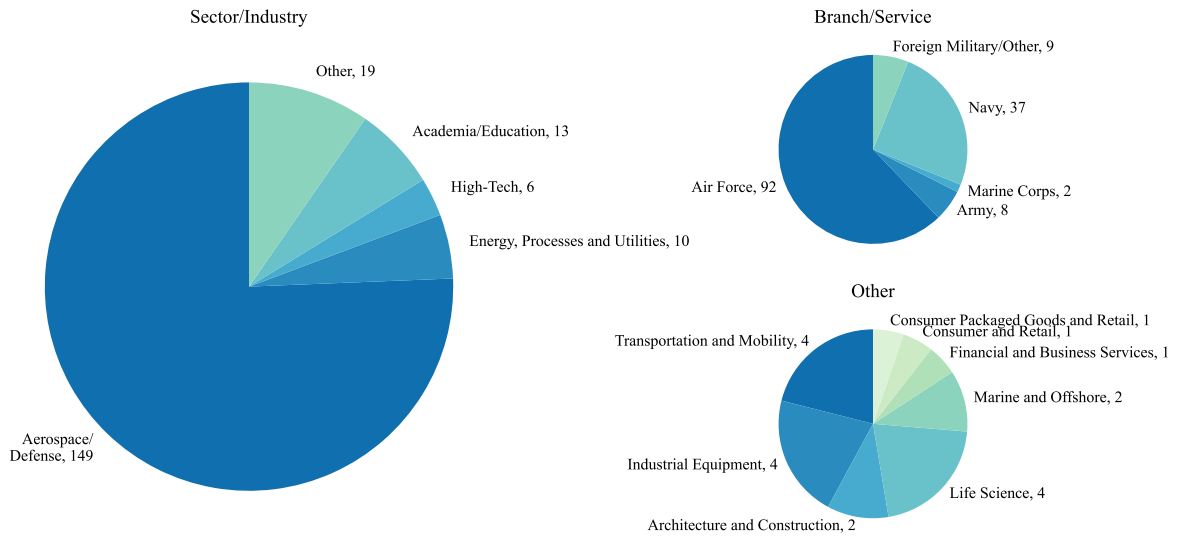


Figure B.1: Response to the question “To what industry/sector does your organization belong?” by all survey participants.

In which life cycle stage(s) is your organization involved? (select all that apply)

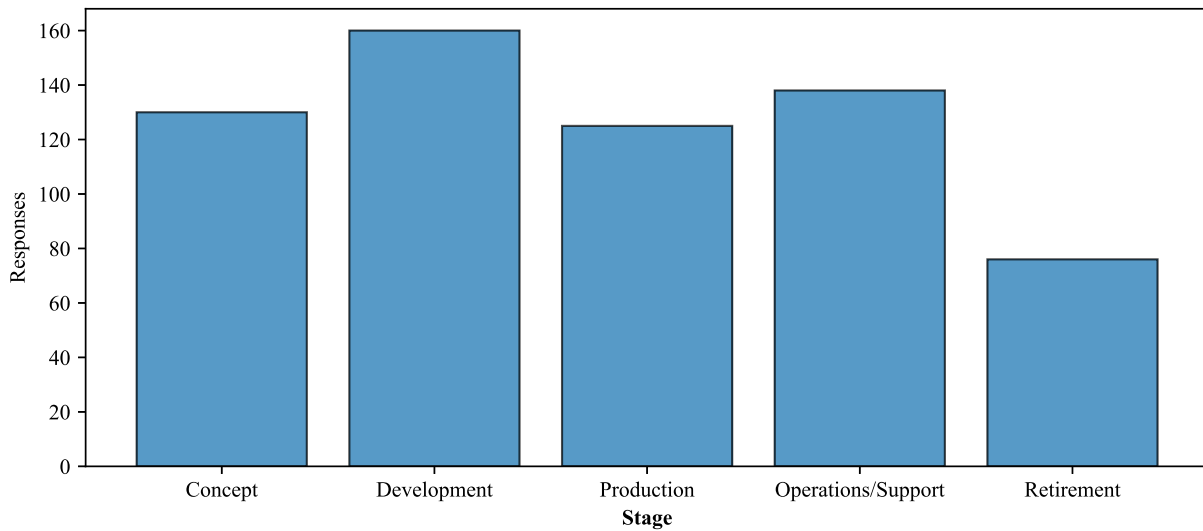


Figure B.2: Response to the question “In which life cycle stage(s) is your organization involved? (select all that apply)” by all survey participants.

Approximately how many people are part of your organization?

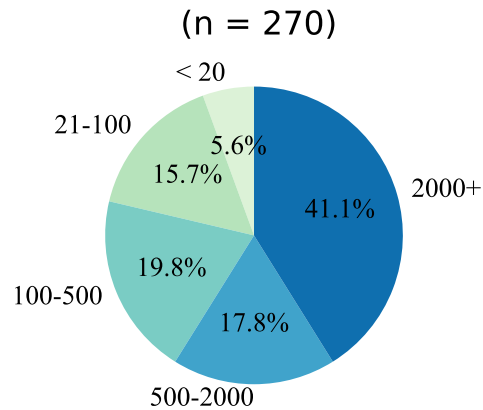


Figure B.3: Response to the question “Approximately how many people are part of your organization?” by all survey participants.

Does your organization have a formal, written systems engineering plan (model-based or otherwise)?

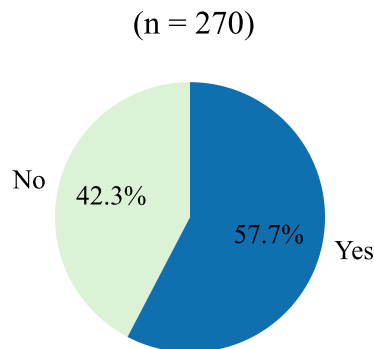


Figure B.4: Response to the question “Does your organization have a formal, written systems engineering plan (model-based or otherwise)?” by all survey participants.

Is your organization subject to any mandates to adopt and/or use digital engineering?

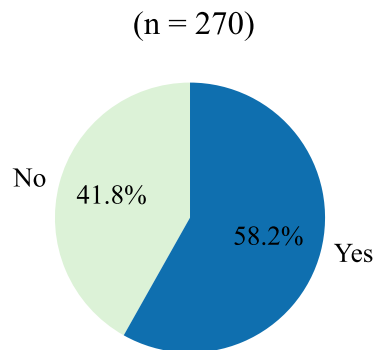


Figure B.5: Response to the question “Is your organization subject to any mandates to adopt and/or use digital engineering?” by all survey participants.

Does your organization encourage innovation and experimentation?

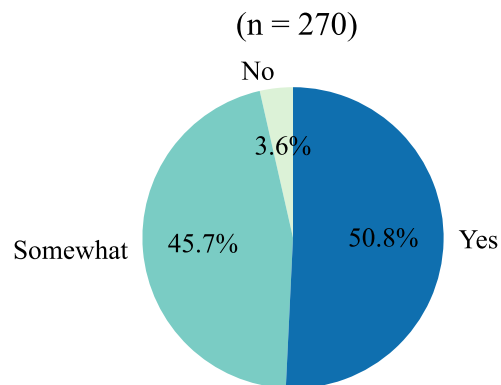


Figure B.6: Response to the question “Does your organization encourage innovation and experimentation?” by all survey participants.

How long have you worked in a systems engineering role?

(n = 270)

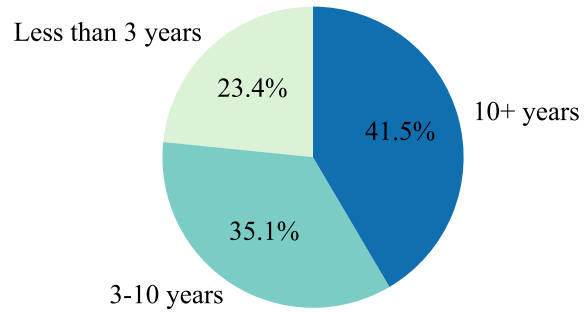


Figure B.7: Response to the question “How long have you worked in a systems engineering role?” by all survey participants.

Appendix C

Subpopulation Analysis Results and Figures

This section contains the tables and figures associated with the subpopulation analyses conducted as part of this research. The results of these analyses are summarized in Table C.1. This table shows the statistically significant ($p < 0.05$) results of either a chi-squared or Fisher Exact test of independence (see Section 5.3). In the table, the “Test” field indicates which test was used (χ^2 or FE). The p value represents the probability that the null hypothesis (that the responses to a particular question are independent of the population from which they were received) is true. The χ^2 statistic for chi-squared tests or Odds Ratio (OR) for Fisher Exact tests represents the strength of the dependence on the population. Δ represents the difference in NAS to the question between the two populations.

The remaining sections of this appendix contain the results of the analysis of each subpopulation.

Table C.1: Summary of subpopulation tests with test used for each question, p value, effect strength statistic, and delta NAS.

	Involvement with MBSE	Organization SE Plan	Subject to DE Mandates	Model Use	Organization MBSE Use
Q3		Test = FE, $p = 0.010$, OR = inf, $\Delta = 19.3\%$			
Q5		Test = FE, $p = 0.048$, OR = 2.4, $\Delta = 25.3\%$			
Q6	Test = χ^2 , $p = 0.000$, $\chi^2 = 23.4$, $\Delta = 41.0\%$			Test = χ^2 , $p = 0.001$, $\chi^2 = 18.3$, $\Delta = 50.6\%$	
Q7	Test = FE, $p = 0.003$, OR = 9.0, $\Delta = 37.8\%$				
Q8	Test = FE, $p = 0.021$, OR = inf, $\Delta = 15.9\%$				
Q9		Test = FE, $p = 0.020$, OR = 2.7, $\Delta = 29.4\%$			
Q11	Test = χ^2 , $p = 0.001$, $\chi^2 = 17.7$, $\Delta = 26.7\%$			Test = FE, $p = 0.010$, OR = 3.4, $\Delta = 42.9\%$	
Q12	Test = χ^2 , $p = 0.000$, $\chi^2 = 49.9$, $\Delta = 71.5\%$		Test = χ^2 , $p = 0.012$, $\chi^2 = 12.8$, $\Delta = 22.5\%$		Test = FE, $p = 0.001$, OR = 21.3, $\Delta = 75.5\%$
Q13	Test = χ^2 , $p = 0.000$, $\chi^2 = 56.3$, $\Delta = 74.5\%$		Test = χ^2 , $p = 0.019$, $\chi^2 = 11.8$, $\Delta = 18.5\%$		Test = FE, $p = 0.019$, OR = 10.7, $\Delta = 45.9\%$
Q14	Test = χ^2 , $p = 0.000$, $\chi^2 = 72.1$, $\Delta = 92.6\%$			Test = χ^2 , $p = 0.000$, $\chi^2 = 22.8$, $\Delta = 59.5\%$	Test = FE, $p = 0.000$, OR = 32.4, $\Delta = 91.3\%$
Q15	Test = χ^2 , $p = 0.000$, $\chi^2 = 62.2$, $\Delta = 75.8\%$		Test = χ^2 , $p = 0.031$, $\chi^2 = 10.6$, $\Delta = 29.1\%$	Test = χ^2 , $p = 0.009$, $\chi^2 = 13.5$, $\Delta = 32.9\%$	Test = FE, $p = 0.000$, OR = 22.3, $\Delta = 79.2\%$
Q16	Test = χ^2 , $p = 0.011$, $\chi^2 = 13.0$, $\Delta = 20.4\%$				Test = χ^2 , $p = 0.045$, $\chi^2 = 9.8$, $\Delta = 7.8\%$
Q17	Test = FE, $p = 0.028$, OR = 6.2, $\Delta = 22.3\%$				
Q18	Test = χ^2 , $p = 0.000$, $\chi^2 = 35.3$, $\Delta = 50.0\%$			Test = χ^2 , $p = 0.000$, $\chi^2 = 22.2$, $\Delta = 44.9\%$	Test = FE, $p = 0.000$, OR = inf, $\Delta = 82.4\%$

C.1 Involvement with MBSE Subpopulation

This section contains the tables and figures associated with the analysis of the subpopulations delineated by “Involvement with MBSE”.

Table C.2: Comparison of the subpopulations “Involved with organizational MBSE efforts” (n = 129) and “NOT involved with organizational MBSE efforts” (n = 94), sorted by the delta between the net agreement score (NAS) of the populations, largest to smallest.

Question Tag	“Involved with organizational MBSE efforts” NAS	“NOT involved with organizational MBSE efforts” NAS	Delta NAS	Test	p-Value
Q14	81.2%	-11.4%	92.6%	χ^2	0.000
Q15	84.6%	8.9%	75.8%	χ^2	0.000
Q13	87.2%	12.7%	74.5%	χ^2	0.000
Q12	82.9%	11.4%	71.5%	χ^2	0.000
Q18	80.3%	30.4%	50.0%	χ^2	0.000
Q6	35.9%	- 5.1%	41.0%	χ^2	0.000
Q7	84.6%	46.8%	37.8%	FE	0.003
Q11	39.3%	12.7%	26.7%	χ^2	0.001
Q17	93.2%	70.9%	22.3%	FE	0.028
Q16	41.9%	21.5%	20.4%	χ^2	0.011
Q8	93.2%	77.2%	15.9%	FE	0.021
Q10	65.8%	45.6%	20.2%	FE	0.308
Q4	91.5%	78.5%	13.0%	FE	0.537
Q2	96.6%	84.8%	11.8%	FE	0.059
Q3	83.8%	72.2%	11.6%	FE	1.000
Q5	22.2%	32.9%	10.7%	χ^2	0.127
Q1	91.5%	84.8%	6.6%	FE	1.000
Q9	- 5.1%	- 7.6%	2.5%	FE	0.849

[Q6] MBSE is compatible with all aspects of my organization s systems engineering approach.

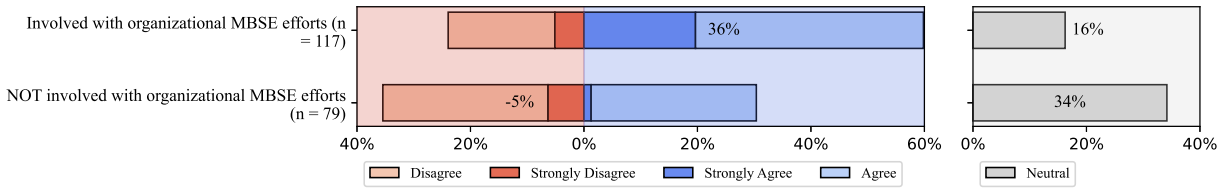


Figure C.1: Agreement with the statement “MBSE is compatible with all aspects of my organization s systems engineering approach.” (Q6) by the subpopulations delineated by “Involvement with MBSE”.

[Q7] An MBSE approach fits my work style.

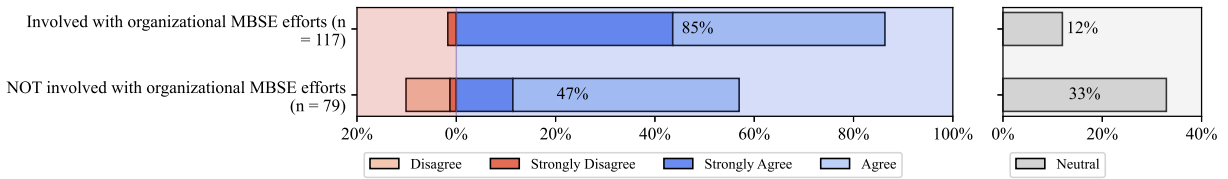


Figure C.2: Agreement with the statement “An MBSE approach fits my work style.” (Q7) by the subpopulations delineated by “Involvement with MBSE”.

[Q8] MBSE addresses a relevant need of my organization.

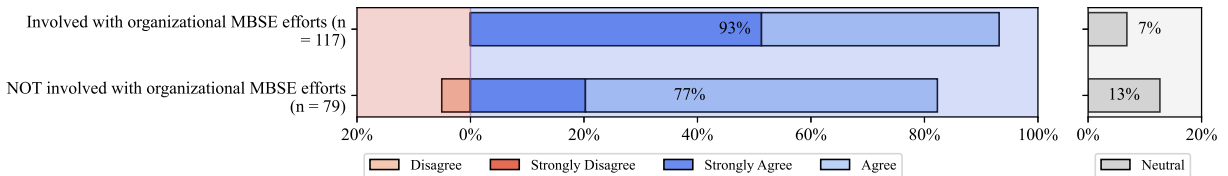


Figure C.3: Agreement with the statement “MBSE addresses a relevant need of my organization.” (Q8) by the subpopulations delineated by “Involvement with MBSE”.

[Q11] *It is easy to remember how to perform tasks using an MBSE approach.

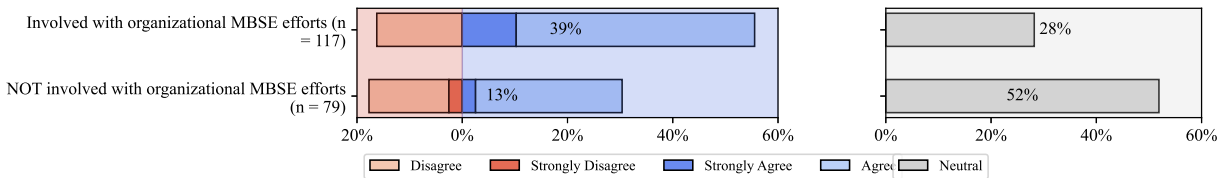


Figure C.4: Agreement with the statement “*It is easy to remember how to perform tasks using an MBSE approach.” (Q11) by the subpopulations delineated by “Involvement with MBSE”.

[Q12] *I am familiar with a system modeling language.

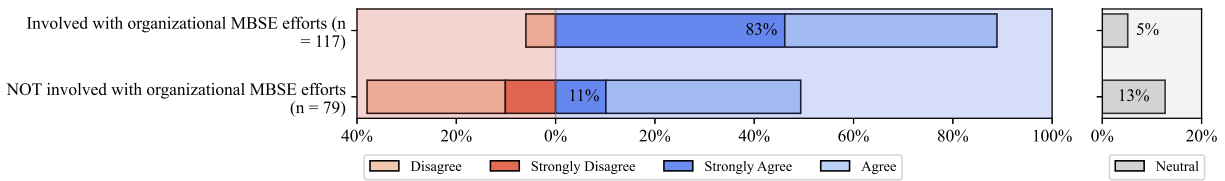


Figure C.5: Agreement with the statement “*I am familiar with a system modeling language.” (Q12) by the subpopulations delineated by “Involvement with MBSE”.

[Q13] *I have experience with a system modeling tool.

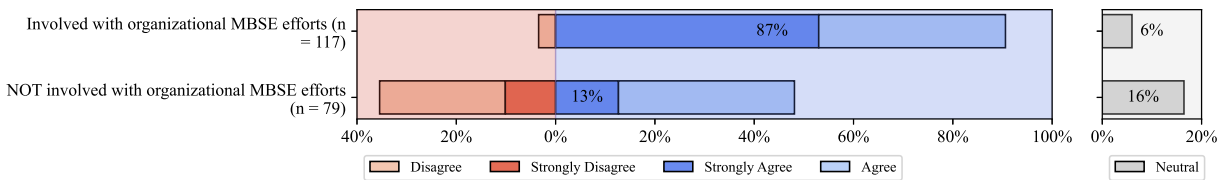


Figure C.6: Agreement with the statement “*I have experience with a system modeling tool.” (Q13) by the subpopulations delineated by “Involvement with MBSE”.

[Q14] I have opportunities to experiment with MBSE.

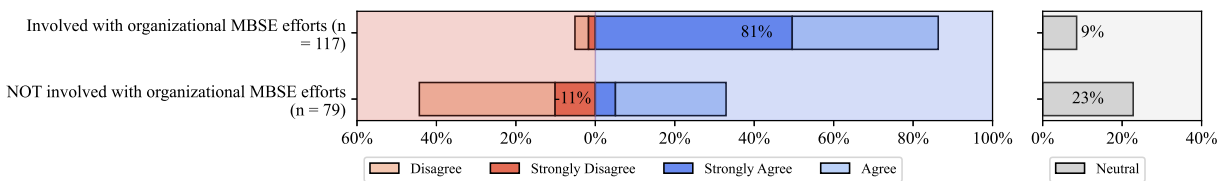


Figure C.7: Agreement with the statement “I have opportunities to experiment with MBSE.” (Q14) by the subpopulations delineated by “Involvement with MBSE”.

[Q15] I have access to a tool to experiment with MBSE.

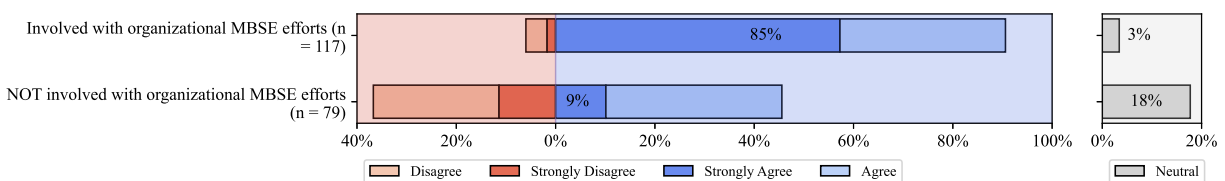


Figure C.8: Agreement with the statement “I have access to a tool to experiment with MBSE.” (Q15) by the subpopulations delineated by “Involvement with MBSE”.

[Q16] An MBSE approach is suited to small scale, pilot projects.

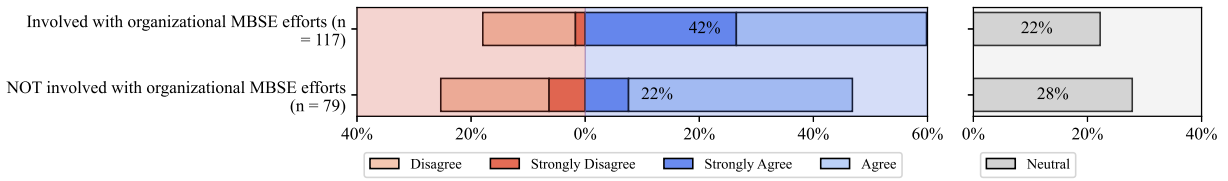


Figure C.9: Agreement with the statement “An MBSE approach is suited to small scale, pilot projects.” (Q16) by the subpopulations delineated by “Involvement with MBSE”.

[Q17] The benefits of an MBSE approach are apparent to me.

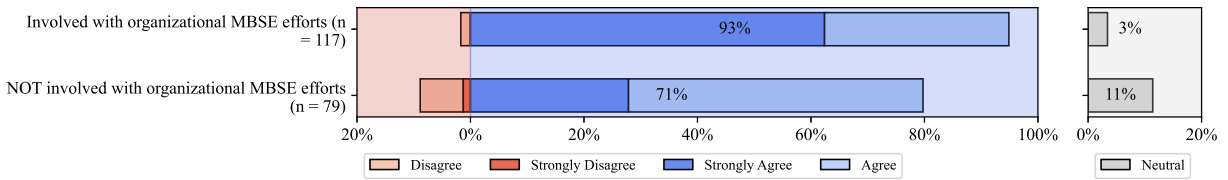


Figure C.10: Agreement with the statement “The benefits of an MBSE approach are apparent to me.” (Q17) by the subpopulations delineated by “Involvement with MBSE”.

[Q18] I have observed an MBSE approach being used by others.

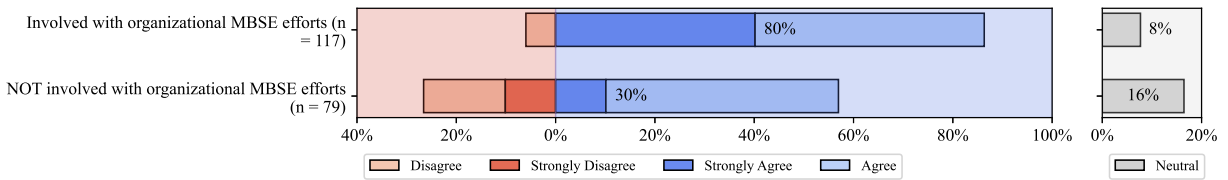


Figure C.11: Agreement with the statement “I have observed an MBSE approach being used by others.” (Q18) by the subpopulations delineated by “Involvement with MBSE”.

Approximately how many people are part of your organization?

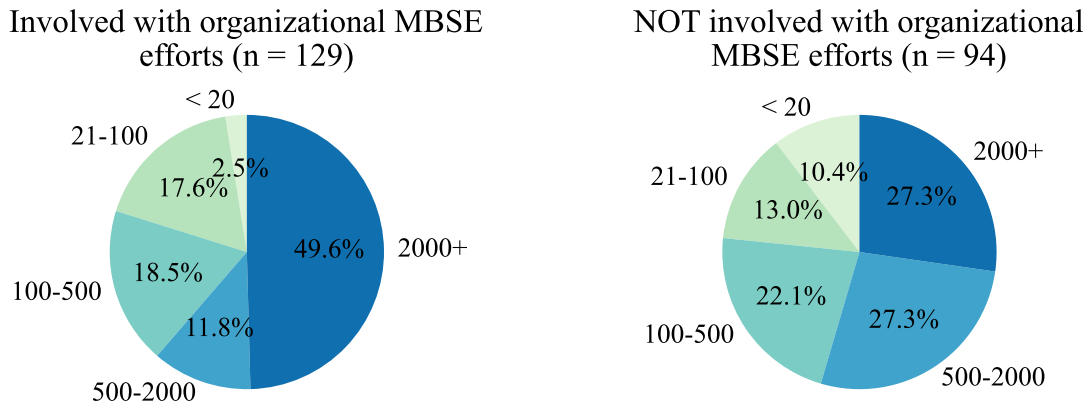


Figure C.12: Response to the question “Approximately how many people are part of your organization?” by the subpopulations delineated by “Involvement with MBSE”.

Does your organization have a formal, written systems engineering plan (model-based or otherwise)?

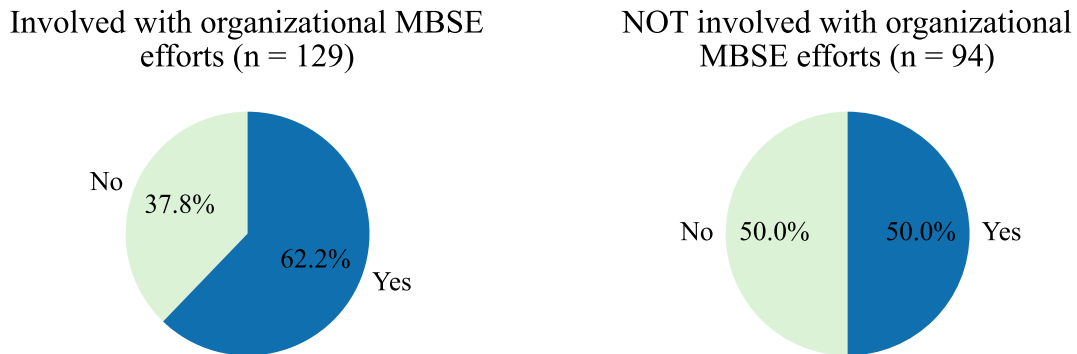
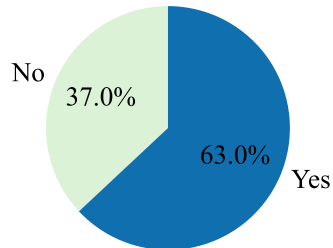


Figure C.13: Response to the question “Does your organization have a formal, written systems engineering plan (model-based or otherwise)?” by the subpopulations delineated by “Involvement with MBSE”.

Is your organization subject to any mandates to adopt and/or use digital engineering?

Involved with organizational MBSE efforts (n = 129)



NOT involved with organizational MBSE efforts (n = 94)

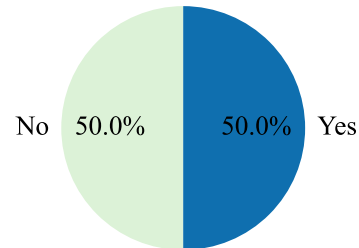
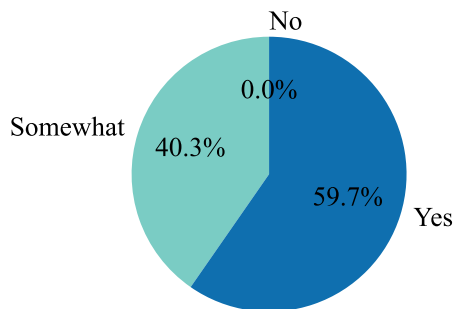


Figure C.14: Response to the question “Is your organization subject to any mandates to adopt and/or use digital engineering?” by the subpopulations delineated by “Involvement with MBSE”.

Does your organization encourage innovation and experimentation?

Involved with organizational MBSE efforts (n = 129)



NOT involved with organizational MBSE efforts (n = 94)

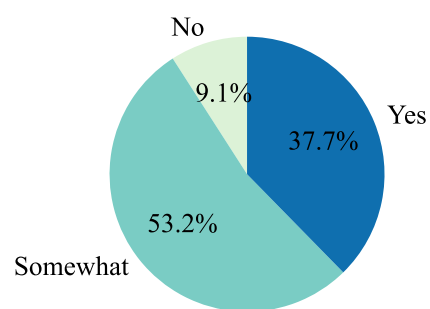


Figure C.15: Response to the question “Does your organization encourage innovation and experimentation?” by the subpopulations delineated by “Involvement with MBSE”.

How long have you worked in a systems engineering role?

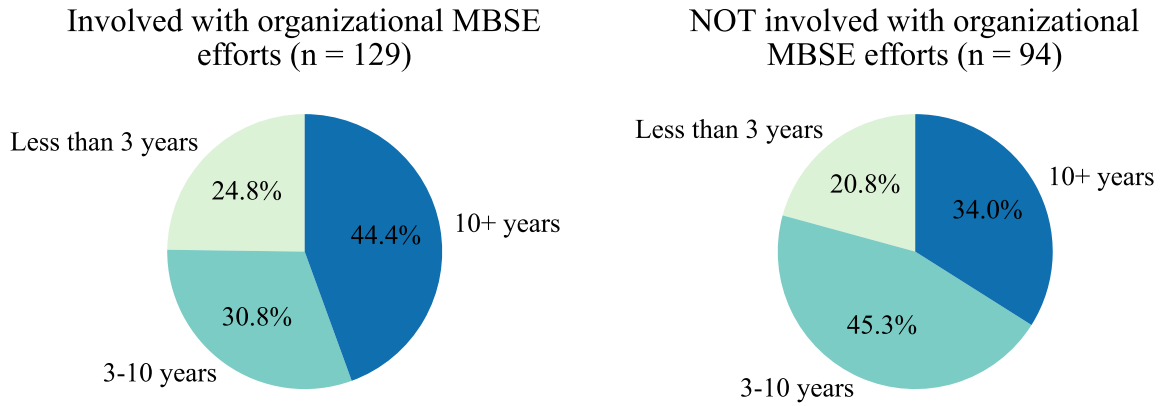


Figure C.16: Response to the question “How long have you worked in a systems engineering role?” by the subpopulations delineated by “Involvement with MBSE”.

C.2 Model Use Subpopulation

This section contains the tables and figures associated with the analysis of the subpopulations delineated by “Model Use”.

Table C.3: Comparison of the subpopulations “Model User” (n = 66) and “NON-model User” (n = 127), sorted by the delta between the net agreement score (NAS) of the populations, largest to smallest.

Question Tag	“Model User” NAS	“NON-model User” NAS	Delta NAS	Test	p-Value
Q14	83.9%	24.4%	59.5%	χ^2	0.000
Q6	54.8%	4.2%	50.6%	χ^2	0.001
Q18	90.3%	45.4%	44.9%	χ^2	0.000
Q11	58.1%	15.1%	42.9%	FE	0.010
Q15	75.8%	42.9%	32.9%	χ^2	0.009
Q13	71.0%	49.6%	21.4%	χ^2	0.155
Q7	82.3%	62.2%	20.1%	FE	0.319
Q16	43.5%	32.8%	10.8%	χ^2	0.783
Q8	95.2%	84.9%	10.3%	FE	0.553
Q12	61.3%	51.3%	10.0%	FE	0.548
Q5	33.9%	24.4%	9.5%	χ^2	0.324
Q17	91.9%	84.0%	7.9%	FE	1.000
Q4	93.5%	85.7%	7.8%	FE	1.000
Q9	-12.9%	- 5.9%	7.0%	FE	0.695
Q3	83.9%	78.2%	5.7%	FE	0.715
Q1	91.9%	87.4%	4.5%	FE	1.000
Q10	59.7%	55.5%	4.2%	FE	1.000
Q2	93.5%	93.3%	0.3%	FE	0.127

[Q6] MBSE is compatible with all aspects of my organization s systems engineering approach.

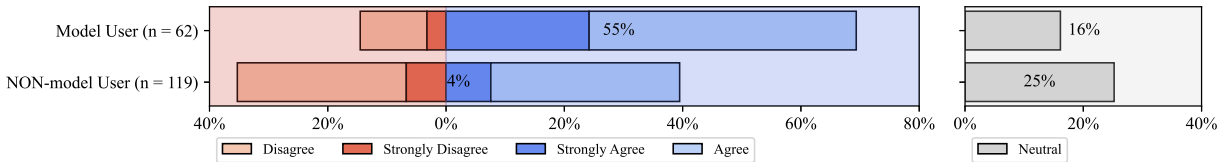


Figure C.17: Agreement with the statement “MBSE is compatible with all aspects of my organization s systems engineering approach.” (Q6) by the subpopulations delineated by “Model Use”.

[Q11] *It is easy to remember how to perform tasks using an MBSE approach.

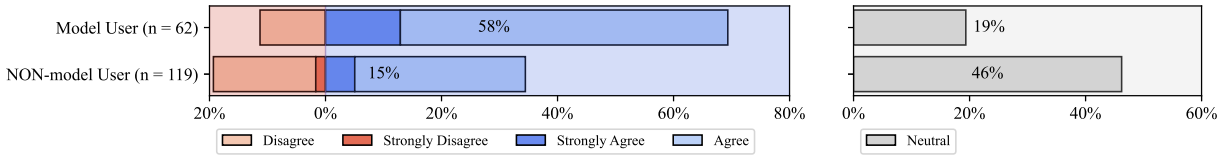


Figure C.18: Agreement with the statement “*It is easy to remember how to perform tasks using an MBSE approach.” (Q11) by the subpopulations delineated by “Model Use”.

[Q14] I have opportunities to experiment with MBSE.

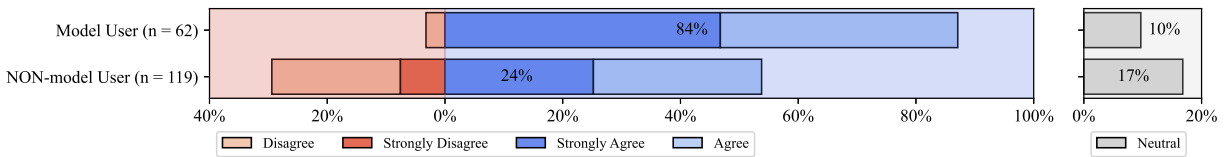


Figure C.19: Agreement with the statement “I have opportunities to experiment with MBSE.” (Q14) by the subpopulations delineated by “Model Use”.

[Q15] I have access to a tool to experiment with MBSE.

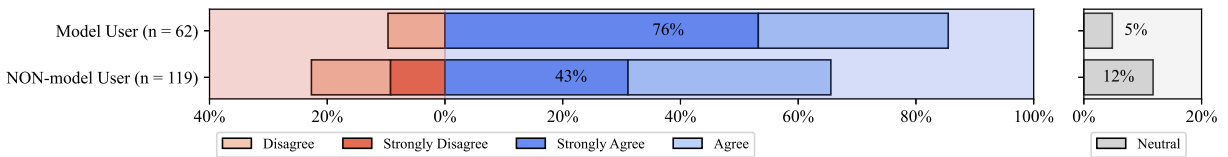


Figure C.20: Agreement with the statement “I have access to a tool to experiment with MBSE.” (Q15) by the subpopulations delineated by “Model Use”.

[Q18] I have observed an MBSE approach being used by others.

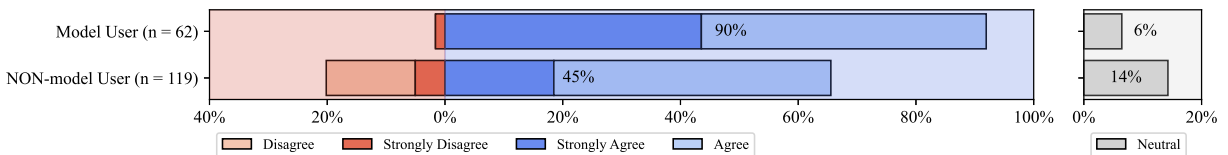


Figure C.21: Agreement with the statement “I have observed an MBSE approach being used by others.” (Q18) by the subpopulations delineated by “Model Use”.

Approximately how many people are part of your organization?

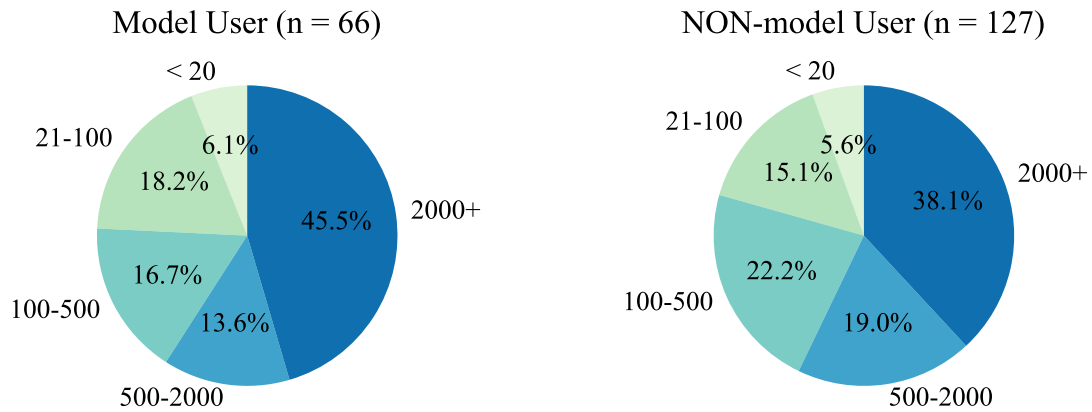


Figure C.22: Response to the question “Approximately how many people are part of your organization?” by the subpopulations delineated by “Model Use”.

Does your organization have a formal, written systems engineering plan (model-based or otherwise)?

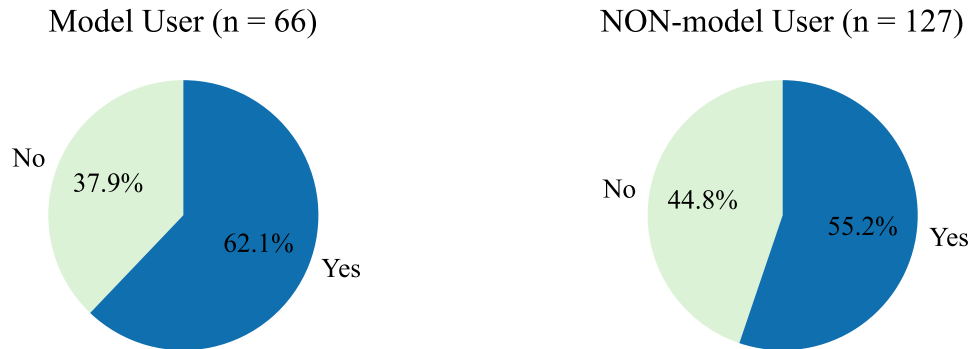


Figure C.23: Response to the question “Does your organization have a formal, written systems engineering plan (model-based or otherwise)?” by the subpopulations delineated by “Model Use”.

Is your organization subject to any mandates to adopt and/or use digital engineering?

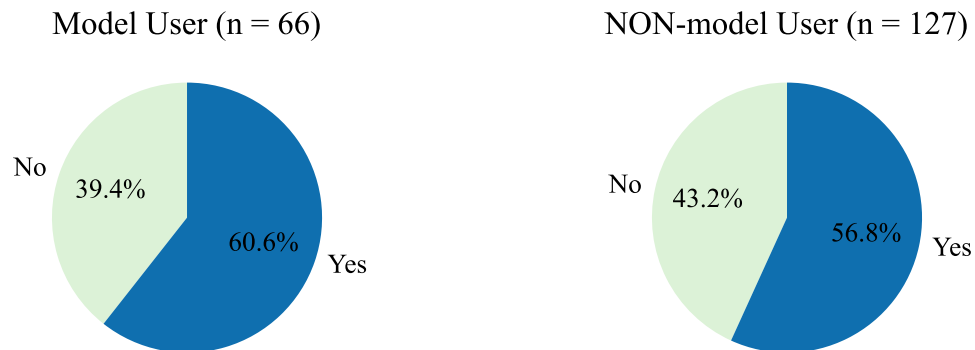


Figure C.24: Response to the question “Is your organization subject to any mandates to adopt and/or use digital engineering?” by the subpopulations delineated by “Model Use”.

Does your organization encourage innovation and experimentation?

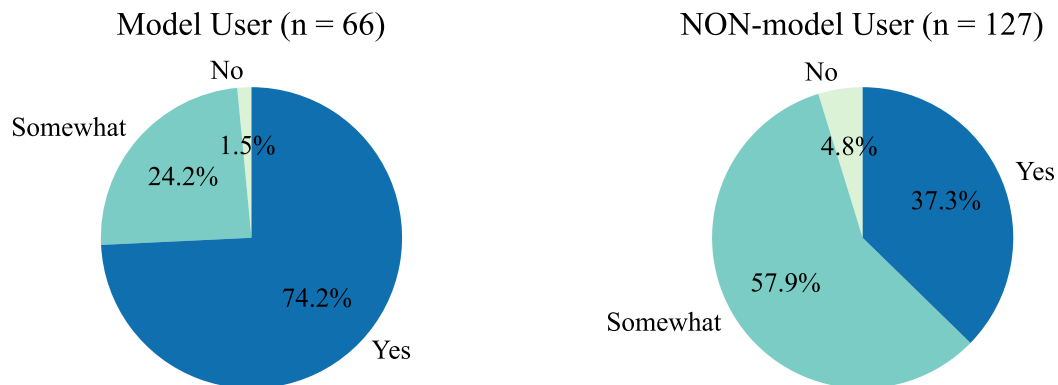


Figure C.25: Response to the question “Does your organization encourage innovation and experimentation?” by the subpopulations delineated by “Model Use”.

How long have you worked in a systems engineering role?

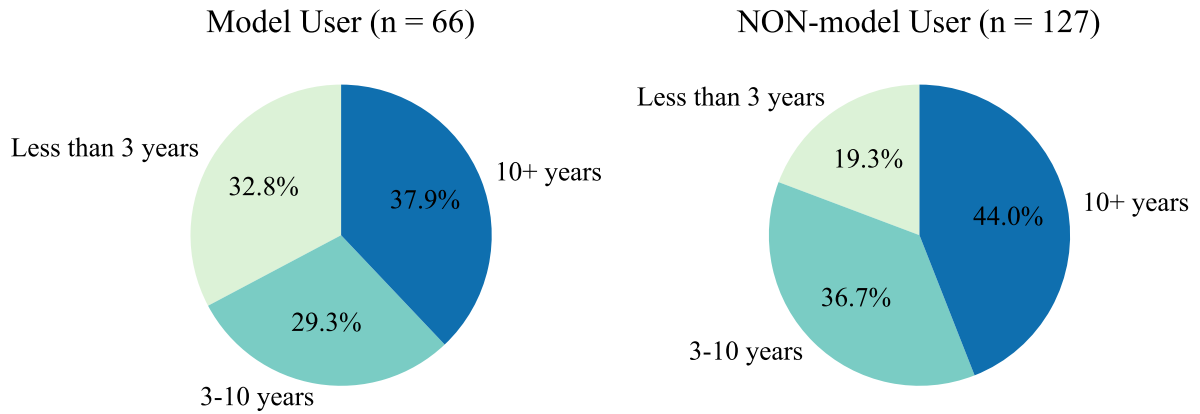


Figure C.26: Response to the question “How long have you worked in a systems engineering role?” by the subpopulations delineated by “Model Use”.

C.3 Organization MBSE Use Subpopulation

This section contains the tables and figures associated with the analysis of the subpopulations delineated by “Organization MBSE Use”.

Table C.4: Comparison of the subpopulations “Organization uses MBSE extensively” (n = 35) and “Organization does not use MBSE at all” (n = 31), sorted by the delta between the net agreement score (NAS) of the populations, largest to smallest.

Question Tag	“Organization uses MBSE extensively” NAS	“Organization does not use MBSE at all” NAS	Delta NAS	Test	p-Value
Q14	83.9%	- 7.4%	91.3%	FE	0.000
Q18	93.5%	11.1%	82.4%	FE	0.000
Q15	90.3%	11.1%	79.2%	FE	0.000
Q12	90.3%	14.8%	75.5%	FE	0.001
Q13	90.3%	44.4%	45.9%	FE	0.019
Q16	22.6%	14.8%	7.8%	χ^2	0.045
Q6	41.9%	- 3.7%	45.6%	FE	0.118
Q8	96.8%	59.3%	37.5%	FE	0.155
Q9	9.7%	-25.9%	35.6%	FE	0.079
Q7	80.6%	48.1%	32.5%	FE	0.372
Q10	80.6%	48.1%	32.5%	FE	0.549
Q11	51.6%	25.9%	25.7%	FE	0.678
Q17	90.3%	70.4%	20.0%	FE	0.320
Q2	96.8%	77.8%	19.0%	FE	0.202
Q3	93.5%	77.8%	15.8%	FE	1.000
Q4	93.5%	81.5%	12.1%	FE	1.000
Q1	90.3%	81.5%	8.8%	FE	0.462
Q5	25.8%	29.6%	3.8%	FE	1.000

[Q12] *I am familiar with a system modeling language.

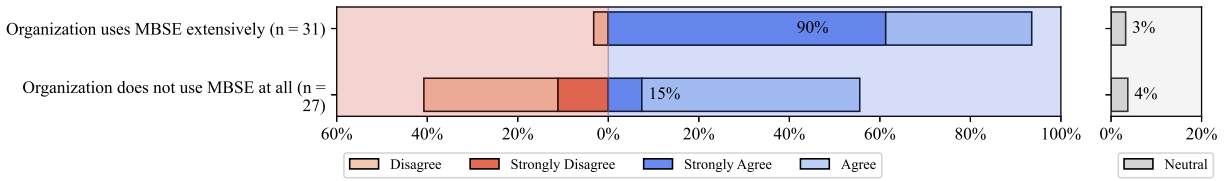


Figure C.27: Agreement with the statement “*I am familiar with a system modeling language.” (Q12) by the subpopulations delineated by “Organization MBSE Use”.

[Q13] *I have experience with a system modeling tool.

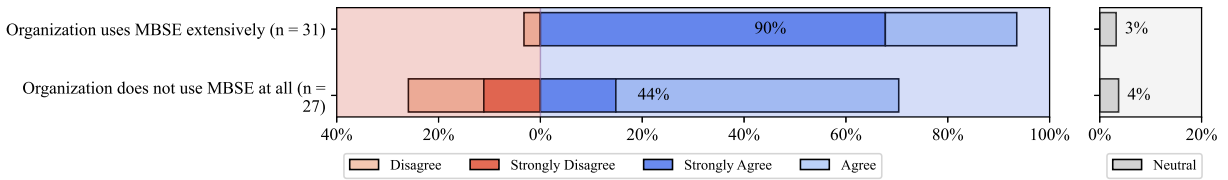


Figure C.28: Agreement with the statement “*I have experience with a system modeling tool.” (Q13) by the subpopulations delineated by “Organization MBSE Use”.

[Q14] I have opportunities to experiment with MBSE.

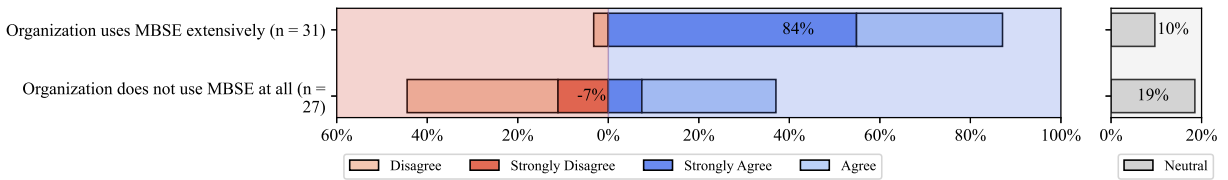


Figure C.29: Agreement with the statement “I have opportunities to experiment with MBSE.” (Q14) by the subpopulations delineated by “Organization MBSE Use”.

[Q15] I have access to a tool to experiment with MBSE.

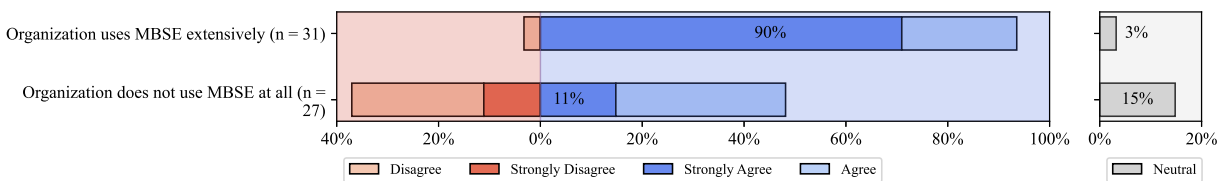


Figure C.30: Agreement with the statement “I have access to a tool to experiment with MBSE.” (Q15) by the subpopulations delineated by “Organization MBSE Use”.

[Q16] An MBSE approach is suited to small scale, pilot projects.

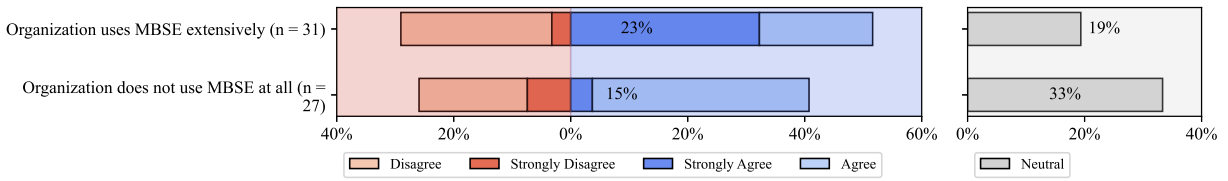


Figure C.31: Agreement with the statement “An MBSE approach is suited to small scale, pilot projects.” (Q16) by the subpopulations delineated by “Organization MBSE Use”.

[Q18] I have observed an MBSE approach being used by others.

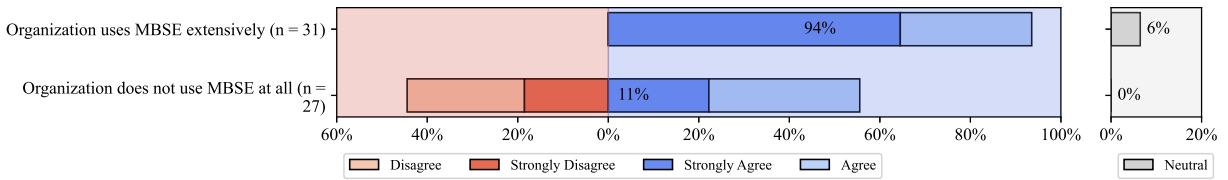


Figure C.32: Agreement with the statement “I have observed an MBSE approach being used by others.” (Q18) by the subpopulations delineated by “Organization MBSE Use”.

Approximately how many people are part of your organization?

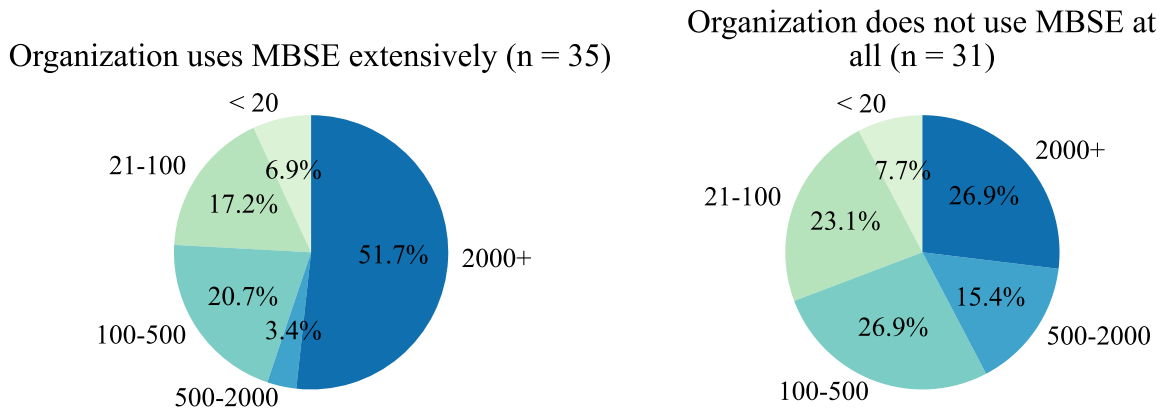


Figure C.33: Response to the question “Approximately how many people are part of your organization?” by the subpopulations delineated by “Organization MBSE Use”.

Does your organization have a formal, written systems engineering plan (model-based or otherwise)?

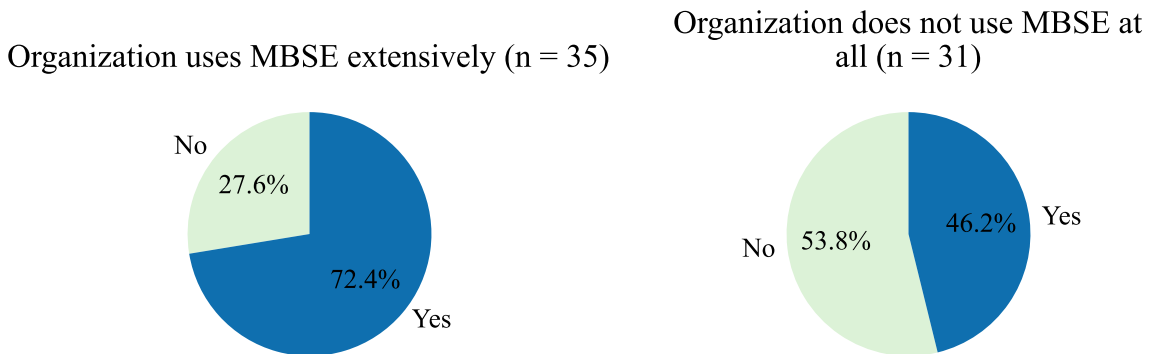


Figure C.34: Response to the question “Does your organization have a formal, written systems engineering plan (model-based or otherwise)?” by the subpopulations delineated by “Organization MBSE Use”.

Is your organization subject to any mandates to adopt and/or use digital engineering?

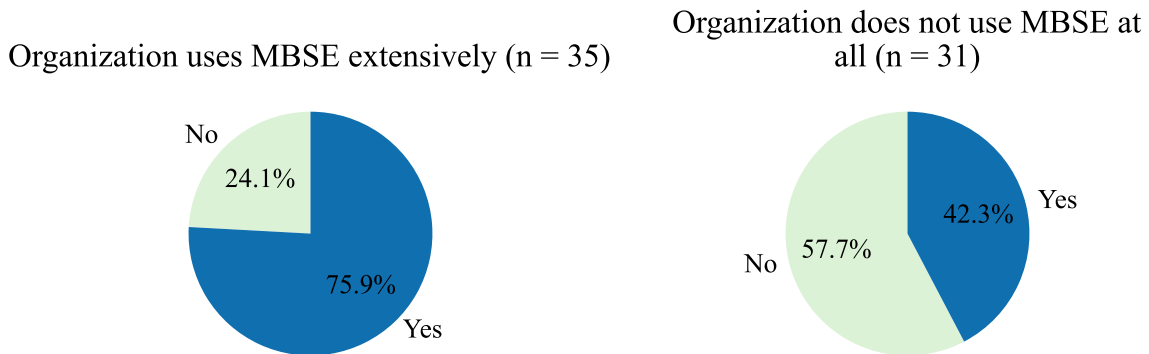
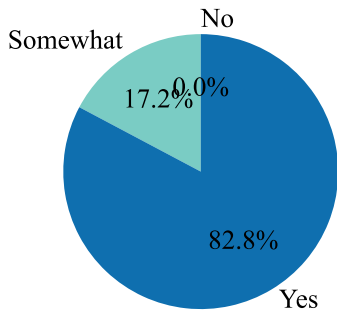


Figure C.35: Response to the question “Is your organization subject to any mandates to adopt and/or use digital engineering?” by the subpopulations delineated by “Organization MBSE Use”.

Does your organization encourage innovation and experimentation?

Organization uses MBSE extensively (n = 35)



Organization does not use MBSE at all (n = 31)

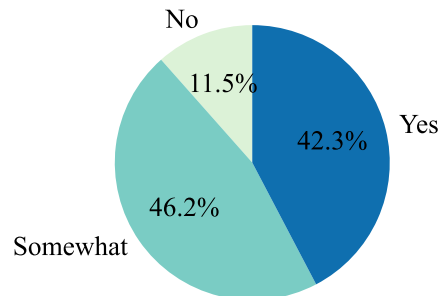
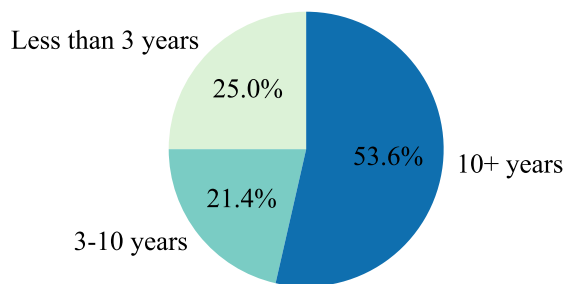


Figure C.36: Response to the question “Does your organization encourage innovation and experimentation?” by the subpopulations delineated by “Organization MBSE Use”.

How long have you worked in a systems engineering role?

Organization uses MBSE extensively (n = 35)



Organization does not use MBSE at all (n = 31)

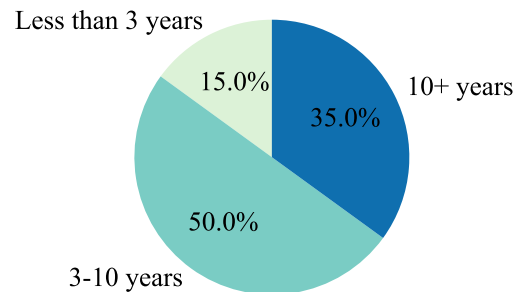


Figure C.37: Response to the question “How long have you worked in a systems engineering role?” by the subpopulations delineated by “Organization MBSE Use”.

C.4 Organization SE Plan Subpopulation

This section contains the tables and figures associated with the analysis of the subpopulations delineated by “Organization SE Plan”.

Table C.5: Comparison of the subpopulations “Organization has an SE plan” (n = 113) and “Organization does NOT have an SE plan” (n = 83), sorted by the delta between the net agreement score (NAS) of the populations, largest to smallest.

Question Tag	“Organization has an SE plan” NAS	“Organization does NOT have an SE plan” NAS	Delta NAS	Test	p-Value
Q9	3.8%	-25.6%	29.4%	FE	0.020
Q3	71.7%	91.0%	19.3%	FE	0.010
Q5	17.0%	42.3%	25.3%	χ^2	0.279
Q15	59.4%	44.9%	14.6%	χ^2	0.482
Q11	24.5%	33.3%	8.8%	χ^2	0.323
Q6	17.0%	25.6%	8.7%	χ^2	0.948
Q18	63.2%	56.4%	6.8%	χ^2	0.620
Q13	60.4%	53.8%	6.5%	χ^2	0.974
Q17	82.1%	88.5%	6.4%	FE	0.734
Q7	67.0%	71.8%	4.8%	FE	0.754
Q10	59.4%	55.1%	4.3%	FE	0.803
Q14	46.2%	42.3%	3.9%	χ^2	0.237
Q1	89.6%	85.9%	3.7%	FE	1.000
Q8	89.6%	85.9%	3.7%	FE	1.000
Q12	57.5%	53.8%	3.7%	χ^2	0.351
Q2	91.5%	94.9%	3.4%	FE	0.509
Q4	86.8%	87.2%	0.4%	FE	0.512
Q16	35.8%	35.9%	0.0%	χ^2	0.796

[Q3] An MBSE approach enforces consistency amongst systems engineering artifacts.

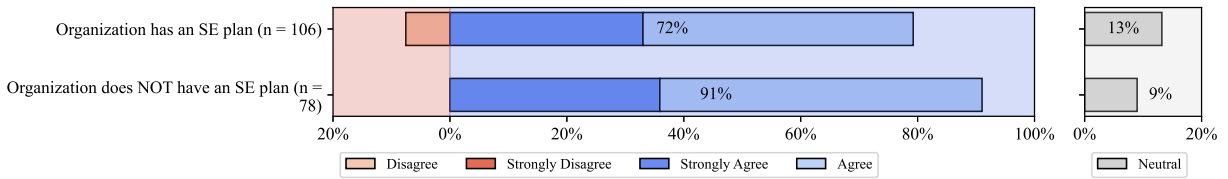


Figure C.38: Agreement with the statement “An MBSE approach enforces consistency amongst systems engineering artifacts.” (Q3) by the subpopulations delineated by “Organization SE Plan”.

[Q9] MBSE is cumbersome.

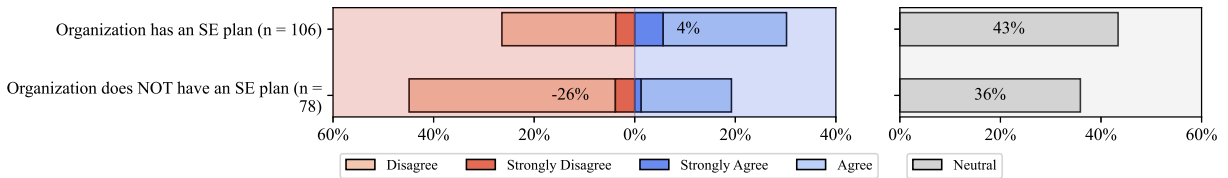


Figure C.39: Agreement with the statement “MBSE is cumbersome.” (Q9) by the subpopulations delineated by “Organization SE Plan”.

Approximately how many people are part of your organization?

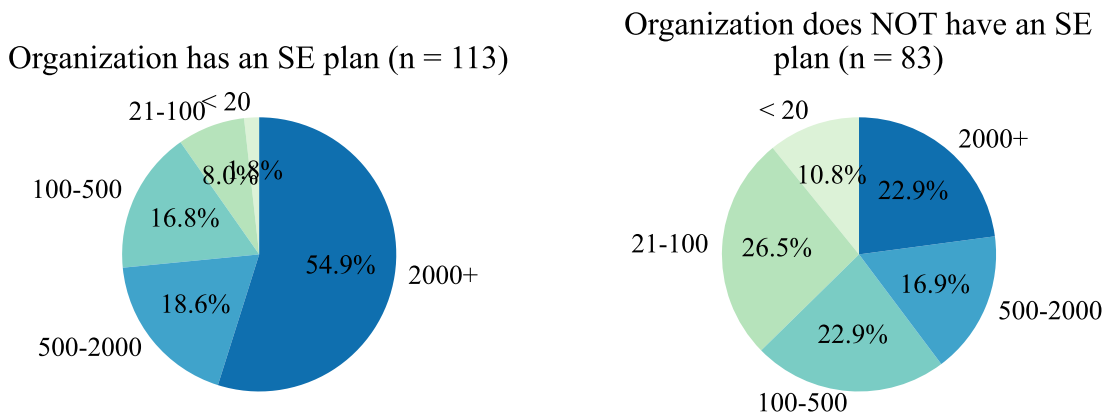


Figure C.40: Response to the question “Approximately how many people are part of your organization?” by the subpopulations delineated by “Organization SE Plan”.

Does your organization have a formal, written systems engineering plan (model-based or otherwise)?

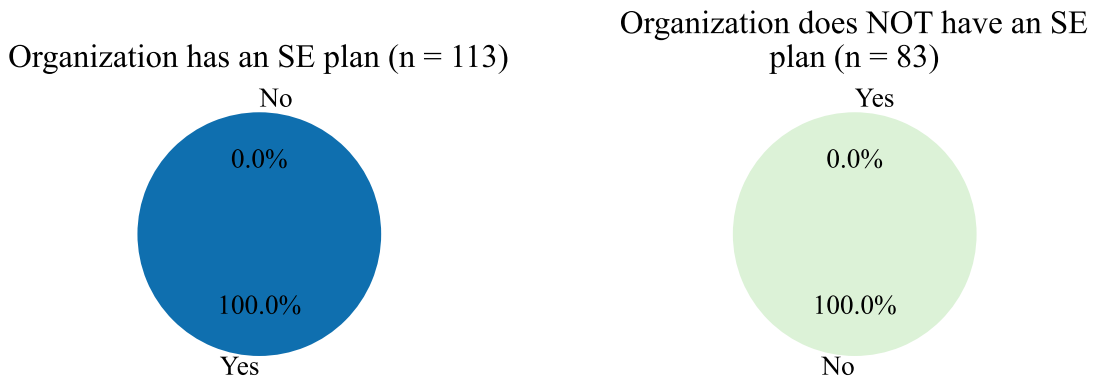


Figure C.41: Response to the question “Does your organization have a formal, written systems engineering plan (model-based or otherwise)?” by the subpopulations delineated by “Organization SE Plan”.

Is your organization subject to any mandates to adopt and/or use digital engineering?

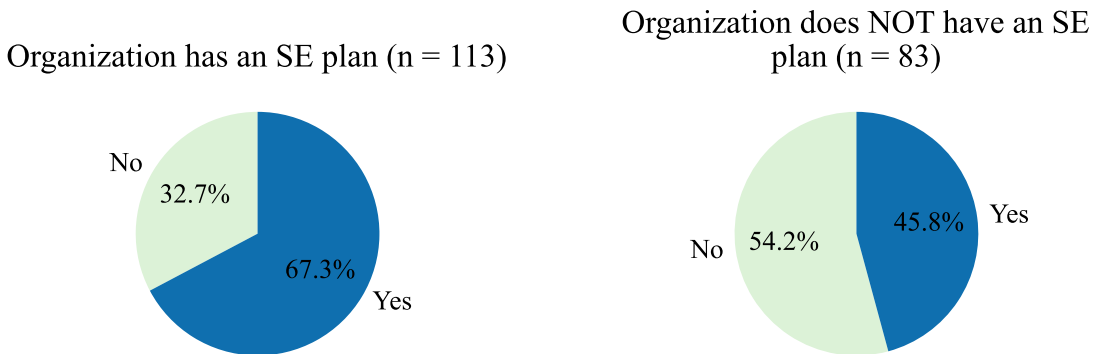


Figure C.42: Response to the question “Is your organization subject to any mandates to adopt and/or use digital engineering?” by the subpopulations delineated by “Organization SE Plan”.

Does your organization encourage innovation and experimentation?

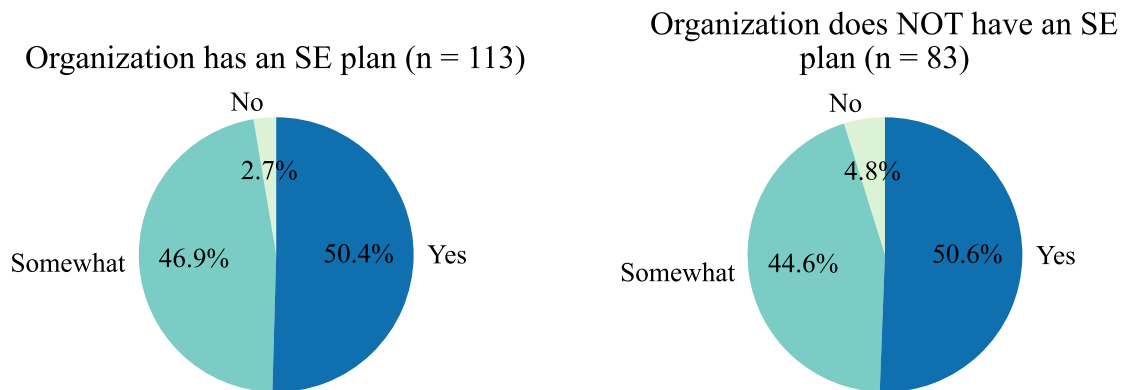


Figure C.43: Response to the question “Does your organization encourage innovation and experimentation?” by the subpopulations delineated by “Organization SE Plan”.

How long have you worked in a systems engineering role?

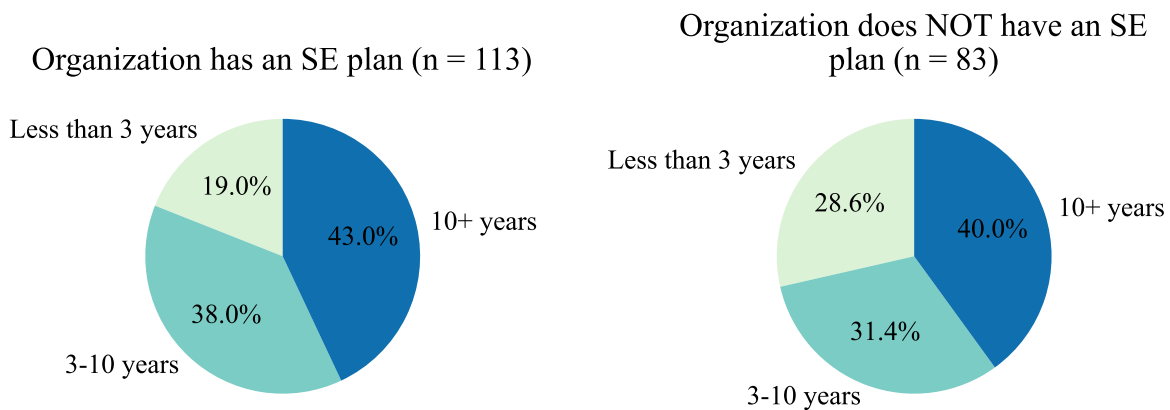


Figure C.44: Response to the question “How long have you worked in a systems engineering role?” by the subpopulations delineated by “Organization SE Plan”.

C.5 Subject to DE Mandates Subpopulation

This section contains the tables and figures associated with the analysis of the subpopulations delineated by “Subject to DE Mandates”.

Table C.6: Comparison of the subpopulations “Organization subject to mandates to use DE” (n = 114) and “Organization NOT subject to mandates to use DE” (n = 82), sorted by the delta between the net agreement score (NAS) of the populations, largest to smallest.

Question Tag	“Organization subject to mandates to use DE” NAS	“Organization NOT subject to mandates to use DE” NAS	Delta NAS	Test	p-Value
Q15	65.1%	36.0%	29.1%	χ^2	0.031
Q12	65.1%	42.7%	22.5%	χ^2	0.012
Q13	65.1%	46.7%	18.5%	χ^2	0.019
Q18	67.0%	50.7%	16.3%	χ^2	0.303
Q14	50.5%	36.0%	14.5%	χ^2	0.448
Q5	22.0%	36.0%	14.0%	χ^2	0.114
Q1	92.7%	81.3%	11.3%	FE	0.560
Q11	23.9%	34.7%	10.8%	χ^2	0.320
Q6	24.8%	14.7%	10.1%	χ^2	0.080
Q9	- 4.6%	-14.7%	10.1%	FE	0.436
Q4	89.9%	82.7%	7.2%	FE	1.000
Q10	60.6%	53.3%	7.2%	FE	0.447
Q16	38.5%	32.0%	6.5%	χ^2	0.643
Q17	87.2%	81.3%	5.8%	FE	0.489
Q8	89.9%	85.3%	4.6%	FE	1.000
Q7	70.6%	66.7%	4.0%	FE	1.000
Q2	94.5%	90.7%	3.8%	FE	0.168
Q3	80.7%	78.7%	2.1%	FE	0.260

[Q6] MBSE is compatible with all aspects of my organization's systems engineering approach.

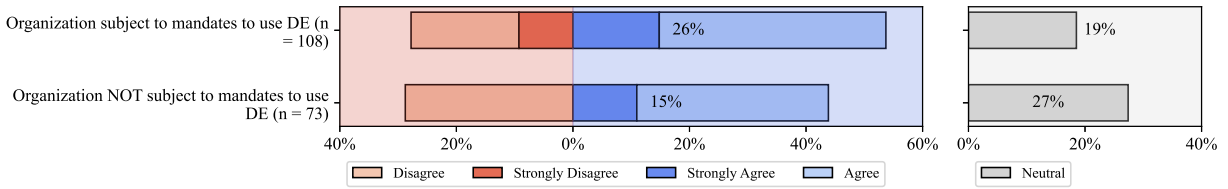


Figure C.45: Agreement with the statement “MBSE is compatible with all aspects of my organization s systems engineering approach.” (Q6) by the subpopulations delineated by “Subject to DE Mandates”.

[Q12] *I am familiar with a system modeling language.

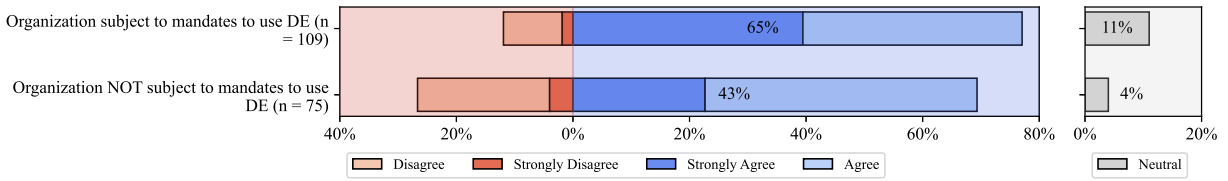


Figure C.46: Agreement with the statement “*I am familiar with a system modeling language.” (Q12) by the subpopulations delineated by “Subject to DE Mandates”.

[Q13] *I have experience with a system modeling tool.

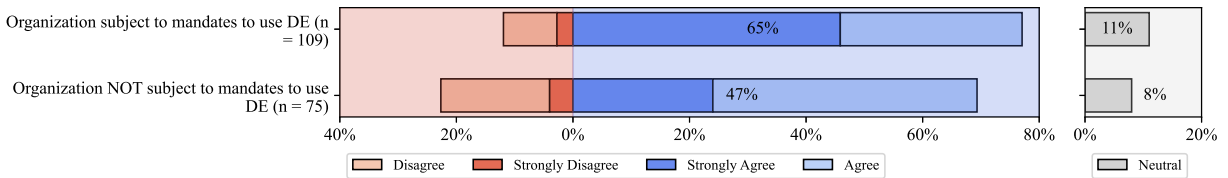


Figure C.47: Agreement with the statement “*I have experience with a system modeling tool.” (Q13) by the subpopulations delineated by “Subject to DE Mandates”.

[Q15] I have access to a tool to experiment with MBSE.

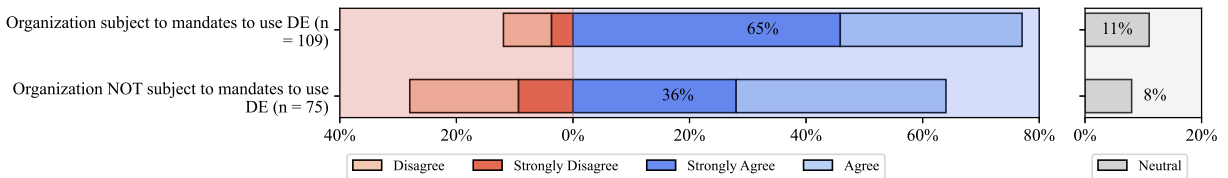


Figure C.48: Agreement with the statement “I have access to a tool to experiment with MBSE.” (Q15) by the subpopulations delineated by “Subject to DE Mandates”.

Approximately how many people are part of your organization?

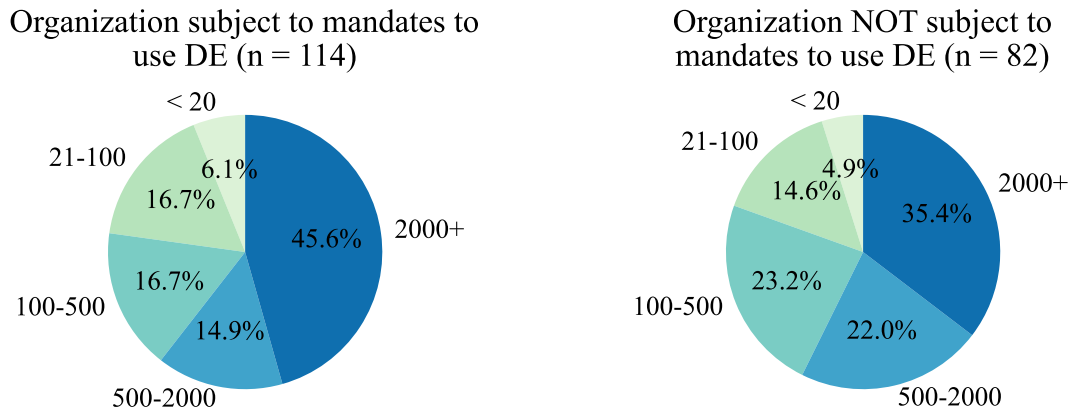


Figure C.49: Response to the question “Approximately how many people are part of your organization?” by the subpopulations delineated by “Subject to DE Mandates”.

Does your organization have a formal, written systems engineering plan (model-based or otherwise)?

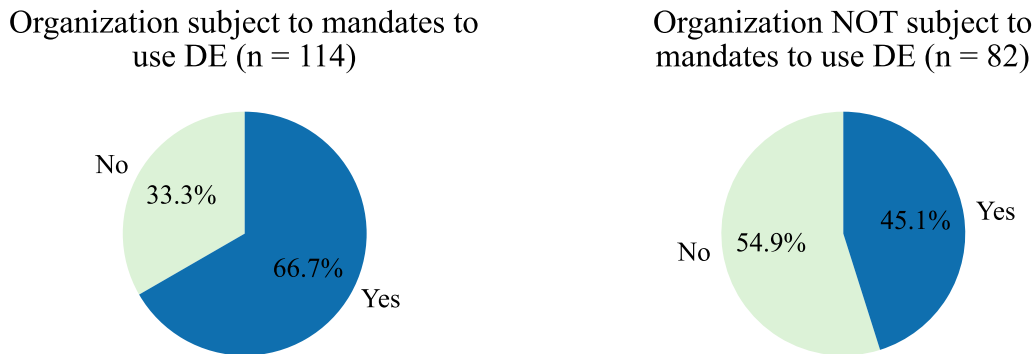
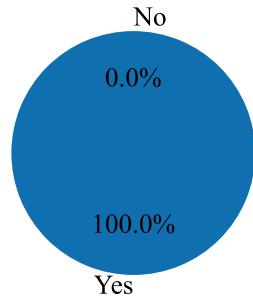


Figure C.50: Response to the question “Does your organization have a formal, written systems engineering plan (model-based or otherwise)?” by the subpopulations delineated by “Subject to DE Mandates”.

Is your organization subject to any mandates to adopt and/or use digital engineering?

Organization subject to mandates to use DE (n = 114)



Organization NOT subject to mandates to use DE (n = 82)

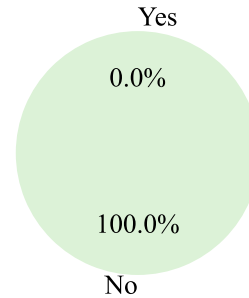
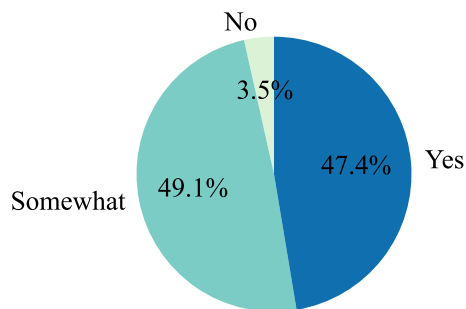


Figure C.51: Response to the question “Is your organization subject to any mandates to adopt and/or use digital engineering?” by the subpopulations delineated by “Subject to DE Mandates”.

Does your organization encourage innovation and experimentation?

Organization subject to mandates to use DE (n = 114)



Organization NOT subject to mandates to use DE (n = 82)

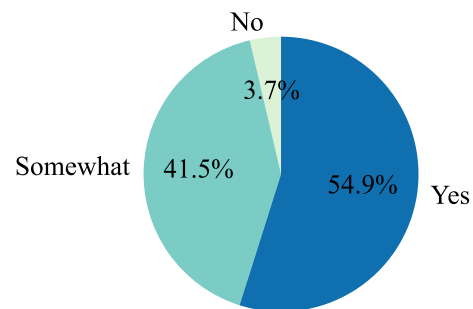


Figure C.52: Response to the question “Does your organization encourage innovation and experimentation?” by the subpopulations delineated by “Subject to DE Mandates”.

How long have you worked in a systems engineering role?

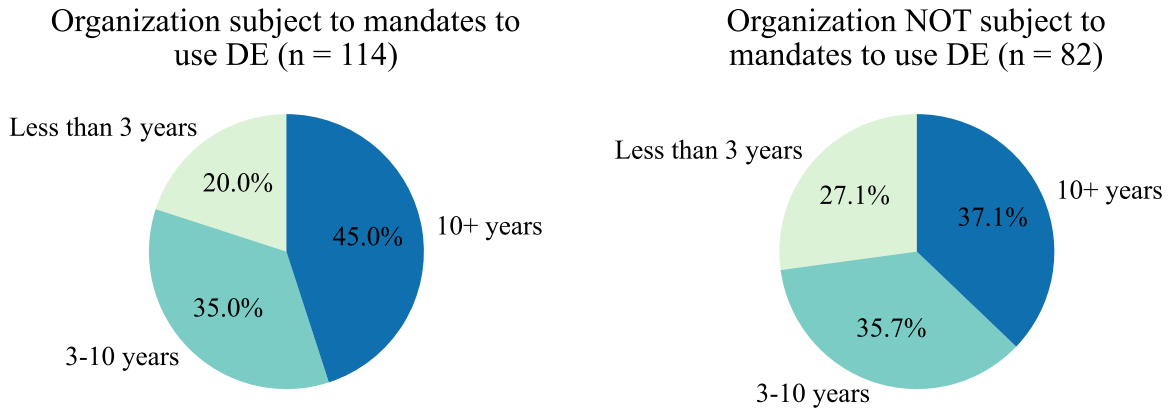


Figure C.53: Response to the question “How long have you worked in a systems engineering role?” by the subpopulations delineated by “Subject to DE Mandates”.

C.6 Associated with Air Force Subpopulation

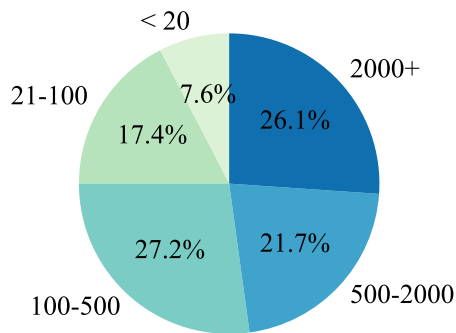
This section contains the tables and figures associated with the analysis of the subpopulations delineated by “Associated with Air Force”.

Table C.7: Comparison of the subpopulations “Associated with the Air Force” (n = 92) and “NOT associated with the Air Force” (n = 178), sorted by question tag.

Question Tag	“Associated with the Air Force” NAS	“NOT associated with the Air Force” NAS	Delta NAS	Test	p-Value
Q1	90.0%	87.7%	2.3%	FE	1.000
Q2	93.3%	90.6%	2.8%	FE	1.000
Q3	76.7%	81.1%	4.5%	FE	0.473
Q4	84.4%	87.7%	3.3%	FE	1.000
Q5	18.9%	33.0%	14.1%	χ^2	0.289
Q6	25.6%	14.2%	11.4%	χ^2	0.141
Q7	67.8%	70.8%	3.0%	FE	1.000
Q8	94.4%	80.2%	14.3%	FE	0.621
Q9	-15.6%	1.9%	17.4%	FE	0.139
Q10	52.2%	62.3%	10.0%	FE	0.148
Q11	14.4%	40.6%	26.1%	χ^2	0.072
Q12	54.4%	53.8%	0.7%	χ^2	0.558
Q13	44.4%	67.9%	23.5%	χ^2	0.171
Q14	36.7%	50.0%	13.3%	χ^2	0.393
Q15	45.6%	61.3%	15.8%	χ^2	0.396
Q16	37.8%	30.2%	7.6%	χ^2	0.412
Q17	84.4%	84.0%	0.5%	FE	1.000
Q18	53.3%	66.0%	12.7%	χ^2	0.355

Approximately how many people are part of your organization?

Associated with the Air Force (n = 92)



NOT associated with the Air Force (n = 178)

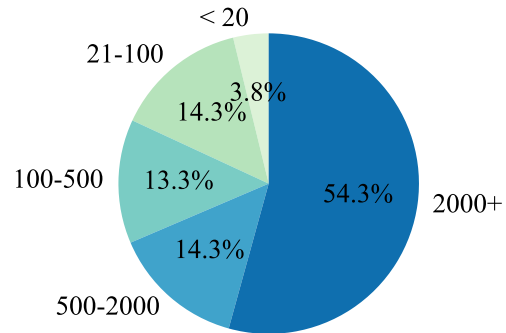
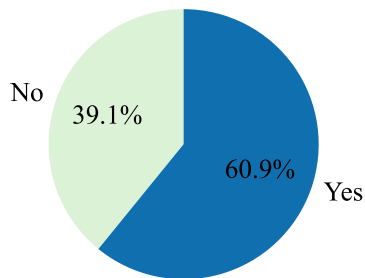


Figure C.54: Response to the question “Approximately how many people are part of your organization?” by the subpopulations delineated by “Associated with Air Force”.

Does your organization have a formal, written systems engineering plan (model-based or otherwise)?

Associated with the Air Force (n = 92)



NOT associated with the Air Force (n = 178)

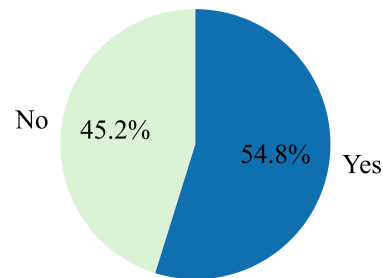


Figure C.55: Response to the question “Does your organization have a formal, written systems engineering plan (model-based or otherwise)?” by the subpopulations delineated by “Associated with Air Force”.

Is your organization subject to any mandates to adopt and/or use digital engineering?

Associated with the Air Force (n = 92) NOT associated with the Air Force (n = 178)

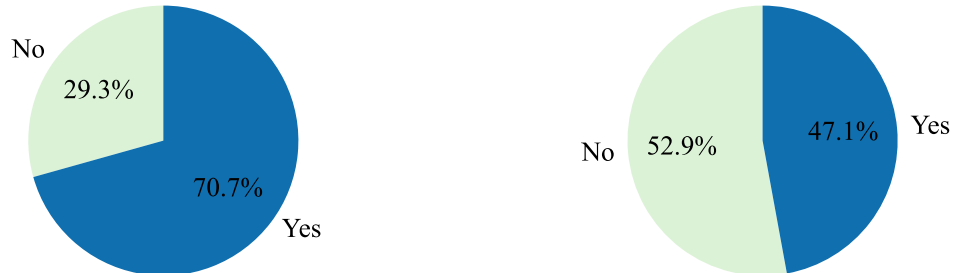


Figure C.56: Response to the question “Is your organization subject to any mandates to adopt and/or use digital engineering?” by the subpopulations delineated by “Associated with Air Force”.

Does your organization encourage innovation and experimentation?

Associated with the Air Force (n = 92) NOT associated with the Air Force (n = 178)

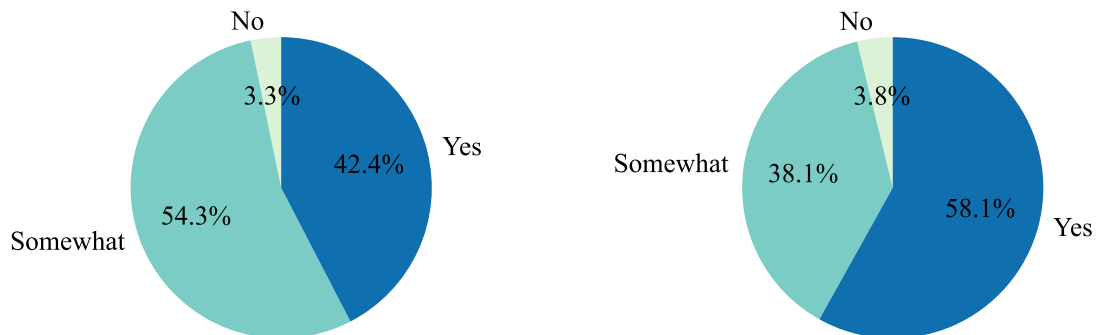


Figure C.57: Response to the question “Does your organization encourage innovation and experimentation?” by the subpopulations delineated by “Associated with Air Force”.

How long have you worked in a systems engineering role?

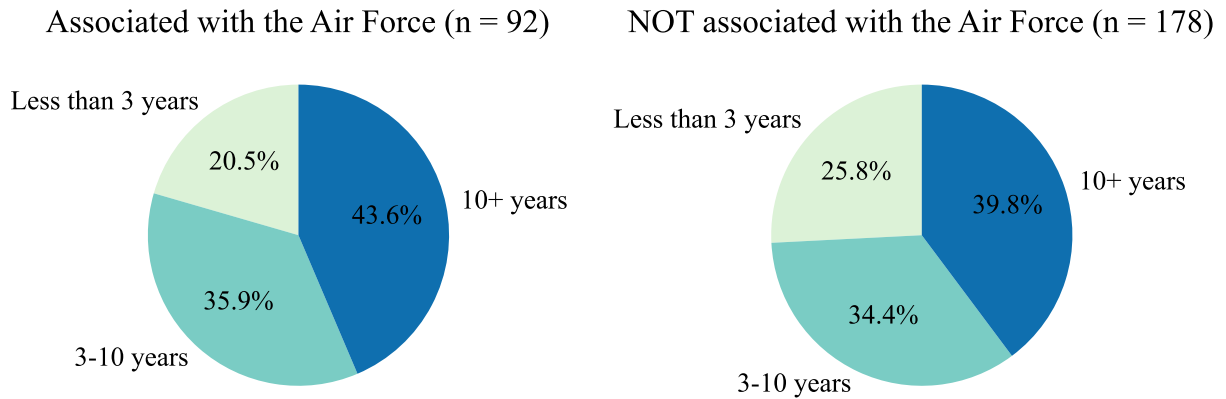


Figure C.58: Response to the question “How long have you worked in a systems engineering role?” by the subpopulations delineated by “Associated with Air Force”.