Exploring the Adoption Process of MBSE: A Closer Look at Contributing Organizational Structure Factors

Kaitlin A. Henderson

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Alejandro Salado, Chair

Eileen M. Van Aken

Brian M. Kleiner

Darius Šilingas

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ACADEMIC ABSTRACT

Over the past few decades, not only have systems continued to increase in complexity, but they are expected to be delivered in the same timeframe and cost range. Technology has advanced us into what some refer to as the 4th Industrial Revolution. Digital is becoming the expectation in all areas of people's lives. Model-Based Systems Engineering (MBSE) represents the transition of systems into this new digital age, promising many improvements over the previous Document-Based Systems Engineering. This transition, however, is not simple. MBSE is a major paradigm shift for systems engineers, especially for those who have been in this field for many years. In order to work as intended, MBSE requires the participation of many different disciplines and functionalities in an organization. Gaining this level of organizational collaboration, however, is no easy task. Organizational structure and culture have intuitively been believed to be critical barriers to the successful adoption of MBSE, but little work has been done to discover what the impacts of these organizational factors are. The purpose of this research is to further explore the MBSE adoption process in the context of the organization. There were three research objectives designed to address the research question: how does organizational structure influence the adoption and implementation of MBSE? Research objective one was: relate organizational structure characteristics to MBSE adoption and implementation measures. Research objective two was: discover how organizational factors contribute to decisions made and other aspects of the MBSE adoption process. Research objective three was: connect different organizational structure and adoption variables together to derive critical variables in the adoption process.

Research objective one was carried out using a survey as the instrument. The objective of the survey was to examine what the effects of organizational structure are on MBSE adoption and implementation. Organizational structure was represented by seven variables: *Size, Formalization, Centralization, Specialization, Vertical Differentiation, Flexibility*, and *Interconnectedness*. These are different characteristics of organizational structure that can be measured on a scale. MBSE adoption and implementation was represented by one adoption and three implementation variables. These include *Adoption Process, Maturity of MBSE, Use of MBSE,* and *Influence on organizational outcomes*. A total of 51 survey responses were received that met the inclusion criteria. Factor analysis was done for variables with multi-item measures. The factors were then analyzed using pairwise correlations to determine which relationships were significant. *Formalization*, *Flexibility*, and *Interconnectedness* were found to have positive correlations with adoption and implementation variables. *Size* and *Vertical Differentiation* had a negative correlation with *Use of MBSE* (implementation). *Centralization* was found to have negative correlations with adoption and implementation. *Specialization* did not have any significant correlations.

Research objective two utilized semi-structured interviews as the main instrument. Survey participants had the opportunity to provide more detailed explanations of their organizations' experiences in the form of follow-up interviews. Eighteen survey participants agreed to this

follow-up interview focused on MBSE adoption. Two of the participants shared failed adoption experiences, with the rest were at various stages of the adoption process. One of the most emergent themes out of the interviews was the idea of integration. Integration needs to occur at the organizational level, and the technical level. The technical level refers to the fact that tools, models, and/or data repositories need to be linked together in some way. Integration also has to occur at the organizational level, because a lot of different functional areas need to come together for MBSE. The way that organizations can address the issue of integration is through coordination mechanisms. *The* ultimate goal is to achieve implicit coordination through the use of connected models, but getting to that point will require coordination between different subunits. Interview responses were evaluated for coordination mechanisms, or situations that showed a distinct lack of a coordination mechanism. The lack of coordination mechanisms largely consists of a lack of standardization, lack of communication between subunits, and issues of authority.

The final research objective of this work was carried out through a causal analysis using the data obtained from the survey and interviews. The purpose of this analysis was to visualize and better understand the adoption process. According to the calculated measures of centrality, the important nodes in this model are *Improved organizational outcomes*, *Coordination between subunits*, *Projects use tools/methods*, and *People willing to use tools*. *Improved organizational outcomes* is part of a key loop in the causal model. *Improved organizational outcomes* contributes to leaders and employees' willingness to support and use MBSE methods and tools, which contribute to actual use of tools and methods. This creates more *Improved organizational outcomes*, completing the loop. The survey results showed that *Formalization*, *Decentralization*, *Flexibility*, and *Interconnectedness* all have positive correlations with the *Influence on organizational outcomes*. So these organizational structure components are external factors that can be used to positively impact the adoption loop.

Overall, this work provided several contributions to the field regarding the MBSE adoption process in an organizational setting. Organizational structure was shown to have significant correlations with adoption and implementation of MBSE. Coordination mechanisms were identified as a method to achieve integration across different functional areas of the organization. *Improved organizational outcomes* was shown to be a critical variable in the adoption process as an avenue for organizational structure factors to have a positive effect on the adoption process.

Exploring the Adoption Process of MBSE: A Closer Look at Contributing Organizational Structure Factors

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GENERAL AUDIENCE ABSTRACT

Over the past few decades, not only have systems continued to increase in complexity, but they are expected to be delivered in the same timeframe and cost range. Technology has advanced us into what some refer to as the 4th Industrial Revolution. Digital is becoming the expectation in all areas of people's lives. Model-Based Systems Engineering (MBSE) represents the transition of systems into this new digital age, promising many improvements over the previous Document-Based Systems Engineering. This transition, however, is not simple. MBSE is a major mindset change for systems engineers, especially for those who have been in this field for many years. In order to work as intended, MBSE requires the participation of many different disciplines and functionalities in an organization. Gaining this level of organizational collaboration, however, is no easy task. Organizational structure and culture have intuitively been believed to be critical barriers to the successful adoption of MBSE, but little work has been done to discover what the impacts of these organizational factors are.

This research looks into how organizational structure may have an impact on MBSE adoption and implementation. This research was carried out with the use of three different methods: an online survey, semi-structured interviews, and a causal analysis. The data obtained from the survey and interviews was used to construct a causal model depicting the MBSE adoption process.

Overall, this work provided several contributions to the field regarding the MBSE adoption process in an organizational setting. Organizational structural variables were shown to have significant correlations with adoption and implementation of MBSE. *Formalization*, *Flexibility*, and *Interconnectedness* were found to have positive correlations with adoption and implementation variables, while *Centralization* had negative correlations with adoption and implementation. Coordination mechanisms were identified as a method to achieve integration across different functional areas of the organization. Interview responses were evaluated for coordination mechanisms, or situations that showed a distinct lack of a coordination mechanism. The lack of coordination mechanisms largely consists of a lack of standardization, lack of communication between subunits, and issues of authority. The causal analysis showed that *Improved organizational outcomes*, *Coordination between subunits*, *Projects use tools/methods*, and *People willing to use tools* were the critical variables in the MBSE adoption process.

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Table of Contents

Table of Figures

Table of Tables

Ch. 1 Problem Setting

1.1 Background

Model-Based Systems Engineering (MBSE) is the result of the Systems Engineering (SE) practice shifting from a document-based to model-based paradigm as part of the larger digital engineering transformation happening in the industry (Papke, Wang, Kratzke, & Schreiber, 2020). MBSE is becoming more commonly practiced and is expected to eventually become the standard for SE (Friedenthal, Moore, & Steiner, 2014; Ramos, Ferreira, & Barceló, 2011).

MBSE "formalizes the practice of performing systems engineering" (Friedenthal et al., 2014). Despite this statement of formalization, MBSE means different things to different people and organizations. Some consider MBSE a modeling language, and others believe it is a specific framework (Vaneman, 2018). Table 1 shows examples of this discrepancy found in the literature.

Table 1: Definitions of MBSE

Definition	**Source**
"Model-based systems engineering 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."	INCOSE (Friedenthal, Griego, & Sampson, 2007)
"MBSE is fundamentally a thought process. It provides the framework to allow the systems engineering team to be effective and consistent right from the start of any project. At the same time, it is flexible enough to allow the 'thought' process to adapt to special constraints of circumstances present in the problem."	(Long & Scott, 2011)
"MBSE is 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 systems engineering in a model-based or model-driven context."	(Vaneman, 2016)
"MBSE is the formalized application of modeling principles, methods, languages, and tools to the entire lifecycle of large, complex, interdisciplinary, sociotechnical systems."	(Ramos et al., 2011)
"MBSE is simply the notion that we can construct a model of a system that we can transform into the real thing."	(Mellor, Clark, & Futagami, 2003)

In this dissertation, I consider that MBSE requires the use of tools, modeling languages, and methods, often grouped together in a methodology (Estefan, 2007; Friedenthal et al., 2014; Papke, 2017; Selvy, Claver, & Angeli, 2014; Weilkiens, Scheithauer, Di Maio, & Klusmann, 2016). Furthermore, I contend that MBSE can be characterized in two different contexts: a process, and a method (Henderson & Salado, 2021a). According to Martin, a process is "a logical sequence of tasks performed to achieve a particular object," and a method is a set of "techniques for performing a process" (Martin, 1996). MBSE can be classified as a method of performing the SE process, as it describes how SE tasks should be carried out. MBSE is also a process itself because

it describes what activities are to be performed without specifying how. Therefore, MBSE requires a designated method to specify how the tasks will be accomplished.

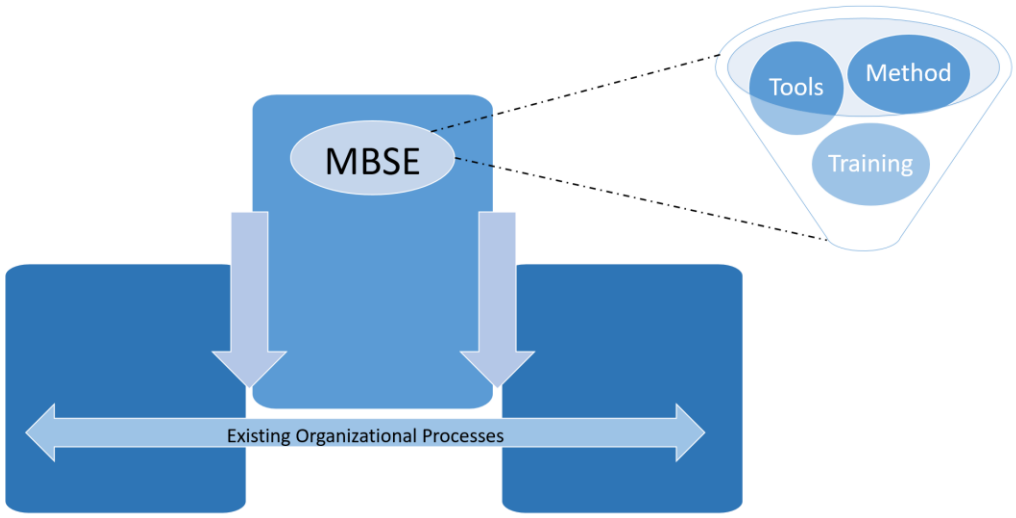

Figure 1: Visual depiction of MBSE adoption as a process and method

The driving force behind MBSE is the establishment of an authoritative source of truth (ASoT) (Long & Scott, 2011; Madni & Sievers, 2018; Papke et al., 2020; Vaneman, 2018). With MBSE, information is captured and maintained via data repositories in a system modeling tool. Any change that is made in the system design data is reflected across all elements of the model. Since MBSE connects to different disciplines through the SE process, it is often necessary to integrate different tools together to exchange information (Papke et al., 2020; Vaneman, 2018). This is necessary to maintain the model as the ASoT, so that different departments in an organization can also make changes that are reflected across the entire model. Thus, for MBSE to operate as intended, more than just the systems engineers need to have some level of understanding regarding MBSE.

1.2 Problem Setting

The adoption and implementation of MBSE is a widely reported problem throughout the industry (Broodney, Dotan, Greenberg, & Masin, 2012; Chami & Bruel, 2018; Papke et al., 2020; Wang, Izygon, Okon, Wagner, & Garner, 2016; Weilkiens et al., 2016). The process to adopt MBSE is difficult and the "lack of support on how to efficiently implement MBSE" is a critical barrier to adoption (Huldt & Stenius, 2019). Since there is not a singular path to implement MBSE, the decision to adopt MBSE comes with a variety of questions that need to be answered (Wang et al., 2016):

- *What training is needed for whom?*
- *What is the right mix of team skills needed?*
- *What modeling methodology to use?*
- *What tool to use?*
- *What modeling language to use?*

- *[Is] there some guideline or a process to follow?*

There are many reported barriers to MBSE adoption (Chami & Bruel, 2018; Haskins, 2011; Huldt & Stenius, 2019; Lu, Wen, Liu, Gürdür, & Törngren, 2018; Papke, 2017; Ramos et al., 2011; Wang et al., 2016). The barriers to MBSE adoption can be grouped in three categories: economic, technical, and organizational. In order to adopt MBSE in the first place, the economic barrier of cost needs to be addressed. There is a known initial investment to adopt MBSE (Foster, 2011; Parrott, 2016), but the value it will provide and success stories are not communicated appropriately (Cloutier, 2015; Haskins, 2011; Huldt & Stenius, 2019; McDermott et al., 2020; Motamedian, 2013; Vogelsang, Amorim, Pudlitz, Gersing, & Philipps, 2017). Leadership needs to be convinced that MBSE is worth the cost and effort, otherwise they will not endorse the investment (Trauth, Carroll, Matta, Salguero, & Griego, 2017).

Technical barriers include immaturity of products, lack of understanding of MBSE methods and processes, and the difficulty of teaching others how to perform MBSE. In a recent survey of those in the SE field (including industry, government, and academia), around 63% of respondents believe MBSE processes and tools to be immature (McDermott et al., 2020). This belief is echoed in the literature, as Haskins concludes: "just using models with today's current maturity of tool support… does not meet the full criteria of MBSE" (Haskins, 2011). If some current tools and processes are indeed immature, then they are not functioning at the capability level outlined in descriptions of MBSE. In order to achieve activities such as model-based verification and validation (Madni & Sievers, 2018; Selvy et al., 2018), trade-off analysis (Hause, 2018; Hause, Ragon, Chen, & Karlsson, 2019; Spyropoulos & Baras, 2013), and others, additional tools and processes need to be integrated to make up for the lack of maturity of MBSE tools.

The effort of adoption and all of the decisions that need to be made necessitates a knowledge of MBSE tools, methodologies, training procedures, and adoption processes. The lack of knowledge and skills of tool operations is often cited as a top hindrance to adopting MBSE (Chami, Aleksandraviciene, Morkevicius, & Bruel, 2018; Cloutier, 2015; Huldt & Stenius, 2019; Lu et al., 2018; Vogelsang et al., 2017). To compound that sentiment, MBSE is claimed to be difficult to teach and train others to do (Carson, 2015; Friedenthal, 2009; Huldt & Stenius, 2019; Mitchell, 2014; Vogelsang et al., 2017).

Organizational barriers are well documented in any industry. The root cause is often a resistance to change (Kotter, 2012), examples of which are well-documented in the MBSE literature (Chami et al., 2018; Cloutier, 2015; Lu et al., 2018; Parrott, 2016). If the culture of the organization is not compatible with adopting the new technology, it will be very difficult to successfully implement (Bone & Cloutier, 2010). People need to be willing to learn and use the new tools and methods for MBSE to work (Mitchell, 2014; Vogelsang et al., 2017). This can be made even more difficult if the organizational structure and current processes do not facilitate an MBSE environment (Huldt & Stenius, 2019).

Because MBSE ideally involves more than just the systems engineers, it is beneficial for the organization where it is being adopted to be invested in its successful implementation (Trauth et al., 2017). Formally, an organization can be conceptualized as "a consciously coordinated social

entity, with a relatively identifiable boundary, which functions on a relatively continuous basis to achieve a common goal or set of goals" (Robbins, 1990). Essentially this involves a group of people working for a common goal, and the efforts required to coordinate and manage those people (Kennedy, Scott, Shirvani, & Campbell, 2020). The division of labor and the resulting need for coordination are well established in the literature as the central features of an organization (Burton, DeSanctis, & Obel, 2006; Groth, 1999). Since MBSE requires input from potentially multiple disciplines and/or departments, there needs to be consideration in how those groups will be coordinated. If the division of labor and/or coordination mechanisms do not support an MBSE environment, there will likely be difficulties in establishing a long-term use.

An important distinction in modern organizations is that they are intentionally designed, and that design impacts the functionality and output of the organization. The organization's primary structure and characteristics should support the purpose and central outcomes of the organization (Huber & McDaniel, 1986). Therefore, when designing an organization's structure, it is critical to consider what are the required processes and information processing needs to achieve the desired strategy/goals of the organization (Burton et al., 2006; Groth, 1999). This interdependent relationship is most notably captured in Conway's Law: "organizations which design systems are constrained to produce designs which are copies of the communication structures of these organizations" (Conway, 1968). Similarly, "structure not only shapes the competence of the organization, but also the processes that shape performance" (Tran & Tian, 2013). This sentiment is echoed across the organizational literature (Burton et al., 2006; DeCanio, Dibble, & Amir-Atefi, 2000; Hax & Majluf, 1981; Johari & Yahya, 2009). In other words, how the organization is designed could impact the efficacy of the MBSE adoption and implementation.

1.3 Problem statement

MBSE can significantly change "how systems engineers and engineers of all disciplines perform design and development activities" (Papke et al., 2020). MBSE adoption needs "the right personnel setup and utilization" to be successful (Chami et al., 2018). Method, tool, and language should work with the skills and experience of the people who have to carry it out. How the people and the system interact needs to be considered when making those key adoption decisions (Madni & Sievers, 2018). This may require examining currently established processes, structures, and roles to see if they support or detract from MBSE efforts. According to Papke et al. (2020), "understanding potential or needed changes in organizational structure, responsibilities and competencies required for successful MBSE adoption is critical." These organizational changes need to be identified and addressed in the adoption process. As reported by 61% of responders in an MBSE survey, "improving organizational structures would be the most effective way to improve the impact of MBSE" (Huldt & Stenius, 2019). Structure in this survey specifically referred to a lack of designated responsibilities regarding MBSE and lack of designated MBSE departments. Lu et al.'s survey (2018) responses echo this notion, as respondents who had a centralized department for MBSE at the company level reported using MBSE more frequently than other structures. Those other structures include: a specific group for MBSE in department, specific roles for MBSE in department, specific roles as part time, and no specific roles or department.

Organizational structure and culture have intuitively been believed to be critical barriers to the successful adoption of MBSE (as discussed above), but little work has been done to discover what the impacts of these organizational factors are. Making the wrong decision during the adoption process can result in a failed adoption effort; which would likely set the organization back financially, and negatively impact the perspectives those in the organization have about MBSE. So understanding how organizational structure factors impact adoption should have a significant positive effect on future MBSE adoption efforts.

1.4 Research question and objectives

The purpose of this research is to examine the relationship between organizational structure and the adoption of MBSE. Organizational structure is the environment where MBSE adoption happens. It is the foundation upon which other decisions related to adopting MBSE must operate. In this way, organizational structure has the potential to have a significant impact on the actual process of adopting and implementing MBSE. To that end, this dissertation seeks to answer the question: **how does organizational structure influence the adoption and implementation of MBSE?** Determining these effects will provide insights that can be incorporated into the adoption process of MBSE, which is often not well understood (as mentioned in Section 1.2).

This research question will be addressed in three research objectives:

Research objective 1: Relate organizational structure characteristics to MBSE adoption and implementation measures.

There exist many reports from experiences adopting MBSE stating observations about how organizational structural factors may have impacted adoption efforts (Andersson, Herzog, Johansson, & Johansson, 2010; Bayer et al., 2012; Simpson, Sindiy, & McVittie, 2012; Weiland & Holladay, 2017). Additionally, many of these reports also recommend what structural characteristics would allow for successful adoption (based on their experiences). But because these recommendations are based on that one organization's experience, they cannot reliably indicate if those characteristics have positive effects on adoption. The structural factors may not have actually influenced the success of the adoption effort. Evaluating structural factors across different organizations should provide some indication of whether those structural factors are significantly impacting outcomes. Since there is little-to-no data measuring MBSE adoption and use in organizations, achieving this research objective will provide an exploratory data set for the topic.

Research objective 2: Discover how organizational factors contribute to decisions made and other aspects of the MBSE adoption process.

The adoption process of MBSE has been explored up to this point largely through surveys (Bone & Cloutier, 2010; Chami & Bruel, 2018; Cloutier, 2015; Huldt & Stenius, 2019; Lu et al., 2018; McDermott et al., 2020; Motamedian, 2013; Tower, 2013). A notable similarity between all these surveys is they ask participants to articulate barriers or challenges with MBSE adoption. Many of these surveys were distributed with the purpose of capturing the current state of MBSE adoption, and in some cases specifically the barriers to adoption. The fact that every survey includes questions about adoption challenges may indicate that adoption is still a prevalent issue. As mentioned previously, the process to adopt MBSE is difficult and the "lack of support on how

to efficiently implement MBSE" is a critical barrier to adoption (Huldt & Stenius, 2019). The goal behind this research objective is to further explore and build on the relationships discovered from research objective 1.

Research objective 3: Connect different organizational structure and adoption variables together to derive critical variables in the adoption process.

As mentioned previously, most information about MBSE adoption comes from descriptions of challenges from surveys or lessons learned from single organizations that implemented MBSE. The more holistic representations of MBSE adoption obtained from research objectives 1 and 2 provide the fodder to examine the adoption process at a deeper level. By depicting the adoption process as the variables that contribute to it and how those variables relate, one can determine where the critical points in the process are.

1.5 Merit of research

There is a need to address questions of organizational factors' influence in SE reported by systems engineering practitioners. "There was particular interest regarding possible differences [in communication] between heavily hierarchical and largely flat structures… Of particular research interest are the challenges expressed relating to collaboration between organizational units" (White & Mesmer, 2020). Organizational factors are commonly reported as barriers to the introduction of MBSE. Recommendations of effective structure for MBSE are largely ad hoc and based on observations of a singular experience. Overall, there is a perception amongst those in industry that there is some connection between organizational structure and the effective adoption of MBSE.

This work will provide the following contributions:

1) A structured analysis of organizational structure characteristics in organizations that are adopting MBSE. Relevant characteristics will be determined from an understanding of the organizational design literature. This should provide a more comprehensive representation of organizational structure as a concept.

2) An indication of whether organizational structure factors have an impact on adoption, or if the reported recommendations are beneficial only in the environment of that specific implementation effort. In other words, are organizational structure factors responsible for variations in the adoption and implementation of MBSE.

3) Insight on factors influencing decisions made in the adoption and implementation of MBSE.

4) An exploration of the MBSE adoption process through the creation of a causal model with a focus on organizational structure.

Ch. 2 Literature Review

2.1 Taxonomy

The literature review used to support this study was conducted in two stages. The first stage was a general exploration of the literature related to organizational structure and MBSE. This included looking through papers I had already read on MBSE, as well as searching databases in a more unstructured manner. The purpose of this initial phase was to get a sense of what work had been done in this area, as well as discover what smaller topics would be relevant. From the initial exploration of the literature, four subtopics emerged that would allow for more targeted searches in the next phase. Organizational structure fundamentals is a necessary area of research in order to describe and define the variables that will be used to represent organizational structure. An overview of this field will be presented in Section 2.2. Section 2.3 presents studies that have examined the impact of organizational structure on adoption of technology other than MBSE. This subtopic shows that there is a precedent for conducting this type of research. It also supports the hypothesis that there could be a relationship between organizational structure and adoption of MBSE. Sections 2.4 and 2.5 describe literature that discusses organizational structure in the context of MBSE or SE. The two distinctions in these subtopics emerged from the first phase of the literature exploration. Table 2 describes the keywords that were used to search for papers related to each of the subtopics in the second stage.

Table 2: Keywords used in literature search

Subtopic	**Keywords**
Organizational structure fundamentals	Organizational structure, organizational design
Impact of organizational structure on adoption of technology	"Organizational structure" + adoption of technology
Related work on effects of organizational structure on MBSE/SE	(MBSE, SE) + "organizational structure"
Structural recommendations from literature	MBSE + (adopt, implement, introduce) + (lessons learned, organizational structure, observed benefits, experience from)

The databases used to conduct the searches include Google Scholar, IEEE Xplore, EBSCO, and Wiley Online Library.

2.2 Organizational structure

There are many different theories and conceptualizations about organizational structure in the literature (Tran & Tian, 2013). Table 3 shows a brief summary of the most well-known theories about organizational structure. All of the theories here represent different perspectives of how organizations function. The information processing view of organizations is an effective lens to examine how systems, especially those using MBSE, operate in an organization. Therefore, I will be primarily using concepts from this theory in the rest of the analysis.

Table 3: Theories of organizational structure

Theory	*Definition*
Classical theory	Regardless of the nature of the organization there are certain universal principles that should be followed to obtain a successful performance (Hax & Majluf, 1981)
Human relations theory	Performance of an organization depends exclusively on human characteristics and behavior in an organizational setting (Hax & Majluf, 1981)
Contingency theory	The best organizational design is contingent upon the environmental conditions that the organization faces (Hax & Majluf, 1981)
Organizational decision-making theory	Organizational structure is seen as a set of decision making units in a communication network. Organizations should be designed to facilitate the making of organizational decisions (Hax & Majluf, 1981; Huber & McDaniel, 1986)
Information processing theory of organizations	The basic function of the organization's structure is to create the most appropriate configuration of work units (as well as the linkages between these units) to facilitate the effective collection, processing and distribution of information (Tushman & Nadler, 1978)

Despite the differing theories behind how an organization operates and how structure should be designed, there is a general agreement that the fundamental aspects to address when designing an organization are (Burton et al., 2006; Hax & Majluf, 1981; Johari & Yahya, 2009; Meijaard, Brand, & Mosselman, 2005; Tran & Tian, 2013; Tushman & Nadler, 1978):

> *(1) How to divide the whole organization into subunits that perform tasks that contribute to the overall product of the organization in some way.*
>
> *(2) How to coordinate and facilitate communication among those subunits to realize the bigger task of the organization.*

Simply put, an organizational structure can be defined as the "sum total of the ways in which it divides its labor into distinct tasks and then achieves coordination among them" (Mintzberg, 1989).

Organizational systems can be considered recursive (Kennedy et al., 2020). In other words, each subunit (i.e. team, department, division) can be structured as its own organization, with unique characteristics that are appropriate for that subunit (Burton et al., 2006). Instead of focusing on the static definition of the structure of the whole organization, Tushman and Nadler (1978) advocate focusing the design at the level of the subunit. In the organizational design process proposed by Burton et al. (2006), design of the organization occurs at the highest "unit of analysis," then works down the levels recursively. For example, those designing an organization's structure would determine the strategy/goal of the organization, departments, and teams, and design a structure at each level that correlates to that strategy. This means that structure can be more specifically tailored to the needs of that unit. Additionally, the subunits may need to adjust structural characteristics over the course of a project in order to deal with different levels of problem solving and uncertainty (Kennedy et al., 2020). Having structures designed at each subunit allows for this level of flexibility. Hence, it is important not only to consider how the

structure of the organization impacts MBSE adoption, but also the structure of those subunits where MBSE activities are carried out.

Subunits are created (especially as organizations grow) that have "specialized tasks and/or deal with specific aspects of the organization's task environment (Tushman & Nadler, 1978). While subunits have distinct tasks, there is a level of interdependency since all of the subunits are working towards creating a collective outcome. The more dependent a subunit's tasks are on the work of other subunits, the greater need for coordination and communication (Tushman & Nadler, 1978). Therefore, task design is another important aspect of organizational design at the subunit level. Task design specifically refers to "decomposing work into subtasks while considering the coordination among the subtasks to meet organizational goals" (Burton et al., 2006). Several factors to consider when designing and allocating tasks include: the predictability/uncertainty of the task, level of complexity, intra- and inter- unit task interdependence, and the environment of the subunit (Tushman & Nadler, 1978). How MBSE-related tasks are divided in the organization will necessitate different methods of coordination/communication to enable a successful MBSE implementation.

Thus far, we have discussed elements of formal organizational structure. The formal structure determines how roles and responsibilities are assigned, how control structures are maintained, and how information is shared across the organization (Kennedy et al., 2020; Zenger, Lazzarini, & Poppo, 2000). However, informal organizational structures tend to emerge to overcome the constraints and limitations of the formal (Bonanomi, Hall, Staub-French, Tucker, & Talamo, 2019). Informal structures consist of roles and relationships that are created unofficially outside the formal organizational structure (Cross & Sproull, 2004). Furthermore, the dynamic nature of informal structures allows the organization a level of flexibility and adaptability that the formal structure typically does not (Kennedy et al., 2020). For example, in a digital transformation case study, the formal authority chains were not connecting people to those with knowledge about the new digital technologies (Bonanomi et al., 2019). To compensate, employees sought help from knowledgeable peers who became new informal leaders in the transformation effort. However, this resulted in the new informal leaders being unhappy with their lack of formal recognition for the extra work they were doing. This could have been avoided if the relationships had been formally codified, potentially as mentors or coaches, with designated tasks related to helping others. These factors should be considered when deciding how to coordinate between subunits, especially with the introduction of MBSE to those unfamiliar with it.

2.2.1 Division of labor

The first central consideration for organizations is how to divide the organization into subunits. Another way to view this is how to divide the tasks necessary to produce the desired outcome, whether that be a product or a service. The typical way of making this decision is to consider which tasks have the most immediate interdependencies, and group those functions together (Groth, 1999). Having interdependent tasks occur in close physical/organizational proximity should allow for better communication and coordination, which is especially important the more that tasks are dependent upon one another. In this way, how labor is divided can impact what level of coordination or communication channels are necessary.

There are two basic ways an organization can be partitioned (Burton et al., 2006). If the organization has more of a product/service/customer orientation, the firm should be divided based on the output of the firm. If the organization has a higher emphasis on functional specialization, the firm should be partitioned based on internal activities. At the highest level, this is represented in the organization chart and is typically characterized as one of the archetypal "types of structure" (see Section 2.2.4).

2.2.2 Coordination and communication

The second consideration for organizations is how to connect the divided subunits so they can work together to enact the organization's purpose. This is done through the establishment of coordination and/or communication systems. These concepts are closely coupled: communication is a necessary mechanism for coordination, and coordination is the formal definition of how communication will occur (Groth, 1999). Communication is often lauded as one of the most important factors contributing to organizations operating effectively and efficiently (Bardia, 2010). Communication that is fast and easy is necessary for the exchange of knowledge and information, which is critical for implementing new technologies or methods (Nahm, Vonderembse, & Koufteros, 2003).

Generally, coordination can occur in two ways: coordination by feedback (e.g. direct supervision) and coordination by program (e.g. standardization of work) (Groth, 1999). Feedback focuses on relationships between people, while program focuses on formal structures and procedures. Coordination needs to occur vertically through the different levels of the organization, and laterally across different subunits. The degree to which these mechanisms are required will depend on how the organization has defined it subunits. Different examples of coordinating mechanisms are presented below (Groth, 1999; Hax & Majluf, 1981):

- Vertical mechanisms: formal hierarchy, standard rules and procedures, planning and information systems
- Lateral mechanisms: direct informal contacts, liaison roles between groups, task forces, permanent coordinating teams, coordinating manager or department, use of the matrix structure

Additionally, the use of technology (i.e. central databases of information) can provide implicit coordination because there is a common base of information that is updated when changes are made (Groth, 1999). For example, if aspects of MBSE are successfully implemented (such as an ASoT), this could serve as coordination between different groups/stakeholders because they can see when changes are made across the model. This coordinating mechanism can be used for vertical and lateral coordination.

2.2.3 Model-driven organizations

The book *Future Organizational Design: The Scope for the IT-based Enterprise* explores how advancing technology could impact organizations (Groth, 1999). Specifically, it explores how the use of models could lead to what it calls 'Model-driven organizations.' In other words: "the model and the suite of systems built on it must incorporate so much of the organization's

functionality and dynamics that the organization members will work and communicate mainly with the system and model itself." The improved information access and knowledge exchange can lead to middle management becoming obsolete. It will also, as mentioned in section 2.2.2, have implicit coordination built in with an improved level and quality of communication and collaboration. Groth (1999) presents a hypothetical example of how this organization will operate:

> *Changes were primarily not communicated directly to those concerned and those who might possibly be concerned; they were simply entered into the system (model). Those who were concerned could then extract that part of the information they needed when they needed it. Just as importantly, the information was not entered into the system in separate, dedicated operations, it was in fact created there as a part of the normal work process, as the designers and others used the system as a tool for their day-to-day work. The system thus provided the main tools for work, structured the communication by acting as medium, made the communication a lot more precise because of its criteria for information entry and information creation, and made the communication process much more selective by eliminating most of the communication that takes place.*

MBSE as it is intended should be able to facilitate this model-driven organization. However, this requires MBSE to be adopted and implemented successfully and uniformly, which is currently a challenge (see Chapter 1).

2.2.4 Organizational structure archetypes

There are several widely-used archetypes of organizational structure. These are commonly understood and are good reference points for discussion about structure. Typically, these types of structures are evident from the organization chart, which is an artifact that shows the lines of authority and communication between the subunits of the organization. Table 4 presents the most frequently used structure archetypes.

Table 4: Common organizational structure archetypes

Archetype	**Definition**
Simple	Characterized by a lack of structure. Best for small firms. (Burton et al., 2006)
Functional	Characterized by an emphasis on hierarchies and job specialization. Can accommodate large organizations and a high degree of information processing. Works well for tasks that are repeated frequently and in high volume. (Burton et al., 2006; Hax & Majluf, 1981)
Divisional/ Product/ Project	Organization is divided into subunits based on a specific product, project, or service. Subunits are relatively independent and externally focused. Flexible and responsive to external markets. (Burton et al., 2006; Hax & Majluf, 1981)
Matrix	The organization is simultaneously divided based on function and product. Lateral divisions with functional hierarchy that are coordinated by matrix managers. Challenges can occur with conflicts between function and division as employees will have a manager for both. (Burton et al., 2006; Hax & Majluf, 1981)

Hybrid	Organizations in real life are rarely seen as purely functional, divisional, or matrix. Typically, there is a combination of these forms. For example, division of labor at highest level includes product focused divisions and function focused divisions. (Groth, 1999; Hax & Majluf, 1981)

Another way structures are typified is through the organic versus mechanistic (inorganic) paradigm (Nahm et al., 2003). These paradigms as described by Nahm et al. are presented below:

- **Organic**: "*The organic paradigm recognizes the unstable, even chaotic nature of the external environment. Technologies are typically non-routine, and size is less important. Organizations are based more on teamwork, face-to-face interactions, learning, and innovation. Qualities traditionally considered egalitarian such as equality, empowerment, horizontal relationships, and consensus building become more important.*"

- **Mechanistic**: "*The mechanistic (inorganic) paradigm is effective when environments have a high degree of certainty, technologies tend to be routine, organizations are designed for large-scale, and employees are treated as another resource. Internal structures tend to be vertical, functional, and bureaucratic. The organization uses rational analysis and is guided by parochial values reflected in the superior-subordinate power distinctions.*"

2.2.5 Dimensions of organizational structure

There are a great number of dimensions or characteristics used to define different aspects of organizational structure (Nahm et al., 2003). Because most structures are not a pure form of the typical archetypes, these dimensions which can be evaluated on a scale may be better able to characterize organizational structure. This is especially relevant at lower levels of evaluation (e.g., projects or teams).

Formalization (job codification): The extent an organization precisely prescribes rules and procedures related to jobs in different situations (Burton et al., 2006; Johari & Yahya, 2009; Meijaard et al., 2005; Nahm et al., 2003; Oliveira & Martins, 2011; Tran & Tian, 2013). In organizations with high formalization, there are "explicit rules which are likely to impede the spontaneity and flexibility needed for internal innovation" (Tran & Tian, 2013). Organizations with low levels of formalization still have rules and procedures, but these policies encourage "creative, autonomous work and learning" (Nahm et al., 2003). Essentially, the level of formalization dictates the degree to which the behavior of individuals is strictly defined in their different roles.

Centralization (locus of decision-making): The degree to which power and control are distributed or concentrated across an organization (Burton et al., 2006; Hax & Majluf, 1981; Huber & McDaniel, 1986; Johari & Yahya, 2009; Nahm et al., 2003; Oliveira & Martins, 2011; Tran & Tian, 2013). In organizations with high centralization, authority is closely held by a few positions higher up the hierarchy. These organizations often have lower levels of commitment and involvement in workers at lower levels of the hierarchy. In organizations with low centralization, decisions are delegated to lower levels of the organization which makes those lower subunits more autonomous. This variable is also measured conversely by some authors as decentralization

(Meijaard et al., 2005). Organizations that are more decentralized (less centralized) have less information processing requirements because less information needs to be communicated up the hierarchy to make decisions (Groth, 1999; Hax & Majluf, 1981).

Specialization (horizontal integration**)**: The degree that different organizational units perform tasks and use skills that are different from one another (Burton et al., 2006; Huber & McDaniel, 1986; Meijaard et al., 2005; Nahm et al., 2003). In organizations that are highly specialized (low horizontal integration), subunits have highly specified tasks, but the scope of responsibilities in the unit is low. Departments are functionally separated and have a narrow understanding of problems and issues. In organizations with low specialization (high horizontal integration), workers are responsible for a greater number of tasks and require a wider breadth of knowledge and skills. Departments are more integrated in their work and training needs.

Vertical differentiation (layers in hierarchy): The number of separate organizational units, hierarchical levels, and/or managers an organization has (Burton et al., 2006; Meijaard et al., 2005; Nahm et al., 2003). Organizations with high vertical differentiation have many levels of management and hierarchy. Organizations with low vertical differentiation are more flat, with few levels of management in the organization.

Professionalism (complexity): The level of knowledge, expertise, and education that an organization's members have (Oliveira & Martins, 2011). An organization with a high level of complexity will have members that are highly educated, knowledgeable, and skilled. Organizations with low levels of professionalism typically have tasks that require less knowledge and therefore education, so the workforce reflects that.

Flexibility: The ease that an organization's structures and processes can be changed (Huber & McDaniel, 1986). Organizations that are highly flexible are better capable of adjusting to non-routine decisions and situations. In an organization with low flexibility, there is difficulty changing any processes or structures. This characteristic should be determined by how dynamic or static the environment an organization is.

Interconnectedness (level of communication): The degree to which communication across units is easy, fast, and abundant (Nahm et al., 2003; Oliveira & Martins, 2011). Organizations that are highly interconnected have units that are linked by strong interpersonal networks that make communication more likely to occur. In organizations that have a low level of interconnectedness, communication is slow, difficult, and infrequent.

2.3 Effects of organizational structure on the adoption of technology

The relationship between organizational structure and the adoption of new technologies has been thoroughly explored in the literature for various different technologies. The relationship was explored in both directions. Many authors believed that the adoption of new technologies would either facilitate different types of organizational structures, or would require different organizational structures to effectively use the technology (Bonanomi et al., 2019; Colombo & Delmastro, 2002; Febrianti, Yudhistira, & Kusrini, 2020; Garrido Azevedo, Ferreira, & Leitão, 2007; Gorchakova & Sazonova, 2017; Healy & Iles, 2003; Huber, 1990; Kretschmer & Khashabi, 2020; Y. Spanos, Prastacos, & Poulymenakou, 2000; Tiron-Tudor, Deliu, Farcane, & Dontu, 2021;

Vilkas, 2011; Zammuto, Griffith, Majchrzak, Dougherty, & Faraj, 2007). This was especially explored when the internet and IT innovations were enabling organizations to communicate and collaborate at a new level of ease and quality.

Conversely, the effect organizational structure has on the adoption of different technologies was also explored. Authors used statistical analyses of survey data, meta-analyses of literature, and case studies to see if different organizational characteristics influenced the adoption of new technologies. Some authors found there was no relationship between certain organizational structural characteristics and technology adoption (Sharma, 1994). One study specifically used the *decision to adopt new technologies* as the variable and found there was no relationship with organizational structure (Lai & Guynes, 1997). However, many studies did find significant relationships between organizational factors and technology adoption. Variables such as *organizational culture* (Akano & Campbell, 2014; Harper & Utley, 2001; C. M. McDermott & Stock, 1999; Park, Ribière, & Schulte, 2004; Sharma, 1994); *organizational readiness* (Hameed, Counsell, & Swift, 2012; Iacovou, Benbasat, & Dexter, 1995); *organizational slack* (Al-Shohaib, Al-Kandari, & Abdulrahim, 2009); *organizational processes* (Massini, Lewin, Numagami, & Pettigrew, 2002; Mettler & Rohner, 2009; Oliveira & Martins, 2011); and *organizational structure* (Cross & Gray, 2013; Gonçalves Silveira Fiates, Azevedo Fiates, Ribeiro Serra, & Portugal Ferreira, 2010; Hausman, Johnston, & Oyedele, 2005; Johnson, Klassen, Leenders, & Awaysheh, 2007; Kamaruddin & Udin, 2009; Khanagha, Volberda, Sidhu, & Oshri, 2013; Liu, Lu, & Yang, 2008; Patience & Toycan, 2016; Ramsey, Lord, Torrey, Marsch, & Lardiere, 2016; Sinde-Cantorna, Álvarez-Llorente, & Diéguez-Castrillón, 2013; Soja & Paliwoda-Pękosz, 2009; Sukmasetya, Purwandari, Kumaralalita, & Juraida, 2018) all were found to have an influence on the adoption of their respective technologies.

Many studies examined specific characteristics of organizational structure as their main variable(s), and found a significant effect on the adoption of technology. These examples serve as a precedent for the examination of organizational structure characteristics in the context of MBSE adoption.

Size. The size of an organization was found to have a significant relationship with the adoption of technology (Bondarouk, Parry, & Furtmueller, 2017; Garrido Azevedo et al., 2007; Johnson et al., 2007; Kamaruddin & Udin, 2009; Kouzari, Gerogiannis, Stamelos, & Kakarontzas, 2015; Oliveira & Martins, 2011; Sinde-Cantorna et al., 2013). One study specifically looked at size in terms of the size of teams, and found that there was a relationship between team size and technology adoption (Bradner, Mark, & Hertel, 2005). While some consider size a factor of organizational structure, others view size as an external condition that impacts organizational structure (Hall, Johnson, & Haas, 1967; Scott, 1975).

Formalization. Levels of formalization in an organization were found to have a relationship to the adoption of technology (Al-Shohaib et al., 2009; Alexiou, Khanagha, & Schippers, 2019; Cohn & Turyn, 1984; Ning, 2011). Formalization was generally found to be negatively associated with technology adoption. One study specifically noted that increased emphasis on detailed job descriptions had a negative association with technology adoption (Y. E. Spanos, Prastacos, & Poulymenakou, 2002). Another study divided the process of adopting technology into stages:

initiation, adoption, and implementation (Grover & Goslar, 1993). Formalization was found to be negatively associated with initiation and adoption (pressure to change and decision to adopt), but positively associated with implementation (installation and development of technology). This distinction demonstrates the importance of clearly defining what adoption is and to develop a measure that captures that.

Centralization. The degree of centralization in an organization was found to have a relationship with technology adoption (Al-Shohaib et al., 2009; Alexiou et al., 2019; Cohn & Turyn, 1984; Stoneking & Bievenue, 2019). Centralization was generally found to have a negative relationship with adoption. In the study from Grover and Goslar, centralization was found to have a positive relationship with initiation and adoption, and negative with implementation (1993). Contrarily, another study found that use of adopted technology increased as centralization increased (Johnson et al., 2007). It may be that centralization could have positive or negative effects depending on a number of factors (type of technology, size of organization and subunits, specific leadership, etc.).

Specialization. The level of specialization of a firm was found to have a positive relationship with technology adoption (Grover & Goslar, 1993). On the other hand, the ability of employees to perform multiple tasks/roles had a positive effect on adoption behaviors, specifically through job rotation and cross-functional roles (David-West, Iheanachor, & Kelikume, 2018; Rai & Patnayakuni, 1996). High specialization may be beneficial if the new technology is championed by subunits who have detailed knowledge of it. Low specialization may be beneficial to ensuring the technology is adopted and continued to be used across the organization because more people are familiar with it.

Vertical differentiation. The number of hierarchical levels in an organization was found to have a relationship with technology adoption (Ettlie & Reza, 1992; Garrido Azevedo et al., 2007; Millham & Eid, 2010). Structures that were more "flat" often had a positive relationship with adoption, while organizations with more levels in the hierarchy had more problems with adopting technology. Size and the type of technology may have an influence on the nature of this relationship. For example, Kouzari et al. claim that small organizations with flat structures have a hard time adopting one type of software process, but those same factors make them ideal candidates for a different type of process (Kouzari et al., 2015). Furthermore, the type of technology could negate the effects of vertical differentiation on adoption (e.g. if the technology enables better communication such as IT) (Forman & Gron, 2005; Garrido Azevedo et al., 2007).

Professionalism. The skills and knowledge of employees in the organization was found to have a positive relationship with the adoption of technology (Al-Shohaib et al., 2009). Technology expertise especially was found to have a significant relationship to the adoption of new technology (Hameed et al., 2012; Kwon & Zmud, 1987; Raymond, 1985).

Flexibility. The level of flexibility of an organization was found to have a positive relationship with the adoption of new technologies (David-West et al., 2018; Kouzari et al., 2015; Ning, 2011).

Interconnectedness. Communication was found to have an influence on the adoption of technology (Edmondson, Winslow, Bohmer, & Pisano, 2003). Open communication and established communication processes had a positive impact on technology adoption (David-West

et al., 2018). Formal and informal networks of contacts also had a positive effect on adoption (Jelinek, Ahearne, Mathieu, & Schillewaert, 2006; Oliveira & Martins, 2011). Furthermore, communication and coordination between subunits had a positive impact on technology adoption (Bruque-Cámara, Vargas-Sánchez, & Hernández-Ortiz, 2004; Ettlie & Reza, 1992).

2.4 Organizational structure and SE/MBSE

Since MBSE is a method of applying the SE process, looking at existing research of organizational structure for SE should provide insight into effective organizational structure for MBSE.

2.4.1 Incorporating SE into an existing organizational structure

"Systems Engineering often leads to new organizational structures and roles within a company" (Hause & Wilson, 2017). Because SE relates so many different disciplines/ departments, implementing SE into an existing organizational structure has to be intentional. Process, methods, and tools should ideally fit the conditions of a company, especially the organization's structure, business processes, and employee competencies (Czaja, Dumitrescu, & Anacker, 2016). Particularly in organizations that have rigid structures, organizational structures and processes may not be able to be changed in a timely manner due to slow decision making processes (Bretz, Kaiser, & Dumitrescu, 2019; Bretz, Könemann, Anacker, & Dumitrescu, 2020; Heihoff-Schwede, Bretz, Kaiser, & Dumitrescu, 2019). Organizations that can be flexible may have an advantage when it comes to effectively incorporating SE (Conway, 1968). In light of this, many recommend questioning and potentially adapting existing processes, structures, and ways of thinking (Heihoff-Schwede et al., 2019).

Furthermore, Bretz et al. (2019) state that SE should be introduced simultaneously across an organization. If SE is introduced from one department, there is a risk of not considering all stakeholder's needs and missing support from other departments (Bretz et al., 2019). Employees across the company need to understand SE and what their roles are in the SE process (Heihoff-Schwede et al., 2019). Documentation (e.g. rules, template, etc.) should be provided to create a common understanding of SE and SE artifacts.

2.4.2 Designing organizational structures for SE

According to Blanchard and Blyer (2016), systems engineering aligns closely with the product (or in this case project) organizational structure, but may also require some elements present in a functional organizational structure. A purely functional organization lacks an individual who is responsible for the whole project, which makes integration of cross-functional activities difficult. SE is heavily involved throughout the lifecycle of a project, and systems engineers need to "maintain effective communications" with all subunits involved in a project (Blanchard & Blyer, 2016). This is best facilitated through the project organizational structure. On the other hand, SE personnel need to have current knowledge of the latest technology applications and methods as well as access to technical expertise in other relevant disciplines. Functional units are in a better position to achieve these goals. Since a variety of organizational structure approaches can be applied in one firm, a combination of project and functional departments may be necessary to facilitate SE.

"To support the systems and system-of-systems perspective, knowledge from different disciplines needs to be integrated and merged in new roles (e.g. systems engineers)." (Calà, Lüder, Vollmar, & Foehr, 2017). The points where different development teams will interact or exchange information should be planned ahead of time. One paper recommends creating a team interaction matrix (Gausemeier, Gaukstern, & Tschirner, 2013). This involves mapping what team needs information from other teams in order to facilitate communication and collaboration at appropriate times. The organizational structure should allow for this level of flexibility and interaction between its subunits. Another technique for integrating disciplines is integrated product and process development (IPPD). IPPD is a "management technique that simultaneously integrates all essential acquisition activities through the use of multidiscipline teams" (Blanchard & Blyer, 2016). These teams (called integrated product teams) consist of individuals from the appropriate disciplines to solve a specific problem or execute a specific task. Regardless of the method, a high level of communication is necessary within the SE group, and between related functions for a given project (Blanchard & Blyer, 2016; Conroy, Mazzone, & Lin, 2013).

Whether SE functions should be dispersed through the organization or centralized in one department is debated in the literature. One survey examined the difference in the performance of organizations who have a separate SE department versus those who distribute SE functions throughout the organization (Elm & Goldenson, 2012). The results show that organizations with centralized SE are more effective at deploying SE best practices, but found virtually no difference in overall project performance. The authors hypothesize that this discrepancy may be due to certain SE tasks and artifacts being less integrated in the actual work of the project.

Bretz et al. (2020) present the concept of separating out SE units into different functions so it can be determined how centralized each function should be. Four structural archetypes emerge: decentral, central guidelines, central guide and support, and central. *Decentral* and *central* have all functions operate either decentralized or centralized respectively. The *central guidelines* categorization has SE as applied to projects and technical support roles decentralized, with a centralized unit that dictates guidelines and best practices for SE. The *central guide and support* archetype has both technical support and SE advancement functions in a central unit with only SE as applied to projects being decentralized. There are advantages and disadvantages to each level of centralization, selection should depend on what is important to the organization.

Friedenthal et al. (2014) describe a SE department that is divided into five teams with different tasks they are responsible for. These teams include the systems engineering management team, systems analysis team, requirements team, integration and test team, and architecture team.

The concept of shared services is also presented as a method of organizing SE. Shared services "centralize a subset of existing decentralized business functions in semi-autonomous business units" (Bansmann, Tschirner, & Dumitrescu, 2015). A shared service unit is made up of two real organizational units (shared service center and competence pool) and two virtual organizational units (networking expertise and internal capacity balancing). The virtual units support the real units. These units are defined further:

- *Shared service center*: centralizes processes that can be standardized

- *Competence pool*: specialists from different fields that create a knowledge base to support system development
- *Networking expertise*: identifies similar activities in different departments and encourages the corresponding specialists to communicate with each other
- *Internal balancing capacity*: allocates tasks to employees based on their profile and availability

Once these units are defined in an organization, SE processes are mapped to determine which unit is responsible for each process and which units will need to contribute but are not ultimately responsible.

2.4.3 Org structure influences how systems are designed

According to Melvin Conway: "there is a very close relationship between the structure of a system and the structure of an organization which design it" (Conway, 1968). Organizational structure, communication mechanisms, and channels between organizational units influence the system development process and ultimately a product's structure (Blanchard & Blyer, 2016; DeLaurentis, 2017; Qamar, Meinhart, & Walley, 2017). Specifically, requirements definition can be effected by organizational structure. For example, how different parts of the organization interact to generate the end product is often reflected as internal requirements in the system (Maheshwari, Davendralingam, Raz, & DeLaurentis, 2018). In other words, an ineffective organizational design can result in poor requirements being set (Calà et al., 2017). Additionally, the structure of an organization determines the modeling required at multiple abstraction levels, in order to address specific concerns of design teams or cater to different levels of technology understanding (Qamar et al., 2017).

2.4.4 Roles

A workshop with SE experts designated three important functions in SE: application, support, and advancement (Bretz et al., 2020). The roles required for the application of SE are laid out in Table 5.

Table 5: Role definition for the application of SE

Project Role	**Description**
SE manager	Manages technical efforts, mediates conflicts, plans/controls resources
Validator	Plans/ implements V&V efforts
Requirements Developer	Obtains stakeholder needs, translates needs into requirements, creates functional architecture
Integrator	Integrates subsystems and facilitates internal interfaces
Architect	Creates high-level architecture and sub-level specification, selects solutions
Analysis Engineer	Confirms planned system can meet requirements through simulation and analysis

Supporting roles include tasks that enable and support the application of SE, and advancement focuses on the continuous improve of SE. These supporting and advancement roles exist outside of project-related roles and can focus on keeping up with new tools and methodologies in SE.

Sheard defines twelve roles that make up the practice of systems engineering (Sheard, 1996). Table 6 defines those roles with a brief description of each. The first eleven roles were confirmed through a literature review of other papers which also refer to these roles, possibly under different names.

Table 6: Sheard systems engineering roles

SE Role	**Description**
Requirements owner	Translates customer needs into requirements, ensures functional architecture correctly captures requirements, creates and maintains subsystem specification
System designer	Creates high-level system architecture and design
System analyst	Confirms designed system will meet requirements through analysis and simulation
V&V engineer	Plans and implements system verification program
Logistics/ operations engineer	Owns primary responsibility in later phases of system life cycle, assists customer with system as needed
Glue among subunits	Serves as system integrator, manages interfaces for potential issues
Customer interface	Serves as primary interface for technical customers
Technical manager	Controls costs, schedules resources, maintains support groups
Information manager	Serves as manager of configuration management, data management, and metrics
Process engineer	Documents, follows, owns, and improves the project's and the organization's systems engineering processes
Coordinator	Coordinates groups and resolves issues
Classified Ads SE	Misc. tasks that advertisements for SE positions ask for

A literature review and analysis was recently conducted to determine what roles are necessary to allow for a successful adoption and implementation of MBSE (Gräßler, Wiechel, & Pottebaum, 2021). A role in this context is defined as "the user-neutral description of a function, a task, or an activity." This iteration of roles evolved from an updated version of Sheard's roles. The resulting roles include: project leader, requirements engineer, implementation engineer, process owner, V&V engineer, configuration manager, security engineer, system architect, modeling engineer, technical manager, system interface manager, information manager, life cycle engineer, stakeholder interface manager, systems analyst, entrepreneur, and subject-matter expert. It should be noted that one person can perform several roles simultaneously.

The Systems Modeling Toolbox methodology defines roles that apply to personnel including the project manager, requirements engineer, and system architect (Weilkiens et al., 2016). These roles are described in Table 7. Similarly, a case study implementing MBSE delegated

a requirements manager and a functional architect to each project (Chami et al., 2018). But in addition to that, each project had a designated modeler.

Table 7: Allocation of roles in the systems modeling toolbox methodology

Primary Performer	**Defined role/task**
Project manager	Describe the system idea and objectives
Requirements engineer	Identify stakeholders, model requirements, identify systems context, identify system use cases, identify system processes, model use case activities, model the domain knowledge
System architect	Describe the base architecture, model the logical architecture, model the product architecture, verify architecture with scenarios, define system states

2.4.5 MBSE adoption simulation

One study looked generally at adoption of MBSE at an organizational level and a project level (Naugle, Gunda, & Doyle, 2019). Specifically, they conducted a social network analysis to analyze if introducing MBSE at the organization level or the project level had an influence on the number of people in the organization who adopted MBSE. They also simulated different cognitive policies that could impact number of adopters. Adoption in this case referred to the decision to adopt MBSE. The most impactful policy tested was increasing the number of staff that were trained. Having a low number of staff who know MBSE initially lead to struggles at the organizational and project levels.

Adopting at the project level was found to have a more stable population of adopters than at the organizational level. Specifically, adoption at the project level if managers are the initial adopters as opposed to staff. This distinction did not matter at the organizational level. The level of network connection also influences the rate of adoption, so it is important for those who know MBSE to interact with others in their projects. Additionally, flat networks had virtually no adoption at the organization level. Multilevel organizational structures and manager involvement were important factors in the spread of adoption.

The goal behind this project was to understand what factors have an influence on the decision to use MBSE. It also tested which of these factors could be adjusted to positively affect adoption. While there are some similarities to the methods used in this dissertation study (such as the use of causal mapping), my work has several distinctions. First, this study focused specifically on the decision to adopt MBSE, while my work will examine both adoption and implementation at the organizational level. The causal model created by Naugle et al. is centered on the individual and heavily features perceptions as variables. Second, my research is targeting organizational structure factors specifically. The study by Naugle et al. (2019) did not appear to have a particular way of selecting what "factors" they tested. Third, the structural effects (organizational versus project level) were examined by Naugle et al. (2019) using a simplified infection simulation. In

other words, the only thing that impacted the adoption was contact with others in the network. It is not surprising that the project structure had a faster adoption under these conditions. My work will incorporate more factors that impact behavior of adoption. Furthermore, the causal model I create will include organizational structure factors. Naugle et al. (2019) separated the examination of structural effects and adoption factors into two different analyses.

2.5 Structural recommendations from MBSE case studies

In many reports of experiences adopting MBSE in organizations, the authors provide recommendations on how to adopt MBSE based on their experiences. Often these are recommendations related to organizational structure factors. A sample of these recommendations are reported in the following sections. These recommendations are based on a particular experience of adoption, so there is no way to tell if what was observed is due to aspects of organizational structure, or any number of other factors. However, these observations serve as a good source of information to base more systematic testing on.

2.5.1 Centralization v. decentralization

A common source of negative experiences from MBSE adoption efforts came from engineers not having the level of autonomy they would like. As one survey respondent reported: "Not enough autonomy given to the MBSE team; leadership, with no real MBSE knowledge, mandates 'terms and conditions' that can inhibit MBSE from reaching its true potential on a program or slow its adoption, against the recommendations of the MBSE champions" (Cloutier, 2015). Another organization had a substantial amount of conflict with their employees because the engineers wanted "to decide their working methodology themselves as opposed to hav[ing] methodology specialists dictating how the tools should be used" (Andersson et al., 2010). The problem with this was that the methodology the system architects chose lead to communication issues and misunderstandings between subunits in the project. Similarly, another organization had difficulty with the management of their MBSE effort because there was not a consistent modeling methodology defined at the beginning of the project (Herzog, Hallonquist, & Naeser, 2012). A considerable amount of effort and resources were needed to find a consensus on a modeling methodology.

Furthermore, one survey reports that organizations that are successful in adopting MBSE have addressed barriers to adoption at an upper management level. Reports from this study indicated that organizations that delegated authority and resources to lower levels of management "failed to establish a long-term capability" of MBSE (Huldt & Stenius, 2019). Another survey indicated that organizations which had a centralized MBSE department at the enterprise level used MBSE more frequently than those that did not (Lu et al., 2018).

2.5.2 Enterprise structure

It is common for organizations to create a team or teams which exist at the enterprise level to support various different projects that are adopting MBSE. This is done to take advantage of specialization and avoid excessive time on training/learning MBSE.

Core MBSE team. A frequent recommendation is to establish a core MBSE team (Chami et al., 2018; Kellner, Ringhofer, Hehenberger, Weingartner, & Friedl, 2016), but how that was defined varied. In one organization, it was effective to establish a small, core MBSE team that employed the modeling methods, and managed the model and all related data (Simpson et al., 2012). This team would export views to stakeholders in order to facilitate communication amongst the subunits of the project. Instead of all stakeholders directly contributing to the model, they used the model (which they still claim is the authoritative source of truth) as a reference. This approach requires more communication and coordination, but less knowledge/skills of how to use MBSE tools and methods across the subunits. Chami et al. (2018) call their definition of a core team a "center of competence." This group is typically a mix of internal personnel and external consultants, since it is often difficult to find enough skilled practitioners to perform all the tasks necessary. This mix should also involve domain experts who focus on the quality of content in the models, and project managers who "play the modeling governance role."

Papke et al. (2020) reported that a core MBSE team should provide guidance, training, and technical support for systems engineers who are still learning MBSE. This core team would also conduct technical reviews of the models. The authors also stated that a designated model manager/curator role should be created as reuse libraries are being established. In this configuration, the team supports multiple projects or programs that are first adopting MBSE. Thus, this MBSE core team exists at the enterprise level. Wang et al. (2016) also recommend having a team of expert modelers that can be deployed by the organization to any individual project. These designated MBSE modelers should be "matrixed" into each project, so they can continue to improve their MBSE skills and the time invested in learning MBSE is not wasted.

Adoption management team. An MBSE initiative can become an isolated effort if there is not a clear structure for the management of MBSE, as well as an appropriate level of understanding and skills in operating within the new model environment (Huldt & Stenius, 2019).

Boeing reported the creation of new positions referred to as business system managers who formed the bridge between the engineering division and IT division (Friedland, Malone, & Herrold, 2016). This new role assisted in the successful adoption and implementation of MBSE by addressing the lacking communication structures between subunits on the project. With this new role also came a new definition of how the departments are to relate with each other, which is another component of organizational structure.

Similarly, another organization found that establishing a team to manage the adoption of MBSE was effective (Weiland & Holladay, 2017). This team kept everyone organized and focused on learning and applying MBSE. By taking on tasks such as scheduling meetings and finding modeling experts when people are struggling, the rest of the MBSE team could concentrate on modeling efforts.

2.5.3 Project structure

In order to gain all the advantages MBSE has to offer, the organizational form has to be adjusted (Kellner et al., 2016). According to Kellner et al., "walls and borders" between different subunits need to be broken up to create a cohesive team where all disciplines are involved from

the start of a project. This reduces misunderstandings and the rework that comes from those mistakes.

The Jet Propulsion Laboratory center in NASA found that a three-tiered structure for MBSE projects was effective (Bayer et al., 2012). This translated to a set of core modeling experts within the larger systems engineering team, who are one component of the overall project (see Figure 2). For this specific project they had around six core modelers within a team of around 20 systems engineers. The authors stress that it is important to "avoid fencing [the core modeling team] off from the rest of the project" so that the models created are useful.

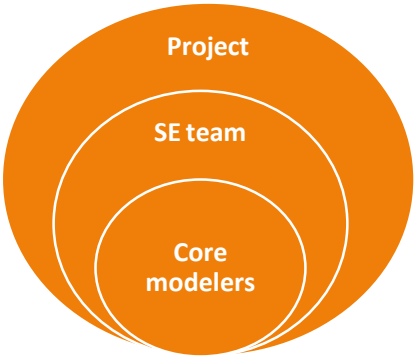

Figure 2: JPL project organization

The core modeling team provided rigor and consistency in modeling, while the experienced systems engineers provided guidance to make sure the team was modeling useful information. It was also important for the rest of the project team to have some training in order to understand and interact with the model and modeling team. Otherwise the model would have served no useful purpose in the project.

Similarly, European Aeronautic Defense and Space Company also found that "using modeling experts increase[d] acceptance of the MBSE approach" by other systems engineers (Asan, Albrecht, & Bilgen, 2014). The systems engineers were used as knowledge sources and analysis experts whom the modeling experts collected information from to develop models. Because they did not have to learn the modeling languages and tools right away, they were more accepting of the MBSE approach and over time developed skills in the language and tools.

Saab Aerosystems recommended establishing "short term knowledge circles" as opposed to traditional team structures (Andersson et al., 2010). In this approach, the nature of a project is examined in order to determine what knowledge or skills are needed to address aspects of the problem. Then those who can fill in the missing knowledge gaps are brought in to work on the problem. This is enabled through collaborative modeling environments where everyone can work on issues and communicate effectively. This also avoids the issue static organizations have with collaboration due to each department/division choosing its own tools and methods.

2.5.4 Training, coaching, mentor support

Those skilled in MBSE are needed to execute MBSE projects, educate/train management and other practitioners, and serve as a resource to those learning (Cloutier, 2015). Sufficient training and support of experienced modelers who can quickly answer questions is important to the sustained adoption of MBSE among teams and individuals (McVittie, Sindiy, & Simpson, 2012). It may be necessary to hire additional people or employ consultants who are familiar with modeling and MBSE to facilitate this (Gräßler et al., 2021). It is recommended to have at least two people on a project who are familiar with MBSE methods and tools (Andersson et al., 2010; Chami et al., 2018).

Many argue that all stakeholders involved should have some level of training in the MBSE tools and methods as well as the selected modeling language (Bayer et al., 2012; Gräßler et al., 2021; Papke et al., 2020; Piggott, Melanson, Hartman, & Adourian, 2008). One organization reported that focusing training on the prime users of MBSE lead to other engineering teams in the project being unable to interpret the models (Andersson et al., 2010). The level of training needed varies with how involved the stakeholder will be in the modeling efforts. One way to provide different levels of training is to divide training courses into generic courses provided by consultants, and more customized, in-depth topics provided by internal personnel (Chami et al., 2018).

Bonnet et al. described coaching as "help[ing] operational engineers implement MBSE on their own projects" (Bonnet, Voirin, Normand, & Exertier, 2015). Coaching and training opportunities should be provided from the corporate level to assist the operational engineers working at the project level. Mentors is another term that is used for those skilled in MBSE who can partner with systems engineers on different projects. Wang et al. (2016) recommended providing "project mentors who participate as part of the project team" and assist in system design and integration efforts. Having a "core network of MBSE key users" facilitates reuse and avoids loss of knowledge, while ensuring proper collaboration across subunits (Chami et al., 2018). Saab Aerosystems recommends having one experienced mentor for every 5-7 developers based on their experience (Andersson et al., 2010).

Ch. 3 Research Methodology

In order to address the proposed research question and objectives, a multi-method research design was employed. Figure 3 shows the methodology divided into tasks and the precedence between those tasks. The tasks designated as green represent the data collection tasks, which are the pivotal tasks that support all three research objectives.

To obtain data to assist with research objective 1, a survey was created and distributed to those who have been part of an organization that has adopted MBSE. The survey was also supported by semi-structured interviews. This interview data was evaluated to identify if there have been any relationships between organizational structural factors that have already been employed by an organization, and the adoption of MBSE. This will contribute to research objective 2. The data was used to develop a causal model of the MBSE adoption process. This will support research objective 3.

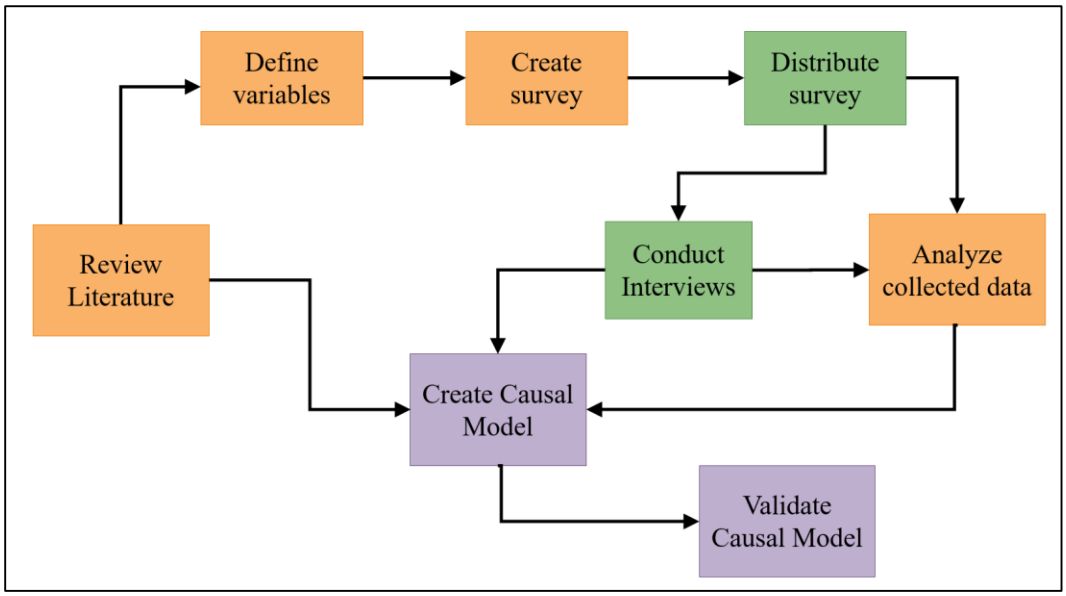

Figure 3: Research design - precedence diagram

3.1 Assessment of research instruments/methods

3.1.1 Survey

MBSE adoption has largely been measured through surveys. Table 8 shows questions that were used to measure adoption in previous notable surveys about MBSE. Many of these measures are addressed at the individual level, while others attempt to capture adoption at the organizational level. For example, Motamedian's survey (2013) asks the individual if they are using MBSE, but also asks about MBSE usage in projects and programs.

Table 8: Adoption measures in previous MBSE adoption surveys

Adoption Measure	Survey Paper
• What disciplines were involved in modelling with SysML? • To what extent does your customer/ client/ management/ stakeholders support your use of SysML?	(Bone & Cloutier, 2010)
• Are you using MBSE in your current position? • What is the extent of MBSE usage on pilot projects, R&D projects, and real programs?	(Motamedian, 2013)
• Do you use modelling in your work? • Do you believe your organization implements MBSE? • How mature is MBSE within your organization? • Which departments use MBSE in your organization?	(Tower, 2013)
• To what extent have you increased your usage of MBSE in the last 3 years within your organization?	(Cloutier & Bone, 2015)
• How long have you been working with MBSE?	(Chami & Bruel, 2018)
• Do you use MBSE in your team? • How frequently is MBSE used in projects?	(Lu et al., 2018)
• To what extent in the last 3 years has the company/ organization applied MBSE? • Approximately what is the general number of sites involved in an MBSE based project or program?	(Huldt & Stenius, 2019)
• How long has your organization been working toward MBSE? • Adoption gauged through questions related to the maturity of the organizations use of MBSE (based on MBSE Maturity Matrix)	(McDermott et al., 2020)

Surveys have also been shown to be one of the more efficient ways of collecting organizational data (Edwards & Thomas, 1993; Rogelberg & Stanton, 2007). The quantitative data obtained from survey results can also be used effectively to calculate correlations and other relationships between variables (Dresch, Lacerda, & Antunes, 2015).

3.1.2 Interviews

Interviews combat a weakness of surveys by allowing the participant to provide detailed explanations to questions (Dresch et al., 2015). There is also an enhanced ability to capture cause and effect relationships and other interdependencies (Vogelsang et al., 2017). The more descriptive nature of interviews should allow for a more detailed and holistic look at the MBSE adoption process. Due to the exploratory nature of this research, semi-structured interviews were used to allow for flexibility and the ability to "probe" participants to further explain or clarify responses (Saunders, Lewis, & Thornhill, 2009). So, the specific questions and order of questions varied depending on the experience/context of the participant's responses. This was particularly important given the potential range of understanding or experience different organizations have with MBSE.

3.1.3 Causal model

A causal map is a "directed graph representing perceptions of situations as statements (nodes) connected by causal links" (Ackermann & Alexander, 2016). There are two main components of the causal map that need to be determined: the nodes and the causal links between them. Causal maps are used in a variety of different contexts and as such have different methods used to create them (Narayanan & Armstrong, 2004). Causal models have been effectively used to determine "true drivers" of the outcomes of a process (Bourne, Neely, Platts, & Mills, 2002; Ittner & Larcker, 2003; Keats & Hitt, 1988; Lebas, 1995; Othman, 2006; Schmidt & Hunter, 1992).

There is one study that has previously looked at MBSE adoption using causal mapping (Naugle et al., 2019). Through the use of simulations, Naugle et al. (2019) looked at spread of adoption. Specifically, they looked at if introducing MBSE at the organizational level or the project level had an impact on the number of people who adopted MBSE. They also simulated different cognitive policies that could affect adoption, such as training more staff. This study showed that causal mapping is a pertinent method of looking at the MBSE adoption process.

Therefore, as a final step of exploring the MBSE adoption process, the insights gained from the survey and interviews were combined with adoption models from literature to create an MBSE adoption causal model. The causal model developed here is more focused on organizational characteristics, with an aim to better understand the adoption process and what are critical components of it. The results of this causal model should indicate where organizational structure is most influential in the adoption process.

Ch. 4 Survey

4.1 Study variables defined

4.1.1 Adoption variables

There are many different conceptualizations and theories about the adoption of an innovation in an organization. Generally, adoption is "the point in the innovation process where the user moves from not having the innovation to having it" (Tornatzky, Fleischer, & Chakrabarti, 1990). The point of adoption is often classified in terms of the decision to use the new innovation or to commit resources to it (Grover & Goslar, 1993; Straub, 2009). There is also a difference between the adoption of a technology and the acceptance of that technology (Jaffee, 1998). The innovation has to go through the process of diffusion throughout the organization. According to Katz, Levin, and Hamilton (1963): "the process of diffusion is defined as the acceptance, over time, of some specific item - an idea or practice, by individuals, groups or other adopting units, linked to specific channels of communication, to a social structure, and to a given system of values, or culture." In other words, just because an innovation is adopted does not mean it will be successfully incorporated into the organization or utilized long-term.

Adoption is often characterized at the individual level, where the patterns of these adoptions across the organization are indicative of a successful effort (Rogers, 2010; Straub, 2009). On the other hand, the successful implementation of a technology depends on more than the sum of individual's behaviors (Tornatzky et al., 1990). Organizations, as a collection of individuals, have systemic properties due to the emergent behaviors and characteristics that arise from the interactions of people and not the actions of a single individual (Groth, 1999; Kennedy et al., 2020). Furthermore, organizations function as open systems which must cope with a level of uncertainty from the environment they operate in (Groth, 1999; Kennedy et al., 2020; Tushman & Nadler, 1978).

Additionally, it is important to consider that when adopting a new process or methodology, there may be a series of adoption points (Julian, Noble, & Anslow, 2019; Tornatzky et al., 1990). Adoption in this case is not a singular point in time. After studying teams that adopted agile practices, Julian, Noble, and Anslow report that there is "a process of iteration and improvement" for personnel to learn the processes and evaluate if the processes need to be adapted to fit into their organization or team's needs. When adopting a new process or methodology, there are two main strategies: an incremental adoption approach or a wholesale adoption approach (Chami et al., 2018; Mahanti, 2006). An incremental approach may promote an easier organizational transition (Qumer & Henderson-Sellers, 2008), but takes a longer amount of time. Using a wholesale approach involves teams adopting all of a process and tailoring it as they go along (Julian et al., 2019). However, this can become overwhelming and may be more difficult for everyone to accept. Which approach an organization should use depends on the culture and readiness for change of the organization.

Theoretically, adoption of a new technology or process is one step in the process of innovation (Grover & Goslar, 1993). The innovation process can be divided into three stages.

First, there is some type of *Initiation*, where the organization realizes the need for a change and starts evaluating different options. Next is the *Adoption*, where a decision at some level is made to commit to the innovation. Then there is *Implementation*, which is the actual effort to install the innovation into the organization. For the purposes of this research, "adoption" represents both the initiation and adoption steps of the innovation process, and implementation is captured separately through its own variables (Keathley, 2016). Due to the complexity of adopting a process, the points of adoption and implementation are often intertwined. So, it is important to capture variables that typically represent adoption, and that typically represent implementation. There is not a binary point that can be used to evaluate adoption of MBSE, because it is a process as well as a method. The adoption and implementation variables that are used in this study are listed below:

A1: Adoption Process (Adoption)

A2: Maturity of MBSE (Implementation)

A3: Use of MBSE (Implementation)

A4: Influence on Organizational Outcomes (Implementation)

4.1.2 Organizational structure variables

Due to the minimal amount of data that exists related to organizational structure in the MBSE context, this research was developed using an exploratory design. Since there are many factors or characteristics involved in organizational structure, a selection of the dimensions discussed in Section 2.2 were chosen to represent organizational structure. These include: *Size*, *Formalization*, *Centralization*, *Specialization*, *Vertical Differentiation*, *Flexibility*, and *Interconnectedness*. *Professionalism* was not included as a variable in this study, since it is more of an individual characteristic than an organizational one.

4.1.3 Hypotheses

Many studies have found a significant relationship between the size of an organization/teams, and the adoption of new technologies (Bondarouk et al., 2017; Bradner et al., 2005; Garrido Azevedo et al., 2007; Kamaruddin & Udin, 2009; Kouzari et al., 2015; Oliveira & Fraga, 2011; Sinde-Cantorna et al., 2013). This effect was found to be positive or negative, depending on the nature of the technology and other organizational characteristics. For example, it may require more effort to adopt a new technology in a larger organization, but that organization likely has more resources to put towards those efforts than smaller organizations would. Given the varying results from past case studies, the following hypotheses are proposed.

H1a. Size has a significant relationship with the adoption process of MBSE.

H1b. Size has a significant relationship with the implementation of MBSE.

An increased emphasis on job descriptions and adherence to rules/procedures has had a negative relationship with adoption of technology (Alexiou et al., 2019; Ning, 2011; Y. E. Spanos et al., 2002). Employees in these organizations have less flexibility in their roles and are not empowered to try new things. Adopting MBSE may require changes to job roles and processes

followed (Chami et al., 2018), which often involve dealing with more "red-tape" to change. On the other hand, formalization has been found to be positively associated with the implementation of new technologies (Bourgault, Drouin, & Hamel, 2008; Grover & Goslar, 1993). The emphasis on following documented rules and procedures may support the continued use of that new technology/process, by aligning the interpretations and expectations of the employees (Pesch, Endres, & Bouncken, 2021). Therefore, the following hypotheses are proposed.

H2a. Formalization has a negative impact on the adoption process of MBSE.

H2b. Formalization has a positive impact on the implementation of MBSE.

As seen in several accounts of MBSE adoption, engineers prefer the autonomy to choose their own MBSE methodologies (Cloutier, 2015; Herzog, Andersson, & Hallonquist, 2010). Leadership or another outside source setting the terms of the adoption has led to conflict, negative perceptions of adoption, or even slowed the adoption process (Andersson et al., 2010; Cloutier, 2015). Organizations that are more centralized typically do not let individual subunits make their own decisions; the conditions are decided centrally, and all subunits need to follow. A centralized decision regarding MBSE could lead to MBSE being applied more consistently across subunits, which could contribute to long-term success (Herzog et al., 2010; Huldt & Stenius, 2019). Furthermore, there have been reports of higher levels of centralization contributing to the continued use of new technologies (Grover & Goslar, 1993; Johnson et al., 2007; Lu et al., 2018). Based on this evidence, the following hypotheses regarding centralization are proposed.

H3a. Centralization has a negative impact on the adoption process of MBSE.

H3b. Centralization has a positive impact on the implementation of MBSE.

Two opposing aspects of specialization were both found to have a positive effect on the adoption of technology (David-West et al., 2018; Grover & Goslar, 1993; Rai & Patnayakuni, 1996). These are the specialization of subunits, and the ability of employees to perform multiple tasks/rolls. Subunits that are highly skilled in a relevant area to the new technology will likely have an easier time learning and adapting to the change. Whereas organizations with generalists who can perform many rolls may have the flexibility to better address potential issues from an organizational change. Given this uncertainty, the following hypotheses are proposed.

H4a. Specialization has a significant relationship with the adoption process of MBSE.

H4b. Specialization has a significant relationship with the implementation of MBSE.

Organizations with more hierarchical levels have often had more problems with adopting new technology (Ettlie & Reza, 1992; Garrido Azevedo et al., 2007; Millham & Eid, 2010). A greater number of levels requires a larger infrastructure for communication and knowledge exchange. In other words, the information processing capabilities of this type of organization are much higher than one that is low in vertical differentiation, or flat (Tushman & Nadler, 1978). However, the negative effects of vertical differentiation could be negated if the technology enables better communication (Forman & Gron, 2005). MBSE is expected to provide better

communication (Friedenthal et al., 2014), but only if implemented correctly. Given these perspectives, the following hypotheses are proposed.

H5a. Vertical differentiation has a negative impact on the adoption process of MBSE.

H5b. Vertical differentiation has a negative impact on the implementation of MBSE.

H5c. High interconnectedness reduces the effect of vertical differentiation on the adoption process of MBSE

H5d. High interconnectedness reduces the effect of vertical differentiation on the implementation of MBSE

Organizations that have a high level of flexibility are better capable of adjusting processes and structures to new situations. Additionally, flexibility was found to have a positive impact on the adoption of new technologies (David-West et al., 2018; Kouzari et al., 2015; Ning, 2011). Since adopting MBSE involves incorporating new methods and tools into existing processes, and potentially altering those processes, it is likely that organizations that are flexible will have an easier time adjusting to MBSE. Therefore, the following hypotheses are proposed.

H6a. Flexibility has a positive impact on the adoption process of MBSE.

H6b. Flexibility has a positive impact on the implementation of MBSE.

Communication has been found to have a positive impact on technology adoption (David-West et al., 2018; Edmondson et al., 2003). Communication between subunits in an organization specifically was also found to positively impact technology adoption (Bruque-Cámara et al., 2004; Ettlie & Reza, 1992). Contact with peers is often a key driver of technology adoption at the individual level in organizations (Rogers, 2010; Sterman, 2000; Straub, 2009). Connecting new MBSE users to experienced ones is often recommended to assist in the adoption process (Andersson et al., 2010; McVittie et al., 2012). Additionally, a high level of communication between subunits is necessary to effectively carry out SE functions, which require different disciplines to participate (Blanchard & Blyer, 2016; Conroy et al., 2013). Based on this evidence, the following hypotheses are proposed.

H7a. Interconnectedness has a positive impact on the adoption process of MBSE.

H7b. Interconnectedness has a positive impact on the implementation of MBSE.

4.2 Survey design

In order to collect data for the adoption and organizational structure variables, a survey was selected as the instrument to be used. I had initially planned to collect direct observational data instead of relying on the survey method alone, however, there were several difficulties with this. For adoption, the aim was to get data from organizations on their *Use of MBSE* (variable A3). The problem is the capability for most programs to be able to provide that information is just not mature enough currently. Most programs do not have hard data or metrics they collect, and so could not provide that information without first establishing a framework in their organization to collect that data, which is outside the scope of this project. Another avenue explored to attempt to gather *Use*

of MBSE data is through MBSE tools. Several tool vendors were contacted to discuss if there were any metrics that collected this type of data in their tools. Most tools do not have this capability. There were some vendors that suggested a way to derive this kind of information through the activity logs the tools kept, but in order to convert this to a usable metric would require a significant amount of additional work. There is also the issue that user activity in one tool is likely not a good representation of an organization's use of MBSE, especially since multiple tools are often involved.

For organizational structure, using artifacts such as an organizational chart were considered as potential sources of data. This also had several issues (Buchanan & Bryman, 2007). First, not every organization has an organizational chart that is available and not-classified. Second, the structure that is on paper may not be how the organization functions. The artifact may not be updated consistently, or there are "informal" structures in place that are not reflected in the artifact. Finally, using an artifact such as the organizational chart would have required the author to derive the organizational structure characteristics, which introduces a level of bias to those results.

Given these difficulties, a survey was determined to be the most appropriate and efficient instrument to collect the data (Edwards & Thomas, 1993).

4.2.1 Survey structure

The survey is structured to obtain three categories of data: classifying information, adoption information, and organizational structure information. Classifying information consists of questions that characterize the respondent and their organization. This provides identification of demographical information of the participants. Furthermore, the identification of MBSE tools, methods, and modeling languages provides the ability to test if these variables have an influence on results, and to see if the sample is skewed in terms of tools used.

Adoption information consists of questions that relate to the adoption and implementation of MBSE. This provides data for adoption variables as well as information for the model. Questions about adoption and implementation are written based on information from the following sources: (Al-Shohaib et al., 2009; Baldrige, 2021; Grover & Goslar, 1993; Hoheb & Hale, 2020; Tornatzky et al., 1990).

Finally, organizational structure information contains general organizational structure scales, along with tailored questions relating to the MBSE experience for all variables. These questions are based on the following sources: (Burton et al., 2006; Hage & Aiken, 1967; Huber & McDaniel, 1986; Huldt & Stenius, 2019; Meijaard et al., 2005; Nahm et al., 2003; Palanisamy, 2003; Pennings, 1973; Steiger, Hammou, & Galib, 2014). Questions regarding organizational structure are in one of two categories. First: indexes and scales from the literature that have been shown to be valid and reliable measures of organizational structure[1]. These mostly were questions

[1] One study that examined the scales of centralization and formalization by Aiken and Hage used here found an ambiguity with the concept of autonomy (Dewar, Whetten, & Boje, 1980). There are aspects of autonomy in questions relating to job codification and centralization. Other studies did not find there to be an issue with the validity and reliability of the formalization measures (Ramayah & Abdullah, 2007). In the created MBSE questions,

only addressing organizational structure. Second: specifically tailored questions to organizational structure as it relates to MBSE. The purpose of including both categories is to utilize the reliable measures from the literature, but also tailor the classification of that variable towards how it relates to MBSE (when possible). The resulting structure variables are therefore more relevant to the research question.

4.2.2 Operational definitions

Table 9 defines the operational definitions of each variable through the relevant survey questions that are intended to measure them. The majority of variables were measured using a multi-item scale. Multi-item measures are better able to capture complex concepts, and multi-item scales have been shown to have better predictive validity (Diamantopoulos, Sarstedt, Fuchs, Wilczynski, & Kaiser, 2012). Single-item measures were only used for two variables that could be succinctly defined. The variable Size used a single-item measure, due to the quantitative nature of the variable. *Maturity of MBSE* has a unique set of values from the rest of the variables that used the agreement scale. The answer choices for this variable were inspired by the Baldrige Excellence Framework (Baldrige, 2021). 'Reacting to problems' is the lowest level of maturity, where there is a focus on individual activities instead of processes. Next is 'Early systematic approaches,' at this stage the organization is starting to utilize processes with some early coordination among organizational groups. Third is 'Aligned approaches,' where operations are repeatable, and coordination occurs among organizational groups. The final stage of maturity is 'Integrated approaches,' where the processes are not only repeatable, but are regularly evaluated for improvement in collaboration with other affected units.

Table 9: Operational definitions based on survey questions

Variable	Scale	Closed Question Items
A1: Adoption process (Adoption)	Agreement	• Project personnel were provided with sufficient training to use the necessary MBSE tools • Project personnel showed interest in adopting MBSE to accomplish job tasks • Existing processes were adjusted to support MBSE
A2: Maturity of MBSE (Implementation)	Stage of capability	• What stage of capability best represents MBSE in your organizational unit?
A3: Use of MBSE (Implementation)	Percent range	• What percentage of projects in your organizational unit use MBSE (out of those that could benefit from using MBSE)? • What percentage of people in your organizational unit use MBSE (out of those that could benefit from using MBSE)?
A4: Influence on organization outcomes (Implementation)	Agreement	• Velocity/agility of system development in my organizational unit has improved due to MBSE • Quality of systems developed in my organizational unit has improved due to MBSE

autonomy of the group will be classified as centralization, and autonomy of the individual will be classified as formalization.

		• Knowledge transfer between projects within my organizational unit has improved due to MBSE • Using MBSE has improved the experience of engineering systems for people in my organizational unit
OS1: Size	Number range	• Approximately how many employees are in your organizational unit?
OS2: Formalization	Agreement	• How MBSE-related tasks are carried out here is left up to the person doing the work* • There are written formal procedures that people in my organizational unit must follow in their MBSE-related work • Written formal procedures/ guidelines are updated promptly after changes are implemented in my organizational unit
OS3: Centralization	Agreement	• Employees are empowered to address small matters without needing supervisor approval* • Employees can decide whether or not to use MBSE for a given task* • Project personnel using MBSE participated in the decisions of which MBSE tools and/ or methods to use*
OS4: Specialization	Agreement	• Subunits in my organizational unit perform highly specified tasks that differ from other subunits • People in my organizational unit generally have similar skills and knowledge as others in the unit* • There are designated people in my organizational unit who create and manage the MBSE models
OS5: Vertical differentiation	Agreement	• There is a large middle management that passes information between top and bottom levels of the organizational hierarchy • In my organizational unit, the members of project teams have equal status hierarchically within their projects* • The organizational chart of my organizational unit is relatively flat with few levels of management*
OS6: Flexibility	Agreement	• My organizational unit can easily adapt to environmental changes • My organizational unit has strategies oriented towards promoting organizational innovation and growth • Organizational skills and technologies are updated often
OS7: Interconnectedness	Agreement	• People in my organizational unit are willing to assist others with problems • People in my organizational unit feel strongly connected to one another • People from different projects/ teams interact informally on a regular basis

* Responses were reverse scored

4.2.3 Additional survey questions

Table 10 shows the additional survey questions that were used to collect data that did not directly contribute to the organizational structure or adoption variables. The purpose behind including these questions was to gain additional information to understand the adoption process of MBSE. Some of these questions do relate to a structural variable but were not able to be formatted in a way that could contribute to the variable calculations. For example, the question: 'To what degree is the use of MBSE tools and methods standardized across your organizational unit' is related to the structural variable *Formalization*.

Table 10: Additional survey questions

Classification	• What is your formal job title? • What organization are you apart of? • What is the name of the department/division that you work most immediately in? • Do you have a designated leadership role in your organizational unit? • What MBSE tool(s) does your organizational unit use? • What SE tasks are executed using these tools in your organizational unit? • How does your organizational unit use these tools?
Inclusion criteria	• How long has your organizational unit been using MBSE?
Fixed response	• Were people in your organizational unit formally assigned a coach or mentor to help with MBSE? • Is there a core MBSE team facilitating the adoption across the organizational unit? • To what degree is the use of MBSE tools and methods standardized across your organizational unit? • To what extent is there a separate department to manage personnel and/or resources regarding MBSE?
Qualitative questions	• How has MBSE changed how people in your organizational unit accomplish tasks? • How are SE tasks allocated in your organizational unit?

4.3 Survey distribution

The survey was created using online survey development software[2]. One feature of the software used is the ability to prevent multiple responses from being submitted. This is done through creating a cookie on the browser after the survey is complete. While it is still technically possible from someone to submit another response if they use a different computer or delete their cookies, this feature provides a reasonable level of security against this. A minimal amount of personal information was recorded to ensure privacy. The survey was set to anonymously collect

[2] Due to software licensing issues, there were two different software programs used to create and distribute the survey. Qualtrics XM was the initial software used to create the survey. After a period of time, the survey was transferred to QuestionPro for the rest of the study. The functionalities of these programs are similar, so the survey maintained the same structure and layout between the two versions.

data, which means no personal information (i.e. IP address, location, etc.) is stored with the data. Emails were used to contact those interested in participating in the follow up survey. After the participant's emails were used to set up follow up interviews, the emails are removed from the data set. For the rest of analysis, numerical identifiers were used instead of the emails. These identifiers are associated with the corresponding interview data when relevant.

The targeted demographic for taking the survey was people who have been part of an organization that has adopted (or attempted to adopt) MBSE. There were two main methods of distributing the survey. The first was through personal/professional networks and contacts. The social media platform LinkedIn was the main channel for this method. Particularly, Groups in LinkedIn that were related to Systems Engineering. The second distribution method is through professional SE organizations. Table 11 shows the different distribution sources and methods that were used. A description of the survey's purpose and desired respondent characteristics along with a link to the survey was distributed to contacts at these organizations via email. I requested those contacts distribute the description and survey link to their organization's members. Any further dissemination by members of those groups was also encouraged.

Table 11: Survey distribution sources and methods

Source	**Distribution Method**
Aerospace Industries Association (AIA) Engineering Management Committee	Email
National Defense Industrial Association (NDIA) Systems Engineering Division Committees	Email
International Council on Systems Engineering (INCOSE) Washington Metro-Area Chapter	Email
Systems Engineering Research Center (SERC)	Website and social media posting
LinkedIn Systems Engineering groups	Social media posting

Utilizing these organizations as distribution channels has some limitations that are worth noting. There is a certain level of bias that is likely to emerge based on the respondents' levels of professional involvement. However, since professionalism was not included as a variable for the survey, this should not have a significant impact on the results. Additionally, these groups (especially INCOSE) have advocated for the industry moving towards MBSE as a standard. This may influence the level of understanding of MBSE and the opinions held about it by the respondents.

Survey recruiting occurred from January – March and June of 2022. A total of 73 responses were collected during this time. Out of the total number of responses, there were 60 complete responses. A further 9 responses were excluded that did not disclose their organizational unit, or did not meet the criteria of using MBSE for over 1 year. The resulting 51 responses each represent different organizational units with varying years of experience using MBSE. The implications of having a lower sample size than desired and other threats to validity will be discussed later in this chapter.

4.4 Survey evaluation

There were several conditions a survey response needed to meet in order to be included in the data set for analysis. The following represent the exclusion criteria:

- Incomplete responses were only included if there were five or fewer questions unanswered. More than that lead to the response to be excluded.
- Responses that did not indicate their organization and organizational unit were excluded from the data. Each data point should represent a different organizational unit. This is to prevent one organizational unit from being over-represented in the results. Since the unit of analysis is the organizational unit, multiple entries from the same unit could skew the data, giving more weight to one organizational unit over another.
- Participants that indicated '12 months or less' to the question: *How long has your organizational unit been using MBSE?* were excluded from the data. This is to ensure that participants had at least an "intermediate" level experience with MBSE (Lu et al., 2018; Motamedian, 2013).

For variables that had more than one question contributing to their values, a confirmatory factor analysis was performed. The factor analysis sample size heuristic was used to determine minimum acceptable sample size (Nunnally, 1978; Pett, Lackey, & Sullivan, 2003). This heuristic approximates the number of responses needed to conduct a factor analysis as:

$$N\ responses = Total\ number\ items * 10$$

There were six organizational structure variables with three items for each, so a total of 180 responses would have been necessary to conduct a factor analysis on all the variables. Since there were only 51 usable responses received, each variable had to undergo an individual factor analysis.

A variety of tests and criteria were used to evaluate each factor (Sarstedt & Mooi, 2014). Bartlett's significance test is the main criterion that was used to determine if a factor could be used as a variable for further analysis. Bartlett's Test of Sphericity measures the correlations between the data included in the factor. Specifically, it tests the probability that the correlation matrix has significant correlations among some variables in the set using a Chi-Square test. Essentially, this test indicated whether there could be a factor explaining the variables or not.

There were several additional tests conducted to show the strength of each factor:

- Cronbach's α tests the internal consistency reliability between the questions in each factor. A value of 0.6 or higher is generally seen as acceptable for exploratory studies.
- The pairwise correlations between the questions in each factor have also been included. If the questions in a factor are significantly correlated, it is more likely that they are measuring a similar concept. Not all the questions need to be correlated for a factor to be statistically significant.
- The Kaiser-Meyer-Olkin (KMO) test is a measure of sampling adequacy. For this criterion, under 0.49 is deemed "unacceptable".

- Factor loading and communality are measures of how each individual variable is represented by the overall factor. Values below 0.5 for these measures should be re-evaluated and potentially removed from the factor.

4.5 Survey results

4.5.1 Demographics

The demographical information collected included the identification of each survey participant's job title and leadership status. Figure 4 shows the distribution of roles the participants held in their organizational units. About two-thirds of the participants indicated they had a formal leadership role, but only around 40% had a job title that indicated some type of leadership role. This may indicate that some organizations had formally appointed people as leaders without the additional authority a job title can provide. Future research should look deeper into formal and informal leadership in MBSE adoption, especially since leadership is often reported as a top barrier for adoption.

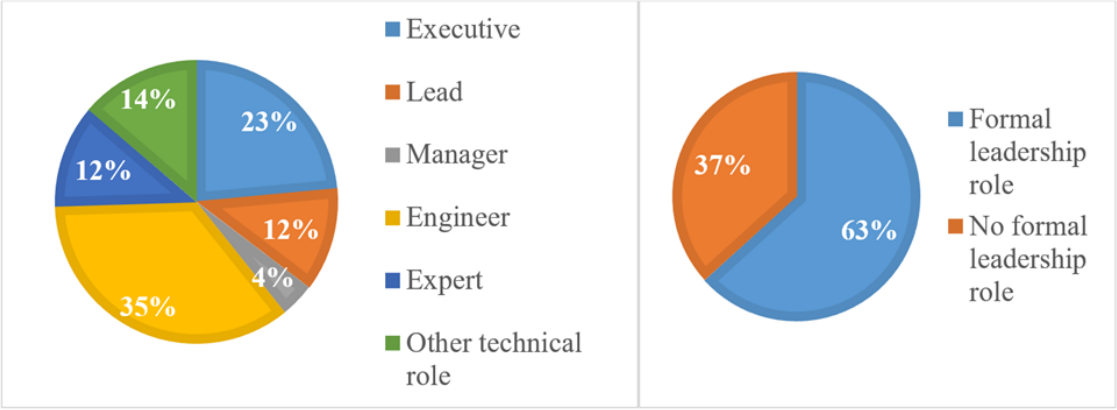

Figure 4: Job titles and leadership roles results

There was a varied distribution in the length of time organizational units had been using MBSE (see Figure 5).

Figure 5: Organizational unit's time using MBSE results

The largest number of organizational units fell into the 'Advanced' level of MBSE experience at 2 – 5 years of use[3]. The 'Intermediate' level of experience from 1 – 2 years of use was the second highest response category. More than 5 years of use is deemed as an 'Expert' level of know-how, which included around 37% of respondents overall, equal to the number in the 2 – 5 year category. In other words, the distribution of Intermediate, Advanced, and Expert levels of experience was fairly even.

Table 12 shows the different adoption/training resources that were available in each organizational unit. The assignment of a coach or mentor was the most frequent resource that was not available, with just over 40% of organizations not providing this resource. An additional 30% of responses indicated their organizations only sometimes assign coaches/mentors. Formal training was the most available resource, only around 20% of respondents did not have formal training.

Table 12: Adoption resource results

Resource	Number of organizations that utilized this resource
Core MBSE team	38
Formal training	41
Network of experienced peers	38
Assigned coach or mentor	14

Figure 6 shows how MBSE tasks and/or roles were allocated in the organizational units. Most units have MBSE roles or tasks dispersed throughout the organization. Additionally, 43% of respondents indicated that 'Projects/teams/divisions decide how they will use MBSE independently' (see Figure 7). These facts seem to indicate there is not a centralized entity that governs or dictates how MBSE will be used in many of the organizational units.

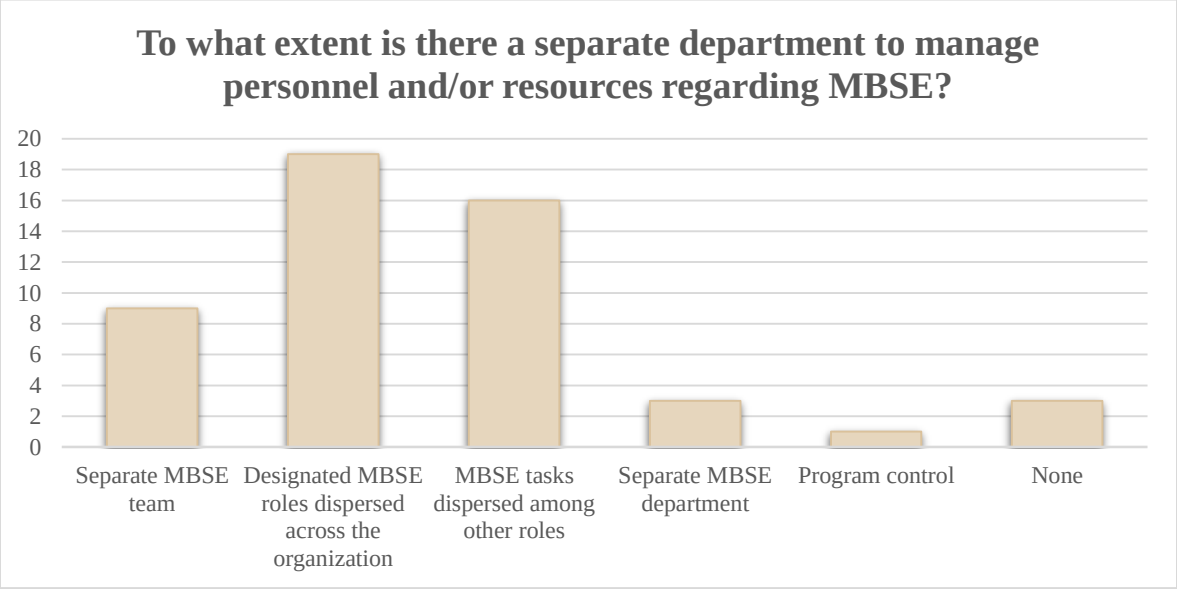

Figure 6: MBSE task/role allocation results

[3] These classifications are taken from Motamedian's MBSE adoption survey (Motamedian, 2013).

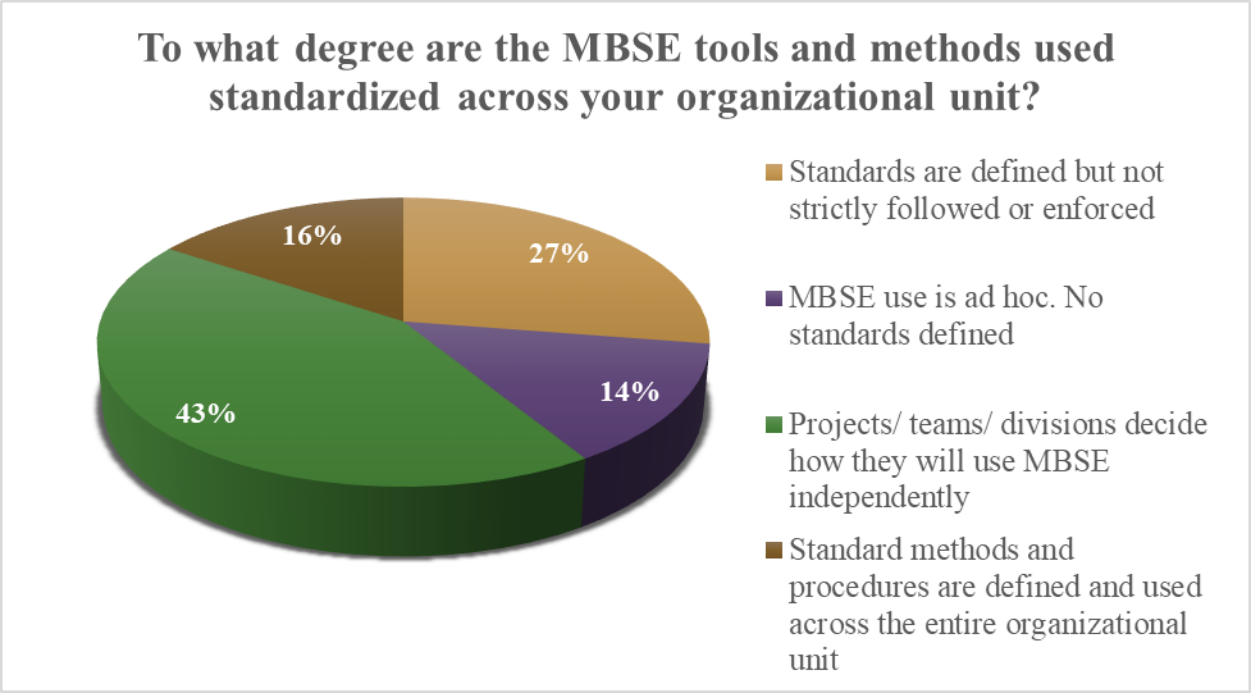

Figure 7: MBSE standardization results

4.5.2 Survey testing and factor analysis

As mentioned previously, due to the sample size of 51, each variable went through an individual factor analysis. The results of the factor analyses are presented in this section.

Variable A1 (Adoption process). The questions included in this factor address training, employee interest, and process changes. The responses for these questions were fairly normally distributed, with the majority of responses falling in the *Somewhat disagree* to *Agree* categories.

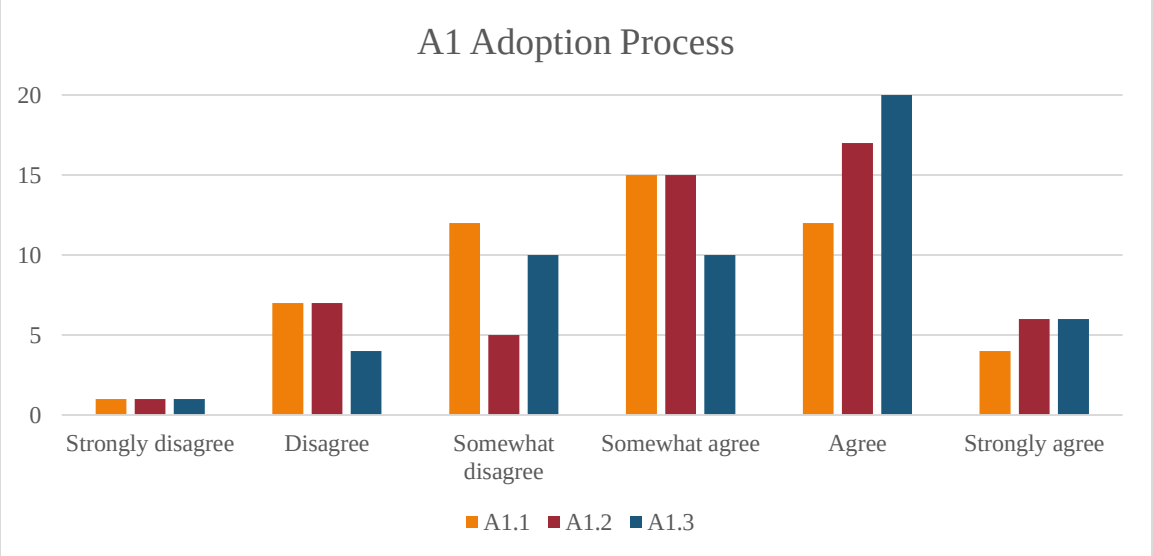

Figure 8: A1 Adoption process variable results

Table 13: A1 question correlations

Variable	by Variable	Correlation	Count	Lower 95%	Upper 95%	Significance Probability
A1.2	A1.1	0.6132	51	0.4063	0.7603	<.0001*
A1.3	A1.1	0.3544	51	0.0874	0.5739	0.0107*
A1.3	A1.2	0.4602	51	0.2115	0.6530	0.0007*

All three pairwise correlations for this variable show significant correlation[4] (see Table 13), with a high internal consistency reliability measure of 0.732. This indicates that the three questions are highly likely to be measuring the same underlying concept. The A1 factor was also found to be statistically significant, and explains over half of the variance of the data.

Table 14: A1 factor analysis

A1 (Adoption Process) Factor	**Cronbach's α:** 0.732	**Statistically Significant**
Variance explained: 51.152%	**Bartlett's Significance:** 34.698	**KMO:** 0.634
Question	**Factor loading**	**Communality**
A1.1 Project personnel were provided with sufficient training to use the necessary MBSE tools	0.687	0.472
A1.2 Project personnel showed interest in adopting MBSE to accomplish job tasks	0.892	0.796
A1.3 Existing processes were adjusted to support MBSE	0.516	0.266

Variable A2 (Maturity of MBSE). Maturity of MBSE is the first variable representing Implementation for the adoption variables. Unlike the others, this variable was represented with only one question, so factor analysis was not necessary. Figure 9 shows the distribution of MBSE capabilities across the respondents.

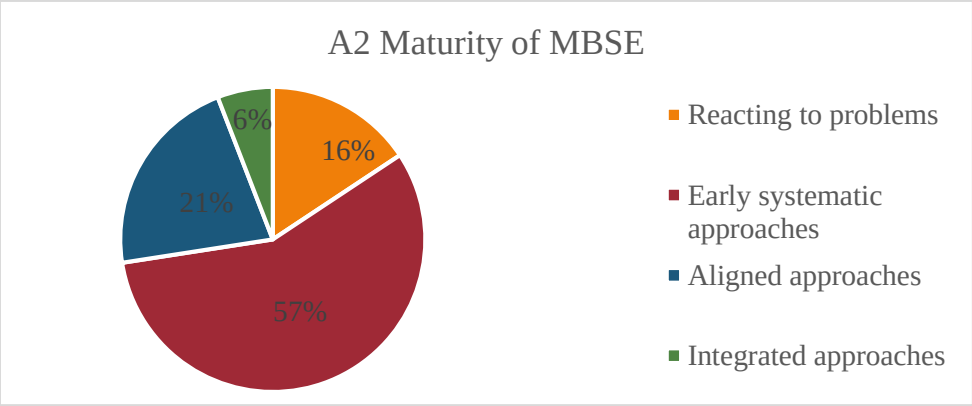

Figure 9: A2 Maturity of MBSE variable results

[4] Pairwise correlations that were statistically significant are indicated with an asterisk (*) in the 'Significance probability' column

Only 6% of the organizational units have reached the highest level of maturity ('Integrated approaches') in this sample. The largest grouping is the 'Early systematic approaches.' This suggests that many of the organizational units are beginning to reach the level of maturity where they can start to have processes and coordination established in a regular manner.

Variable A3 (Use of MBSE). This variable was measured in terms of project use and employee use. The results tend towards the lower percentages, with one noticeable spike of 70% of projects in an organization using MBSE. This follows the trend evident in the maturity of MBSE responses, with a majority leaning towards the low-mid range of maturity and use.

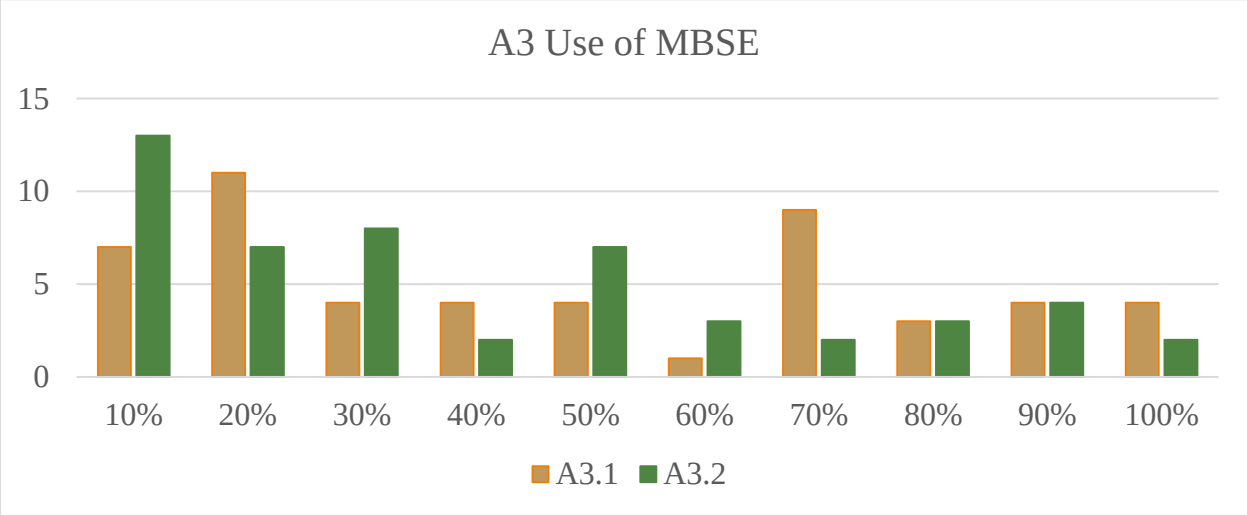

Figure 10: A3 Use of MBSE variable results

The questions used to measure Use of MBSE were found to be significantly correlated, as shown in Table 15. Furthermore, the internal consistency reliability has a value of 0.854, surpassing the minimum threshold. This indicates that the two questions are highly likely to be measuring the same underlying concept.

Table 15: A3 question correlations

Variable	by Variable	Correlation	Count	Lower 95%	Upper 95%	Significance Probability
A3.2	A3.1	0.7467	51	0.5932	0.8478	<.0001*

This conclusion is furthered by the high values for the factor analysis criteria (see Table 16). Both questions have a high factor loading and communality, indicating the factor sufficiently represents the variances in the full data.

Table 16: A3 factor analysis

A3 (Use of MBSE) Factor	**Cronbach's α: 0.854**	**Statistically Significant**
Variance explained: 74.675%	**Bartlett's Significance:** 39.557	**KMO:** 0.5

Question	Factor loading	Communality
A3.1 What percentage of projects in your organizational unit use MBSE?	0.864	0.747
A3.2 What percentage of people in your organizational unit use MBSE?	0.864	0.747

Variable A4 (Influence on organizational outcomes). The intent of variable A4 was to measure how/if the use of MBSE affects organizational outcomes that are typically valuable. The results trend towards the side of agreement. This means that there is at least a perception among participants that MBSE is positively providing value to what the participants consider to be valuable for the organization.

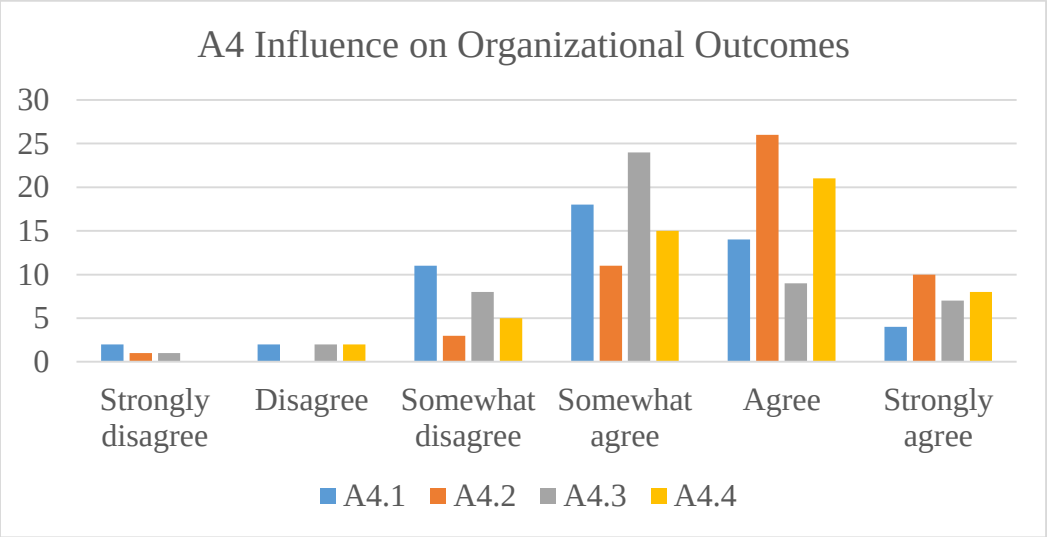

Figure 11: A4 Influence on organizational outcomes variable results

Table 17: A4 question correlations

Variable	by Variable	Correlation	Count	Lower 95%	Upper 95%	Significance Probability
A4.2	A4.1	0.5954	51	0.3826	0.7482	<.0001*
A4.3	A4.1	0.5776	51	0.3592	0.7360	<.0001*
A4.3	A4.2	0.5546	51	0.3294	0.7201	<.0001*
A4.4	A4.1	0.6088	51	0.4004	0.7573	<.0001*
A4.4	A4.2	0.7379	51	0.5803	0.8422	<.0001*
A4.4	A4.3	0.6241	51	0.4209	0.7676	<.0001*

The four questions representing this variable were all significantly correlated with each other, with a high internal consistency reliability measure. This suggests that the questions in this factor are capturing the same underlying concept. This is also reflected in the very high value for Bartlett's significance test. The KMO measure of sampling adequacy is also very high, which provides strong confidence in the use of factor analysis for this variable.

Table 18: A4 factor analysis

A4 (Influence on Organizational Outcomes) Factor	**Cronbach's α:** 0.857	**Statistically Significant**
Variance explained: 62.005%	**Bartlett's Significance:** 92.677	**KMO:** 0.806
Question	**Factor loading**	**Communality**
A4.1 Velocity/agility of system development in my organizational unit has improved due to MBSE	0.722	0.521
A4.2 Quality of systems developed in my organizational unit has improved due to MBSE	0.826	0.683
A4.3 Knowledge transfer between projects within my organizational unit has improved due to MBSE	0.712	0.509
A4.4 Using MBSE has improved the experience of engineering systems for people in my organizational unit	0.876	0.767

Variable OS1 (Size). Size was measured numerically with a single question: *How many people are in your organizational unit?* The results for Size are shown in Figure 12. There is a large difference in the responses to the question of size. This shows there may have been various different interpretations for what an "organizational unit" is. Some potential units of measure include: organization, firm, team, company, enterprise, business unit, division, department, project, group, etc. Another possibility is that respondents were not specifically thinking of a unit, but the overall organization. Future studies measuring values for organization related to MBSE should attempt to more narrowly define what the unit of organizational measure is. Given how widely organizational structures vary (Burton, DeSanctis, & Obel, 2006), it is difficult to determine a unit of measure that is specific enough to be consistently understood, general enough to apply to all organizations, and exist at a meaningful level of evaluation[5].

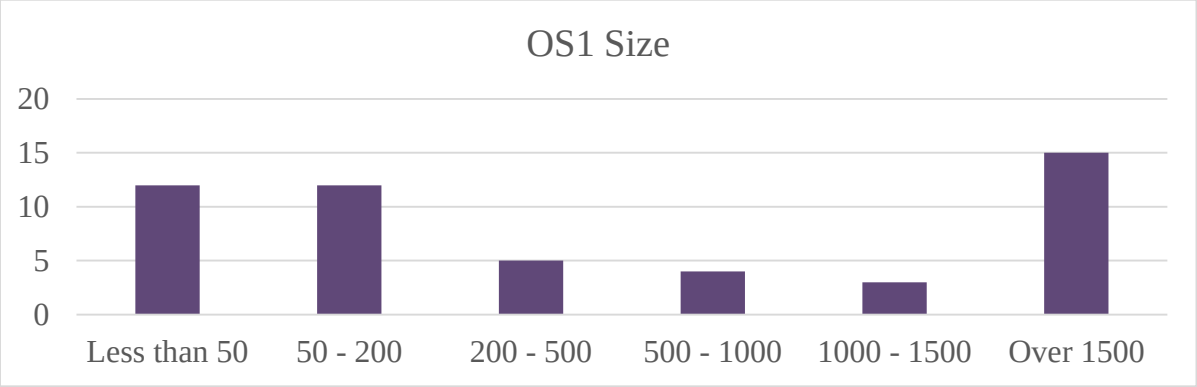

Figure 12: OS1 Size variable results

[5] Measuring at the enterprise level of an organization may be easier to understand and convey to others the meaning of. However, organizations are often so large and complex that there could not be one response to a question that applies to an entire organization. In other words, the response of a single person is significantly less likely to represent a whole organization with any degree of accuracy.

Variable OS2 (Formalization). The values for the factor analysis criteria for Formalization are fairly low (see Table 20). Especially notable is the low KMO sampling adequacy value, which is below the typical 0.5 minimal acceptable value. On the other hand, the Bartlett's test found this factor to be statistically significant. Specifically, this test rejects the null hypothesis that there are no common factors between the three questions. The factor scores explain 45% of the variance in the data, which is a decent amount. Since the factor is statistically significant, it will be used in further analysis.

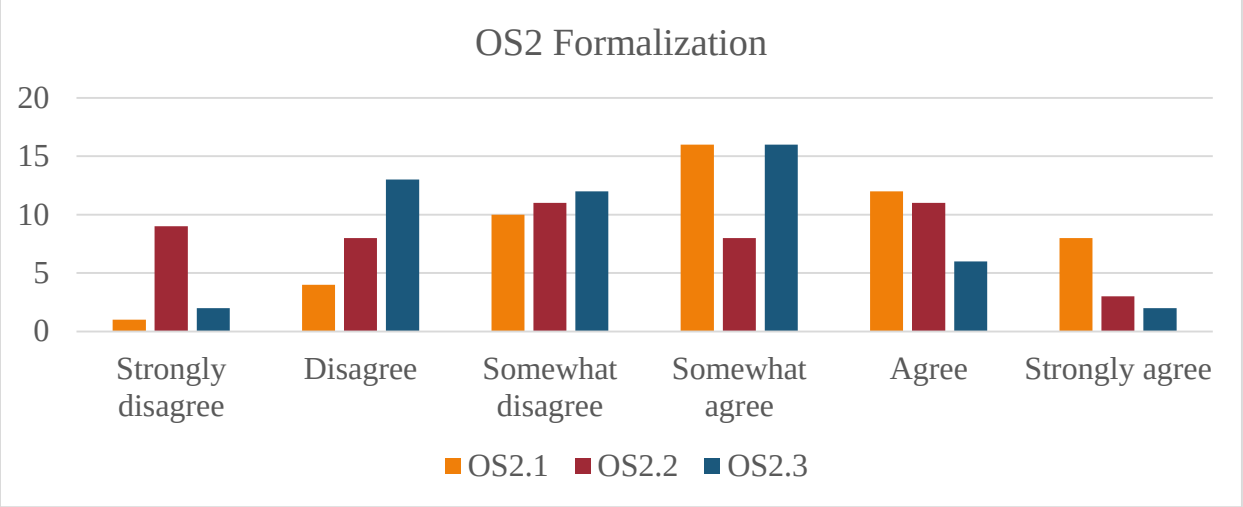

Figure 13: OS2 Formalization variable results

Table 19: OS2 question correlation

Variable	by Variable	Correlation	Count	Lower 95%	Upper 95%	Significance Probability
OS2.2	OS2.1	0.3088	50	0.0333	0.5407	0.0291*
OS2.3	OS2.1	0.0172	51	-0.2596	0.2914	0.9045
OS2.3	OS2.2	0.5298	50	0.2949	0.7043	<.0001*

Table 20: OS2 factor analysis

OS2 (Formalization) Factor	**Cronbach's α:** 0.556	**Statistically Significant**
Variance explained: 45.661%	**Bartlett's Significance:** 21.843	**KMO:** 0.450
Question	**Factor loading**	**Communality**
OS2.1 How MBSE-related tasks are carried out here is left up to the person doing the work*[6]	0.306	0.094

[6] Table 20 indicates that the question was reverse scored with the asterisk (*), consistent to how it was depicted earlier in Table 9. In other words, the bar graphs that include reverse scored questions should not be the sole source of understanding the results for that variable.

OS2.2 There are written formal procedures that people in my organizational unit must follow in their MBSE-related work	1.000	1.000
OS2.3 Written formal procedures/ guidelines are updated promptly after changes are implemented in my organizational unit	0.525	0.276

Variable OS3 (Centralization). All three questions measuring the Centralization (O3) variable were reverse scored. So can actually be interpreted as showing a largely positive trend of ***decentralization.*** In other words, the organizational units in this sample tend to be less centralized. All three questions were found to be significantly correlated. The value for internal consistency reliability also passes the 0.6 threshold. The points provide support that these questions are measuring a common factor.

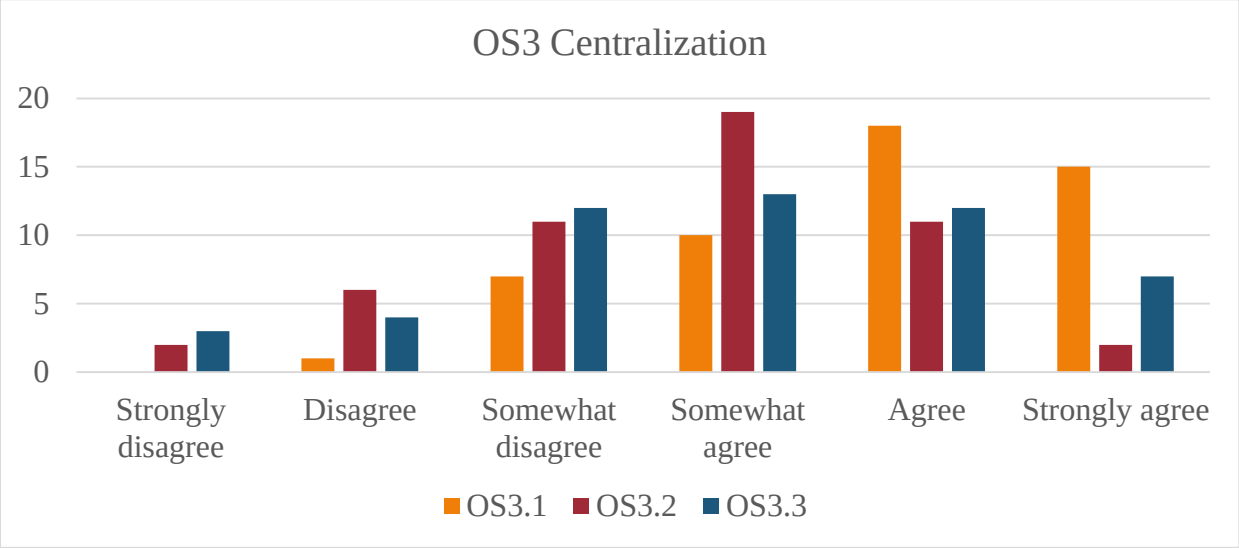

Figure 14: OS3 Centralization variable results

Table 21: OS3 question correlation

Variable	by Variable	Correlation	Count	Lower 95%	Upper 95%	Significance Probability
OS3.2	OS3.1	0.3733	51	0.1089	0.5883	0.0070*
OS3.3	OS3.1	0.4044	51	0.1450	0.6118	0.0032*
OS3.3	OS3.2	0.2883	51	0.0138	0.5224	0.0402*

Despite the significant correlations and significance test for the factor overall showing statistical significance, the variance explained with this factor is fairly low at 36%. This is echoed by the lower communality values, indicating there is a considerable amount of variance in the data that has not been reproduced in the factor. This could also indicate that there are one or more outliers in the data that are skewing the results.

Table 22: OS3 factor analysis

OS3 (Centralization) Factor	**Cronbach's *α*:** 0.615	**Statistically Significant**
Variance explained: 36.735%	**Bartlett's Significance:** 17.108	**KMO:** 0.633
Question	**Factor loading**	**Communality**
OS3.1 Employees are empowered to address small matters without needing supervisor approval*	0.724	0.524
OS3.2 Employees can decide whether or not to use MBSE for a given task*	0.516	0.266
OS3.3 Project personnel using MBSE participated in the decisions of which MBSE tools and/or methods to use*	0.559	0.312

Variable OS4 (Specialization). The variable of Specialization had only one pairwise correlation of signifciance, and it is moderate signficance at that (see Table 23). The factor analysis showed that Specialization was found to be not statistically significant (through Bartlett's test). The measure of internal consistency is also very low. Because the significant correlations were between questions 4.3 and 4.1, question 4.2 was considered for removal for analysis.

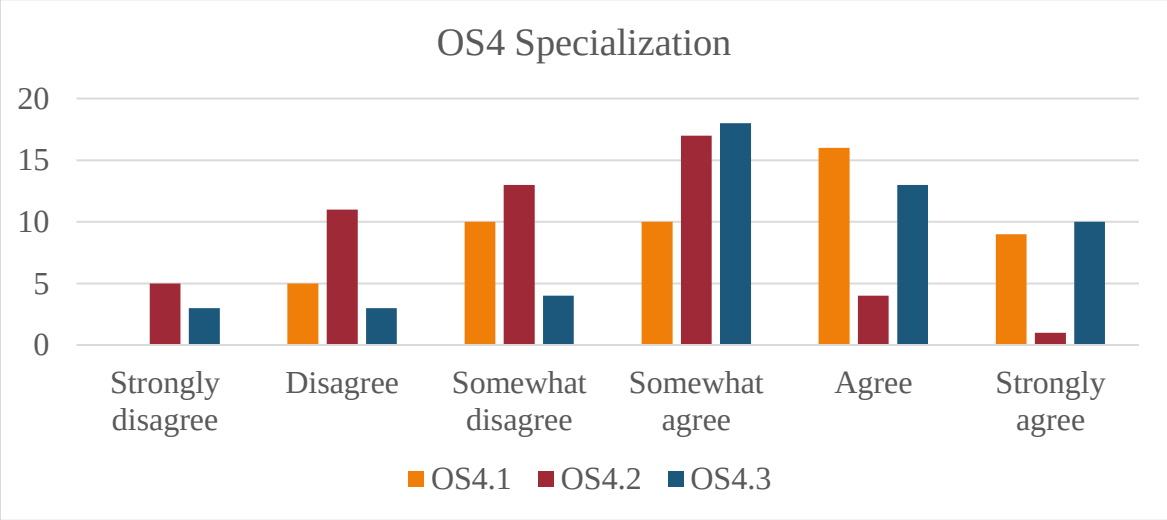

Figure 15: OS4 Specialization variable results

Table 23: OS4 question correlation

Variable	**by Variable**	**Correlation**	**Count**	**Lower 95%**	**Upper 95%**	**Significance Probability**
OS4.2	OS4.1	-0.0005	50	-0.2788	0.2779	0.9971
OS4.3	OS4.1	0.2840	50	0.0061	0.5211	0.0456*
OS4.3	OS4.2	-0.0501	51	-0.3212	0.2287	0.7272

Table 24: OS4 factor analysis

OS4 (Specialization) Factor	**Cronbach's α:** 0.211	**NOT Statistically Significant**
Variance explained: 36.058%	**Bartlett's Significance:** 4.106	**KMO:** 0.498
Question	**Factor loading**	**Communality**
OS4.1 Subunits in my organizational unit perform highly specified tasks that differ from other subunits	N/A	N/A
OS4.2 People in my organizational unit generally have similar skills and knowledge as other in the unit*	N/A	N/A
OS4.3 There are designated people in my organizational unit who create and manage the MBSE models	N/A	N/A

The resulting factor analysis after excluding question 4.2 is shown in Table 25. The new factor was found to be statistically significant, so it will be used later for analysis. But any results that involve this factor should be taken with a grain of salt, because the values for the tests of the factor are still low.

Table 25: Updated OS4 factor analysis

OS4 (Specialization) Factor	**Cronbach's α:** 0.438	**Statistically Significant**
Variance explained: 28.147%	**Bartlett's Significance:** 4.003	**KMO:** 0.500
Question	**Factor loading**	**Communality**
OS4.1 Subunits in my organizational unit perform highly specified tasks that differ from other subunits	0.531	0.281
OS4.3 There are designated people in my organizational unit who create and manage the MBSE models	0.531	0.281

Variable OS5 (Vertical differentiation). According to the pairwise correlations in Table 26, there are two questions that were not significantly correlated with each other: 5.2 and 5.1. These questions address middle management, and project team hierarchy. This indicates that whether there is a large middle management in the organization is not related to people's status within a project. Since the results from OS3 tell us that the majority of the organizational units tended to be decentralized, this may result in the ability of project teams to have more autonomy to create the structure they want. In other words, in a decentralized organization, whether there is a large middle management or not does not have a strong impact on the structure of project teams.

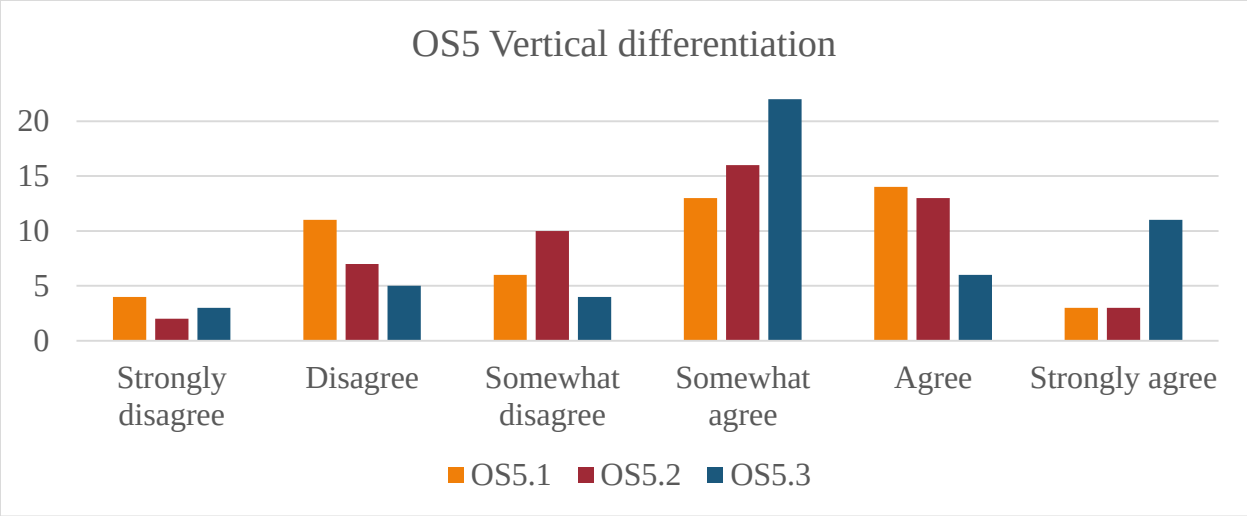

Figure 16: OS5 Vertical differentiation variable results

Table 26 : OS5 question correlation

Variable	by Variable	Correlation	Count	Lower 95%	Upper 95%	Significance Probability
OS5.2	OS5.1	0.1361	51	-0.1450	0.3968	0.3411
OS5.3	OS5.1	0.5086	51	0.2710	0.6878	0.0001*
OS5.3	OS5.2	0.3608	51	0.0947	0.5789	0.0093*

The internal consistency of this factor surpassed the necessary threshold of 0.6, in spite of the lack of correlation between two of the questions. This shows that the correlations 5.3 has with both of the other questions are significant enough to overcome that lack of correlation. Furthermore, the results of the Bartlett's test indicate that there is likely a common factor the questions are measuring. Since it is statistically significant, OS5 can be used as a factor in later analysis.

Table 27: OS5 factor analysis

OS5 (Vertical Differentiation) Factor	**Cronbach's α:** 0.608	**Statistically Significant**
Variance explained: 46.296%	**Bartlett's Significance:** 21.305	**KMO:** 0.526
Question	**Factor loading**	**Communality**
OS5.1 There is a large middle management that passes information between top and bottom levels of the organizational hierarchy	0.509	0.259
OS5.2 In my OU, the members of project teams have equal status hierarchically within their projects*	0.361	0.130
OS5.3 The organizational chart of my organizational unit is relatively flat with few levels of management*	1.000	1.000

Variable OS6 (Flexibility). The questions measuring Flexibility were strongly correlated with one another. This is also reflected by the high internal consistency score of 0.834.

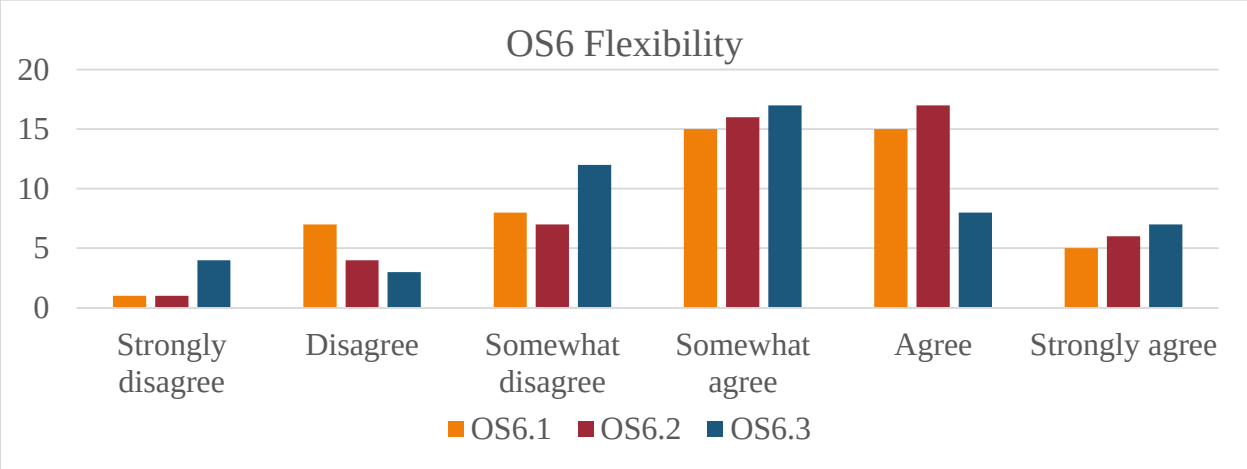

Figure 17: OS6 Flexibility variable results

Table 28: OS6 question correlation

Variable	by Variable	Correlation	Count	Lower 95%	Upper 95%	Significance Probability
OS6.2	OS6.1	0.5321	51	0.3006	0.7044	<.0001*
OS6.3	OS6.1	0.7236	51	0.5597	0.8331	<.0001*
OS6.3	OS6.2	0.6201	51	0.4155	0.7650	<.0001*

The factor analysis also produced very strong results. The factor loadings for all questions are over 0.7, indicating the factor sufficiently reflects the data. This factor also has the highest percentage of variance explained out of all of the organizational structure variables. These results indicate that the OS6 factor can be confidently used as a representation of the data.

Table 29: OS6 factor analysis

OS6 (Flexibility) Factor	**Cronbach's α:** 0.834	**Statistically Significant**
Variance explained: 64.008%	**Bartlett's Significance:** 60.225	**KMO:** 0.689
Question	**Factor loading**	**Communality**
OS6.1 My organizational unit can easily adapt to environmental changes	0.788	0.621
OS6.2 My organizational unit has strategies oriented towards promoting organizational innovation and growth	0.788	0.456
OS6.3 Organizational skills and technologies are updated often	0.918	0.843

Variable OS7 (Interconnectedness). The values for questions measuring Interconnectedness trend towards the positive side. This indicates that the majority of respondents felt their organizational units have a strong connection amongst the members, whether that be willingness to help with problems or chatting informally outside of job tasks.

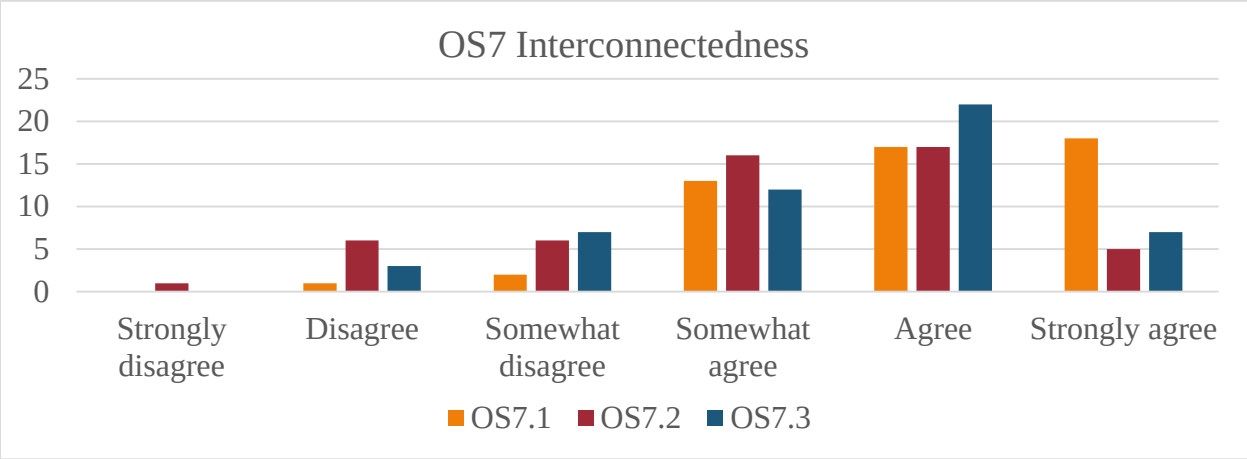

Figure 18: OS7 Interconnectedness variable results

As seen in Table 30, there is one pair of questions that was not significantly correlated. These questions include willingness to assist others (7.1) and feeling strongly connected to other employees (7.2). This could be interpreted as meaning that employees don't need to feel strongly connected to one another to be willing to assist with problems.

Table 30: OS7 question correlation

Variable	by Variable	Correlation	Count	Lower 95%	Upper 95%	Significance Probability
OS7.2	OS7.1	0.5568	51	0.3322	0.7217	<.0001*
OS7.3	OS7.1	0.2563	51	-0.0208	0.4968	0.0695
OS7.3	OS7.2	0.5162	51	0.2805	0.6932	0.0001*

Even though one of the pairs of questions is not correlated, there is still a high value for internal consistency reliability. The variables also have strong factor loadings, with over 50% of variance in the data explained by the factor. As a result, OS7 can be confidently utilized as a factor in further analysis.

Table 31: OS7 factor analysis

OS7 (Interconnectedness) Factor	**Cronbach's α: 0.708**	**Statistically Significant**
Variance explained: 52.549%	**Bartlett's Significance:** 32.892	**KMO:** 0.572
Question	**Factor loading**	**Communality**
OS7.1 People in my organizational unit are willing to assist others with problems	0.557	0.310
OS7.2 People in my organizational unit feel strongly connected to one another	1.000	1.000

OS7.3 People from different projects/ teams interact informally on a regular basis	0.516	0.266

4.6 Threats to validity – survey

One common limitation attributed to surveys is their reliance on more "subjective" data based on the perception of the respondent. I do not personally consider this a risk in this situation due to the nature of the data being collected. Both organizational structure and adoption (especially the adoption decision) are heavily dependent on the perception and experience of the people involved (Alvesson, 2003; Bogner, Littig, & Menz, 2009).

Another limitation of this study is that due to the number of usable responses, the data had to be analyzed separately. That is, organizational and adoption factors were evaluated individually instead of all together. This limited the type of statistical analysis that could be done on the data. A complete factor analysis also would have allowed for conducting an exploratory factor analysis, which could show if some of the organizational structure variables could have been part of the same factor. There was correlation between some of the organizational structure factors, so it is possible there could be an underlying factor that was unable to be seen just by doing the confirmatory factor analysis.

Four areas that are threats to validity for surveys will be discussed for the rest of this section. Three are common to all surveys: sampling bias, instrumentation bias, and non-response bias. One is specific to surveys about organizations, which is capturing the emergent properties of an organization using an individual survey response.

Sampling bias. "Results of online surveys must be regarded as tentative when the surveys are distributed to an unknown audience" (Andrade, 2020). The example Andrade gives is when the targeted audience of the survey is the general population. Factors such as literacy and access to technology can come into play and result in a biased sample. The population for this study consisted of systems engineers who had used MBSE in their organization for at least one year. Given these criteria, the distribution method of sending the survey to SE professional groups or posting to SE-related social media should minimize the potential for bias from inappropriate sampling.

Instrumentation bias. In an attempt to minimize instrumentation bias (Rubenfeld, 2004), survey questions were adapted from existing surveys when possible. Questions were designed intentionally to ensure the meaning and potential response of each question is clear. Each question asked about an individual topic and was framed as positive. The agreement scale was used for all organizational structure variables to maintain consistency. All the questions using the agreement scale had 6-point response options. This is to avoid the ambiguity that can arise from a 5-point or 7-point scale's middle value. Two adoption variables used the agreement scale. One adoption variable captured a numerical value directly in the form of percentages of people and projects. The final adoption variable addressed maturity. This variable was made up of a single question, and the response options for that questions were sourced from the Baldrige Excellence Framework.

One area of concern for potential instrumentation bias in this study is through the interpretation of "organizational unit" as the unit of measure. This term was defined at the

beginning of the survey, and participants were asked to keep that definition in mind when answering survey questions. However, it is possible that some respondents interpreted the organizational unit as their entire organization. This is not necessarily an issue, if the organization is small it may be appropriate to consider the entire organization as the unit of measure. The issue would arise if participants answered some questions thinking of their "organizational unit", and others thinking of the entire organization. Given how widely organizational structures vary, it is difficult to determine a unit of measure that is specific enough to be consistently understood, general enough to apply to all organizations, and exist at a meaningful level of evaluation.

Non-response bias. Non-response bias occurs when the people from the sample population who responded have different characteristics from those who did not respond, thus questioning whether the sample results can be generalized to reflect the true population (Rogelberg & Stanton, 2007). Nonresponse is a common concern with survey distribution, and appears to be getting worse over time (Rogelberg & Stanton, 2007). A low response rate does not automatically mean the results are biased, but there are several ways that non-response can affect results. One of the ways this can occur is when the topic of the survey is one that can elicit a strong opinion-based response (e.g. gun control) (Wells, Cavanaugh, Bouffard, & Nobles, 2012). In other words, people with extreme opinions in either direction may be overrepresented because they are more compelled to respond to the survey. The topic of this survey, MBSE, is also tied to the sample population, people who use MBSE. Whereas in the example from Wells (2012), the respondents were general college students who tended to be extremely pro- or anti-gun control. The portion of the population that was underrepresented were people who had mid-level opinions. The respondents in this survey had to use MBSE in an organization for at least one year. Since the questions in this survey are largely not opinion-based, this type of non-response bias should not be an issue.

Another area where non-response bias can affect the results is when the proportional characteristics of the people that responded do not reflect the true population. For example, one survey on Model-Based Conceptual Design captured the geographical regions of its participants and found a significantly high portion of respondents from the Oceania region (Morris, Harvey, Robinson, & Cook, 2016). The survey in this study did not capture geographical region of participants, but interview participants were located in the United States, Canada, the U.K., Germany, and New Zealand. The survey reached global populations through the use of social media and professional organizations. Out of the other classification data obtained, there were no abnormally high responses to one category that would raise concern of potential non-response bias.

Emergent properties. There is controversy in the literature over the measurement of structural properties based on responses of individuals. This elicits a threat to the validity of the results. That is, that the emergent properties of the organization may not be captured through individual responses (Pennings, 1973). There are two other means of obtaining data that are believed to maintain the integrity of the organization as the unit of measure. These methods include: interviewing an institutional spokesperson such as a top manager, and evaluating artifacts such as organizational charts or job descriptions (Pennings, 1973). Information obtained using these

methods is often less ambiguous and avoids the issue of the individual[7]. However, there is some debate whether managerial perceptions are actually objective (Sharfman & Dean Jr, 1991). Additionally, using artifacts as a data source assumes that those documents are up-to-date and an accurate reflection of what actually occurs in the organization (Pennings, 1973). A further hurdle arises in the availability of these organizational artifacts to analyze, especially for a specific organizational unit in a company. This type of information is often confidential or not readily available.

This risk has been addressed through the designation of the "organizational unit" as the unit of analysis. In each question, the respondent answered for the organizational unit based on their own perceptions (Walton, 1981). In this way, each response received and analyzed reflects a unique organizational unit. There is some risk that is worth noting in terms of response bias, since one person is likely to be influenced by their personal experiences when answering questions. Also, as discussed earlier, the term organizational unit depended on the interpretation of the survey respondent, which may lead to some level of bias.

4.7 Survey results analysis and discussion

In order to address the hypotheses posed earlier, correlations were examined between each of the organizational structure variables and adoption variables, using the factors to represent variables when applicable. Figure 19 shows a matrix of all these variables paired with their respective correlations. Values that are red are positively correlated, and values that are blue are negatively correlated. The scatterplots of each pair are also included, along with density areas showing the spread and direction of the correlations. Squares that are darker red or blue represent stronger correlations.

Figure 19: All factor correlation matrix

[7] When interviewing a top level executive as the source of organizational structure characteristics, researchers often interview more than one executive and aggregate the responses.

Table 32 summarizes the statistically significant correlations between organizational structure and adoption variables. Correlations for OS1 and OS3 variables have p-values that are fairly small, indicating significance. Correlations for OS2, OS5, OS6, and OS7 variables have p-values small enough to indicate very convincing significance.

Table 32: Statistically significant correlations between OS and A variables

Organizational Structure Variable	**Significantly Correlated Adoption Variable**	
OS1	A3	Implementation
OS2	A1, A2, A4	Adoption & Implementation
OS3	A1, A4	Adoption & Implementation
OS5	A3	Implementation
OS6	A1, A2, A3, A4	Adoption & Implementation
OS7	A1, A2, A4	Adoption & Implementation

OS4 did not have any significant correlations with any of the adoption variables. The OS4 factor was also the weakest in terms of the tests and criteria discussed in Section 5. Given these two points, it can be concluded that the data provides no support for hypotheses H4a and H4b.

OS1 and OS5 variables both had statistically significant correlations with implementation variables. Based on the strength of the correlations, this provides moderate support for hypothesis H1b and strong support for hypothesis H5b. Since these variables did not have any significant correlations with *Adoption process* (A1), the data does not provide support for hypotheses H1a and H5a. H5c and H5d hypothesized that *Interconnectedness* (OS7) had a moderating effect on the relationship between *Vertical Differentiation* (OS5) and the adoption variables. For this to be the case, there would have to be a significant correlation between OS5 and the adoption variables, between OS7 and the adoption variables, and also between OS5 and OS7. In order to have a moderating effect on *Vertical Differentiation*, there would have to be some type of correlation between those variables. The correlation between OS5 and OS7 is not significant. Therefore, Hypotheses H5c and H5d were not substantiated by this study.

Variables OS6 and OS7 had strong correlations with both adoption and implementation variables. The factors for these variables were also shown to have a high internal consistency reliability. Based on the results from this study, there is strong support for hypotheses H6a, H6b, H7a, and H7b.

Formalization (OS2) was hypothesized to have a negative impact on the *Adoption process*, but a positive relationship with implementation. Contrarily, the correlation between those variables was positive. The correlation with implementation was also positive. So although hypothesis H2a is not supported by this data, there is evidence that *Formalization* may have a positive effect on adoption. Hypothesis H2b is strongly supported by the data, in fact, the correlation between OS2 and A2 was one of the highest values of all the correlations.

Similarly, *Centralization* (OS3) was hypothesized to have a negative impact on adoption, but a positive impact on implementation. In this case, *Centralization* was found to have negative correlations with both variables. Based on the strength of the correlations, this provides moderate support for hypothesis H3a. Hypothesis H3b, once again, is not supported by the data, but there is moderate support for there being a relationship between *Centralization* and implementation in the opposite direction.

The conclusions reached on the hypotheses are summarized in Table 33. It should be noted that the data used to evaluate these hypotheses originates from perceptions of MBSE practitioners.

Table 33: Hypothesis evaluation (based on survey data)

Hypotheses	**Conclusion from data**
H1a. Size has a significant relationship with the adoption process of MBSE	No support
H1b. Size has a significant relationship with the implementation of MBSE	Moderate support
H2a. Formalization has a negative impact on the adoption process of MBSE	Strong support for the reverse- formalization has a positive correlation with adoption
H2b. Formalization has a positive impact on the implementation of MBSE	Strong support
H3a. Centralization has a negative impact on the adoption process of MBSE	Moderate support
H3b. Centralization has a positive impact on the implementation of MBSE	Moderate support of reverse, centralization has a negative correlation with implementation
H4a. Specialization has a significant relationship with the adoption process of MBSE	No support
H4b. Specialization has a significant relationship with the implementation of MBSE	No support
H5a. Vertical differentiation has a negative impact on the adoption process of MBSE	No support
H5b. Vertical differentiation has a negative impact on the implementation of MBSE	Strong support
H5c. High interconnectedness reduces the effect of vertical differentiation on the adoption process of MBSE	No support, vertical differentiation did not have a significant correlation with adoption
H5d. High interconnectedness reduces the effect of vertical differentiation on the implementation of MBSE	No support, interconnectedness and vertical differentiation have a significant correlation with implementation; but interconnectedness and vertical differentiation are not significantly correlated with each other
H6a. Flexibility has a positive impact on the adoption process of MBSE	Strong support

H6b. Flexibility has a positive impact on the implementation of MBSE	Strong support
H7a. Interconnectedness has a positive impact on the adoption process of MBSE	Strong support
H7b. Interconnectedness has a positive impact on the implementation of MBSE	Strong support

Size (OS1) and *Vertical Differentiation* (OS5) were both found to be negatively correlated with *Use of MBSE* (A3). In other words, organizations that were larger and/or had more hierarchical levels tended to have less *Use of MBSE* across their projects and personnel. Larger organizations have more people, which makes it more difficult to get to a higher percentage of use. Organizations with higher levels of vertical differentiation tend to have more levels of management/leadership from the executive level to the people actually "doing" the engineering. As found in previous MBSE adoption surveys, it is often difficult to convince leadership of the value of MBSE, and leadership support can be a critical factor in the success or failure of an MBSE adoption. Since there are more levels of management in organizations with higher levels of *Vertical Differentiation*, it may be more difficult to have to get buy-in from multiple levels of leadership.

Centralization (OS3) also was negatively correlated, but with the *Adoption process* (A1) and *Influence on organizational outcomes* (A4). *Formalization* (OS2), as mentioned previously, has a lot of similarities conceptually regarding the issue of autonomy. However, *Formalization* was positively correlated with both adoption and implementation variables. Since these two similar structural variables had opposite relationships with the adoption variables, it is worth examining the differences between the questions that were asked. The questions regarding *Formalization* addressed issues of how work is to be done. In other words, do employees have autonomy to choose *how* to do MBSE, or are there defined procedures and guidelines defining how MBSE should be used. *Centralization* deals more with the decision making power of employees. In other words, did employees have authority to decide *if* they wanted to use MBSE or not. It also asks if employees participated in the decision making process of selecting MBSE tools and/or methods would be used. Based on these differences, it seems that organizational units that had more autonomy to participate in these decisions had a more successful experience with adoption and implementation. However, standards should be defined to some level with guidance on how MBSE should be carried out in the organization.

Flexibility (OS6) and *Interconnectedness* (OS7) both had strong positive correlations with the adoption and implementation variables. *Flexibility* had significant positive correlations with all four adoption variables, and the correlation with the *Adoption process* (A1) was the highest out of all the structure-adoption relationships. *Flexibility* and *Interconnectedness* additionally had a strong positive correlation with each other. One reason for this similarity may be that conceptually, both of these characteristics are more related to cultural aspects of an organization. There is actually an organizational paradigm dichotomy that addresses both of these factors. This is the mechanistic vs. organic organizational paradigm, discussed in Chapter 2 (Nahm et al., 2003). Organizations that are classified as organic are high in *Flexibility* and *Interconnectedness*, and those factors are the driving force of the organization. In other words, these concepts are often

closely coupled in organizations, which is reflected in the survey results. Future studies may consider combining the concepts of *Flexibility* and *Interconnectedness* and instead measure organizations on the scale of organic to mechanistic. This would reduce the amount of questions needed to be asked from six to one or two, which may positively affect the response rate.

4.8 Additional survey questions analysis

Table 34 shows significant correlations featuring the additional survey questions (found in Table 10). These correlations all have p-values of less than 0.01, which provides a high level of confidence that the relationship is significant.

Table 34: Additional question correlations

Variable	by Variable	Correlation	Count	Lower 95%	Upper 95%	Significance Probability
Coach/Mentor	OS2 Formalization	0.4304	50	0.1727	0.6329	0.0018*
Network of Peers	OS4 Specialization	0.4066	51	0.1475	0.6134	0.0031*
Network of Peers	Formal Training	0.3828	51	0.1199	0.5956	0.0056*
Standardization	OS2 Formalization	**0.5802**	50	0.36	0.7392	<.0001*
Standardization	A1 Adoption Process	0.437	51	0.1835	0.636	0.0013*
Standardization	A2 Maturity	**0.6197**	51	0.4149	0.7647	<.0001*
Standardization	A3 Use	0.3762	51	0.1122	0.5906	0.0065*
Time	A2 Maturity	**0.5204**	51	0.2858	0.6962	<.0001*
Coach/Mentor	A2 Maturity	0.465	51	0.2173	0.6565	0.0006*

Standardization of MBSE was found to be strongly correlated with several variables. Out of the organizational variables, OS2 (*Formalization*) was the most significant correlation. This was expected since the standardization question is another measure of formalization. Standards were also strongly correlated with *Maturity of MBSE* (A2) and *Adoption process* (A1). This provides further confidence for the correlations found between those variables and OS2, and also supports hypothesis H2b. Similar to the OS2 correlation, the correlation between standards and adoption is also positive. This is the reverse of the hypothesized relationship from H2a. Standardization is also significantly correlated with *Use of MBSE* (A3). This could mean that the more MBSE tools and methods are standardized, the greater percentage of people and projects that use MBSE in the organization.

Another strong correlation to note is between time organizations have been using MBSE and *Maturity of MBSE* (A2). Organizational units that have been using MBSE longer tend to have more mature capabilities of MBSE. Again, this was an expected relationship conceptually, so the statistical proof provides further confidence in the content validity of the survey.

Adoption related resources also had several strong correlations in the data. Formal training and network of experienced peers were significantly correlated. The assignment of coaches or mentors was strongly correlated with *Formalization* (OS2) and *Maturity of MBSE* (A2). In other words, coaches tended to be assigned in organizations that had a higher level of maturity and more

formalized practices. The assignment of coaches or mentors was also correlated with the level of standardization, although the correlation here is not as strong as for OS2.

The presence of a network of experienced peers was found to be strongly correlation with *Specialization* (OS4). Interestingly, both questions that ended up in the final OS4 factor are both more strongly correlated with the network of experienced peers than they are with each other. These questions addressed differences in subunit tasks and designated modelers. Both of these correlations were positive. So, in organizations where subunits perform specified tasks that are different from other subunits, there was a higher tendency to have a network of experienced peers. Also, in organizations that had designated people to create and manage models, there was a higher tendency to have a network of experienced peers. So the network of experienced peers may be a result of having people in the organization who are highly knowledgeable or experienced in a specific part of MBSE or modeling. In other words, if an organization wanted to establish a network of experienced peers, one way to contribute would be to designate people as MBSE specialists or modelers, and make sure that these people were known to others in the organization.

Ch. 5 Interviews

5.1 Interview strategy and preparation

Those who completed the survey had the opportunity to indicate if they were willing to participate in a follow up interview. The purpose of these interviews was two-fold: to supplement the data obtained from the survey, and to help validate the causal model. Given these uses of the interviews, there should not be an issue methodologically with using the same participants from the survey. Similar to the survey, anyone who has been part of an organization that has attempted to adopt MBSE could be included as participants. Any interview volunteers who had not completed the survey were asked to do so before their scheduled interview. The interviews were conducted and recorded over Zoom. Permission to record the interview was obtained verbally before the interview began. Participants had the option to turn off their video if they did not want their face recorded. These recordings were later transcribed and coded in Microsoft Excel.

Participants were asked to generally recount their adoption experience, and provide elaboration/explanation for responses from the survey that may require further detail. Participants were also asked to explain how their organization and project is structured, and how MBSE performed in those settings. The semi-structured interview format allowed for a more holistic representation of project/organizational structures than the survey can provide. It also provided the opportunity for the interviewer to ask follow-up or clarifying questions based on the responses given.

Interview questions were of a similar subject matter as the survey. The significant variables found from the survey results (Formalization, Centralization, Flexibility, and Interconnectedness) were emphasized in the interviews. Table 35 shows the interview prompt questions that were used to guide the interview if needed. The first and last questions listed in the table were given to every subject.

Table 35: Interview prompt questions

Tell me about how MBSE is defined/characterized/understood in your organization?
What Systems Engineering tasks do you use MBSE for?
What does your day-to-day use of MBSE look like?
Is MBSE used on all projects?
Does everyone in an MBSE project use MBSE?
Has there been any effort to standardize the use of MBSE across the organization?
Tell me about the process of first adopting/learning MBSE?
Was there a defined plan/process to adopt/learn/teach MBSE?
How often does your organization adopt new technologies/methods?
How does your organization determine the success of an adoption effort?

Is there a future plan on how to adapt to new/improved MBSE tools/capabilities?
If not adopted At what point did you stop using MBSE?
If not adopted Is there a plan to implement or adopt anything in place of MBSE?
Is there anything else you want to tell me about your experience with adopting and using MBSE?

5.2 Threats to validity – interviews

While interviews provide the benefits of flexibility and more detailed response data, there are some disadvantages. There are several different types of reliability and validity concerns that are worth discussing.

Reliability. Researchers typically aim for their studies to have a high level of reliability, because the ability to reproduce the same results in a different study provides support for the validity of those results. In the context of interviews, reliability would measure if a different researcher conducting an interview with the same goal and participant would reveal the same information (Saunders et al., 2009). However, semi-structured interviews are not necessarily meant to be repeatable, since the context or environment of the interviewee is likely to change (Marshall & Rossman, 2014). The value of the semi-structured interview method is the flexibility, so an attempt to standardize the interview would undermine its purpose (Saunders et al., 2009).

Interviewer bias. Interviewer bias occurs when the comments, tone, or behavior of the interviewer biases the participant to respond a certain way (Dresch et al., 2015). For example, the interviewer may have a certain outcome in mind and tries to guide the participant to respond in a way that aligns with it. One of the key ways to defend against this is in the wording of questions, with a particular emphasis on avoiding leading questions (Saunders et al., 2009). When asking questions, I attempted to keep question wording neutral and take cues from what the participant was saying and how they were saying it. I also asked every participant as a last question if they had anything else they wanted to share about their experience. This was to make sure that the participant had the opportunity to say whatever they wanted to about the subject, without the constraints of my questioning.

Response bias. One of the difficult components of interviewing is that any data you get is reliant on the participant being willing to share it. Interviewees could withhold important or sensitive information, which would bias their responses (Dresch et al., 2015). The interviewee controls the information, so the only measure the interviewer can take is to try and create an environment that feels safe for the participant (Saunders et al., 2009). Some ways to mitigate this risk are demonstrating active listening, assuring the participant their responses will be anonymous or confidential, and probing for further explanation on questions when necessary. All of these techniques were used for this study.

Participation bias. Interviewing is a time-consuming and intrusive process. A bias could arise based on "the nature of the individuals or organizational participants who agree to be interviewed" (Saunders et al., 2009). Based on my experience with the interviews, I do not think this bias

affected the results obtained from the interviews. There was a wide representation of different opinions and experiences that the interviewees had with MBSE.

Interviewer interpretation. One of the potential biases in qualitative research is that the researcher has to interpret the data (Dresch et al., 2015). The data in its raw form is a transcript of a conversation. It is up to the researcher to transform those responses into analyzable data. This involves some interpretation on the researcher's part. If the questions were phrased well, and details were probed for when the situation was unclear, these effects will hopefully be lessened. It is important to include raw quotes from the interviews as support when presenting the interpreted survey results.

5.3 Interview evaluations

Interviews were conducted April 2022 – June 2022 utilizing the video conferencing platform Zoom. The target length for each interview was 30 minutes, but several interviews were shorter or longer depending on the participant's availability. A total of 18 interviews were conducted, representing 18 different organizational units.

Interviews were recorded through the Zoom platform and were transcribed after they were completed. This resulted in a transcript of the conversation that took place over the interview. Responses were transferred to Microsoft Excel for processing. First, responses were separated into separate rows by each question. Then, within the response to a single question, the data was further separated so each row contained a unique idea/topic. There was a level of subjectivity to this, since the division was based on the researcher's perception of what the theme or key point of a response was. The approach I took to this separation was that each row should be able to be defined by one main theme.

Separated responses were coded in four categories: content orientation, organizational structure variables, adoption components, and key themes. If one row had multiple codes it could represent for a single category, that response was divided so that each row was represented by one code per category. Content orientation refers to the nature of the response. The three possibilities for this category were: Problems/challenges, Reports of experience, and Recommendations. So if the response was discussing a challenge with adoption, that row would be coded as 'Problems/challenges.'

The next two categories were specifically designed to assist with comparing the interviews to the survey results. The options for organizational structure variables were the seven identified variables from the survey, or 'None.' The options for the adoption components category included: training/resources, reception, process changes, maturity of MBSE, use of MBSE, and influence on organizational outcomes. Variable A1 (*Adoption process*) was divided into three parts which correlated to the three questions that made up the variable. These were Training/resources, Reception, and Process changes.

The final category was the key theme of the quote. This was coded using two schemas. One was created inductively as responses were being processed. The codes that emerged from this method are shown in Table 36.

Table 36: Key themes inductive codes

Adoption difficulty	Management/ leadership
Lack of understanding	Legacy programs/ cost
Adoption activity	Tools
Knowledge retention/ decision making	Culture/ organizational change
Interconnectedness	Integration
Consistency/ standardization	SE fundamentals
Customer requirements	Training

An additional coding schema was used to categorize the responses using an a priori set of codes shown in Table 37. These were codes used to categorize lessons learned from a literature review on MBSE implementation efforts (SE Modernization SERC project, Unpublished). As responses were being processed, there was a noticeable overlap with the lessons learned codes, so this additional set of codes was used in conjunction with the inductive key themes.

Table 37: Lessons learned codes

Domain/tool knowledge	Reusability	Sharing model
MBSE over the whole life cycle	Complexity	Model reviews
Skills/abilities	Legacy systems	Measurement/value
Maturity of MBSE	Culture	Model definition/guidelines
Upfront investment	Traceability	Diagram layouts
Integration	Process changes	Automation
Consistency of MBSE practices	Infrastructure	Tools
Necessity of MBSE method	Dedicated modelers	Target programs
Importance of mentorship	Organizational design	Importance of training
Importance of tool support	Provide examples	Adoption strategy
Leadership	Configuration management	Traditional SE artifacts
Modeling practices	Data	Knowledge capture/representation
ASoT	Communication	Deliverables
Stakeholder involvement	Model analysis	Security

The two theme coding schemas were essential to managing the data, categorizing responses, and finding specific quotes.

5.4 Interview results

Certain demographical information was extracted from the interview transcripts. Figure 20 shows the different industries that the organizations represented by the interviews were a part of. Nearly half of the organizational units were in the Aerospace/Defense industry, which is typical in the Systems Engineering discipline.

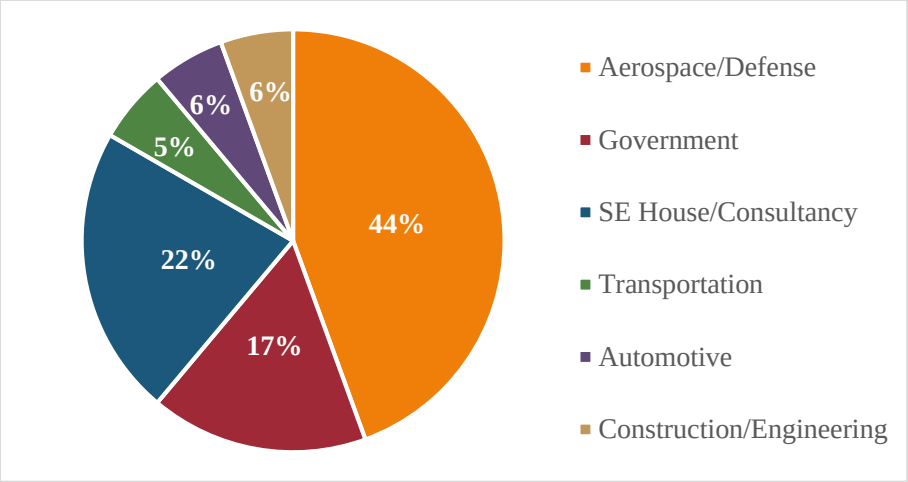

Figure 20: Industries of organizations from interviews

The second highest category was SE House/Consultancy, which included companies that do SE consulting as well as provide MBSE tools and services. These organizations often help other organizations adopt MBSE, which provided another perspective on MBSE adoption. Because these are SE organizations, they typically already have adopted and are using MBSE. In Figure 21, which shows the adoption statuses of the different organizations, these SE organizations are represented by the 'N/A' category. Two of the organizations had attempted to adopt MBSE and were unsuccessful. Another organization had started the adoption process, but is currently at a stand-still. The rest of the organizations were in various stages of the adoption process.

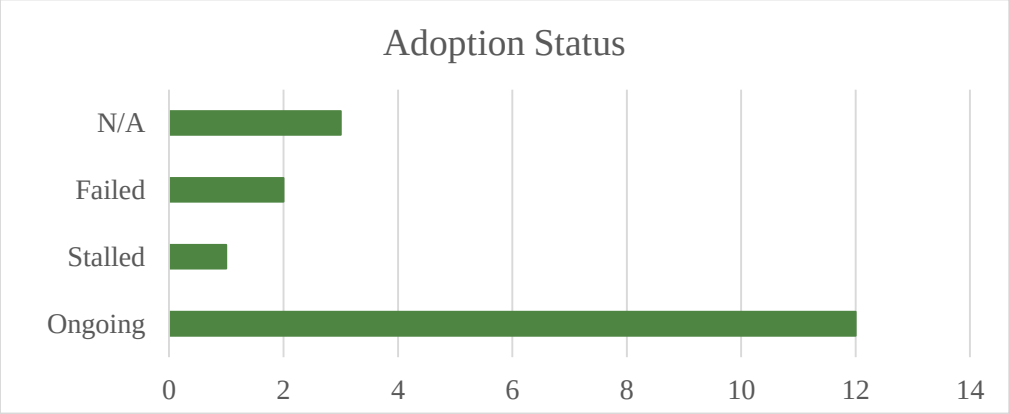

Figure 21: Adoption status of organizations from interviews

Every interview began with the same question: 'How is MBSE defined or understood in your organization?' Figure 22 shows the differing views of MBSE among the organizations. In some organizations, MBSE is defined in terms of the tools. These participants often used the name of the main MBSE tool (e.g. Cameo, Enterprise Architect) as a synonym for MBSE. Others defined MBSE in terms of the models or model artifacts. These participants tended to focus on modeling or diagrams in the description of their adoption efforts. About 22% of the participants were not able to convey a clear definition for MBSE, whether this was because the organization did not have a common understanding, or the participant did not actually define MBSE in response to this

question. The remaining organizations had an understanding of MBSE similar to how it is defined in this paper: as a method and a process. These results are continued proof that MBSE is not well understood or clearly defined in the industry.

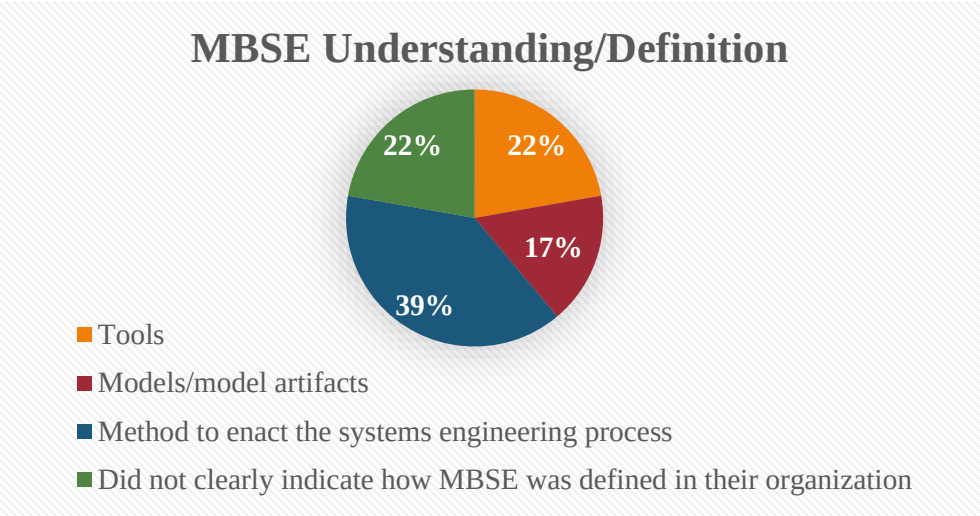

Figure 22: Interview organizations understanding of MBSE

One of the defining characteristics of an MBSE adoption effort is where the effort originated from. Figure 23 shows the distribution of adoption directions in the organizations. 'Top-Down' refers to an adoption effort that originated from upper levels of leadership or management. These efforts were often due to someone at the executive level supporting the adoption of MBSE. Another source of the Top-Down effort was some type of mandate or policy at a high level, especially for organizations who work with the government. 'Bottom-Up' refers to an adoption effort that originated from the engineers and other technical personnel. In these cases, people often started using MBSE because they wanted to or saw the potential value, and then had to push the effort up the hierarchy. This typically involved having to convince management of the value of MBSE, which is a difficult task. In some organizations, the adoption effort came from 'Both Directions'. In these organizations, not only were engineers and others organically using MBSE because they wanted to, but there was some direction from management also pushing for adoption.

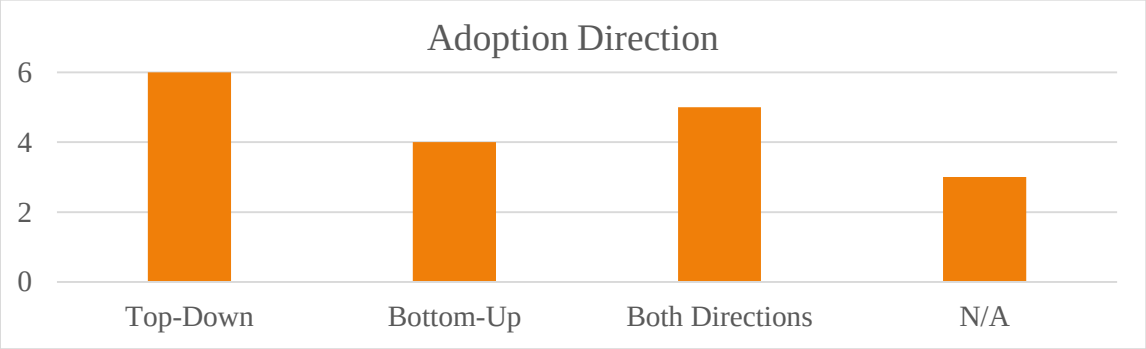

Figure 23: Direction of MBSE adoption from interviews

Figure 24 shows a summary of key factors that were catalysts behind the decision to adopt MBSE. There are some similarities between the *Adoption Direction* categories from Figure 23 and several influencing factors in Figure 24. 'Personal preference of personnel' is in line with the Bottom-Up organizations, while Mandate/Customer requirements overlaps with the Top-Down direction. The other two key factors are related to the potential capabilities MBSE could provide. Project or system complexity was a frequently cited reason for looking to MBSE. This differs from the final category 'Desire to improve' in the mindset of the organizations. Having a desire to improve the organization through MBSE has a more positive point of view. Whereas project complexity is a problem and the organization is hoping MBSE can be the solution. In other words, one is motivated by the presence of negative factors, and the other is motivated by the potential of positive factors.

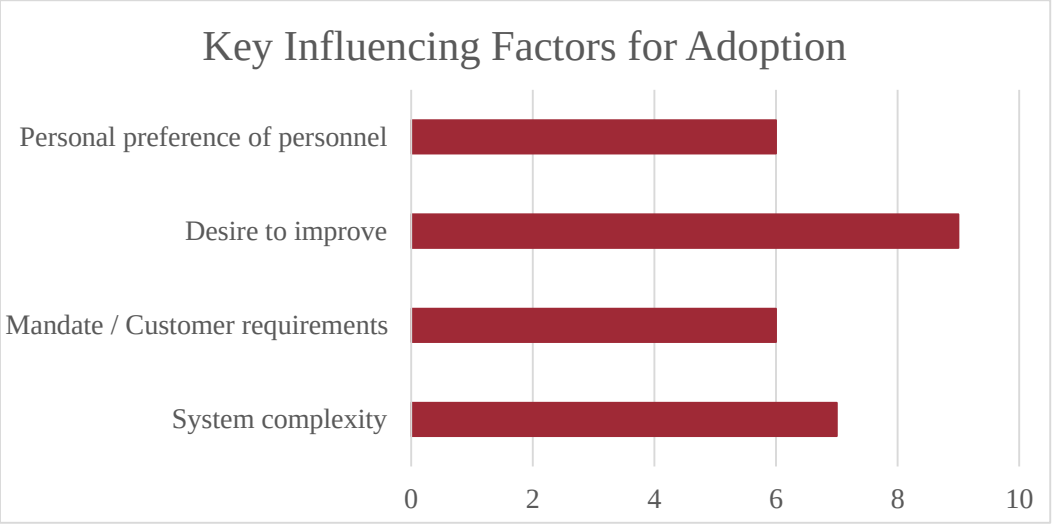

Figure 24: Reasons behind the initiative to adopt MBSE from interviews

5.3.1 Adoption strategies/activities

There were differing opinions among the interview participants on the adoption strategy that should be taken for MBSE. Some participants believed that "*MBSE only works if you go all or nothings [47]*[8]." According to one participant: "*You have to make a clean cut for MBSE. You have to build it up, consolidate the data, ensure that the models are built right with the right information. We cannot just dump everything in there and recreate a mess [40]*." On the other hand, some advised starting small with MBSE adoption. These participants suggested to "*find out where that organization's needs are and tailor your MBSE delivery to that particular aspect [35]*." Certain programs should be selected to adopt MBSE "*based upon the monetary value, the probability of success, and the must-win aspect [41]."* As one participant recommended, "*Start with one project, identify what SE concerns you want to improve with MBSE, [and] focus modeling activities on only this concern. The you learn and grow from that [59]*."

[8] Direct quotations from interviews are italicized with the ID number related to the participant in brackets [example] at the end of the quote

Regardless of the adoption strategy, the participants agree that training is a crucial part of the adoption process. Over half of the participants specifically mentioned the importance of training. According to the participants, there are four categories of people who need to be trained to various levels (see Table 38). The first group of people are the Model Reviewers. These are leaders, stakeholders, or customers who need to know how to use the models to make decisions. The second group is the Developers, or the modelers. These are the people who are building and maintaining the models in the tools, so they will need detailed knowledge of how the tool works. The third group is the Architects. These are the people who will be working in the model to some capacity. These people are often senior engineers or people from other disciplines who are helping with the content of the model. This group does not need as deep of training as the modelers, but they do need to be able to operate within the models. The last group is the Administrators. These are people who work in IT or software who will be managing the relevant accounts, licenses, tools, etc. According to a participant, "*They don't need to know how to use the tool in a hands-on way, but they need to know the limitations and all of the details of the tool [41]*." Forgetting to train this group is a common problem, and according to one participant, it is "*part of the reason [organizations] aren't seeing value [9]*" from the MBSE implementation. These people are often senior systems engineers who help with the content of the model.

Table 38: Categories of people that need MBSE training

Model reviewers	*"The leaders and decision makers are the ones who should day 'I need a model that tells me this information,' so we need to teach them how to do that. Digital Engineering fundamentals, reviewing digital artifacts, and some tool courses [9]."*
Developers	*"These are the people who are going to be modeling in the tool. So these people need to know the tool mechanics, and also the why/how of MBSE [41]."*
Architects	*"Engineers who have knowledge of the system who are the people who you would actually want to lay out the architecture in the model [47]."*
Administrators	"*If you hand out the specifications in a new way or a new language, are we absolutely prepared as a downstream engineering within the software community… they need to understand how to deal with a large amount of inputs coming in related to MBSE [41]."*

Several participants pointed out that training that is too generic may not be actually useful. As one participant noted, a basic training class that says "*let's build a flashlight*" would not be helpful when the product is as complicated as a helicopter or a missile [5]. One participant discussed how their training approach takes this into account. According to the participant, "*If there is a project in need they come to me, or my team, and ask for training for onboarding. Then we define the scope: what do they want to model, which outcome? Then we align on the first steps and provide relevant training for the process and the tool. So the outcome can be used in a real development [40]*."

Another common adoption activity amongst the participants was establishing a Core MBSE team. Some of these Core MBSE teams were created to imbed a common way of working

across the organization. One participant described their MBSE team that had personnel based out of the different sites in the organization. According to them, "*It is kind of putting the tendrils out in those different areas and inundate a common way of working instead of an ad hoc type of modeling approach [18]*." Other organizations established Core MBSE teams as a place to go for help and to share ideas. These teams were often categorized as communities of practice or working groups. According to one participant, the purpose of their organization's MBSE team is "*to form a center of excellence where you can help people in need and coordinate ideas [20]*." Another participant described the informal network across the organization that was established through a core MBSE team. According to the participant, "*If I have a question or am struggling, I tend to be able to know who has done this in the past with the help of the communities, various forums, [and] meetings [45]*."

5.3.2 Adoption challenges

Cultural and organizational challenges were frequently cited by the participants. Several participants found a cultural resistance to adopting MBSE. As one participant noted, "*MBSE requires a mindset change [5]*," and that was often difficult to achieve. In one organization, leadership was particularly concerned about the cultural changes necessary. According to the participant, "*New people expect everything to already be in a digital realm, and the generation that is phasing out*" believes they can still use slide rulers to do their engineering [20]. One participant disclosed that "*there's very little resistance from our direct customers, now they have resistance from their customers sometimes that we have to deal with [6]*."

Organizational factors were another common issue for adoption (see Table 39). According to one participant, "*It's not about the technical problem of introducing MBSE, it's about company change [40]*." "*Organizational change management [44]*" is a critical component of the adoption process. Several participants noted that it was difficult to get something standardized or consistently applied across their organizations because they were so fragmented. Learning MBSE was not always prioritized in organizations by teams that wanted to focus on their typical work. One participant noted that people create issues "*due to a lack of holistic systems thinking [41]*." Teams prioritized their other tasks over learning MBSE, and especially when project costs are considered, "*the model building work is going to be the first thing that is going to go [47]*."

Table 39: Organizational and cultural challenges from interviews

Challenge	**Number of participants**
Cultural resistance	11
Organizational change	7
Staffing and turnover	7
Leadership/management support	7
Communication	6
Middle management difficulty	4

In that vein, management and leadership[9] buy-in and support is a critical factor to MBSE adoption. For both organizations who were not able to successfully adopt MBSE, the main cause was that management did not support it. But when there is management support, the adoption effort is vastly improved. One participant discussed the efforts their organization's corporate management took to support MBSE adoption. Because of the contributions of corporate management, "*there is a complete system put together on how to execute the [adoption] strategy at a high level, [and] there have been a lot of activities going on [41]."*

Several participants noted specifically having problems with middle management. One participant recounted their organization's experience: "*We're trying to convince our managers and follow through on it, since the executives have said they want it. But middle managers can ignore that because it doesn't impact their day-to-day [45]*." Efforts to convince this level of middle management was often unsuccessful. It has been "*through the natural progression of people retiring, moving on, or moving sideways [45]*" that the void of middle management has begun to disappear.

Table 40 shows examples of some other MBSE adoption challenges according to the interview participants. A lot of these challenges related to the maturity of MBSE as a field: tool limitations, people not understanding what MBSE is or how to adopt it, the ability to apply MBSE to legacy systems. As the field continues to mature, these challenges should be addressed by tool vendors and other MBSE thought leaders. One common challenge addresses the difficulty of adopting a process: the length of time it takes to adopt. These same concerns were found in other process adoption efforts from different fields (Julian et al., 2019; Kouzari et al., 2015; Mahanti, 2006; Sidky, Arthur, & Bohner, 2007).

Table 40: Other commonly cited MBSE adoption challenges

Other adoption challenges	Number	Example quote
Tool limitations	7	*"Because the tools are still immature, you kind of have to play with them to figure out what is worth it and what are potential challenges [20]."*
"It's a long road ahead"	9	*"To get people up to speed is going to take some time. We have to have patience, I believe, over the long run. To see the ROI we're going to have to see programs actually establish this [3]."*
Lack of understanding, confusion about MBSE	11	*"They didn't understand the breadth and depth of what exactly is MBSE. So they misunderstood the requirements, misunderstood activities around it, and they did not put enough strength in the teams to actually develop artifacts that are essential in MBSE [41]."*
Legacy systems	3	*"[MBSE] is not practical financially to apply it to legacy products… there really isn't a process for transition [10]."*

[9] The terms leadership and management were used interchangeably by interview participants

5.3.3 Integration

One of the critical issues in MBSE adoption that is relevant to organizational structure is the idea of integration. Integration needs to occur at the organizational level, and the technical level. The technical level refers to the fact that tools, models, and/or data repositories need to be linked together in some way. This is how an authoritative source of truth is established. Some tools have to integrate with others by virtue of their functionality. One participant discussed an architecture tool which "*has to be able to integrate with other tools [59]*" because it cannot do everything, such as requirements management. Some organizations also want to accommodate engineers from "*classically trained disciplines [44]*" that have their own tools they prefer to use, so there needs to be a way to transfer the data between those tools. Another reason integration needs to happen is many systems are spread out over different companies. They all create a part of a system that have to integrate together for the final product. One participant described the different scenarios this type of integrations can currently be achieved:

> *"We haven't found a solution for exchanging architecture models digitally, which is an important part of MBSE. My assumption is all my suppliers are going to use their own tool- they all have their favorite brand. But at the end I need to have an integrated model or the product will be a failure… There are two scenarios we can try to implement. One is direct communication of our models. So you take my model, I'll take yours and we're going to use it out of the box. So… in order to do direct communication, I am going to stamp my feet and say 'we're all going to use one brand' everyone has to switch to that brand. Or we're going to use a 3rd party translator. I'm going to pay a 3rd party to translate their model into my tool and vice versa. The other scenario [indirect communication] is we're going to put our models in a third party tool and they're going to be magically combined into one model. So instead of us having our own model, we will use a tool to build a single model [10]."*

Integration also has to occur at the organizational level, because "*a lot of different functional areas need to come together for MBSE [3]*." Especially in the context of Digital Engineering, it "*effects every aspect of the business [44]*." The way many organizations are structured, this often means that different departments or teams are going to have to work together. One participant's organization specifically had difficulty adopting MBSE because they could not get the IT department "*to do five minutes of work for three to four months [35]*." Another participant discussed the difficulty of getting collaboration across the organization: "*The other area that still frustrates me… is getting that collaboration across the organization. You can't think of MBSE as just what the systems engineers do, because it's Systems Engineering, as a good systems engineer you need to appreciate things like electrical, mechanical, environmental, economics. So using models allows you to bring all of that together into a source of truth [45]."* Even when an organization has been instructed by upper management to integrate across different disciplines, it is still a challenge. According to a participant, "*We are getting commands from the top-down to try to get the other teams integrated, but they're having the problem of it's not as important to do as other things, investing time into the model is not as important as other issues [47]*."

The way that organizations have to address the issue of integration is through coordination mechanisms. As discussed in Chapter 2, one of the two main components of organizational structure is how to coordinate and facilitate communication among subunits to realize the bigger task of the organization. Table 41 shows the results of evaluating all of the interview transcripts for mention of coordination mechanisms. The coordination mechanisms were taken from the literature reviewed in Chapter 2. Several examples of a distinct lack of a coordination mechanism where one was needed were also found and noted.

Table 41: Coordination mechanisms extracted from interviews

Coordination Mechanism	**Number of Organizational Units**
Implicit coordination through technology	4
Formal hierarchy	10
Standard rules/procedures	9
Direct informal contact	9
Liaison roles between groups	2
Task forces	3
Permanent coordinating team/department/manager	8
Matrix organizational structure	2
Lack of coordination mechanism	11

Implicit coordination through technology. Implicit coordination through technology is achieved with MBSE when tools, models, or data are integrated. By "*connecting all these different disparate models that we've always been developing in engineering [9]*," a team can look at all of the constraints on a product, which helps them make better decisions. As discussed earlier, this type of coordination can be achieved through direct or indirect communication of models. One participant discussed their organization's integration plan: "*So if somebody on a CAD tool introduces a new component, I need to know about it in the requirements tool. So that information flows out through our intermediary systems into the requirements tool so I can allocate requirements to it [44]*." Connecting models is one of the key ways MBSE can provide value. According to one participant, "*Just by linking two groups together (outputs of their model are inputs to your model) you're going to save so much time and money rather than producing interface documents and throwing them over the fence [45]."* The drawback to this coordination mechanism is that it is difficult to achieve. The tools do not always allow for this type of integration, so many organizations are struggling with this.

Formal hierarchy. Formal hierarchy is one of the classic methods of coordination in organizations. This mechanism is straightforward and makes it clear who has authority to make decisions. The main issue with this mechanism is that it often results in "*accidental complexity [18]*." As one participant said, "*We have so many bosses and middle managers, and very few people doing actual work [9]*." This can lead to organizational resistance in response to changes that upset this status quo.

Standard rules/procedures. As seen in the survey results, higher levels of standardization of MBSE was positively correlated with MBSE use and maturity. Standard rules or procedures are an effective way to achieve coordination in an organization is more fragmented or has less of a formal hierarchy. The difficulty of that is that there may not be a way to enforce those standards. For example, several interview participants mentioned that their organization did have a "standard way" of doing MBSE, but they did not know what those standards were. Another issue with standards relates to customers or contractors that are outside of the organization. As one participant reported, "*While we have a standard suite we want to move to corporately, we can't always stay in the standard suite because our customers have their preferences [44]*."

Direct informal contact. Direct informal contact is one of the more general types of coordinating mechanisms. One of the most frequent uses of this mechanism from the participants occurred within teams who have dedicated modelers or people who are more proficient with the tools. In cases where this is effective, the non-modeler makes changes using a different software they are familiar with (e.g. Visio, PowerPoint), and give that to the modeler who would make the relevant changes in the model. The issue with relying on this informal contact to coordinate is when teams end up operating too independently. One participant reported this issue in their organization: "*It's good to have a modeling team set aside that does the modeling and it's their responsibility to manage and maintain that, but right now they are operating very independently to build that model up…They created a model, but no one sees it as the source of truth. That team didn't have the information and buy-in needed from designers to lay out the model correctly [47]*." Another type of direct informal contact occurred with training; having people who you can reach out to for help, or to self-organize training classes, when these trainings have not been formally established in the organization. The issue with this is that it can only occur "***if*** *you know the right people [5]*."

Liaison roles between groups. Based on the way certain organizations define the job of a systems engineer, they sometimes serve that liaison-type role between different teams. One participant described how this occurs in their organization: "*Systems Engineering owns the integration of all the components of the system. So they make specifications to the design team and generate requirements; that's how they communicate with everyone else [47]*." At this organization, the system engineer is formally given the task of integrating all of the components of the system, and they need to communicate with those groups to make that happen. A liaison role is an effective way to coordinate horizontally among different groups without having to make a lot of changes to the formal structure of the organization.

Tasks forces. Task forces are an effective way to temporarily get a lot of people to work together who may not interact otherwise. One participant described how their organization assembled a task force at the beginning of the MBSE adoption journey. "*All the senior SE leads across all sectors, we came together and met about a years ago and talked about how we should take this forward. We partnered with several outside agencies to actually do some initial studies, and we participated in those studies [41]*." Often a task force is created to address a specific problem, and once that problem is addressed the group is dissolved; so it is not a long term solution.

Permanent coordinating team/department. A permanent coordinating team typically took the form of a formal (and permanent) working group, community of practice, or centralized MBSE

team/department. This mechanism can be similar to a task force in concept in that it can bring together people who would not otherwise interact. The difference is that it is permanent. In the participants' organizations, these permanent groups were either informal (working group, community of practice) where people go for help and to share best practices voluntarily, or formal (MBSE team, standardization group) where best practices and standards are published, methodologies and tools are managed, and training occurs. Informal groups function outside of the organization's structure, while formal groups are part of the formal hierarchy.

Matrix organizational structure. Two of the participants specifically noted that their organizations operate with a matrix structure. In both cases, there is part of the organization that is structured around products, projects, or customers. Separate from that is part of the organization that is divided based on specialized disciplines. One participant described that their organization "*has different engineering disciplines that are matrixed in. So when [they] go do a new program, the program basically goes and asks a [specialized discipline] that does systems engineering to give them a couple systems engineers to support the program [47]*." The benefit of this structure is that the disciplines are able to specialize in their field and bring that expertise to different projects. Another benefit is that "*organization is responsible for making sure the same practices are followed between programs [47]*," which is how the coordination occurs.

Listed below are some of the examples of a lack of coordination mechanism from interviews. These quotes discuss a lack of standardization, lack of communication between subunits, and issues of authority.

> *"But the problem is, even if we standardize how we do our piece, with all these contractors and other performers do things differently and try to integrate with what we're doing [5]."*

> *"The other part is organizational. I can't tell you how many organizations I've tried to help that have a requirements group, and an architecture group, and an interfaces group, and an analysis group that never meet [9]."*

> *"They're just trying to coordinate all these efforts like MBSE in a lot of ways without real authority. And everyone has their opinion about what tool and method is best. Since so many people just have control over a small part of the kingdom, not one has control of everything [20]."*

> *"It's kind of separate. That's kind of my complaint, we don't have a chief technology officer. So we don't have someone, groups kind of do their own thing [33]."*

> *"We have different business units and they are not well-connected, it's like having different silos. And everyone tried their own way [40]."*

> *"It would be a little different across, because the needs are different, customers are different. So you will see those differences. But slowly you will see those differences vanish over time. As we communicate more closely, let's establish communication pathways between programs so we can learn from each other. So overtime it will improve [41]."*

"It's more of a 'who has the charge line to do what part of the work' type of obstacle. And a resource limitation [47]."

5.4 Interview – survey comparisons

In order to provide qualitative support for the content validity of the survey, the interview responses were analyzed for similarities and differences. After the interviews were transcribed, the responses were divided into individual statements. A statement in this case meant a singular idea. This could be in the form of a few sentences to a sentence fragment. Once the responses were separated, each statement was coded if it was related to an organizational structure variable or an adoption variable. It should be noted that a statement could represent both and organizational variable and an adoption variable. After the responses were coded and separated by variable, the statements were reviewed again to determine relevance to the actual survey questions. Some participants discussed general thoughts, hypothetical examples, or past experiences, all of which did not relate to their current organizational unit. The relevant statements which remained were reviewed to determine if there were any conflicting or contradictory statements with regards to the survey results.

Table 42 and Table 43 show the amount of interview participants which had relevant statements to a survey question/variable. There were 18 interviews in total. The adoption variable A1 was analyzed by its three questions separately, since the subject of each A1 question were all different components of the adoption process. In the table, this is represented as Process, Reception, and Training. Process refers to question A1.3 that addressed if processes were changed to incorporate MBSE. Reception refers to question A1.2 that addressed if employees were interested in MBSE. Training refers to question A1.1 which asked if employees had received sufficient training.

Table 42: Amount of survey - interview comparisons for adoption variables

Process	**Reception**	**Training**	**Maturity**	**Use**	**Influence**
9	12	16	13	15	7
50%	67%	89%	72%	83%	39%

Table 43: Amount of survey - interview comparisons for organizational variables

OS1	**OS2**	**OS3**	**OS4**	**OS5**	**OS6**	**OS7**
4	10	11	6	5	12	7
22%	56%	61%	33%	28%	67%	39%

Adoption variables were more commonly found in interview statements. This is likely due to the nature of the interview questions which focused heavily on adoption. *Formalization*, *Centralization*, and *Flexibility* were all also well represented in the interview statements. Although the comparisons are largely qualitative in nature, statements that seemed to conflict with survey results were noted. Around 5% of the related statements were conflicting, while the rest appear to

support the survey results. This provides an additional level of confidence in the validity of the survey questions.

The rest of this section contains the summarized comparisons by variables. The survey response the individual gave for each relevant question is included next to the description of the interview statements.

A1.3: Existing processes were adjusted to support MBSE

Subject 3 ***(Somewhat agree)***: The participant indicated there had been consideration in their organizational unit on how to transition from DBSE to MBSE. According to the respondent: "*The models need to be able to generate the documentation so that we can do this crawl-walk-run thing and get various stakeholders up to speed*." The respondent also indicates there is a "*digital engineering strategy*" that the organization is trying to implement.

Subject 9 ***(Agree)***: The participant indicated that there have always been models used in projects, the difference with MBSE is "*how we're integrating [models] and using them across the lifecycle*." This is leading to improved "*engineering lifecycles, engineering processes, [and] decision making*."

Subject 18 ***(Somewhat disagree)***: The participant indicated that there is a need to change how the organization operates to keep up with increasing complexities. "*We can't do things the way we have been.*" The organization is not at this point, however. According to the participant: "*There hasn't been that level of buy-in here. That reuse angle that you could get with MBSE has not been realized*."

Subject 35 ***(Disagree)***: This organization was unsuccessful at ultimately adopting MBSE. One if the main issues was the inability to get certain departments to help with getting the software installed and working. Management "*lost interest*" and the adoption effort "*fell apart*."

Subject 40 ***(Disagree)***: This organization has conducted several pilot projects and studies into MBSE use in the organization. The participant remarked about the state of the adoption: "*I think we could slowly build things up by switching from Excel, PowerPoint, Visio documents to block diagrams. But I don't think we will jump into model-based with a big bang*."

Subject 41 ***(Somewhat agree)***: The respondent indicated there has been positive progress in the MBSE adoption but there is still a long way to go. Initial efforts struggled because "they didn't understand the breadth and depth" of MBSE. But "*now there is a strategy*" and "*a complete system put together on how to execute that strategy*", and that "*there have been a lot of activities going on*."

Subject 44 ***(Agree)***: This organization had "*an actual roadmap*" on how they are going to transition to a full Digital Engineering organization. The participant explained: "*Right now, we are getting to roll out a 1.0 that is basically be transforming the stack. Basically the projects are not going to notice it because they will be continuing to do their work processes but now they have a new stack that is powering it. Because that new stack is powering it, we now have all these capabilities built-in and we can start introducing new digital elements on top of that stack. It will make it much*

easier to get out the 2.0 version which will then include certain new capabilities and the 3.0 version and the 4.0 version. We have an idea of what these versions are going to contain."

Subject 46 ***(Strongly agree)***: The participant disclosed that their organization has funding and approval to adopt MBSE, so they are "*going to do it*".

Subject 47 ***(Somewhat disagree)***: The participant indicated that there is interest to use MBSE in the organization, but the actual adoption is proving difficult. Due to the legacy nature of the system, "*trying to incorporate MBSE*" and build up a model "*while making changes to the product*" is difficult and often not a top priority.

A1.2: Project personnel showed interest in adopting MBSE to accomplish job tasks

Subject 5 (***Somewhat disagree***): The participant sited a substantial amount of resistance to MBSE, including not having training, improper equipment to run models, and the classic "*this is not how we have done it*" complaint.

Subject 6 (***Strongly agree***): The participant is the president of the company, so MBSE has been accepted from "*when the term got coined*." Furthermore, the participant mentioned that "*it's hard to imagine why people are still dragging their feet*" and notes that "*there is very little resistance*" from their customers who are "*excited about using the tool and the technique.*"

Subject 18 (***Somewhat agree***): The participant indicated that "*there's a groundswell of this new generation who is pushing for [MBSE] and thinks this is the way forward*." Overall there seems to be a mix in perception of MBSE. "*There are some areas that really embraced it very quickly, there are some areas where there is a certain reticence to use it*."

Subject 20 (***Disagree***): According to the participant: *"[MBSE] still hasn't fully caught on. I was and still am one of the people pushing for it*."

Subject 33 (***Agree***): The participant indicated that they "*can see the advantage of having a model that works throughout the whole system lifecycle, but that hasn't been the case in the past*."

Subject 34 (***Strongly disagree***): The participant indicated that "*management was not convinced that [MBSE] was worth the investment*" so it never went past the initial consideration period

Subject 40 (***Strongly agree***): The participant indicated that the interest for MBSE was originated in the software team, who "*had the energy and motivation*" to push for MBSE and the effort for adoption has largely been a "*bottom-up*" effort.

Subject 41 (***Somewhat agree***): The participant mentioned that there was strong support for MBSE from corporate leadership, but stakeholders still needed to be educated because they often did not understand what it was, which caused problems.

Subject 44 (***Somewhat agree***): The participant indicated that there were people in the company who recognized that the industry is trending towards digital. The "*principle person who sold [MBSE] to senior management spent over a year getting buy-in.*"

Subject 45 (***Somewhat agree***): The participant indicated that the executive level and the engineering level of the organization were supportive of the initiative to adopt MBSE. "*The challenge was and remains what I call the middle layer, between the executives and those who actually do MBSE*." Because MBSE is not the "*day-to-day environment*" of the middle managers they were often not convinced of its value.

Subject 47 (***Disagree***): The participant indicated that the systems team has wanted to use MBSE, but other teams are "*unaware of MBSE*" and that they do not understand the value. Furthermore, "*investing time into the models is not as important as other issues*."

Subject 62 (***Agree***): The participant relayed that there were some people who were more comfortable with MBSE than others. But the participant also indicated that they "*told everybody [MBSE] is what we needed to do and they all agreed*," even stating that "*people kind of drank the Kool-Aid*."

A1.1: Project personnel were provided with sufficient training to use the necessary MBSE tools

Subject 3 (***Somewhat disagree***): The participant mentioned that the organization is "*trying to get [their] personnel*" trained, but that takes a "*concentrated effort*."

Subject 5 (***Somewhat disagree***): According to the participant, "*they are slowly but surely trying to get people trained*" but training and equipment are going to be an issue. They emphasized that training classes that are used only cover basic examples (e.g. a flashlight), which aren't relevant to the product the organization actually makes.

Subject 6 (***Strongly agree***): This participant discussed providing training at the theoretical level, and the practical level. Specifically, this included methodologies and processes, and the MBSE tool and how it works.

Subject 9 (***Somewhat agree***): This participant discussed how clients react to training for MBSE. According to the participant: "*When I go in to facilitate a workshop discussion with a client the very last thing I talk about us tools. The first thing they want to talk about is tools because tools are shiny.* " Additionally, training can teach someone how to use an MBSE tool, but "*that doesn't teach [them] how to be an architect...we need to figure out how to do training on that*."

Subject 18 (***Somewhat disagree***): The participant disclosed that "*resources have been made available*" and "*training courses have been arranged*." The organization also provided experienced MBSE contractors as mentors. This appears to contradict the response the subject gave to the question about sufficient training.

Subject 20 (***Somewhat disagree***): According to the participant, "*training is either self-training or finding universities that offer classes*." So there is no indication that the organization provided training.

Subject 33 (***Somewhat agree***): The participant indicated that "*most people haven't had training*", which appears to contradict the somewhat agree response to the sufficient training question. The

participant did share that they are "*working on an SE guidebook for transportation*," but that does not appear to be MBSE-specific.

Subject 34 (***Strongly disagree***): This organization did not adopt MBSE. The participant specifically called out "*the cost of training staff*" as a factor deterring the adoption.

Subject 35 (***Somewhat disagree***): The participant discussed how the organization began the process of adopting MBSE, but ultimately did not succeed. In the organization, "*6 people [went] to training within 3 months of getting the license*," but there was virtually no follow up or other training provided to additional people.

Subject 40 (***Strongly agree***): This participant discussed a robust lineup of training options that are being provided or being developed. These include: self-organized classroom trainings, online material and videos, and e-learnings

Subject 41 (***Agree***): The participant discussed a plethora of training-related considerations. They provided online and live training, luncheons, one-on-one meetings, "*office hours*", and a startup kit. There was also considerable attention given to who should be trained, and to what degree.

Subject 44: (***Somewhat agree***) The participant discussed "*briefing*" senior and middle management "*as to what is coming and why it is coming and trying to get them ready*" for the transition to digital. This has been occurring over the last four years and is an ongoing effort. There was not a specific mention of training, which appears to contradict the somewhat agree response to the survey question.

Subject 45 (***Somewhat agree***): The participant discussed a portfolio of training courses the organization has developed that is given by a centralized group, so it is consistent across the organization. However, the participant also recounts that they have to train people "*while they do their day job as well*," because they did not have a good understanding of MBSE when they were hired. "*So even now, we're supporting the adoption of MBSE on projects where a majority of the people on that project have not had formal MBSE training*."

Subject 46 (***Somewhat agree***): The participant discussed training for a select portion of the organization, as well as giving training to their government customer. But the training will need to be improved for "*people who actually have to develop in [the tool]*," who will need additional training.

Subject 47 (***Somewhat agree***): The participant discussed training efforts for people outside the SE discipline. There is training for select people who will be working out of the model, but there hasn't been "*great training for engineers who have knowledge of the system*". Specifically, people who "*deeply understand*" the product and system overall.

Subject 62 (***Somewhat agree***): The participant recounted an inconsistent journey through training people in MBSE. While there have been people sent to training classes several times, "*there is no formal, repeatable training*" that the organization itself provides. The participant also notes that "*getting people to fund training is one of [their] principle challenges*."

A2 Maturity of MBSE

Subject 3 (***Early systematic approaches***): The participant remarked that *"[MBSE] is going to take some time to become inherent in the normal SE processes that [they] deal with*." But the organization is considering how to "*have metrics to measure the success*" of how well MBSE is being executed, which shows a level of maturity.

Subject 6 (***Integrated approaches***): According to the participant, MBSE "*has been going on for decades*" and "*is not a new topic*."

Subject 10 (***Aligned approaches***): The participant is a member of a consortium of groups that "*get together to share best practices*" and "*try to agree on vocabulary, methodology, and tools*" for MBSE.

Subject 18 (***Aligned approaches***): The participant indicated that there had been progress on adopting MBSE but it has taken longer than expected. The organization is also using the INCOSE MBSE maturity model to track the adoption effort.

Subject 20 (***Reacting to problems***): The participant discussed how the organization is at the point of "*gathering information on what processes should be used*," and does not have any processes for MBSE in place. The participant also remarks that "*MBSE is consistently inconsistently applied*."

Subject 33 (***Early systematic approaches***): According to the participant, MBSE is "*not engrained in the company's culture*" and that if they were not doing MBSE, someone likely would not do MBSE in the same way as them. This seems to indicate a lower level of maturity than was selected for the survey response.

Subject 35 (***Reacting to problems***): The participant discussed how the adoption effort has essentially stalled. Servers were not installed, licenses weren't issued, and management "*had different priorities*" than when the effort began 2 years ago.

Subject 40 (***Early systematic approaches***): The participant discussed how the organization has progressed in their MBSE adoption. The effort began with showcasing, followed by case studies, and followed by pilots.

Subject 41 (***Early systematic approaches***): The participant conveyed the discussions that went on in their organization to select a maturity model to evaluate the progress of the MBSE adoption.

Subject 44 (***Early systematic approaches***): This participant conveyed the time and effort the organization has invested into planning out the complete transformation to digital. Efforts have begun to set the foundation up for that transformation. According to the respondent, *"[They] have enough of the whole big picture*" that they can actually start to implement various pieces of the process. "*It has been a long journey and it still has a way to go*."

Subject 45 (***Early systematic approaches***): This participant discussed how the organization is "*still on that roadmap to full adoption because everything keeps changing*," specifically technology and staff. However, "*the last 5-6 years now, a model-based approach has been normal and expected*." The organization prepares projects based on a model-based approach, and "*there is a formality in terms of policies and procedures*."

Subject 47 (***Early systematic approaches***): This participant discussed issues the organization is having with building up a model to be an authoritative source of truth. The modeling team "*didn't have the information and buy-in needed from designers to layout the model correctly*." The participant indicated that "*the vision is to have MBSE go all the way through on programs*" but right now it is mostly in development.

Subject 62 (***Early systematic approaches***): The participant discussed the range in ability of different teams and people to do MBSE. The people who are proficient in the modeling tool have had to help others as the transition to model-based in occurring. According to the participant, *"[they] have not transitioned fully*" to complete MBSE, but "*have progressed beyond the point where it is just drawing diagrams.*"

A3 Use of MBSE (% Projects / % People)

Subject 5 (***10% / 10%):*** According to the participant, "*most performers are still using [the previous requirements management tool] as their source of truth, but using [the MBSE tool] as a side thing to meet the contractual requirement*." The participant speculated that "*a lot of people are just not going to do [MBSE]*" because it requires "*a whole mindset change*."

Subject 9 (***90% / 90%***): The participant remarked that *"[they] do models and model-based engineering across the entire lifecycle*."

Subject 10 (***70% / 80%***): The participant remarked that *"[MBSE] is certainly used on new products,*" but "*it is not practical financially to apply it to legacy products*." The participant also discussed how the first implementation of MBSE began over 15 years ago.

Subject 18 (***20% / 20%***): The participant indicated that the decision to use MBSE "*was more of a personal preference*." The participant also discussed how a core team has started working with teams and programs to help them learn the MBSE methodology and apply it.

Subject 20 (***10% / 10%***): According to the participant, the use of MBSE is "*on a project by project basis*." They describe MBSE as "*trickling in*" and being "*inconsistently applied*."

Subject 33 (***30% / 50%***): According to the participant, it is "*up to the engineer(s) on the project*" whether or not they use MBSE. The participate remarked that *"[they] tend to use it on [their] projects, and others tend not to or ask [them] for help with it.*"

Subject 34 (***0% / 0%***): The participate indicated that *"[they] don't have any formalized MBSE practice.*"

Subject 41 (***20% / 20%***): The participant conveyed that "*parts of [MBSE] will be easier for some programs*" to do, since they all think about it differently.

Subject 44 (***20% / 10%***): The participant discussed how the organization has a plan to go fully digital, but that is currently not in place. According to the participant, "[*They] have some projects that use SE because customers want [them] to use it or [the team] find[s] that it helps [them]*."

Subject 45 (***80% / 60%***): According to the participant, almost all projects are using MBSE to some extent. There are different policies in place indicating that "*a model-based SE approach has to be considered*" but "*applied pragmatically*."

Subject 46 (***100% / 90%***): According to the participant, "*a little bit of everybody*" need to be trained in MBSE, depending on how involved in the modeling process they will be. The participant also speculated that many people will not make the switch over to MBSE. This seems to contradict the high percentages of people and projects that are using MBSE.

Subject 47 (***50% / 30%***): The participant discussed how "*everyone on the program [has to] at least be able to read information from the model, and most of them also have to have access to edit it*." However, the program "*still [has] people build architectures in [the previous tool] and then hand that to a separate person who has to construct that in [the MBSE tool]*."

Subject 62 (***70% / 30%***): The participant indicated that MBSE is being used on most projects, but some people on the project need a modeler to be paired up with them to convert their work to MBSE. There is a range from people who see the model as their workspace, and others "*who work outside the system and pull what they need from the model and paste it into their Word files.*"

Table 44: Survey-interview comparison variable A4

A4 Influence on organizational outcomes		Velocity/ Agility Improved	Quality of Systems Improved	Knowledge Transfer Improved	Experience Improved
3	The participant indicated that MBSE allows them to "*do early virtual integration and analysis to catch problems before they become problems in the physical integration*" that would involve "*a lot of costly rework*."	Agree	Agree	Somewhat agree	Somewhat agree
6	The participant discussed how MBSE tools can "*help you better do your job*."	Strongly agree	Strongly agree	Strongly agree	Strongly agree
9	The participant discussed a variety of ways MBSE provides value. They specifically mention automation, improved decision making, reduced time, and traceability. The participant also discussed understanding change impact across the system. According to the participant: "*I can go electronically into that change and it will show me all the impacts across the rest of the system; from cost, schedule, performance, sustainment, and other perspectives. We could not do that before*."	Somewhat agree	Agree	Agree	Agree

18	The participant discussed the improved traceability that came from modeling. The participant also discussed the discrepancy between errors you find using MBSE and a "*paper system*." When there is a paper system, it is easier to hide problems which never get addresses. But MBSE has "*a crispness and precision to it, so it's easy to see all your errors very clearly*" so it appears that there are more errors with MBSE, when the reality is it is just better at discovering errors.	Somewhat agree	Agree	Somewhat disagree	Somewhat agree
20	The participant mentions several benefits of MBSE, including accessibility of data and improved decision making. The participant also noted that, with MBSE, people are "*seeing information they otherwise wouldn't see, presented in a way that is more useful or comprehendible*."	Somewhat agree	Agree Agree	Somewhat agree Somewhat agree	Agree Agree
34	The participant's organization did not adopt MBSE, so none of the benefits were realized. The participant did note that MBSE "*might be a technically good thing to do, and might save [them] money*." But due to the way their contracts are structured, there is "*no incentive to pursue that kind of optimization*." In order to convince others, there needs to be a more "*compelling argument for why MBSE is better*" supported by data.	Strongly disagree	Strongly disagree	Strongly disagree	Strongly disagree
40	The participant's organization did some work to estimate the effects of MBSE. The conclusion they reached was: "*There will be no fast increase in efficiency in the first pilots, on the contrary, it becomes much slower at first*." The understanding and the model needs to be built up, so it is an investment that will pay off later. The participant did mention improvements that were observed already through using MBSE, such as reduced effort, better data visualization and understanding.	Strongly disagree	Somewhat agree	Somewhat agree	Agree

44	The participant discussed the potential cost savings from better requirements management. The participant also discussed the improved ability to process changes using MBSE.	Agree	Agree	Somewhat disagree	Agree
45	The participant discussed examples where the organization has found issues early that would have been costly to resolve later. According to the participant, "*using model-based techniques for analysis and architecture, [they] have been able to quickly identify issues [they] would not have seen until the system was in service... or later in the development cycle*." The participant also conveyed the value of integrating models. "*Just by linking two groups together, outputs of their model are inputs to your model, you are going to save so much time and money rather than producing interface documents and throwing them over the fence*."	Somewhat agree	Somewhat agree	Somewhat agree	Somewhat agree

Table 45: Survey-interview comparison variable OS1

OS1 Size		**Size**
33	Participant noted that their organization is "*not very big*."	50 - 200
41	Participant mentioned the large size of the organization.	1000 - 1500
44	Participant mentioned the large size of the organization.	Over 1500
45	Participant mentioned the large size of the organization.	Over 1500

Table 46: Survey-interview comparison variable OS2

OS2 Formalization	How MBSE-related tasks are carried out here is left up to the person doing the work*	There are written formal procedures that people in my OU must follow in their MBSE-related work	Written formal procedures/ guidelines are updated promptly after changes are implemented in my OU

5	Participant discussed the issue of inconsistent modeling. According to the participant, "*implementation and usage of actual models can be derived in multiple ways depending on how your thought process and flows are*."	Agree	Strongly disagree	Somewhat disagree
20	The participant discussed the formation of a steering committee whose job it is to gather information on what processes should be used in order to eventually formalize a plan.	Agree	Strongly disagree	Strongly disagree
33	According to the participant, "*we don't really have a policy. I authored a process for SE but I don't know how well that is being followed.*"	Agree	Strongly disagree	Somewhat disagree
40	The participant emphasized the importance of having documented processes and procedures. Having documented processes makes the effort more "*sustainable*" and helps "*prove everything is traceable*" for safety concerns.	Somewhat agree	Agree	Somewhat agree
41	The participant discussed how processes and policies were first set up "*to perform good systems engineering*." Due to a recent merger of companies, "*the processes, procedures, and policies were very different between many areas*" of the organization.	Somewhat agree	Somewhat agree	Agree
44	The participant discussed a roadmap of how MBSE and digital processes will be adopted in the future, but currently there is not that documentation. How a project uses MBSE depends on the person and what the customer wants.	Agree	Somewhat disagree	Somewhat disagree

45	The participant discusses various policies on how to approach MBSE for projects. According to the participant, "*there are policies in place where a model-based SE approach has to be considered in the early stages of a program. But it needs to be considered and applied pragmatically*."	Somewhat disagree	Somewhat disagree	Somewhat disagree
46	The participant relayed how engineers from the organization's SE specialty group taught his group the company standard way of modeling.	Disagree	Strongly agree	Somewhat disagree
47	The participant acknowledged that the organization does have a standards document related to MBSE, but they were not familiar with it. According to the participant, the standards afford programs a lot of room to tailor the practices to suit the program's needs.	Disagree	Somewhat disagree	Somewhat disagree
62	The participant mentioned that there are different documentations that their chief architect has released, including "*how to execute Model-Based Systems Engineering*."	Somewhat agree	Agree	Somewhat agree

Table 47: Survey-interview comparison variable OS3

OS3 Centralization		Employees are empowered to address small matters without needing supervisor approval	Employees can decide whether or not to use MBSE for a given task	Project personnel using MBSE participated in the decisions of which MBSE tools and/or methods to use
3	The participant disclosed the nature of collaboration between industry and government to develop standards, requirements, and specifications for the whole organization.	Somewhat disagree	Disagree	Somewhat disagree

5	According to the participant, whether MBSE is used "*depends on where you're at and who is implementing what requirements on what contracts.*" The contracts and requirements they receive determine if MBSE will be used on a project.	Somewhat disagree	Strongly disagree	Somewhat disagree
18	The participant discussed how there are different regions and divisions spread out across the company, and that there is a centralized MBSE team that is geo-dispersed throughout all those different regions. According to the participant, their organization had previously used MBSE based on "*personal preference*," but now it is being "*rolled out deliberately*" across the organization.	Somewhat agree	Somewhat agree	Somewhat agree
20	According to the participant, MBSE is used "*on a project by project basis. In several cases, every project is working differently*."	Somewhat disagree	Agree	Somewhat agree
33	According to the participant, "*it is up to the engineer(s) on the project*" whether or not they want to use MBSE.	Strongly agree	Strongly agree	Somewhat agree
40	According to the participant, the effort to adopt MBSE was bottom-up. Project members decided how to do "*model-based in different ways with different aspects… everyone tried their own way*."	Strongly agree	Somewhat agree	Strongly agree

41	The participant discussed how the senior SE leadership helped decide how to move the adoption of MBSE forward along with corporate. However, the participant also indicated that "*each program thinks about [MBSE] differently, so it takes time*" to get everyone on board.	Agree	Somewhat agree	Somewhat agree
44	According to the participant, the organization has "*a standard suite [they] want to move to corporately*," but they need to account for customer preferences.	Agree	Somewhat disagree	Somewhat agree
45	The participant discussed a centralized part of the organization that publishes guidance and best practices, as well as providing training. However, MBSE use varies from project to project. According to the participant, "*Some projects will use a small amount of [MBSE], some projects tend to be wholly MBSE driven*."	Agree	Agree	Disagree
47	The participant discussed the difficulty of getting teams outside of SE to invest in learning and using MBSE. According to the participant, "*They are having the problem of [MBSE] not being as important to do as other things*."	Strongly agree	Somewhat agree	Agree
62	According to the participant, use of MBSE varies across teams. The range includes teams that are proficient with MBSE, teams learning MBSE, and teams "*only know it's important*."	Agree	Disagree	Agree

Table 48: Survey-interview comparison variable OS4

OS4 Specialization		Subunits in my OU perform highly specified tasks that differ from other subunits	People in my OU generally have similar skills and knowledge as other in the unit	There are designated people in my OU who create and manage the MBSE models
9	The participant discussed how the organization has "*sponsor-facing*" divisions and discipline-specific divisions. The discipline-specific divisions are a group of people who are each specialized in a different skill or knowledge area.	Somewhat disagree	Somewhat disagree	Agree
18	The participant indicated that there "*is now a dedicated cadre of people*" trying to get up to speed with modeling techniques.	-	Somewhat disagree	Somewhat agree
41	The participant mentioned that there are designated modelers in the organization.	Somewhat agree	Somewhat agree	Somewhat agree
45	The participant mentioned that there are designated modelers in the organization.	Agree	Disagree	Agree
46	The participant mentioned that there are designated modelers in the organization. The participant also conveyed how the team is built of people who are highly specialized experts in different fields.	Agree	Disagree	Strongly agree
47	The participant discussed how separate the group of modelers was from the rest of the team.	Strongly agree	Somewhat disagree	Strongly agree

Table 49: Survey-interview comparison variable OS5

OS5 Vertical Differentiation		There is a large middle management that passes information between top and bottom levels of the organizational hierarchy	In my OU, the members of project teams have equal status hierarchically within their projects	The organizational chart of my OU is relatively flat with few levels of management
5	The participant indicated there is a substantial hierarchy in the organization	Somewhat agree	Somewhat disagree	Strongly disagree
44	The participant discussed different levels of senior and middle management.	Somewhat agree	Somewhat disagree	Somewhat agree
45	The participant discussed different levels of senior and middle management. The participant describes employees "*creeping up the ladder*" to become middle management over time.	Somewhat agree	Disagree	Disagree
46	The participant discussed a number of "*gates they go through to get approval*" with different levels of leadership.	Agree	Strongly agree	Somewhat agree
47	The participant describes the structure of their program as having a number of different teams (such as SE, design, testing) under the leadership of a chief engineer.	Agree	Somewhat agree	Agree

Table 50: Survey-interview comparison variable OS6

OS6 Flexibility		My OU can easily adapt to environmental changes	My OU has strategies oriented towards promoting organizational innovation and growth	Organizational skills and technologies are updated often
3	The participant demonstrated the organization's commitment to innovation through the establishment of R&D efforts in the area of MBSE. Specifically, to "*take tools that are not as mature and improve on them*."	Agree	Strongly agree	Somewhat disagree
5	The participant indicated their organization was very resistant to change. According to the participant, "*it's going to be a long road ahead because of technology changes, mindset changes, training, and resources*."	Somewhat disagree	Somewhat agree	Somewhat disagree
18	The participant indicated that it had taken a long time for their organization to get the momentum to start the adoption process. According to the participant, MBSE is "*working against the grain for cultural adoption*."	Somewhat disagree	Somewhat disagree	Somewhat disagree
20	The participant noted how long and difficult it was to get any changes approved in their organization. According to the participant, it took multiple years just to form a steering committee to start looking into MBSE.	Strongly disagree	Strongly disagree	Strongly disagree
34	The participant indicated that their organization has "*a healthy appetite for new technology, broadly speaking*."	Disagree	Somewhat agree	Strongly agree

35	The participant indicated the difficulty the organization had with dealing with changes. An example they give is "*one person it took 9 months to order a government furnished laptop*." The participant discussed environmental, organizational, and technological setbacks or issues that the organization had.	Somewhat disagree	Somewhat disagree	Somewhat agree
40	The participant discussed the different areas where new technologies are general welcome. According to the participant, "*from the methods side and during development (without impacting the final product) [they] are relatively free to do anything*." But when it comes to the product that the customer will see, there are more restrictions.	Disagree	Agree	Somewhat disagree
44	The participant discussed the forward-looking leadership who "*recognize the trends*" with future technologies. The organizational is also designing their MBSE strategy to "*be able to be nimble and adjust to the dictates of the industry as it evolves*."	Agree	Agree	Somewhat agree
45	The participant discussed the orientation of their organization to be "*continually improving and learning*." However, the organization also can get behind where the technology is. According to the participant, "*sometimes we can try to apply a model-based engineering approach, and by the time we get into the project things have moved on*" and there is a new or improved tool or method.	Somewhat agree	Agree	Somewhat agree

46	The participant gave an example of how they "*recently recommended a new software to [their] boss who tried it and the next day said 'let's use this'*." According to the participant, there is "*a good amount of flexibility*" as long as it is not something the customer will see.	Strongly agree	Somewhat agree	Strongly agree
47	According to the participant, the organization is "*pretty receptive to new approaches of doing things*," especially in development. The participant also relayed how they "*haven't had any cultural issues*" with MBSE adoption. This stronger response appears conflict with the mid-range response values they gave to the related survey questions.	Somewhat agree	Somewhat disagree	Somewhat agree
62	The participant relayed the variety of attitudes towards new technology, especially MBSE, that are present in the organization. There are some people who were able to easily adapt, and a few who refuse. The participant shared an example of someone on the team who had been very resistant to the change, but the organization is now going to make him operate within the modeling tools.	Somewhat agree	Somewhat agree	Somewhat agree

Table 51: Survey-interview comparison variable OS7

OS7 Interconnectedness		People in my OU are willing to assist others with problems	People in my OU feel strongly connected to one another	People from different projects/ teams interact informally on a regular basis
5	The participant mentioned that there were people you could reach out to for help or to ask questions, but only "*if you know the right people.*"	Somewhat agree	Somewhat agree	Somewhat disagree

35	One of the key factors in why the MBSE adoption was ultimately unsuccessful at this organization was the lack of willingness of one department to help. According to the participant, "*you couldn't get them to do five minutes of work*" related to the MBSE adoption.	Somewhat disagree	Somewhat agree	Somewhat agree
40	According to the participant: "*if there is a project in need they come to me, or my team, and ask for training for onboarding*." These trainings are "*self-organized*" among personnel.	Agree	Strongly agree	Strongly agree
41	The participant discussed a working group of people from all over the company related to MBSE. According to the participant, "*if you have a question, you can bring your model and get help from these groups*."	Agree	Somewhat agree	Agree
45	The participant discussed how there are communities of practice creating an "*informal network*" that people can turn to if they need help with MBSE.	Agree	Somewhat disagree	Somewhat disagree
46	The participant conveyed the close-knit feel their organization has. According to the participant, "*everyone is really open to help if they can."* The participant also shared an anecdote: "*I had a guy the other day come up to me and say 'if I buy you a cookie will you explain these requirements to me?*"'	Strongly agree	Agree	Agree
62	The participant remarked that people who are proficient in modeling tools have "*a collateral duty to serve as an instructor or helper*" to other members of their team. This is part of their adoption strategy.	Strongly agree	Somewhat agree	Agree

Ch. 6 Causal Analysis

6.1 First iteration causal model

The first iteration of the causal model was based on a causal model developed to determine what variables will be the most impact to measure to determine the value of MBSE (Henderson et al., 2021). This model includes variables that are potential benefits of MBSE as well as adoption enablers of MBSE. The components of that causal model were obtained through two sources: a literature review on MBSE benefits (Henderson & Salado, 2021b) and an MBSE survey that evaluated adoption enablers and inhibitors of success (McDermott et al., 2020).

This model can be seen in Figure 25. The model was validated by subject-matter experts part of the Digital Engineering Working Group. This group included representatives from government, industry, and academia. Some of the organizations represented include Boeing, L3Harris, the US Army, Massachusetts Institute of Technology, INCOSE, NDIA, Lockheed Martin, and the Aerospace Industries Association. Members of this group are highly experienced in their respective fields, many of which have important leadership positions in their respective organizations (i.e. chairs/ directors/ leads of various divisions, groups, and committees). The SMEs were walked through the different paths of the causal map and provided verbal feedback on the causal links.

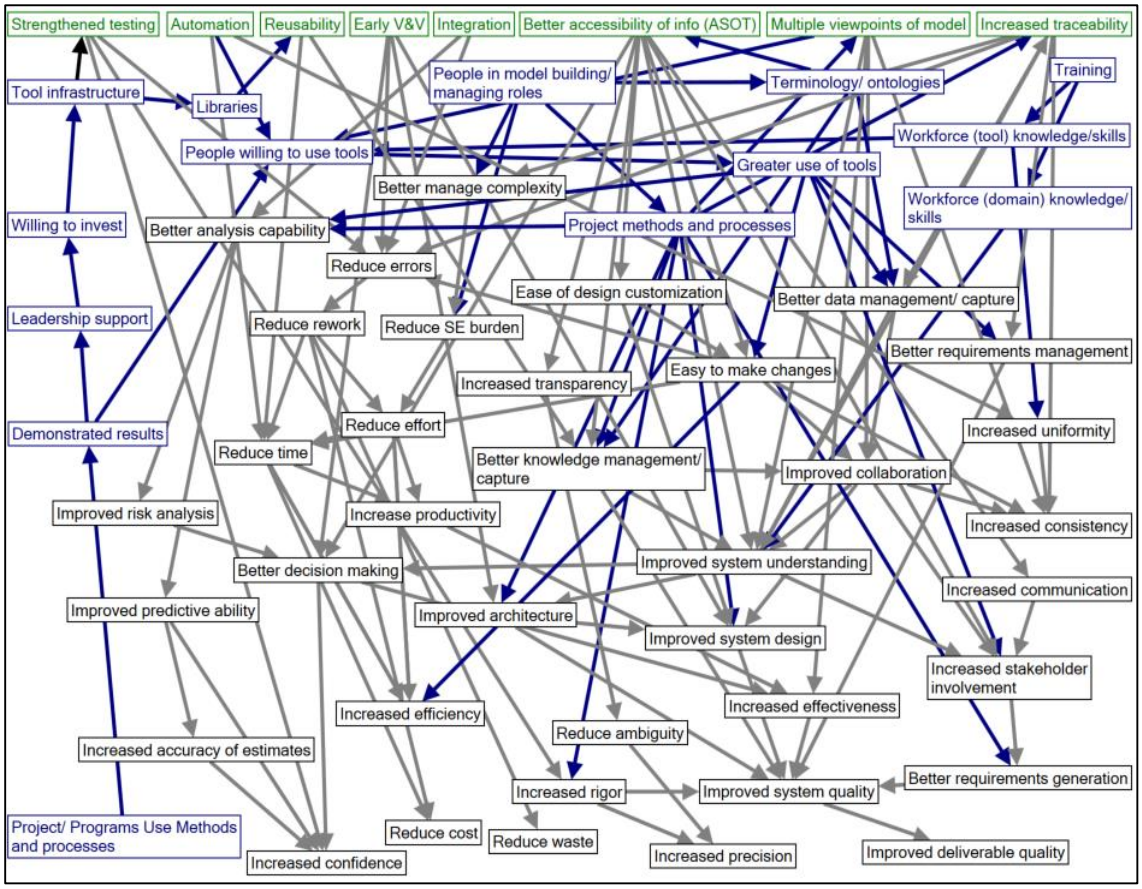

Figure 25: MBSE benefits causal model

The adoption enablers from the MBSE benefits model are the most relevant for this model on MBSE adoption. Table 52 shows the top enabling factors for MBSE adoption from the Maturity survey. Several of these enabling factors were used in the MBSE benefits causal model. These are represented in the model in Figure 25 with navy blue text and causal links.

Table 52: Enabling factors to MBSE adoption from (McDermott et al., 2020)

MBSE methods/processes	Organizational culture	Training
Customer/stakeholder buy-in/ engagement/involvement	MBSE terminology/ ontology/libraries	Communicating success stories/practices
People willing to use MBSE tools	Legacy/current processes	MBSE tools
Cost to use MBSE tools	Demonstrating benefits/results	Leadership support/commitment

The Bass Diffusion model was also used as a foundation for development, since it has been well-tested and is commonly accepted as a model of technology adoption (Bass, 1969). Figure 26 shows a depiction of the Bass diffusion model (Sterman, 2000). One assumption that the Bass model makes is that everyone will eventually become adopters, and no one will stop being adopters (Sterman, 2000). This assumption may need to be addressed in the future if it is found that many people who adopt MBSE initially do not continue use long term. This could be represented through the additional variable *Users*, where the rate between adopters and users is determined by previous knowledge and training. However, the cut-off between when someone is an adopter versus a user may be difficult to determine, especially since not everyone will use MBSE to the same degree.

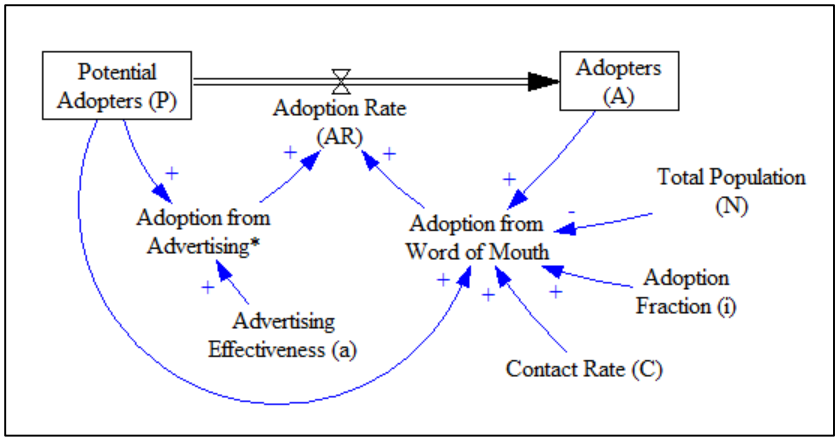

Figure 26: Bass Diffusion Model

The Bass Diffusion Model includes Advertising as a variable. Adoption from advertising refers to external sources of adoption (MacKinnon, 2018). So in this model, this variable will be defined as external sources of adoption other than contact with peers. Another adoption model (the Technology Acceptance Model), includes the variables perceived ease of use and perceived

usefulness which are stated to predict usage of technology (Straub, 2009). Social influence is another determinant of technology use (Straub, 2009). This is represented through the "word of mouth" variables which is a classic component of the Bass Diffusion Model (Borshchev & Filippov, 2004). Word of mouth from professional organizations can be seen as a replacement for "advertising," which is another component of the Bass Diffusion Model.

Figure 27 depicts the first iteration of the causal model. This was developed based on the sources from literature mentioned throughout this section. The purpose of basing the initial model on previous works is to take advantage of the validation that has been able to occur on those past models.

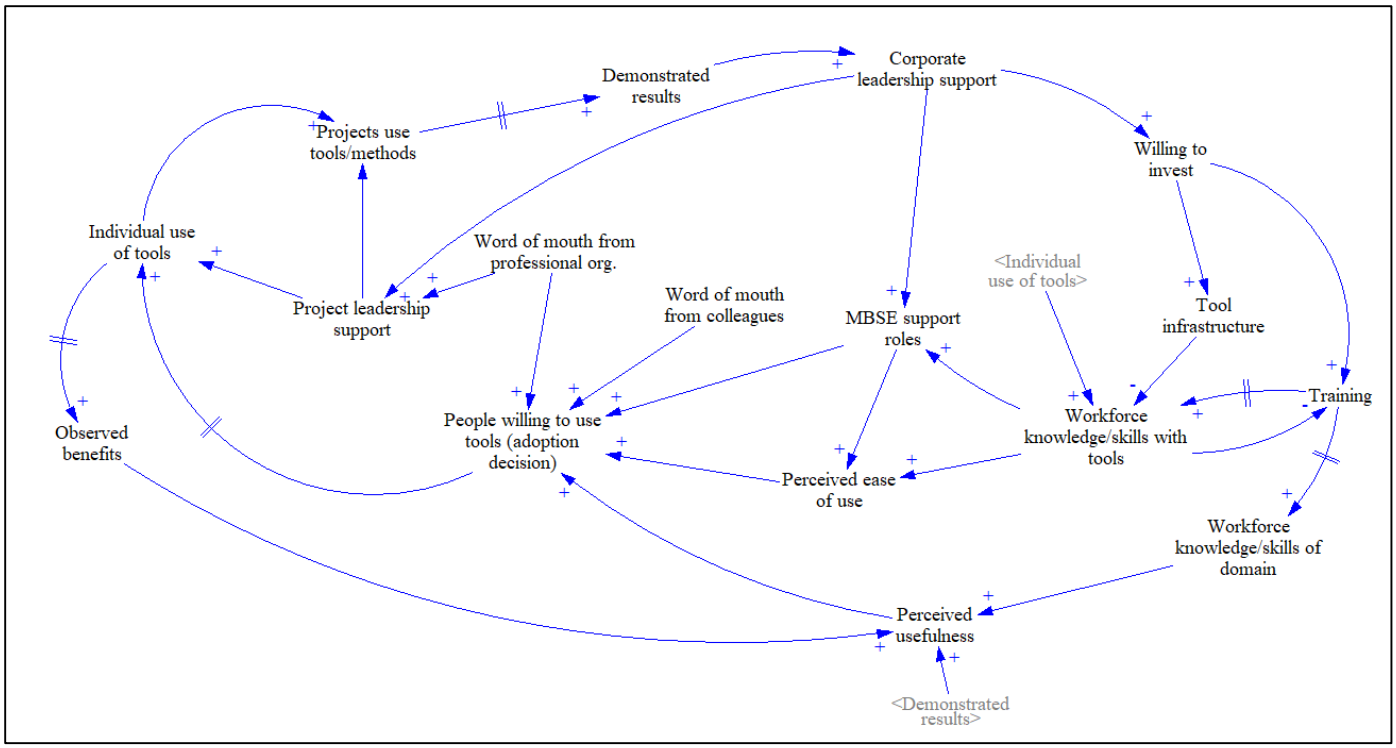

Figure 27: First iteration causal model

6.2 Second iteration causal model

Figure 28 shows the full causal model after additions from the survey and interview results. Nodes in the figure that are enclosed by brackets <example> are shadow variables. These shadow variables are a mechanism for improving readability from the modeling software Vensim. These variables are the same as the nodes without brackets of the same name.

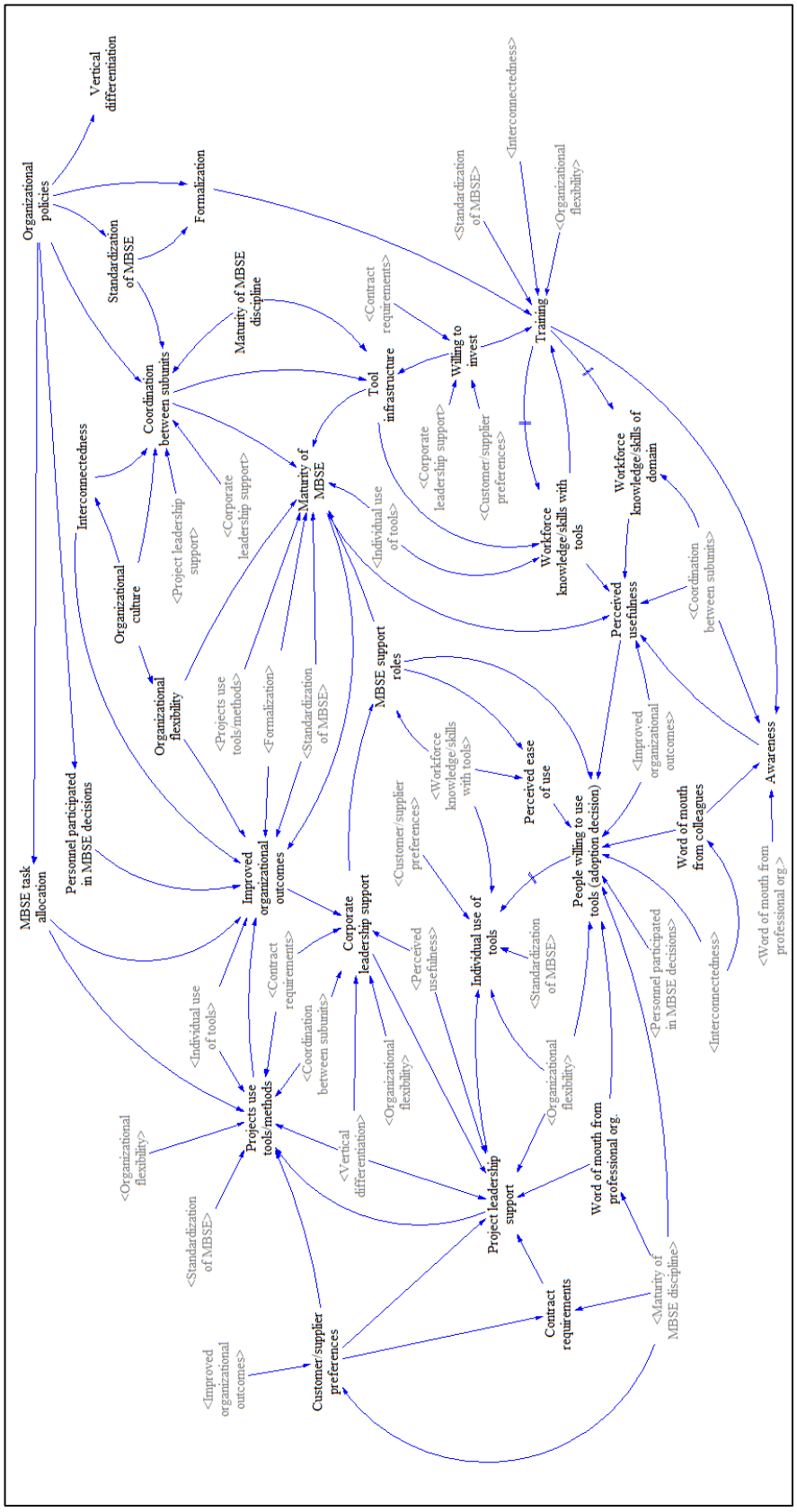

Figure 28: Second iteration causal model full view

Table 53: Causal model analysis: In-degree

Variable	In-Degree
Projects use tools/methods	9
Improved organizational outcomes	9
People willing to use tools	9
Maturity of MBSE	8
Coordination between subunits	7
Project leadership support	7
Individual use of tools	6
Training	6
Perceived usefulness	6
Corporate leadership support	5

Table 53 shows the top nodes in the causal model defined through the In-degree. This refers to the number of links that are going into that node. Variables with high In-degree values are affected by a higher number of preceding factors. So in this graph, *Projects use tools/methods*, *Improved organizational outcomes*, and *People willing to use tools* are all directly influenced by 9 other variables each. This is an indication that these variables are critical components in the model.

Table 54: Causal model analysis: Out-degree

Variable	Out-Degree
Organizational flexibility	8
Standardization of MBSE	7
Coordination between subunits	6
Organizational policies	6
Maturity of MBSE discipline	6
Interconnectedness	5
Customer/supplier preferences	5
Workforce knowledge/skills with tools	5

Table 54 shows the top nodes defined by the Out-degree. Out-degree refers to the number of links that originate from that node. Variables with high Out-degree values have a large impact on the outcomes of the model, since they influence the most variables succeeding them. The top nodes in this model that have the widest influence on the model are largely the organizational structure factors.

Another measure of a variable's importance in a model is the variable's centrality. Table 55 shows the top variables by centrality using two different centrality calculations. Both of these methods measure the relative importance of a node in the network.

Table 55: Causal model analysis: Centrality

Eigenvector Centrality		PageRank	
0.324	Improved organizational outcomes	Coordination between subunits	0.0379
0.303	Projects use tools/methods	Improved organizational outcomes	0.0371
0.282	Coordination between subunits	People willing to use tools	0.0367
0.275	Maturity of MBSE	Projects use tools/methods	0.0351
0.267	Individual use of tools	Training	0.0345
0.260	Project leadership support	Project leadership support	0.0343
0.258	Organizational flexibility	Maturity of MBSE	0.0340
0.230	Perceived usefulness	Corporate leadership support	0.0339
0.229	Standardization of MBSE	Perceived usefulness	0.0336
0.223	Corporate leadership support	Organizational policies	0.0334
0.199	People willing to use tools	Organizational flexibility	0.0331

According to the centrality values, the important nodes in this model are *Improved organizational outcomes*, *Coordination between subunits*, *Projects use tools/methods*, and *People willing to use tools*. Figure 29 shows a view of the model focused on these variables. The use of the tools and willingness of people to use the tools if often a key component in an adoption process. These variables were also key variables in the MBSE benefits causal model (Henderson, McDermott, Salado, & Van Aken, 2021).

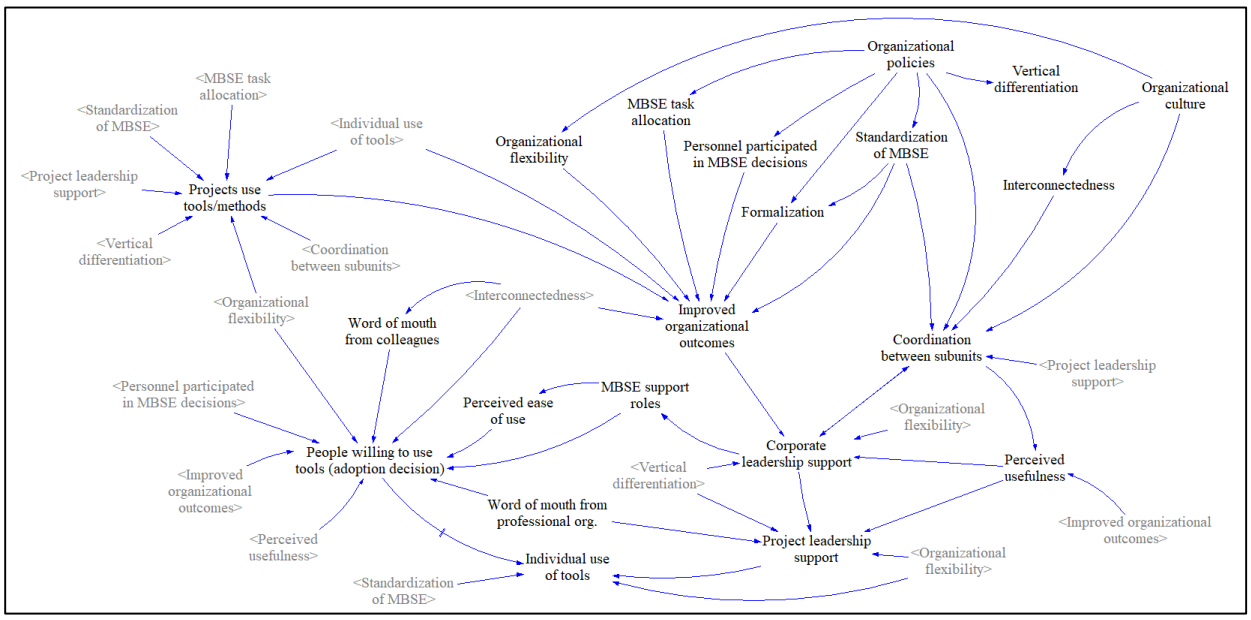

Figure 29: Second iteration causal model partial view

Of these four critical nodes in the model, two are more organization-focused: *Improved organizational outcomes* and *Coordination between subunits*. The survey results showed that *Formalization*, *Decentralization*[10], *Flexibility*, and *Interconnectedness* all have positive correlations with the *Influence on organizational outcomes*. *Improved organizational outcomes* contribute to leaders and employees' willingness to support and use MBSE methods and tools. These factors contribute to actual use of tools and methods, which then creates more *Improved organizational outcomes*, completing the loop. So other than using MBSE, those contributing organizational structure characteristics are a way to positively affect the process. This provides several areas that organizations can make changes to improve MBSE adoption and implementation. Since "*every company is different…and will require different effort [40]*" to change the company in order to adopt MBSE, organizations can look to different areas of the organization's structure that could address that organization's issues or needs for MBSE.

Coordination mechanisms address the critical issue of integration that is often difficult to accomplish. While the ultimate goal is to achieve implicit coordination through the use of connected models, getting to that point will require coordination between different subunits. The

[10] Note: Centralization had a negative relationship with the Implementation variables. Decentralization, the inverse of Centralization, has a positive relationship with these variables.

most frequent coordination mechanisms used by interview participants were: formal hierarchy, standard rules/procedures, direct informal contact, and permanent coordinating groups. Future research should explore which of these coordination mechanisms are more effective for MBSE adoption. The most frequent lack of a coordination mechanism that was noted by interview participants related to too much separation between different functional groups. As one participant said, "*I can't tell you how many organizations I've tried to help that have a requirements group, an architecture group, an interfaces group, and an analysis group that never meet [9]*." Getting the collaboration across the organization is difficult by itself, but it raises another issue of authority. Responsibilities and authorities need to be clearly defined in this cross-functional effort in order to actually accomplish anything. One participant described this issue in their organization: "*They're just trying to coordinate all these efforts like MBSE in a lot of ways without real authority. And everyone has their opinion about what tool and method is best. Since so many people just have control over a small part of the kingdom, no one has control of everything [20]*." Another participant described the issue as "*a 'who has the charge line to do what part of the work' type of obstacle [47]*." This is another aspect of the adoption process that should be explored further in future research.

6.3 Model validation

Validation is a process of building up confidence in the usefulness of a model (Senge & Forrester, 1980). Zagonel and Corbet define five components of models/modeling projects that are each associated with a different level of testing based on the objective of that component (Zagonel & Corbet, 2006). The purpose is to determine which tests are applicable to a modeling project based on the modeling approaches and objectives of that project. An individual modeling project can include one or more of the modeling components. Table 56 describes the five components.

Table 56: Five modeling components from (Zagonel & Corbet, 2006)

Modeling Component	Description
System's mapping	***Qualitative and inductive***. Mapping of system elements. Focus on causal interrelationships and interdependencies.
Quantitative modeling	***Quantitative and descriptive***. System focused. Involves formulation and simulation. Focus on stock and flow dynamics and the effect of delays.
Hypothesis testing	***Quantitative and deductive***. Problem focused. Requires stating hypothesis that explains dynamic behavior from the structure of the system. Focus on exploration of effects of changes in system structure, understanding, and insight.
Uncertainty (Sensitivity) analysis	***Quantitative and exploratory***. Examines behavioral and quantitative sensitivity. Focus on robustness of results from quantitative modeling and hypothesis testing.
Forecasting/ Optimization	***Quantitative and predictive***. Attempts to shed light on future behavioral patterns and values of variables. Focus on determining optimal or robust solutions.

System's mapping is the stage that this causal model is at, so validation for this model was focused on the alignment of the model's structure with descriptive knowledge (face validity).

Forrester and Senge (1980) propose that structure verification includes "comparing model assumptions to descriptions of decision making." While the models which contributed to the first iteration of the causal model were already validated to some extent, the additional nodes and links added for the second iteration have not been. The data obtained from the survey and interviews provided the descriptive knowledge to support the validation of the model. This systems map should reflect the collective perspectives of the participants on the MBSE adoption experience.

It is important to note that the sources supporting this data are based on perception. Specifically, the survey and interview results, which both originate from an individual's perception of their organization and MBSE. Only statistically significant relationships from the survey were used as sources, which gives some level of confidence to the validity of the results. As mentioned previously, there is some debate philosophically as to how to evaluate organizations, with many arguing there isn't an objective truth (Alvesson, 2003). So in this setting, the perception-based data will be accepted as a source for validation. As Zagonel and Corbet (2006) argue, there is value in a qualitative validation of a model based on descriptive knowledge.

Figure 30 shows the causal model defined by the different sources that support the links. Blue arrows represent support from literature, green arrows are relationships from the survey results, purple arrows are relationships from the interview results, and gray arrows are hypothesized relationships. The yellow arrows are indicating whether the organizational structure component originates more from culture or policies.

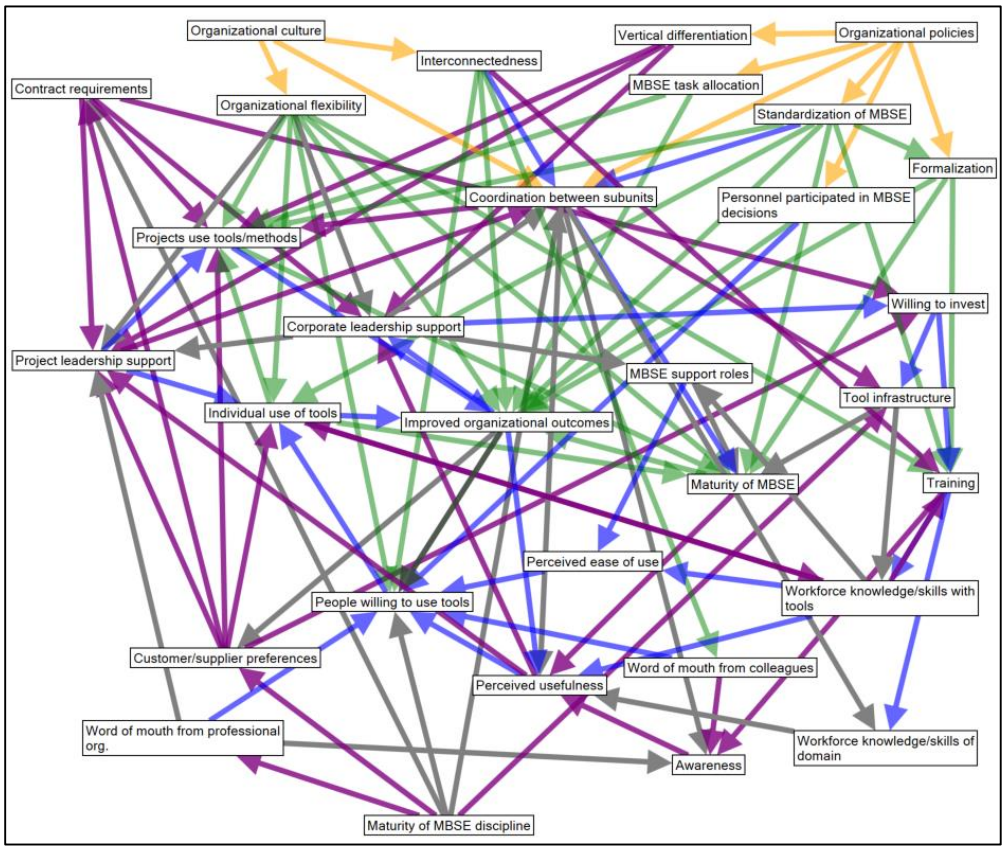

Figure 30: Second iteration causal model sources defined

Table 57 shows each causal relationship, the source supporting it, and an explanation of that support. Survey results were the most frequent source of justification for this causal model.

Table 57: Causal model link justification

Node 1	Node 2	Source	Explanation
Individual use of tools	Projects use tools/methods	Survey results	Strong correlation between the percentage of people who use MBSE and percentage of projects that use MBSE.
Project leadership support	Projects use tools/methods	Literature	Leadership support has been shown to be a major contributing factor in the adoption of MBSE and other technologies/processes (Cohn & Turyn, 1984; Hameed et al., 2012; Premkumar & Roberts, 1999; Thong & Yap, 1995).
Project leadership support	Individual use of tools	Literature	Leadership support has been shown to be a major contributing factor in the adoption of MBSE and other technologies/processes (Cohn & Turyn, 1984; Hameed et al., 2012; Premkumar & Roberts, 1999; Thong & Yap, 1995).
Individual use of tools	Improved organizational outcomes	Literature	From MBSE benefits causal model (Henderson et al., 2021).
Improved organizational outcomes	Perceived usefulness	Literature	From MBSE benefits causal model (Henderson et al., 2021).
Workforce knowledge/skills of domain	Perceived usefulness	Hypothesized	As the employees learn more about MBSE as a discipline, they should learn about the expected benefits (Henderson & Salado, 2021b) – which should be perceived by the employees as useful.
Workforce knowledge/skills with tools	Perceived usefulness	Literature	From MBSE benefits causal model (Henderson et al., 2021).
Perceived ease of use	People willing to use tools	Literature	From Technology Acceptance Model (Straub, 2009).
Word of mouth from colleagues	People willing to use tools	Literature	From Bass Diffusion Model (Bass, 1969).

Word of mouth from professional org.	People willing to use tools	Literature	From Bass Diffusion Model (Bass, 1969).
Word of mouth from professional org.	Project leadership support	Hypothesized	Many people in management or leadership positions are active in professional organizations, so they may be influenced by hearing positive accounts of MBSE from that source.
Projects use tools/methods	Improved organizational outcomes	Literature	From MBSE benefits causal model (Henderson et al., 2021).
Improved organizational outcomes	Corporate leadership support	Literature	From MBSE benefits causal model (Henderson et al., 2021).
Corporate leadership support	Project leadership support	Hypothesized	Corporate leadership often sets the direction or expectations for project teams, so project leadership should support the effort if is being supported at the higher levels.
Corporate leadership support	MBSE support roles	Hypothesized	Dedicated roles for MBSE need to be created with approval from upper management.
MBSE support roles	Perceived ease of use	Literature	From MBSE benefits causal model (Henderson et al., 2021).
Corporate leadership support	Willing to invest	Literature	From MBSE benefits causal model (Henderson et al., 2021).
Willing to invest	Tool infrastructure	Literature	From MBSE benefits causal model (Henderson et al., 2021).
Willing to invest	Training	Literature	By definition, training is often expensive and requires a financial investment.
Workforce knowledge/skills with tools	Training	Interviews	According to interview participants, in some organizations, training is executed by other employees in the organization. "*Self-organized classroom trainings [40]*", *"lunch-and-learns [41]", "unofficial mentoring [46]*", and proficient modelers that "*serve as an instructor or a helper [62]*" were all reported. So some people in the organization need to have

			the necessary knowledge/skills in order for this training to occur.
Workforce knowledge/skills with tools	Perceived ease of use	Literature	From MBSE benefits causal model (Henderson et al., 2021).
Tool infrastructure	Workforce knowledge/skills with tools	Hypothesized	Improvements or changes to the tools/ tool infrastructure should result in employees having to learn more about the tools in order to keep up with the changes.
Individual use of tools	Workforce knowledge/skills with tools	Interviews	One of the best ways to learn about MBSE tools is through using the tools on projects. Several interview participants discussed how employees were "*learning MBSE on the job*."
Training	Workforce knowledge/skills with tools	Literature	From MBSE benefits causal model (Henderson et al., 2021).
Training	Workforce knowledge/skills of domain	Literature	From MBSE benefits causal model (Henderson et al., 2021).
Workforce knowledge/skills with tools	MBSE support roles	Hypothesized	As the workforce knowledge/skills of modeling tools improves, the capability for people to fill MBSE support-type roles increases.
Personnel participated in MBSE decisions	People willing to use tools	Literature	From previous MBSE adoption survey (Cloutier, 2015).
Perceived usefulness	People willing to use tools	Literature	From Technology Acceptance Model (Straub, 2009).
People willing to use tools	Individual use of tools	Literature	From MBSE benefits causal model (Henderson et al., 2021).
Interconnectedness	Coordination between subunits	Literature	Direct informal contact is a coordination mechanism.
Standardization of MBSE	Coordination between subunits	Literature	Standard processes/procedures is a coordination mechanism.
Coordination between subunits	Maturity of MBSE	Literature	MBSE involves multiple disciplines, so coordination between different disciplines that promotes full use of MBSE is a representation of maturity. Improved collaboration results in

			better designed systems (Kossiakoff, Sweet, Seymour, & Biemer, 2011).
Improved organizational outcomes	People willing to use tools	Survey results	Strong correlation in survey results between improved organizational outcomes and project personnel showing interest in adopting MBSE.
Organizational flexibility	People willing to use tools	Survey results	Strong correlation in survey results between flexibility and project personnel showing interest in adopting MBSE.
Organizational flexibility	Training	Survey results	Strong correlation between flexibility and personnel being provided with sufficient training.
Organizational flexibility	Improved organizational outcomes	Survey results	Strong correlation between flexibility and improved organizational outcomes.
Interconnectedness	People willing to use tools	Survey results	Strong correlation between people feeling strongly connected and project personnel showing interest in adopting MBSE.
Formalization	Training	Survey results	Strong correlation between formalization and project personnel being provided with sufficient training.
Organizational flexibility	Individual use of tools	Survey results	Strong correlation between flexibility and percentage of people who used MBSE.
Organizational flexibility	Projects use tools/methods	Survey results	Strong correlation between flexibility and percentage of projects who used MBSE.
Standardization of MBSE	Training	Survey results	Strong correlation between standardization and personnel being provided with sufficient training.
Standardization of MBSE	Maturity of MBSE	Survey results	Strong correlation between standardization and the maturity of MBSE in the organization.
Organizational flexibility	Maturity of MBSE	Survey results	Strong correlation between flexibility and the maturity of MBSE in the organization.
Maturity of MBSE	Improved organizational outcomes	Survey results	Strong correlation between the maturity of MBSE in the organization and improved organizational outcomes.

Formalization	Improved organizational outcomes	Survey results	Strong correlation between formalization and improved organizational outcomes.
Interconnectedness	Improved organizational outcomes	Survey results	Strong correlation between people interacting informally and improved organizational outcomes.
Formalization	Maturity of MBSE	Survey results	Strong correlation between formalization and the maturity of MBSE in the organization.
MBSE task allocation	Projects use tools/methods	Survey results	Moderate correlation between how MBSE tasks are allocated and the percentage of projects that use MBSE.
Standardization of MBSE	Improved organizational outcomes	Survey results	Moderate correlation between standardization of MBSE and improved organizational outcomes.
Standardization of MBSE	Individual use of tools	Survey results	Moderate correlation between standardization and percentage of people who use MBSE.
MBSE task allocation	Improved organizational outcomes	Survey results	Moderate correlation between how MBSE tasks are allocated and improved organizational outcomes.
Standardization of MBSE	Formalization	Survey results	Strong correlation between standardization and formalization.
Interconnectedness	Word of mouth from colleagues	Survey results	People interacting informally is one of the defining characteristics of interconnectedness.
Projects use tools/methods	Maturity of MBSE	Survey results	Strong correlation between percentage of projects that use MBSE and the maturity of MBSE.
Individual use of tools	Maturity of MBSE	Survey results	Moderate correlation between percentage of people that use MBSE and the maturity of MBSE.
Personnel participated in MBSE decisions	Improved organizational outcomes	Survey results	Strong correlation between personnel participating in decisions regarding MBSE and improved organizational outcomes.
Organizational culture	Organizational flexibility	Organizational structure	Culture is a major determinant of flexibility in organizations.

Organizational culture	Interconnectedness	Organizational structure	Culture is a major determinant of interconnectedness in organizations.
Organizational policies	Formalization	Organizational structure	Formalization is largely the result of organizational policies.
Organizational policies	Standardization of MBSE	Organizational structure	Standardization is largely the result of organizational policies.
Organizational policies	Personnel participated in MBSE decisions	Organizational structure	Who has the authority to make decisions is largely the result of organizational policies.
Organizational policies	Vertical differentiation	Organizational structure	The organization's formal hierarchy is set by policies/definitions of structure.
Organizational policies	MBSE task allocation	Organizational structure	How tasks are allocated in the organization are largely the result of organizational policies.
Organizational culture	Coordination between subunits	Organizational structure	Some coordination mechanisms (e.g. direct informal contact) are a result of the organizations culture.
Organizational policies	Coordination between subunits	Organizational structure	More formal coordination mechanisms are defined by the organization's policies and structures.
Vertical differentiation	Corporate leadership support	Interview results	Organizations that are higher in vertical differentiation typically have more levels of management. So levels of middle and upper management are not as effected by MBSE in the day-to-day jobs. According to one interview participant, "*I think the challenge was and remains what I call the middle layer, between the executives and those who believe in MBSE, who actually 'do it.'…We're trying to convince our managers and follow through on [MBSE], since the executives have said they want it. But the middle managers can ignore that, because it doesn't impact their day-to-day [45].*"
Vertical differentiation	Project leadership support	Interview results	Organizations that are higher in vertical differentiation typically have more levels of management. So levels of middle and upper

			management are not as effected by MBSE in the day-to-day jobs. According to one interview participant, "*I think the challenge was and remains what I call the middle layer, between the executives and those who believe in MBSE, who actually 'do it.'…We're trying to convince our managers and follow through on [MBSE], since the executives have said they want it. But the middle managers can ignore that, because it doesn't impact their day-to-day [45]*."
Contract requirements	Corporate leadership support	Interview results	"*Now that the policy level [of government] has bought into [MBSE], it's hard to say no [6]"* to adopting MBSE.
Contract requirements	Project leadership support	Interview results	"*Now that the policy level [of government] has bought into [MBSE], it's hard to say no [6]*" to adopting MBSE.
Contract requirements	Projects use tools/methods	Interview results	It projects have it in their contracts that they need to use MBSE, then projects will need to use MBSE tools/methods to some degree. Even in the worst case where people are just using MBSE tools "*as a side thing to meet the contractual requirement [5]*," the projects are still using it.
Customer/supplier preferences	Project leadership support	Interview results	Having customers that are "*pulling [18]*" for MBSE is a contributing factor to organizations supporting MBSE adoption efforts. Conversely, if "*clients are not asking for it as a capability [34]*," project leaders may not find the investment worth it, as was the case with one organization.
Maturity of MBSE discipline	Word of mouth from professional org.	Interview results	Some interview participants discussed how employees in their organizations keep up-to-date with the state of MBSE through

			professional organizations. As MBSE matures as a discipline and improvements to the practice are made, professional organizations will share those updates.
Maturity of MBSE discipline	Tool infrastructure	Interview results	Many of the interview participants discussed the limitations of current MBSE tools. As MBSE matures as a discipline and tool capabilities improve, the potential applications for tools will increase. As one participant noted, "*There's barely capability from the tool suppliers to support [using MBSE on] new products [10]*."
Maturity of MBSE discipline	Customer/supplier preferences	Interview results	According to one participant, MBSE implementation has reached around 40-50% of its "*potential for implementing MBSE across all products and designs [10]*." One effect of this is that "*clients don't know to ask for [MBSE or models] [34]*." As the discipline matures and more organizations begin using it, or are able to realize its full potential, customers should become more aware and interested in MBSE.
Customer/supplier preferences	Contract requirements	Interview results	Customers or clients are typically the ones who set contract requirements, so if the client is more inclined to want MBSE, the contract requirements will likely reflect that.
Improved organizational outcomes	People willing to use tools	Interview results	One of the points frequently made in the interviews was that seeing benefits or improvement from MBSE helps convince people it's worth using. As one participant observed, "*The more they see it, the more they are willing to adopt it [20]*." The improvements from

			decision making were particularly noted as convincing people of the value of MBSE. According to one participant, "*The only way to really evaluate and measure effectiveness [of MBSE] is how well the program succeeded, how much better can you make decisions, and are those decisions supportable and justifiable [9].*"
Standardization of MBSE	Projects use tools/methods	Survey results	Moderate correlation between standardization of MBSE in organizations and percentage of projects that use MBSE.
Coordination between subunits	Tool infrastructure	Interview results	One participant discussed the plan their organization has for improving the coordination in their organization through tools. According to them, "*Most of our engineers are from the classically trained disciplines and they have particular tools they like to use. And that tool will communicate with the requirements tool… So if somebody on a CAD tool introduces a new component, I need to know about it in the requirements tool. So that information flows out through our intermediary system into the requirements tool so I can allocate requirements to it [44]*."
Coordination between subunits	Projects use tools/methods	Interview results	Participants discussed how coordination between disciplines is a key component of MBSE. According to one participant, "*The other area that still frustrates me, in model-based engineering activities, is getting that collaboration across the organization. You can't think of MBSE as just what the systems engineers do. Because it's systems engineering, as a good system engineer, you need to appreciate things like electrical,*

			mechanical, environmental, economics. So using models allows you to bring all of that together into a source of truth [45].”
Project leadership support	Coordination between subunits	Interview results	One participant shared their experience of coordination in their organization: “*We took all these key programs, we made separate groups to deal with specific areas. 250 people is a lot to deal with at one time, so we made smaller groups. If you have a question, you can bring your model and get help from these groups. It didn’t matter what part of the company you were in. And this all depends on the leadership, I was happy to be part of that for 2 years and have top leadership support [41]*.”
Interconnectedness	Training	Interview results	According to interview participants, in some organizations, training is executed by other employees in the organization. “*Self-organized classroom trainings [40]*”, “*lunch-and-learns [41]*”, “*unofficial mentoring [46]*”, and proficient modelers that “*serve as an instructor or a helper [62]*” were all reported.
Customer/supplier preferences	Projects use tools/methods	Interview results	Many of the interview participants discussed how projects or programs often decided to use MBSE “*because the customers want us to use it [44]*.”
Customer/supplier preferences	Willing to invest	Interview results	One participant described how customer preferences or contract requirements could affect their organization. “*If they mandate that the model is the authoritative source of truth for all requirements that come out on programs, then every person in*

			the [organization] would need to be trained with how to open and traverse the model to get the information they need [5].”
Training	Awareness	Interview results	Training is one of the methods of increasing awareness in an organization. As one participant described, “*We have to develop training to help these individuals [who don’t know about MBSE] … So we put all of these folks through training and made them aware. Awareness is the first step [41]*.”
Word of mouth from colleagues	Awareness	Interview results	Communication from colleagues is another method of increasing awareness of MBSE. As one participant said, “*For the other teams, they’re largely unaware of MBSE. I don’t think they’re opposed to it, you just have to find a good way to articulate the value to them [47]*.”
Awareness	Perceived usefulness	Interview results	MBSE cannot be perceived as useful if people do not know what it is or what its potential benefits are.
Vertical differentiation	Projects use tools/methods	Interview results	Organizations that are higher in vertical differentiation typically have more levels of management. So levels of middle and upper management are not as effected by MBSE in the day-to-day jobs. According to one interview participant, “*I think the challenge was and remains what I call the middle layer, between the executives and those who believe in MBSE, who actually ‘do it.’…We’re trying to convince our managers and follow through on [MBSE], since the executives have said they want it. But the middle managers can ignore that, because it doesn’t impact their day-to-day [45]*.”

Customer/supplier preferences	Individual use of tools	Interview results	Many of the interview participants discussed how projects or programs often decided to use MBSE "*because the customers want us to use it [44]*."
Workforce knowledge/skills with tools	Individual use of tools	Interview results	Interview participants indicated that "*most people won't use the tool if they don't know how to use it. Even if [they] have been through a training course, [they] will get in there and touch some buttons and something will go wrong [46]*."
Tool infrastructure	Maturity of MBSE	Hypothesized	Tools are a major component of MBSE. As the tools and tool infrastructure improves, maturity of MBSE in the organization should increase as a result.
MBSE support roles	Maturity of MBSE	Hypothesized	Having dedicated roles for MBSE could be considered a reflection of a more mature MBSE application.
Organizational flexibility	Corporate leadership support	Hypothesized	Organizations that are more flexible typically are more receptive to innovation. So in a highly flexible organization, it is likely that leadership will be supportive of adopting a new technology/process.
Organizational flexibility	Project leadership support	Hypothesized	Organizations that are more flexible typically are more receptive to innovation. So in a highly flexible organization, it is likely that leadership will be supportive of adopting a new technology/process.
Maturity of MBSE	Perceived usefulness	Interview	One participant discussed how their perception of MBSE has changed with the improvements over time: "*Now that it has advanced, I can see the advantage of having a model that works throughout the whole system lifecycle, but that hasn't been the case in the past [33]*."

			Another participant mentioned that "*MBSE really only works if it's an all-or-nothing kind of thing [47]*." The expectation is that MBSE will solve a lot of problems, but only after it reaches a certain level of maturity.
Perceived usefulness	Corporate leadership support	Interview	One thing that was commonly mentioned by interview participants was that management needed to be convinced that MBSE is worth it and will provide some positive outcomes. So if MBSE is perceived as useful, that should be a positive contributing factor to leadership support.
Perceived usefulness	Project leadership support	Interview	One thing that was commonly mentioned by interview participants was that management needed to be convinced that MBSE is worth it and will provide some positive outcomes. So if MBSE is perceived as useful, that should be a positive contributing factor to leadership support.
Improved organizational outcomes	Customer/supplier preferences	Hypothesized	If customers or suppliers are able to see that MBSE has improved organizational outcomes, they may be more likely to be receptive to it or even request it.
Maturity of MBSE discipline	Contract requirements	Hypothesized	As MBSE has mature as a discipline, it has been slowly adopted at the policy level. This was discussed by several interview participants, now that there is an NDIA mandate, their contracts are now requiring the use of MBSE or other Digital Engineering aspects.
Maturity of MBSE discipline	People willing to use tools	Hypothesized	As the discipline of MBSE matures, tool capabilities are improving, which allows organizations to do more/better with their MBSE applications. As

			the functionality and usability of the tools improve, people should be more willing to use them.
Coordination between subunits	Workforce knowledge/skills of domain	Hypothesized	As coordination increases, more people in the organization will learn what MBSE is, so the knowledge/skills of the workforce overall will increase.
Coordination between subunits	Perceived usefulness	Hypothesized	As more coordination occurs, more subunits will be contributing to the model, which should make it more reflective of the actual system. This will allow any decisions made using that model to be even more reliable.
Corporate leadership support	Coordination between subunits	Hypothesized	Some types of coordination mechanisms are more formal, and thus require some level of leadership involvement/support to be enacted.
Maturity of MBSE discipline	Coordination between subunits	Hypothesized	As the discipline of MBSE and its tools improve, there should be an increased ability to integrate tools. This will allow for implicit coordination through technology.
Contract requirements	Willing to invest	Interview	One participant described how customer preferences or contract requirements could affect their organization. "*If they mandate that the model is the authoritative source of truth for all requirements that come out on programs, then every person in the [organization] would need to be trained with how to open and traverse the model to get the information they need [5]*."
Word of mouth from professional org.	Awareness	Hypothesized	If professional organizations are discussing and advocating more for MBSE, their members will become more aware of it and its potential benefits. One interview participant discussed how people in their organization stay up to date with MBSE through the

			professional organization INCOSE.
Coordination between subunits	Awareness	Hypothesized	Many parts of the organization are not aware of what MBSE is, this was discussed by several interview participants. As coordination between subunits increases, more people will become aware of what MBSE is.

6.3.1 Naugle et al. (2019) study model validation

The goal of the study done by Naugle et al. (2019) was to understand barriers to MBSE adoption. Emphasis was on the individual adoption decision and what contributes to it. Although their model focuses more on individual adoption, the subject matter of MBSE adoption is similar enough that it can serve as a source of validation for this model. To keep the different models identifiable, Naugle et al.'s model will be referred to as the ***individual adoption model***, and the model for this dissertation will be referred to as the ***organizational adoption model***. Figure 31 is a recreation of the causal loop diagram based on the image shared by Naugle et al. (2019). Their report does indicate that there were interviews and other data collection done at the beginning of their study, but it is unclear to what extent that influenced the creation of this model.

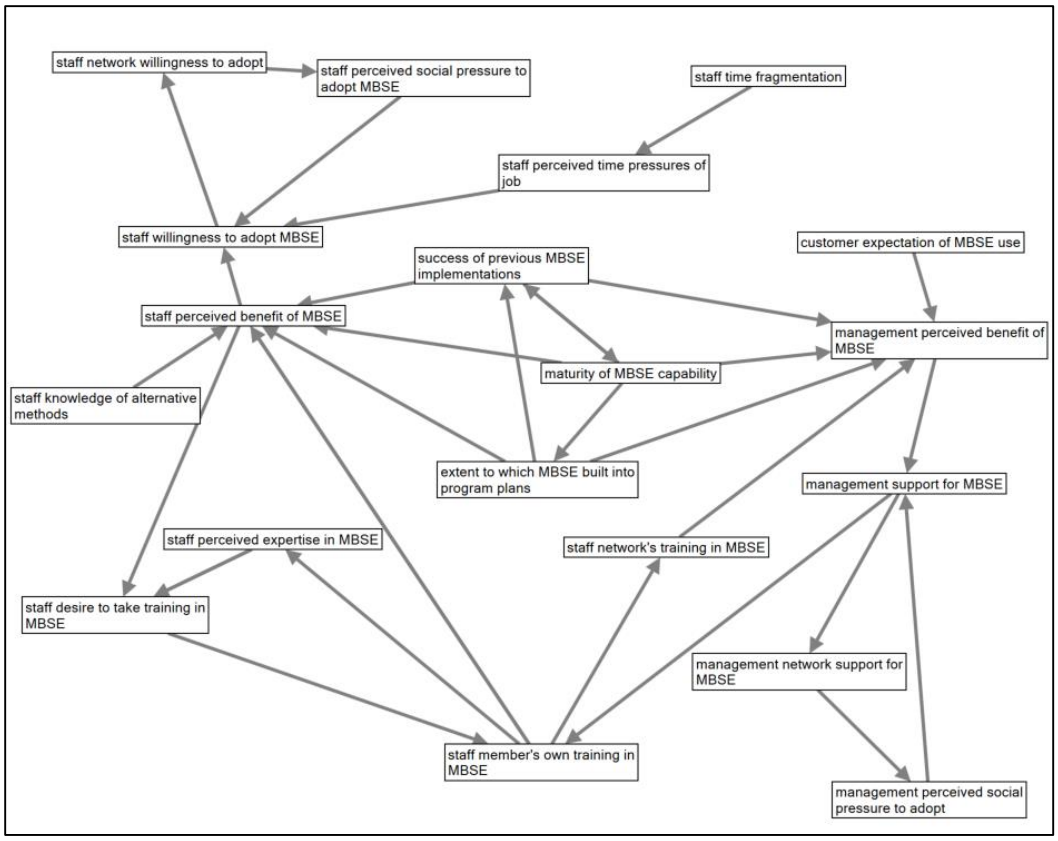

Figure 31: Individual adoption model (Naugle et al., 2019)

In order to use the individual adoption model as validation, the variables were evaluated for an equivalent variable in the organizational adoption model. Table 58 shows the comparative variables between the models. Due to differences in how certain aspects of the adoption process were defined, there are some variables in the individual model that had the same equivalent in the adoption model. For example, the individual adoption model has the variables *management network support for MBSE* and *management perceived social pressure to adopt.* In the organizational adoption model, *Word of mouth from professional org.* conceptually covers both of those concepts, so the two variables were each assigned that one as the equivalent. There were two variables that did not have an equivalent in the organizational model: *staff desire to take training in MBSE* and *staff knowledge of alternative methods*.

Table 58: Variable comparison between individual and organizational models

Individual adoption model variables	**Organizational adoption equivalent**
customer expectation of MBSE use	Customer/supplier preference
extent to which MBSE built into program plans	~Organizational structure factors~
management network support for MBSE	Word of mouth from professional org.
management perceived benefit of MBSE	Corporate / project leadership support
management perceived social pressure to adopt	Word of mouth from professional org.
management support for MBSE	Corporate / project leadership support
maturity of MBSE capability	Maturity of MBSE
staff desire to take training in MBSE	~No equivalent~
staff knowledge of alternative methods	~No equivalent~
staff member's own training in MBSE	Training
staff network willingness to adopt	Word of mouth from colleagues
staff network's training in MBSE	Workforce knowledge/skills with tools
staff perceived benefit of MBSE	Perceived usefulness
staff perceived expertise in MBSE	Workforce knowledge/skills with tools
staff perceived social pressure to adopt MBSE	Word of mouth from colleagues
staff perceived time pressures of job	Perceived ease of use
staff time fragmentation	Perceived ease of use
staff willingness to adopt MBSE	People willing to use tools
success of previous MBSE implementations	Improved organizational outcomes

After the equivalent variables were determined, the causal links in the individual model were converted to the equivalent variables. Table 59 shows the causal relationships from the individual adoption model with the variables converted to the organizational adoption model.

Links that contained the same equivalent variable or had a non-equivalent variable were marked as not applicable (n/a). Out of all the applicable links, around 68% were validated (marked as 'Yes' in the table), which meant they were present in both models. The links that were marked 'No' did not exist in the organizational adoption model, but were in the individual one. Those relationships will be discussed further in the rest of this section.

Table 59: Individual adoption model link validation

Equivalent 1	**Equivalent 2**	**Validated**
~Organizational structure factors~	Corporate / project leadership support	Yes
~Organizational structure factors~	Perceived usefulness	Yes
~Organizational structure factors~	Improved organizational outcomes	Yes
Corporate / project leadership support	Training	Yes
Customer/supplier preference	Corporate / project leadership support	Yes
Improved organizational outcomes	Corporate / project leadership support	Yes
Improved organizational outcomes	Perceived usefulness	Yes
Maturity of MBSE	Perceived usefulness	Yes
Maturity of MBSE	Improved organizational outcomes	Yes
Perceived ease of use	People willing to use tools	Yes
Perceived usefulness	People willing to use tools	Yes
Training	Workforce knowledge/skills with tools	Yes
Training	Workforce knowledge/skills with tools	Yes
Word of mouth from colleagues	People willing to use tools	Yes
Word of mouth from professional org.	Corporate / project leadership support	Yes
Corporate / project leadership support	Word of mouth from professional org.	No
Improved organizational outcomes	Maturity of MBSE	No
Maturity of MBSE	~Organizational factors~	No
Maturity of MBSE	Corporate / project leadership support	No
People willing to use tools	Word of mouth from colleagues	No
Training	Perceived usefulness	No
Workforce knowledge/skills with tools	Corporate / project leadership support	No
~No equivalent~	Training	n/a
~No equivalent~	Perceived usefulness	n/a
Corporate / project leadership support	Corporate / project leadership support	n/a
Perceived ease of use	Perceived ease of use	n/a
Perceived usefulness	~No equivalent~	n/a
Word of mouth from colleagues	Word of mouth from colleagues	n/a
Word of mouth from professional org.	Word of mouth from professional org.	n/a
Workforce knowledge/skills with tools	~No equivalent~	n/a

The links that were not validated were translated back to the individual adoption model variables so they can be evaluated conceptually. Table 60 shows the individual adoption model links that were not found in organizational adoption model.

Table 60: Links not present in organizational adoption model

1	management support for MBSE	management network support for MBSE
2	success of previous MBSE implementations	maturity of MBSE capability
3	maturity of MBSE capability	extent to which MBSE built into program plans
4	maturity of MBSE capability	management perceived benefit of MBSE
5	staff willingness to adopt MBSE	staff network willingness to adopt
6	staff member's own training in MBSE	staff perceived benefit of MBSE
7	staff network's training in MBSE	management perceived benefit of MBSE

Several of the non-validated links are a result of the framing of the model at the individual level (relationships 1 and 5 from Table 60). This model distinguishes between a "staff member" and the "staff network," whereas in the organizational adoption model they would be grouped together as "people" or "workforce."

Relationships 3, 4, 6, and 7 are also not validated due to differences in how the variables are defined. The individual adoption model variable *extent to which MBSE built into program plans* was matched with organizational factors (e.g. *Coordination between subunits*, *MBSE task allocation*, other organizational structure factors). The *maturity of MBSE capability* does not necessarily change these organizational factors, they are more the result of decisions and policies made by leadership. In the organizational adoption model, there is a relationship between the *Maturity of MBSE discipline* and *Coordination between subunits*. This is because the improved maturity of MBSE tools can lead to improved capability to coordinate implicitly using technology.

Relationship 4 was not validated because *management perceived benefit of MBSE* was included in *Corporate/Project leadership support* in the organizational adoption model. The relationship between *maturity of MBSE capability* and *management perceived benefit of MBSE* is represented in the organizational adoption model through several different connections. First, there is a causal relationship between *Maturity of MBSE* and *Perceived usefulness*. *Perceived usefulness* has relationships with *Corporate* and *Project leadership support*. Second, the is a causal relationship between *Maturity of MBSE* and *Improved organizational outcomes*, which leads to *Corporate leadership support*. So the essence of relationship 4 is reflected in the organizational adoption model, there is just not a direct comparison.

Relationship 6 was not validated because in the organizational adoption model there is an intermediate variable between *Training* and *Perceived usefulness*, which is *Workforce knowledge/skills*. As several interview participants mentioned, training does not directly result in improved confidence or positive perception of MBSE. Training needs to be relevant to what systems will actually be modeled by the organization. Relationship 7 has a similar rationale as relationship 6. *Training* in the organizational adoption model relates to *Workforce knowledge/skills*, which affects *Perceived usefulness*. The intermediary step represents the fact

that training needs to actually improve workforce knowledge/skills to change how MBSE is perceived.

Relationship 2 was not validated because the direction of the relationship was opposite in the organizational adoption model. In the individual adoption model, this relationship is represented as *success of previous MBSE implementations* contributing to the *maturity of MBSE capability*. *Success of previous MBSE implementations* is the equivalent to *Improved organizational outcomes*. In the organizational adoption model, *Maturity of MBSE* contributes to *Improved organizational outcomes*. This link is supported by survey results. *Improved organizational outcomes* do not directly contribute to the maturity of MBSE. *Improved organizational outcomes* are outcomes such as cost, quality, and time, that are important to the organization. These outcomes may inspire support from leaders that results in investments to improve the maturity of MBSE, but do not affect the maturity of MBSE.

Ch. 7 Conclusion

7.1 Insights and conclusions from research

7.1.1 Maturity of MBSE

Lack of understanding of MBSE is still a prevalent issue in the industry. When asked how MBSE was defined in their organizations, interview participants had a range of answers. Some defined MBSE in terms of the tools, some defined MBSE in terms of the models, others were not even able to convey how MBSE was defined. Participants that defined MBSE as a method of carrying out the SE process often conveyed that people are confused as to what MBSE was. One participant communicated it this way:

> "*A lot of the time when you talk to people about MBSE they get all excited about MBSE, what they really mean is 'I'm developing architecture models and I've bought a tool like Cameo.' In their mind, buying Cameo equates to doing architecture development, requirements development, limited simulation, and they do it all in that tool and they're doing model-based engineering. It's like no guys, you are not. MBSE to be very precise is how we use models to do SE across the lifecycle, from concept to disposal [9]*."

This lack of understanding translates to challenges with adoption. Confusion about what MBSE was or how to adopt it was one of the most frequently reported adoption challenges by interview participants. This was especially an issue at the management level. According to one survey participant, leadership "*misunderstood the requirements, misunderstood the activities around [MBSE], and they did not put enough [resources] in the teams to actually develop those artifacts that are essential to MBSE [41]*." If this misunderstanding had not been addressed, it is possible the adoption would have been thought as unsuccessful and abandoned.

Maturity of MBSE in surveyed organizations trended towards the lower levels of maturity. Only 6% of organizational units had reached the final stage of maturity of MBSE based on the survey results. This was also echoed in the interviews. According to one participant, MBSE had only reached 40-50% of maturity across the Aerospace industry. Issues with maturity as a field can also affect adoption. Tool limitations were commonly cited as adoption challenges by interview participants, particularly with regards to the ability to integrate tools. Another issue with tools was the lack of capability to capture data as metrics. As part of this study, I attempted to find a way to gather quantitative data measuring *Use of MBSE* in organizations. After speaking to many tool vendors and industry users, it had become clear that capturing this type of data was not something the tools are able to do currently. One survey participant also discussed the inability of MBSE tools to collect metrics, specifically with regards to requirements management. According to them, "*[The tools] fall apart very quickly when you [want to] measure how many requirements did I add or delete this month, how many changed between phases, and others… How do I know if my architecture is good? I can't tell you that. I don't know how to measure those things because of the tool limitations…There is a lot of uncertainty in the tools themselves [41]*."

7.1.2 Importance of improved organizational outcomes to MBSE adoption

Previous research has shown a lack of quantified benefits or value from MBSE (Henderson & Salado, 2021b). The conclusions from these previous efforts indicated that benefits were important to convince others of the value of MBSE. The causal model developed in this study on organizational adoption of MBSE highlights *Improved organizational outcomes* as a key component in the adoption process. *Improved organizational outcomes* contributed to leaders and employees' willingness to support and use MBSE methods and tools. These factors contributed to actual use of tools and methods, which then created more *Improved organizational outcomes*, completing the loop. The survey results also indicated that many of the organizational structure factors had a significant relationship with improved organizational outcomes. This may indicate that making organizational changes could have a positive impact on improved organizational outcomes, which is a key part of the adoption process.

7.1.3 Middle management and organizational change

Vertical differentiation was found to be negatively correlated with the *Use of MBSE* based on the survey results. Organizations with higher levels of *Vertical differentiation* tended to have more levels of management/leadership. As found in previous MBSE adoption surveys, leadership was often difficult to convince of the value of MBSE, and leadership support can be a critical factor in the success or failure of an MBSE adoption. Since there were more levels of management in organizations with higher levels of *Vertical Differentiation*, it may be more difficult to have to get buy-in from multiple levels of leadership. There are also more levels across which the diffusion of MBSE needs to occur, which could increase the time it would take for the whole organization to accept MBSE.

Several participants noted specifically having problems with middle management. One participant recounted their organizations experience: "*we're trying to convince our managers and follow through on it, since the executives have said they want it. But middle managers can ignore that because it doesn't impact their day-to-day [45]*." Efforts to convince this level of middle management were often unsuccessful.

While vertical differentiation (formal hierarchy) is a straightforward coordination mechanism for organizations to use, it can often lead to "*accidental complexity [18]*" if the organization is designed without the whole system in mind. According to one interview participant, "*Organizations don't want to change, because maybe then I don't have as many people who are [team] leads. We have so many bosses and middle managers, and very few people doing actual work [9]*." This can lead to organizational resistance in response to changes that upset this status quo. As one interview participant noted, "*It's not about the technical problem of introducing MBSE, it's about company change [40]*." Change management is critical for navigating how introducing MBSE will affect people's roles and responsibilities.

7.1.4 Training

Interview participants highlighted the importance of training all stakeholders to whatever level was appropriate for them to know. There were four categories of people who need training for MBSE: Model Reviewers, Developers, Architects, and Administrators. Organizations should

identify which people fit in these roles, and provide them training accordingly. Training should also be in the context of what that specific organization works on, when possible. One interview participant discussed how their organization accomplishes this: "*we define the scope: what do they want to model, which outcome? Then we align on the first steps and provide relevant training for the process and the tool [40]*." As a result, the training was actually relevant to a real development.

7.1.5 Network of experienced peers, coaches, experts, mentors

According to the survey results, in organizations that had designated people to create and manage models, there was a higher tendency to have a network of experienced peers. So a network of experienced peers may be a result of having people in the organization who are highly knowledgeable or experienced in a specific part of MBSE or modeling. In other words, if an organization wanted to establish a network of experienced peers, one way to contribute would be to designate people as MBSE specialists or modelers, and make sure that these people were known to others in the organization.

Out of the adoption resources listed in the survey (formal training, network of peers, coach/mentor), the assignment of a coach or mentor was the most frequent resource that was not utilized. Only around 30% of the organizational units had this resource available. The assignment of a coach or mentor was also positively correlated with *Formalization* and *Maturity of MBSE*. In other words, coaches or mentors tended to be assigned in organizations that had a higher level of maturity and more formalized practices.

While having dedicated modelers or MBSE experts has advantages, it can be an issue if that person does not have the necessary system knowledge. One participant whose organization is in the SE consultancy industry discussed this issue:

> "*Especially in North America where SysML is very strong, we see a lot of organizations who have dedicated people who work with the models who are not systems engineers, more modeling experts. We have seen in the past, a few cases where people try to implement MBSE that way and every time they failed. And the reason why they failed is two-fold. First the modeling expert is constantly trying to catch up with what the systems engineers are doing and modifying, so the model is never really up to date. And when you get the project rush the model is not really the priority, so the model ends up being not useful because it is not really reflecting the system [59]*."

Another issue with relying on this informal contact to coordinate occurred when teams operate too independently. One participant reported this issue in their organization: "*it's good to have a modeling team set aside that does the modeling and it's their responsibility to manage and maintain that, but right now they are operating very independently to build that model up…They created a model, but no one sees it as the source of truth. That team didn't have the information and buy-in needed from designers to lay out the model correctly [47]*."

7.1.6 Flexibility and interconnectedness: the organic paradigm

Flexibility and *Interconnectedness* had the strongest correlations with adoption and implementation among all the organizational structure variables. *Flexibility* and

Interconnectedness also had a strong positive correlation with each other. One reason for this similarity may be that conceptually, both of these characteristics are more related to cultural aspects of an organization. There is an organizational structure scale that encompasses these characteristics, that is the organic versus mechanistic organizational paradigms:

> "As environmental uncertainty increases, organizations tend to become more organic, which means decentralizing authority and responsibility to lower levels, encouraging employees to take care of problems by working directly with one another, encouraging teamwork, and taking an informal approach to assigning tasks and responsibility. Thus, the organization is more fluid and is able to adapt continually to changes in the external environment (Daft, 2015)."

Cultural change has been a frequently cited obstacle for adopting MBSE. This was echoed by the interview participants. An organization that is on the organic side of the paradigm is better equipped to adjust to changes at the cultural and organizational level. The components of the organic organization are larger driven by the culture of the organization. In a purely organic organization, there are few rules and less formal control, with communication largely occurring horizontally across the organization. An interesting finding from the survey results showed that employee's willingness to help others was not correlated with whether employees feel strongly connected to on another. These were both questions under the *Interconnectedness* variable. This could be interpreted as employees don't need to feel strongly connected to one another to be willing to assist with problems. The organic paradigm describes a culture where people communicate and are willing to help others and work towards a common goal. This does not have to result from employees feeling connected to each other on a personal level.

A purely organic organization may have difficulties with adopting a technology consistently across the organization. In an organic organization, "technologies are usually non-routine" (Nahm, Vonderembse, & Koufteros, 2003). One study found that while an organic paradigm was appropriate in the initial development/adoption phases, a more mechanistic structure was better suited for the implementation/diffusion stages (Tushman & Nadler, 1978). This is consistent with the positive effects that formalization/standardization had on MBSE adoption from the survey results. So while the aspects of flexibility and interconnectedness are important for a successful MBSE adoption effort, not all aspects of the organic paradigm may be beneficial for long term implementation.

7.1.7 The paradox of centralization and formalization

As seen in the survey results, higher levels of standardization of MBSE was positively correlated with MBSE use and maturity. Standard rules or procedures are an effective way to achieve coordination in an organization is more fragmented or has a less formalized hierarchy. The difficulty is there may not be a way to enforce those standards. For example, several participants mentioned that their organization had a "standard way" of doing MBSE, but they did not know what those standards were. Another issue with standards relates to customers or contractors that are outside of the organization. As one participant reported, "*While we have a standard suite we want to move to corporately, we can't always stay in the standard suite because our customers have their preferences [44]*."

A centralized entity or decision making body would seem to be the answer to this issue of enforcing standardization. However, *Centralization* was negatively correlated with adoption and implementation of MBSE. The majority of organizational units in the survey had MBSE roles or tasks dispersed throughout the organization, as opposed to a dedicated team or department for MBSE. Furthermore, 43% of the organizational units indicated that individual projects, teams, or divisions decide how they will use MBSE independently. Decentralized organizations were prevalent in the sample from the survey. Decentralization is also a characteristic of the organic paradigm. So the question remains, how can formalization/standardization be achieved in a decentralized organization?

7.1.8 Integration and coordinating mechanisms

One of the critical issues in MBSE adoption that is relevant to organizational structure is the concept of integration. Tools, models, and/or data repositories need to be linked together in some way to establish an authoritative source of truth. In order to achieve this integration, "*a lot of different functional areas need to come together for MBSE [3]*." Especially in the context of Digital Engineering, it "*effects every aspect of the business [44]*." The way many organizations are structured, this often means that different departments or teams are going to have to work together.

Coordination mechanisms address the critical issue of integration that is often difficult to accomplish. While the ultimate goal is to achieve implicit coordination through the use of connected models, getting to that point will require coordination between different subunits. Responsibilities and authorities need to be clearly defined in this cross-functional effort in order to actually accomplish anything. One participant described this issue in their organization: "*They're just trying to coordinate all these efforts like MBSE in a lot of ways without real authority. And everyone has their opinion about what tool and method is best. Since so many people just have control over a small part of the kingdom, no one has control of everything [20]*." Especially in more decentralized organizations where authority is spread throughout many different subunits, there needs to be some consideration as to how the cross-functional effort that is MBSE can be coordinated and adopted to some level of consistency.

Several coordination mechanisms were explored in this research and can be seen in the responses from interview participants. There were three that stood out as potential ways to address the formalization/centralization paradox. These are liaison roles, permanent coordinating teams, and the matrix organizational structure. A liaison role is an effective way to coordinate horizontally among different groups without having to make a lot of changes to the formal structure of the organization. If the person in this liaison role also has authority over the MBSE implementation, that could bypass the issue of unspecified responsibility/authority. Several interview participants described the systems engineers in their organization operating as liaisons. Permanent coordinating teams were one of the more frequently used mechanisms by interview participants. A permanent coordinating team can take the form of an informal "community of practice" or working group where people go to share information and best practices. They can also take the more formal form where best practices and standards are published, methodologies and tools are managed, and training occurs. A matrix organizational structure would require the most change for an

organization to make out of the three methods. The benefit of this structure is that the disciplines are able to specialize in their field and bring that expertise to different projects. Another benefit is that the "*organization is responsible for making sure the same practices are followed between programs [47]*," which is how the coordination occurs. Under this mechanism, there is formalization in the SE functional division where people in SE roles can master MBSE and learn a standard way of doing it. But there is also decentralization, because each project/program operates independently, but with people from the SE functional group who know the best ways to do MBSE.

7.2 Comparison to previous works

7.2.1 Adoption strategy

Interview participants were divided on whether to introduce MBSE in an organization all at once or to start small and expand. Different perspectives on adoption strategy were also reflected in the literature. For the adoption of Systems Engineering, Bretz et al. (2019) stated that SE should be introduced simultaneously across an organization. If SE is introduced from one department, there is a risk of not considering all stakeholder's needs and missing support from other departments (Bretz et al., 2019). MBSE adoption literature also has different approaches: off-cycle or on-cycle (Chami et al., 2018). The off-cycle approach occurs "in a sandbox environment," and is considered ideal but expensive. The on-cycle approach is when MBSE is implemented on productive projects and is much more challenging, since the adoption needs to occur while normal project activities are also occurring.

The division among interview participants was not between off-cycle or on-cycle. While some interview participants discussed their organizations use of pilot projects, these were still in the context of productive projects. So all of the adoption approaches were "on-cycle" in the interview participants' organizations. There were two distinct views on how the adoption should occur in that "on-cycle" context. The first perspective was to start small, target certain areas that would benefit the most from MBSE, and build up capabilities over time. This was the most frequently held opinion. On the other side, participants believed that MBSE should be all-or-nothing, that organizations need to make a clean start for MBSE. This division is echoed in the literature, with various authors arguing for an incremental adoption approach or a wholesale adoption approach (Chami et al., 2018; Qumer & Henderson-Sellers, 2008; Julian et al., 2019; Mahanti, 2006).

7.2.2 Training

Authors of previous works argued that all stakeholders involved should have some level of training in the MBSE tools and methods as well as the selected modeling language (Bayer et al., 2012; Gräßler et al., 2021; Papke et al., 2020; Piggott, Melanson, Hartman, & Adourian, 2008). This was consistent with the view of interview participants in this study. They agreed that stakeholders of all levels should be trained, and even identify the different categories of training: Model Reviewers, Developers, Architects, and Administrators. This categorization should provide a helpful way for organizations to easily decide how much training a certain stakeholder needs.

7.2.3 Network of peers, coaches, mentors, dedicated modelers

Mentors and coaches were frequently recommended to help with MBSE adoption in the literature. Employees proficient with MBSE tools within the project team could be paired up with less knowledgeable team members. According to the survey results, this was not a common practice. Only around 30% of the organizations surveyed offered this resource. Additionally, only one interview participant mentioned having designated mentors in their organization. A practice that was more common was having a network of experienced peers. Chami et al. (2018) claimed that having a core network of knowledgeable MBSE users ensured collaboration and avoids loss of knowledge. To that effect, having dedicated modelers was also recommended frequently in the literature. The European Aeronautic Defense and Space Company found that "using modeling experts increase[d] acceptance of the MBSE approach" by other systems engineers (Asan et al., 2014). The systems engineers were used as knowledge sources and analysis experts whom the modeling experts collected information from to develop models. The Jet Propulsion Laboratory center in NASA found that a three-tiered structure for MBSE projects was effective (Bayer et al., 2012). This translates to a set of core modeling experts within the larger systems engineering team, who are one component of the overall project. The authors stressed that it was important to "avoid fencing [the core modeling team] off from the rest of the project" so that the models created were useful. This sentiment was consistent with reports from interview participants. Dedicated modelers can be beneficial, if they either have the appropriate systems knowledge or are paired with people that do. There is no benefit to a model if it is not actually relevant information that is being modeled.

7.2.4 The centralization controversy

Whether SE functions should be dispersed throughout the organization or centralized in one department was debated in the literature. One survey examined the difference in the performance of organizations that had a separate SE department versus those that distributed SE functions throughout the organization (Elm & Goldenson, 2012). The results showed that organizations with centralized SE were more effective at deploying SE best practices. Another survey indicated that organizations which had a centralized MBSE department at the enterprise level used MBSE more frequently than those that did not (Lu et al., 2018). *Centralization* was not significantly correlated with *Use of MBSE* based on the survey results in this study.

This concept of centralization also came into play in MBSE adoption efforts. One organization had a substantial amount of conflict with their employees because the engineers wanted "to decide their working methodology themselves as opposed to have methodology specialists dictating how the tools should be used" (Andersson et al., 2010). The problem with this was that the methodology the system architects chose led to communication issues and misunderstandings between subunits in the project, due to the lack of consistency of methodologies across subunits. Interview participants discussed similar situations, where different "silos" in the same department simultaneously adopted MBSE using completely different methodologies.

On the other hand, a common source of negative experiences from MBSE adoption efforts came from engineers not having the level of autonomy they would have liked. As one survey respondent reported: "Not enough autonomy given to the MBSE team; leadership, with no real

MBSE knowledge, mandates 'terms and conditions' that can inhibit MBSE from reaching its true potential on a program or slow its adoption, against the recommendations of the MBSE champions" (Cloutier, 2015). This sentiment appeared to be reflected in the survey data, with *Centralization* having a negative correlation with MBSE adoption and implementation.

Based on the insights found in this study, it appears that some aspects of MBSE should be centralized and other decentralized. This concept is also recommended in the literature. One paper (Bretz et al., 2020) describes how the allocation of SE tasks can be divided, with some tasks centralized depending on the organization's priorities. SE guidelines and support functions can be centralized, while project specific SE work is decentralized. This is an arrangement that should also be considered for MBSE.

7.2.5 Integration, coordination, and authority

Systems Engineering as a discipline is involved throughout the lifecycle of a project and thus should involve communicating with multiple subunits. A high level of communication is necessary within the SE group, and between related functions for a given project (Blanchard & Blyer, 2016; Conroy, Mazzone, & Lin, 2013). So in order to gain all the advantages MBSE has to offer, the organizational form has to be adjusted (Kellner et al., 2016). According to Kellner et al., "walls and borders" between different subunits need to be broken up to create a cohesive team where all disciplines are involved from the start of a project. This reduces misunderstandings and the rework that comes from those mistakes. Interview participants also discussed the importance of integrating functional areas and communication between tools.

A case study discussing the implementation of MBSE in an organization discussed the creation of a liaison role as a coordinating mechanism. This position, referred to as business system manager, formed the bridge between the engineering division and IT division (Friedland, Malone, & Herrold, 2016). This new role assisted in the successful adoption and implementation of MBSE through addressing the lacking communication structures between subunits on the project. One of the interview participants discussed the difficulty coordinating between the systems engineers and the IT department. The lack of coordination with IT was one of the contributing factors to the adoption effort failing.

A frequent recommendation in the literature was to establish a Core MBSE team (Chami et al., 2018; Kellner, Ringhofer, Hehenberger, Weingartner, & Friedl, 2016), dedicated modeling teams (Bayer et al., 2012; Simpson et al., 2012), communities of practice (Chami et al., 2018), or more formal teams that provide guidance, training, and technical support (Papke et al., 2020). A common adoption activity amongst the interview participants was establishing a Core MBSE team. These Core MBSE teams took the form of all of the examples from literature listed above.

7.2.6 Naugle et al. (2019) MBSE adoption model

The Naugle et al. (2019) individual adoption model was compared to the causal model created in this study in Chapter 6. Approximately 68% of the causal relationships in the Naugle et al. model also existed in this study's causal model. The main difference between the two models was the framing of the model. Naugle et al.'s model focused on the individual decision to use

MBSE, while this study focused on MBSE adoption in the organizational context with the inclusion of key organizational structure contributing factors.

7.3 Novel findings

This work makes several unique contributions to the literature. First, is the finding that organizational structure is significantly correlated with MBSE adoption and implementation. *Formalization*, *Flexibility*, and *Interconnectedness* were all found to have strong positive correlations with MBSE adoption and implementation. *Size* and *Vertical Differentiation* were both found to have negative correlations with *Use of MBSE* (an implementation variable). *Centralization* was found to be negatively correlated with both adoption and implementation. Organizational structure has been intuitively thought to affect MBSE adoption through people's experience with adoption, as shown through surveys and interviews. Participants in the interviews for this study also had this same belief. The results from this survey provide quantitative evidence to support those claims.

The second major contribution comes from the causal model showing the adoption process of MBSE at the organizational level. While people do have to make an adoption decision at the individual level, there are many organizational factors that affect different aspects of the adoption process. This had not been captured in a depiction of the MBSE adoption process up to this point. Causal analysis revealed the key variables in this causal process are *Improved organizational outcomes*, *Coordination between subunits*, *Projects use tools/methods*, and *People willing to use tools*. *Improved organizational outcomes* was a critical variable in facilitating the impact organizational structure has on the adoption process.

Integration is a key component of MBSE adoption that relates to organizational structure. Coordination mechanisms are the key to achieving this integration. Coordination between subunits was also a critical node in the overall MBSE adoption process. The goal of MBSE and Digital Engineering in general is to achieve implicit coordination through technology, which is itself a coordination mechanism. But until the tools have the capability to be fully integrated, other mechanisms will need to be used. Other coordination mechanisms include formal hierarchy, standard rules and procedures, direct informal contact, liaison role between groups, task force, permanent coordinating team, and the matrix organizational structure. The positive and negative aspects of these mechanisms were explored and discussed in the context of the organizations that were represented in the interviews.

Past works have advocated for training for all relevant stakeholders. This study provides a categorization for the types of stakeholder that need training. The first group of people are the Model Reviewers. These are leaders, stakeholders, or customers who need to know how to use the models to make decisions. The second group is the Developers, or the modelers. These are the people who are building and maintaining the models in the tools, so they will need detailed knowledge of how the tool works. The third group is the Architects. These are the people who will be working in the model to some capacity. These people are often senior engineers or people from other disciplines who are helping with the content of the model. This group does not need as deep of training as the modelers, but they do need to be able to operate in the models. The last group is

the Administrators. These are people who work in IT or software who will be managing the relevant accounts, licenses, tools, etc.

According to the survey results, a majority of organizations did not assign coaches or mentors to engineers or developers in their organizations. Case studies from the literature frequently recommended coaches or mentors as an effective way for people to learn MBSE. The assignment of coaches/mentors was positively correlated with *Maturity of MBSE* based on the survey results. This could mean that coaches/mentors assist organizations in becoming more mature, or its more mature organizations that are assigning coaches/mentors.

MBSE task allocation and standardization were found to have significant correlations with adoption and implementation variables. MBSE task allocation refers to the question 'To what extent is there a separate department to manage personnel and/or resources regarding MBSE?' Task allocation had a significant positive correlation with *Use of MBSE* and *Influence on organizational outcomes*. That means that organizations that had more defined groups dedicated to MBSE tended to use MBSE on more projects and have better organizational outcomes. Standardization refers to the question 'To what degree are the MBSE tools and methods used standardized across your organizational unit?' This question was positively correlated with all four adoption and implementation variables. The strongest correlation was with *Maturity of MBSE*. This indicates that standardized methods/tools may be the mark of a more mature MBSE application.

This study identified gaps in the functionality of MBSE tools that should be addressed. First, many tools do not provide a simple way to integrate with other tools. This is a known industry problem. One gap that has not been discussed is related to metrics. Whether it is capturing data related to use of MBSE, or metrics related to requirements management, this is an area that is not reflected in most tools. Work should be done to make this the standard for tool vendors to include. The purpose of a tool is to be a tool to accomplish tasks; they are supposed to make people's jobs easier. The convoluted steps one would have to take in order to extract data from most tools currently is not going to convince anyone that it is worth their time to do so. Since previous studies (Henderson & Salado, 2021b), as well as this study, have concluded that improved organizational outcomes are critical metrics to convince people the investment into MBSE is worth it, tool vendors should look at their tool's functionality to see what can be done in this area. Tool vendors are selling a product that is reliant on organizations using MBSE, so they should have an interest in assisting in the effort to quantify its benefits.

The survey questions addressing adoption and implementation are a good representation of those underlying variables. The factor scores for the three variables with multiple questions were high across the board. The values for internal consistency were 0.732 for A1, 0.854 for A3, and 0.857 for A4. These are all above the 0.7 threshold for this test. To illustrate this point, a tool vendor has already reached out to ask if their company can use these adoption questions to survey their own customers. They want to compare where their customers are in the adoption/implementation process compared to the industry in general. Since there is little capability in the tools to capture metrics, utilizing these questions may be a good way to measure adoption/implementation until that capability is added to the tools.

7.4 Limitations of study

"While in an ideal world we may wish to collect data from participants in a particular organization or a number of organizations, our abilities to do this are dependent upon gaining access to these organizations and our intended participants (Symon & Cassell, 2012)." The main limitation of this study was the sample size of the survey. Due to the number of usable responses, organizational and adoption factors were evaluated individually instead of together. This limited the type of statistical analysis that could be performed on the data. This also would have allowed for an exploratory factor analysis, which could show if some of the organizational structure variables could have been part of the same factor.

One area of concern for potential instrumentation bias was through the interpretation of "organizational unit" as the unit of measure. This term was defined at the beginning of the survey, and participants were asked to keep that definition in mind when answering survey questions. However, it was possible that some respondents interpreted the organizational unit as their entire organization. This is not necessarily an issue, if the organization is small it may be appropriate to consider the entire organization as the unit of measure. The issue would have arisen if participants answered some questions thinking of their "organizational unit", and others thinking of the entire organization. Given how widely organizational structures vary, it was difficult to determine a unit of measure that was specific enough to be consistently understood, general enough to apply to all organizations, and existed at a meaningful level of evaluation.

The prevalent limitation of the interview instrument is the fact that the data analysis consisted of some degree of researcher interpretation. This is necessary in qualitative research, but is still a potential source of bias. To combat this, interview quotes were used as much as possible to support conclusions extracted, especially during the survey-interview comparison.

The causal model provided only limited insights due to the static nature of the model. Data that allowed for simulations would have been able to show in greater detail how the organizational structure and adoption factors interacted. Unfortunately, data in this field is still difficult to obtain. The tools do not have the capacity to capture metrics, and the organizations largely don't have the capability or infrastructure to measure outcomes. This is in line with previous research determining the importance of measurement to the improvement of the field (Henderson et al., 2021; Henderson & Salado, 2021b).

7.5 Recommendations for future research

One area of this work that has potential for future work is the MBSE adoption causal model. The causal model in its current state can tell us which variables in the process are important, which is valuable knowledge. But the model was developed with future capabilities in mind. When there is more data available, the model will be able to simulate MBSE adoption, with the ability to test different values for organizational structure. Since every organization is different and requires different adoption activities, this capability would make the model an extremely valuable tool. The potential for simulation is the main purpose of the inclusion of the exogenous variables: Organizational policies, Organizational culture, and Maturity of MBSE discipline. These would be necessary external factors to consider that could influence the adoption process, but are not necessarily part of the adoption process itself.

Future research should look further into coordination mechanisms and which are more effective for MBSE adoption. The most frequent lack of a coordination mechanism that was noted by interview participants related to too much separation between different functional groups. As one participant remarked, "*I can't tell you how many organizations I've tried to help that have a requirements group, an architecture group, an interfaces group, and an analysis group that never meet [9]*." Getting the collaboration across the organization is difficult by itself, but it raises another issue of authority. Responsibilities and authorities need to be clearly defined in this cross-functional effort in order to actually accomplish anything. One participant described this issue in their organization: "*They're just trying to coordinate all these efforts like MBSE in a lot of ways without real authority. And everyone has their opinion about what tool and method is best. Since so many people just have control over a small part of the kingdom, no one has control of everything [20]*." Another participant described the issue as "*a 'who has the charge line to do what part of the work' type of obstacle [47]*." This is another aspect of the adoption process that should be explored further in future research.

This study identified four categories defining types of stakeholders that need training for MBSE. These are Model Reviewers, Developers, Architects, and Administrators. These categories should be further developed with guidelines on what amount and type of training each of the categories requires. This will further the maturity of the field and facilitate an easier adoption process by having the amount of training needed defined.

Future work should attempt to replicate the survey results of this study in order to support the validity of the findings. While the sample size of this study was sufficient to analyze the data, repeated studies with different samples could serve to support the generalizability of the results. As more data is collected, the feasibility of converting the causal model developed in this study into a dynamic model will improve. A dynamic model that can run simulations would allow for an exploration of different combinations of organizational structure variables and how they impact the adoption process and outcomes.

As evidenced in the interview results, organizations have had success adopting MBSE from the bottom-up and top-down. Organizations have also been unsuccessful using both strategies. This suggests that the direction of adoption may not have a significant impact on the success of the adoption, but this is only based on the sample of organizations that were interviewed. Future work should look into this further, as it is one part of the adoption strategy that has not been thoroughly explored in the research literature.

Role definition and allocation was one organizational structure topic that was not able to be explored in this study. A literature review and analysis was recently conducted to determine what roles were necessary to allow a successful adoption and implementation of MBSE (Gräßler et al., 2021). The resulting roles included: Project Leader, Requirements Engineer, Implementation Engineer, Process Owner, V&V Engineer, Configuration Manager, Security Engineer, System Architect, Modeling Engineer, Technical Manager, System Interface Manager, Information Manager, Life Cycle Engineer, Stakeholder Interface Manager, Systems Analyst, Entrepreneur, and Subject-matter Expert. Future work should look into how these roles are distributed amongst personnel (since one person can perform more than one role). Especially since

integration of different subunits is necessary for MBSE, it is likely that these roles could be allocated to different departments. It would be interesting to study if different role allocation had an effect on MBSE adoption and implementation.

Another area that was not explored deeply in this research is leadership[11]. Interview participants noted the importance of leadership buy-in and support, but this was not measured in the survey. Informal vs. formal leadership is also an area that is worth further study. About two-thirds of the survey participants indicated they had a formal leadership role, but only around 40% had a job title that indicated some type of leadership role. This could indicate that organizations formally appoint some people as leaders without a matching job title, or that what is an informal or formal leadership role is misunderstood. Another aspect of leadership that could be worth researching is the potential mediating effects leadership could have on the relationship between organizational structure and MBSE adoption.

Finally, one of the conclusions from this study was that lack of understanding or confusion about MBSE is still a prevalent issue. The SE community needs to come together to more clearly define what exactly is Model-Based Systems Engineering, and then communicate that to the rest of the field. Without a consistent understanding at the conceptual level, adoption and implementation of MBSE across the industry will continue to be fraught with difficulties.

[11] Interview participants used the terms leader and management interchangeably

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