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Applicability of the diffusion of innovation theory to accelerate model-based systems engineering adoption

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Abstract

Systems engineering (SE) is an interdisciplinary domain that can benefit from incorporating contributions from fields not typically associated with technical disciplines, including integrating relevant research from social sciences. The study of innovation has produced the diffusion of innovation theory, which identifies variables that affect the adoption rate of innovations. Of these variables, the perceived attributes of the innovation have been shown to have the most significant impact on the adoption rate of innovations. Shaping the innovation attributes of relative advantage, compatibility, complexity, trialability, and observability and how they are perceived can accelerate its adoption rate. This theory has the potential to accelerate the adoption rate of SE innovations. Model-based systems engineering (MBSE) is an SE innovation that, despite its benefits, has not been adopted generally. An evaluation of the attributes of MBSE as defined by the diffusion of innovation theory can aid in understanding its slow diffusion and inform methods to accelerate its adoption. Since there is some evidence to suggest that this theory is applicable to SE and MBSE, additional research should be conducted to determine the best way to utilize its principles.

KEYWORDS

adoption rate, diffusion of innovation theory, innovation, model-based systems engineering, process improvement, systems engineering

1 | INTRODUCTION

Systems engineering (SE) is an inherently interdisciplinary field. The body of knowledge and curriculum to advance systems engineering project (BKCASE) has developed a graduate reference curriculum for systems engineering (GRCSE) that, as its name suggests, is meant to codify a curriculum that will prepare SE students for the challenges they will face in engineering the complex systems being developed today. It references a diverse set of disciplines in identifying that "[systems engineering] incorporates skill sets from many disciplines; including traditional engineering disciplines (electrical, mechanical, civil, etc.) as well as more management-focused disciplines (project management, program management, industrial engineering, etc.)."¹ These management-focused disciplines arise from the fact that every system created by a systems engineer has a human element, as SE encompasses the organizations that manage the entire life cycle of the system-of-interest.

Many authors and practitioners recognize that while there are many technical processes associated with SE, there is an art to the discipline that may not exist in other engineering fields.²⁻⁴ Considering the artistic nature of SE and the impact of the human element, there is almost certainly a benefit to looking beyond the traditional fields in educating systems engineers and improving the SE practice. Michael Griffin, while specifically addressing some of the shortcomings in the field of

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SE, observed that "until and unless we begin to delve into the social and cognitive aspects of how engineers work together and how system engineering is performed...possible contributions from fields far apart from engineering will continue to go unrecognized... The study of human interactions, cognitive psychology, social choice theory, and other disciplines must be included in the development of effective theories of system engineering."⁵

Application of "fields apart from engineering" offer benefits in their own right, but they can also serve as a "force multiplier," enabling research and development within the SE discipline to be applied in more effective ways. There are many opportunities to investigate how these disparate fields can be incorporated into the practice of SE. One such field that offers promise is the study of innovation, innovation meaning "an idea, practice, or object that is perceived as new by an individual or other unit of adoption,"⁶ and specifically the consideration of how the *diffusion of innovation theory* can benefit SE.

The diffusion of innovation theory seeks to explain the variation in adoption rate and breadth of innovations.⁶ This is relevant to SE as it is an active field with a constant flow of new research and innovations. Some of these innovations have not been adopted to a degree commensurate with the benefits they offer SE practitioners. One such innovation is the practice of model-based systems engineering (MBSE),^{7,8} defined by INCOSE as "the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases."⁹ MBSE can be characterized as both a process and a behavioral innovation as it introduces new methods, modeling languages, and tools to existing SE activities that often require changes in organizational culture to adopt.¹⁰ It is possible that an understanding and application of MBSE.

In this article, we focus on understanding the diffusion of innovation theory in the context of SE and MBSE and how understanding and addressing the various factors can accelerate MBSE adoption. The remainder of the paper is organized as follows. Section 2 introduces the diffusion of innovation theory along with the key perceived attributes of innovations. Section 3 demonstrates some specific ways that this theory could be applied to accelerate the adoption rate of MBSE. Section 4 outlines future work that will be required to validate the applicability of the diffusion of innovation theory to MBSE, and Section 5 presents the conclusions.

2 DIFFUSION OF INNOVATION THEORY

The most significant innovations in any field do not provide value to an organization until they are adopted or put into practice. The study of the diffusion of innovations is a well-established field pioneered and popularized by Everett Rogers. Rogers first captured this theory in his book "Diffusion of Innovations" in 1962. Since then, he continued his research and published the fifth edition in 2003.⁶ Innovation became a field of study because technologists wanted to understand why some innovations gained rapid, widespread acceptance while others with



FIGURE 1 Adoption s-curve

comparable advantages took much longer or were never adopted at all.⁶ This idea ran contrary to the intuition that if a genuinely improved product or process were introduced, it would be adopted on its own merits.

Even the most popular innovations are not adopted in a population instantaneously. Most innovations follow an adoption s-curve as depicted in Figure 1 where the percentage of a population that has adopted an innovation increases with time. Adoption typically starts off slowly as a small group of innovators and early adopters learn about, refine, and choose to adopt an innovation. Once knowledge and appreciation of the innovation increases, the adoption of the innovation accelerates with adoption by the early majority of adopters. As an innovation is more widely adopted, its pool of potential adopters shrinks, and the adoption rate slows down as the late adopters embrace the innovation. Finally, the adoption curve levels out as the last of the potential adopters that will eventually adopt the innovation, the laggards, adopt it. Figure 1 is a generalized adoption s-curve, and the adoption curves for specific innovations vary significantly. Some innovations reach their maximum adoption percentage in a matter of weeks or months, while others may take years or decades. Also, not every innovation is adopted by the same percentage of potential adopters. Some innovations may reach maximum adoption at 20% of the population of potential adopters, while another may diffuse to 80%.

The diffusion of innovation theory identifies five variables that determine the rate of adoption of innovations (shown in Figure 2): the perceived attributes of the innovation, the type of innovation-decision, the communication channels used to spread knowledge of the innovation, the nature of the social system of the potential adopters, and the extent of change agents' promotion efforts. Of these five variables, the perceived attributes of innovations account for 49%–87% of the variance in the rate of adoption and will be the focus of this paper.⁶

In addition to these variables and attributes, the diffusion of innovation theory introduces some specific terms that will be used in this description. Potential adopters refer to the population that could possibly adopt an innovation. Depending on the innovation, this population could be small (e.g., potential adopters of a specialized piece of scientific equipment) or large (e.g., potential adopters of smartphones). It is important to appreciate that the extent to which an innovation has



FIGURE 2 Variables that affect the rate of adoption of innovations

diffused is measured within its pool of potential adopters, not the general population. A change agent is one who promotes and facilitates the adoption of an innovation. Change agents can be internal or external to an organization or population of potential adopters. An internal change agent could be a member of the organization that has become familiar with an innovation and becomes a "champion" for its adoption. Often times professional organizations or tool vendors act as external change agents.

2.1 | Perceived attributes of innovations

It is worth noting that the diffusion of innovation theory does not identify the attributes of innovations themselves as a key variable in their rate of adoption; rather, it makes the distinction that it is how those attributes are perceived by potential adopters that often causes variability in adoption rates. This is because "if [people] perceive situations as real, they are real in their consequences."¹¹ Furthermore, while efforts have been made to quantify these attributes as they apply to innovations, there are no generally accepted, quantifiable ways to measure these attributes in all domains; they are inherently subjective. The importance of the perception of these attributes presents challenges and opportunities. The challenge is that perception is not always accurate, and adoption of a beneficial innovation can be delayed by the inaccurate perception of its actual attributes. The opportunity is a result of the ability of perceptions to be shaped through various means, including education, without having to change the innovation itself. Table 1 contains a brief explanation of the attributes of innovations as defined in "Diffusion of Innovations."

The relative advantage of an innovation is simply the benefit of the innovation relative to the idea or technology the innovation supersedes. Relative advantage can be measured in many ways (economic, performance, prestige, and so forth) depending on the innovation and adopting group. This is perhaps the most intuitively understood attribute of innovations. Innovations that are perceived as offering an advantage over the status quo are more likely to be adopted. Perceived relative advantage has been shown to be one of the strongest predictors of the adoption rate of an innovation.⁶ This attribute also explains why preventative innovations, that is innovations intended to prevent a potentially negative outcome from occurring (like wearing a seat belt to minimize injury in the event of a car accident), typically take longer to diffuse than incremental innovations that offer more immediate and observable benefits. Because the relative advantage of a preventative innovation is a nonevent that may never be directly observed, its perceived relative advantage is lower. Relative advantage may also lead to over adoption of innovations, which is when an innovation is adopted where it is not warranted (e.g., purchasing a high-end computer to be used primarily for word processing).

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

The complexity of an innovation is characterized by the perceived difficulty of its use. Complexity is the only attribute that, as defined, is negatively correlated with the rate of adoption of an innovation. The more complex an innovation is perceived to be by its potential

TABLE 1 Definitions of the attributes of innovations as defined by "Diffusion of Innovations"⁶

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

adopters, the less likely it is to be adopted. High complexity can be a significant hurdle to the diffusion of innovations that would likely be adopted based upon their relative advantage and compatibility alone. As subsequent iterations or releases of the innovation become less complex and more user-friendly, the rate of adoption will often accelerate even if no new features are added.

High trialability, or the ability to experiment with an innovation before large-scale adoption, is positively correlated with the adoption rate. When faced with a decision to adopt an innovation, like any decision, one of the primary goals of the decision-making process is to reduce the level of uncertainty about the innovation.¹² Personal experimentation with an innovation prior to making the decision is a prime way to reduce uncertainty. Innovations with a lower cost of entry to experimentation and that can be initially implemented on a limited scale have faster rates of adoption than those that require a significant investment of resources to experiment with and require large-scale implementation before any benefits are generated. If the innovation has already been adopted by a significant population of similar organizations or individuals, their experience can serve the purpose of a trial for late adopters.

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

2.2 | The Dvorak keyboard

The Dvorak keyboard is a classic example of how the application of the diffusion of innovations theory can aid in understanding why an innovation that is an improvement over the product it was created to replace has failed to achieve widespread adoption. The Dvorak keyboard was created by Professor August Dvorak of the University of Washington in 1932. Dvorak recognized that the QWERTY keyboard in use on typewriters of his time, and still in use today, was not the most efficient design. The first typewriters would jam if a typist did not allow enough time for the hammer from a key to reset (via gravity) before pressing an adjacent key. The QWERTY keyboard was designed to space out the most commonly used letters to minimize the occurrence of adjacent keys being pressed in order.⁶ As typewriter technology improved, the QWERTY layout was no longer necessary to prevent jamming, yet it persisted as the standard layout.

Dvorak spent more than a decade studying what slows people down as they type, identifying such things as how often keys on different rows are used, the balance of typing between right and left hands, and how much typing each finger is responsible for relative to its dexterity. Informed by these observations, he produced a layout to mitigate these typing inefficiencies (see Figure 3). For example, on a QWERTY keyboard, only 32% of typing is done on the most efficient home row, compared to 70% on the Dvorak. By minimizing the distance that fingers must travel, the Dvorak layout has also been shown to reduce strain and repetitive use injuries in typists and measurable improvements in typing speed.¹³ Despite these advantages over a QWERTY keyboard, the Dvorak keyboard has never gained any degree of widespread adoption.

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

While the Dvorak is objectively no more complex than a QWERTY keyboard, to a population that has only ever seen QWERTY keyboards, a new keyboard layout and typing method is foreign and perceived as very complex. There are no real opportunities to experience the



8 most common alphabetical keys pressed are highlighted

FIGURE 3 Comparisons between the eight most common alphabetical keys pressed using the QWERTY keyboard layout (A) compared to the Dvorak keyboard layout (B)

advantages of the Dvorak without dedicating significant time to acquire specialized skills, so its trialability is limited. The Dvorak keyboard has low observability as most people have never heard of a Dvorak keyboard, let alone seen one used or used one themselves. Additionally, a skilled Dvorak keyboard user would be recognized as a proficient typist, and there would be no readily observable benefit to the keyboard for someone not trained in the physiology of typing.

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

3 | APPLICATION TO MODEL-BASED SYSTEMS ENGINEERING

As introduced above, MBSE is differentiated from a traditional, document-centric SE approach by its use of a system model instead of documents to capture SE work products and overall system understanding throughout the system life cycle. In the document-based approach, SE data are captured in a series of textual specifications, tables, matrices, and figures that span multiple documents, which are exchanged between stakeholders (see Figure 4). Systems failures in modern, complex systems are often a result of insufficient communication between stakeholders and outdated, incomplete, or inconsistent specifications and requirements.¹⁴ These problems are exacerbated by a document-based approach to SE with its point-to-point communication channels and where there is no mechanism to enforce consistency or completeness between SE artifacts.

When using a MBSE approach, SE data are stored in a model repository which consists of model elements and their relationships. Diagrams and textual outputs can be generated from this model, but they are merely views of the model itself. If a model element is changed in one view or within the model repository, that change is captured and reflected in any other view of that element. In this way, the system model serves as a single, authoritative source of truth for all SE data that can be made available to all relevant stakeholders.

Unlike engineers in many domain-specific disciplines, systems engineers have not generally adopted a model or digital-based approach.¹⁵ While there has been an increase in the use of MBSE over the last decade, the fact that it is still referred to as MBSE instead of simply SE is evidence that MBSE has not reached a level of general acceptance¹. MBSE as an approach to SE offers benefits to the practice of SE that other disciplines have achieved through their use of digital and modelbased methods. An understanding of the diffusion of innovation theory and how the perceived attributes of an innovation affect rate of adoption can be applied within organizations practicing SE to accelerate the adoption rate of MBSE.

3.1 | Relative advantage

An often cited barrier to MBSE adoption is the "lack of perceived value of MBSE."¹⁶ While there is wide consensus amongst those familiar with MBSE that it provides a relative advantage over traditional methods,^{10,15,17} the perception of that advantage is lagging in the SE community generally. This disparity can likely be attributed to several factors.

The first is because the advantages of MBSE are not realized early in a system life cycle when using MBSE. In fact, the up-front SE cost and effort are typically significantly higher during the early phases of a systems life cycle than those of a traditional approach due to the costs associated with defining an MBSE process, standing up a modeling environment, training staff, configuration management, and doing the actual modeling work and reviews¹⁸ (see Figure 5). It takes a significant amount of patience and commitment to make this investment over and above what a traditional approach requires.

The second factor depressing the perceived relative advantage is that MBSE is, in many ways, a preventative innovation. This is to say that many of the advantages of MBSE are not due to the production of measurable benefits but from the elimination of undesirable consequences. When MBSE is done effectively, many of these undesirable

 $^{^{1}}$ Lenny Delligatti, personal communication





(A) Traditional document-centric SE approach





FIGURE 5 Systems engineering cost over time for an MBSE approach compared to a traditional approach

consequences are eliminated, but it is difficult to quantify or appreciate problems that are never realized.

Finally, a literature review has shown that much of the published work on the benefits of MBSE¹⁹ do not contain empirical proof but are instead based on anecdotal accounts.²⁰ There has not been an argument made to refute the idea that MBSE is beneficial, just that the quantitative evidence of those benefits is lacking.

To increase the perceived relative advantage of MBSE, more studies should be conducted to provide that empirical evidence to support the benefit claims of MBSE. These studies and charts like Figure 5 will demonstrate to potential adopters that the benefits are real, but will not begin to be realized until after considerable investment has been made. The initial investment in MBSE is significant but will be recouped over time. Additionally, design quality metrics should be

(B) Model-based SE approach

captured for projects done using a traditional approach and MBSE to show the undesirable effects (defects, problem reports, etc.) were reduced using MBSE.

Compatibility 3.2

The acronym "MBSE," while convenient and descriptive, may be working against its adoption. To those unfamiliar with MBSE, use of the acronym can obscure its true meaning. The fact that the "SE" in "MBSE" stands for systems engineering can be overlooked. MBSE should not be presented as a new SE process but an approach that augments and improves current SE work within the organization. To increase the perceived compatibility of MBSE, the organization's current SE methodology should be studied and understood and an appropriate MBSE methodology selected and/or tailored to complement that methodology.²¹² Artifacts produced by the modeling tool can be tailored to present information that is managed in the model in a format that is familiar to the stakeholders. In this way, potential adopters can transfer their existing SE experience to MBSE.

Perhaps the most important factor in increasing the perceived compatibility of MBSE is to emphasize its compatibility with the pressing needs of systems engineers. A need that MBSE is particularly suited to address is the difficulty in maintaining the consistency of SE artifacts in the presence of requirement, constraint, and design changes that are inevitable in modern, complex systems. The difficulty in maintain-

² This assumes the organization already has a sound SE methodology in place.²² If an organization is new to SE generally, then the organization's perception of the attributes of SE should be assessed and addressed. The diffusion of innovations theory likely applies to the diffusion of SE generally, but application of the theory to SE is beyond the scope of this paper.

ing consistency in a document-based approach is because there is no mechanism to propagate changes made to a system element to all other references of that element wherever they may be found dispersed amongst text, figures, tables, and matrices in multiple documents. When a change is made, it must be made manually and repeatedly. With this manual process, there is a possibility for error in inputting the information incorrectly in one of the locations or missing some of the references that should be updated.¹⁰ These errors can be very costly to a program as engineering work in other domains (for example, electrical, mechanical, and software) use the specifications generated by systems engineers, and any errors or inconsistencies in the specifications will be introduced to their designs. Using a well-designed MBSE approach, any change made to the product information contained in the model as a model element is immediately and automatically implemented wherever that element is used. MBSE also offers the possibility of integrating other repositories of product information, such as product lifecycle management tools or requirements databases, with the system model. The need to manage change and enforce consistency is a compelling need with which MBSE is highly compatible.

Another need of potential adopters with which MBSE is compatible is the need for an organization to have an authoritative source of truth for a system. When SE data are captured in documents that are exchanged between project stakeholders, it is often difficult to determine and track: (1) which document contains the desired information, (2) which version or revision of the document contains the most current information, and (3) traceability between stakeholder concerns, requirements, structural and behavioral design decisions, and verification methods. These difficulties are alleviated through the use of a configuration-managed system model that encompasses all SE data and the relationships between system and model elements. The value of a system model as an authoritative source of truth is enhanced as MBSE tools, methods, and processes improve their integration with domain specific models and simulations.²³

3.3 Complexity

For systems engineers that are accustomed to working with textual specifications and creating standalone tables and figures in productivity tools, the idea of creating and working from a model repository in a new tool can result in a high perceived complexity for MBSE. Systems engineers are familiar with managing complexity in the systems they develop, but adopting a new methodology, tool, and language along with new roles and information standards associated with MBSE adds an additional dimension of complexity. To facilitate adoption, organizations should take proactive measures to minimize the perceived complexity of MBSE.

One of the ways that the perceived complexity can be reduced is to establish a clear purpose for the modeling effort from its beginning and communicate that purpose to everyone that is involved. This purpose should identify a set of questions that the model is designed to answer.^{10,24} Without this purpose, the various diagrams, processes,

and other artifacts may appear as a disjointed and foreign collection. Conversely, if stakeholders understand the purpose of the model and what questions it has been developed to answer, they will gain valuable context that reduces the perceived complexity of MBSE.

Another way that complexity can be lowered is to define roles for those who are involved in the SE work of the organization and provide training on elements of MBSE that are appropriate for specific roles.^{25,26} For example, a model user role could be defined for those who need to be able to interpret design decisions that are captured in a model diagram. Model users would not need extensive training in the chosen methodology or tool but would need to be trained on the selected modeling language. With this training, the diagrams they are reviewing would no longer appear foreign and would be perceived as less complex. There may be a role defined for designers that need to understand and received tailored training on the methodology and modeling language but are not responsible for creating models and do not need expertise in the modeling tool. Finally, there may be only a small group of modeling experts that are proficient with the tool and are responsible for capturing decisions made by the SE team in the system model. With an effective training strategy and clearly defined roles, the perceived complexity of MBSE to all specific users and stakeholders can be significantly reduced.

3.4 | Trialability

If an organization is considering adopting MBSE, efforts should be made to identify a specific, limited application where a trial or pilot project can be completed.²⁶ A key point of MBSE to understand in this context is that an entire system does not need to be modeled to yield a benefit and that a model can (and should) be recursively modified to include additional detail as needed to provide additional value to stakeholders. For example, an organization may experiment with MBSE by modeling only the structural and behavioral elements of a system that are required to deliver a single capability or mission thread. If the limited modeling efforts provide benefits to the organization, the modeling effort can be expanded to other capabilities, and over time a complete system model (a model that accounts for all the elements of its intended purpose) will be developed.

For this attribute, what should be done is straightforward, while the how is more difficult as there are obstacles to overcome to experiment with MBSE. To conduct even a limited experiment using MBSE, at least a portion of the spike in initial SE effort shown previously in Figure 5 will need to be invested. Stakeholders must also be willing to accept a certain level of (initial) redundancy as models are developed to capture data that is already contained in other sources (documents, databases, etc.). Developing the expertise within the organization to conduct this experiment takes time. This can be accelerated using commercially available training and consultants, though the cost may be prohibitive for some organizations. While these challenges are significant, the diffusion of innovation theory reveals their importance so that proactive plans can be made to address them.

3.5 | Observability

[∗] WILEY

As noted in the discussion on relative advantage, MBSE is partially a preventative innovation that inherently leads to poor observability of its benefits. The low observability of MBSE is also closely tied to its high complexity. If the perceived complexity of MBSE can be reduced by implementing some of the actions from the complexity section (such as clearly defined roles and an effective training plan), then the observability of its benefits can be improved as stakeholders are exposed to MBSE tools, artifacts, and processes. With adequate training, design reviews and working groups can be conducted from the modeling tool, and stakeholders will be able to directly observe how elements of MBSE. like reuse of model elements and object-oriented principles (modularity, encapsulation, inheritance, and so forth), help to enforce consistency, provide traceability, and improve design quality.²⁷ Conducting meetings and briefings from the modeling tool will allow the stakeholders to see when design ambiguities are discovered and clarified or when conflicting requirements and design decisions are prevented by the tool.

Observability can also be improved by developing metrics that focus on improvements due to an MBSE approach. Compared to documentbased SE, MBSE has been shown to reduce project development costs, improve on time delivery,²⁸ reduce system defect density,²⁹ and improve probability of success of the project.³⁰ However, as no two development projects are identical, comparing them to demonstrate an observable improvement that can be attributed to MBSE is an ongoing challenge.

3.6 An MBSE adoption success story

The NASA MBSE pathfinder projects and follow-on MBSE infusion and modernization initiative (MIAMI) are compelling examples of how elements of the theory of the diffusion of innovations can explain the rate of adoption of MBSE within an organization.³¹ Though the team did not report any awareness of the theory or a deliberate effort to apply its principles, their approach was very much in line with what the theory advocates and would predict successful adoption. For example:

- They increased the perceived relative advantage by identifying quantitative and qualitative benefits of MBSE from their earliest efforts
- They increased the perceived compatibility by integrating their MBSE efforts with existing SE and domain engineering processes
- The perceived complexity was decreased by identifying specific purposes for each of the pathfinder projects and MIAMI and all the stakeholders knew how MBSE contributed to those purposes
- 4. Each of these projects and initiatives represent limited trials of MBSE that demonstrated the trialability of MBSE, and each resulted in an expansion of the scope of MBSE work within the organization leading to plans for enterprise-wide implementation of MBSE

5. They increased observability by publishing the results of the effort

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

4 | FUTURE WORK

The purpose and scope of this article were to demonstrate that the application of elements of the diffusion of innovation theory could benefit the practice of SE, specifically in accelerating the adoption of rate MBSE. It was not meant to be a comprehensive examination of the diffusion of innovation theory as it applies to MBSE or any other field, nor does it present any experimental results of the application of the ideas presented. Certainly, there is still much work to be done to determine the full scope of what the diffusion of innovation theory offers to SE. Additionally, future work will validate if the ideas presented in this article will, in fact, result in an increase in the adoption rate of MBSE.

To produce evidence of the applicability of the diffusion of innovation theory to MBSE adoption, research will be conducted on programs or organizations that have already adopted MBSE to determine how the innovation attributes of MBSE would have been assessed in their domains prior to and during their MBSE adoption efforts. This assessment will utilize survey research and analysis methods to collect data on users perceptions of MBSE.³² The survey will be based on the instrument developed by Moore and Benbasat to measure the perceptions of information technology innovations.³³ If those attributes are assessed as favorable for the diffusion of MBSE, we can conclude that this theory, at least in so far as it has been investigated, applies to MBSE. A discrete choice human behavior model may be developed to quantify the contribution of each of the attributes to successful adoption.³⁴

Additional research will study organizations that attempted but were ultimately unsuccessful in adopting MBSE to determine if the attributes of MBSE in their organizational context would have suggested that diffusion was unlikely. The data from these organizations may be used to further refine the discrete choice model. Additionally, the ideas presented in this article, informed and improved by results from the discrete choice model and additional literature review, will be tested with an organization that is considering adopting MBSE to determine their efficacy. Appropriate metrics will be developed to conclusively determine if they did ultimately lead to any improvement.

This article only offered a brief introduction to the perceived attributes of an innovation, which is itself just one of the five variables that the diffusion of innovation theory suggests affects the adoption rate of an innovation. There is almost certainly value in a more indepth treatment of the perceived attributes of an innovation as well as in studying how the other variables (the type of innovation-decision, the communication channels used to spread knowledge of the innovation, the nature of the social system of the potential adopters, and the extent of change agents' promotion efforts) relate to the adoption rate of MBSE.

5 | CONCLUSIONS

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

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

While the use of MBSE has increased in recent years, it has yet to become standard practice for SE. The diffusion of innovation theory offers valuable insights as to why adoption of MBSE is occurring slower than what may otherwise be expected based on its benefits. The applicability to MBSE of all the variables offered by the diffusion of innovation theory, including further consideration of the perceived attributes of innovations, warrants additional research.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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