Perceptions and the extent of Model-Based Systems Engineering (MBSE) use – An industry survey

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2022 IEEE International Systems Conference (SysCon) | 978-1-6654-3992-3/22/$31.00 ©2022 IEEE | DOI: 10.1109/SysCon53536.2022.9773894

***Abstract*— Model-Based Systems Engineering (MBSE) supports the development of complex systems through capturing, communicating, and managing system specifications with an emphasis on the use of modeling languages, tools, and methods. It is a well-known fact that varying levels of effort are required to implement MBSE in industries based on the complexity of the systems a given industry is associated with. This paper shares the results of a survey to industry professionals from Defense, Aerospace, Automotive, Consultancy, Software, and IT industry clusters. The research goal is to understand the current state of perception on what MBSE is and the use of MBSE among different industry clusters. The survey analysis includes a comparison of how MBSE is defined, advantages on the use of MBSE, project types, specific life cycle stage when MBSE is applied, and adoption challenges, as reported by the survey participants. The researchers also aim to trigger discussions in the MBSE community for identifying strategies to address MBSE related challenges tailored to a specific industry type.**

***Keywords*— Model-based System Engineering, MBSE, survey, industry, systems engineering, industry-specific, system complexity, and adoption challenges.**

I. Introduction

Model-Based System Engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing through the development life cycle phases until its disposal [1]. MBSE has become the preferred approach to support modern complex systems design and engineering [2] and is a growing discipline for applying modeling tools and languages to capture, connect, communicate, verify, validate, and control a wide variety of systems throughout its development life cycle. MBSE is more than a mere technical task, rather it is a "change process" affecting complex systems where the important system elements are humans [3].

Friedenthal et., al [4] identify the importance of MBSE as a) the enhanced ability to capture, evaluate, distribute, and manage information associated with precise product specifications, deriving benefits such as improved communications among stakeholders (e.g. customers, regulation agencies, systems engineers, hardware/software developers, testers, and various specialty engineers), b) increased system complexity management through enabled system models, observed from numerous facades to analyze the impact of changes, and c) upgraded product quality with the provision of a precise model of the system required, that can be verified and validated for correctness and completeness.

Huldt and Stenius [5] determined that the use of MBSE models helps decrease project risks, shorten project timelines, cut costs, and enhance product quality. Moreover, the use of simulation models as a core principle of the MBSE approach ensures results are obtained earlier and are more cost-effective than testing and prototyping.

Estefan J [19] describes Model-Based Systems Engineering (MBSE) methodologies used in industry including IBM Telelogic Harmony-SE, Object-Oriented Systems Engineering Method (OOSEM), IBM Rational Unified Process for Systems Engineering (RUP SE) for Model-Driven Systems Development (MDSD), Vitech Model-Based System Engineering (MBSE) Methodology, JPL State Analysis (SA), Dori Object-Process Methodology (OPM), Model-Driven Architecture, and Executable UML Foundation.

Chami M. and Bruel J [20] identified MBSE adoption challenges and collected feedback from industry professionals on these challenges, the dependencies among them, and the phase in which they occur. Most of the MBSE adoption challenges are associated with human and technological factors such as change-resistant at the executive and engineering levels. They suggested that challenges should be addressed in the early phases and executives should sponsor MBSE with upfront investment.

Knizhnik, J., et al. [21] presented the results of a comprehensive survey by the NASA SE Technical Discipline Team (TDT) to understand the Systems Engineering and Model-Based Systems Engineering Stakeholder State of the Discipline. The survey was across the aerospace industry from over fifty sources including academia, government agencies, NASA partners, and tool vendors. For the question What are your key challenges/opportunities with making SE faster and more efficient (and adopting MBSE)? The highest MBSE adoption challenges indicated by the survey's participants are "Dealing with cultural issues and change" with 42%, "Workforce issues" with 22%, and "Tool issues" with 12%.

Recent digital technology trends provide several advantages in terms of information processing and management but demand engrossed attention for efficient utilization. According to Amorim et al. [6], MBSE ensures systemized decision making, requirements verification to design solutions, and represents vast strides for the systems engineering community. On one hand, based on several

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affirmations of advantages in the use and adoption of MBSE, it is evident that MBSE is not just a buzzword but enables coordinated systems design activities and facilitates meeting stakeholder requirements. On the other hand, Madni & Purohit [7] explored the relationship between the foreseen MBSE implementation efforts required in various industry clusters based on the diverse levels of system complexity that each of them deals with.

The system complexity is a major factor for the varying levels of effort needed to implement MBSE in an organization. On one hand, industry clusters dealing with aerospace systems that have more than ~100,000 unique components and their corresponding interactions entail a significant effort for MBSE implementation. On the other hand, industry clusters dealing with the design and development of systems with ~300 unique components and their corresponding interactions entail a lower level of effort for their MBSE implementation [7]. The objective of this study is to leverage this distinction and investigate the perceptions, use, and adoption challenges of MBSE across different industry clusters categorized on the level of both MBSE implementation effort and system complexity they deal with. The industry clusters considered include defense, aerospace, automotive, software, and IT. A particular difference in this study is asking open questions for MBSE challenges and being neutral on the question avoiding biased answers. This study asks an open question about MBSE challenges rather than providing possible categories to survey participants. Likewise, it asks a neutral question regarding the effect that MBSE had on their organization's output and success rather than assuming a positive business impact.

II. Data Gathering

This research team discussed MBSE challenges with colleagues and reviewed previous industry surveys [19, 20, 21] to prepare the questions and their purpose while preferring open questions and being neutral rather than influencing a preferred answer. The research team also organized an Online Model-based Systems Engineering (MBSE) Bootcamp as part of a Workforce Development Workshop. First, the research team invited the industry participants that attended the Bootcamp to answer the survey, then this research team invited industry professionals in their professional networks.

This study was conducted using a survey created and distributed to personnel from Defense, Aerospace, Automotive, Consultancy, Software and IT, Healthcare, Manufacturing and Engineering, Environmental, and Infrastructure industry sectors. Survey participants were asked open-ended questions to define what MBSE is and state its foreseen advantages in their respective industry clusters. Their answers helped identify perceptions, use, and adoption challenges of MBSE. Dichotomous questions asking survey respondents which projects and respective lifecycle stages their organizations use MBSE for were employed to deduce both the type of projects distinct industries commonly use MBSE for and respective project lifecycle stages that require MBSE. Table I illustrates the questions framed and their respective relevance in meeting the study's overall objective.

TABLE I. SURVEY QUESTIONS AND THEIR OBJECTIVE'S RELEVANCE

Survey Questions	Purpose of the expected response
What type of industry do you work in?	To identify respondent industry classification.
How would you define Model-Based Systems Engineering (MBSE)?	To identify if there exist similarities or differences in how professionals/respondents define MBSE across various industry clusters.
What are the obstacles that you or your team have come across in adopting MBSE in your projects?	Identify challenges industry clusters encounter during MBSE implementation.
What type of projects is your organization using MBSE for?	To identify the type of projects MBSE is preferred and implemented.
In which life cycle stage(s) or phases of a project do you usually use MBSE?	To identify the specific life cycle phases of a project MBSE is preferred and implemented.
What effect has MBSE had on your organization's output and success?	Identify the varying effects of MBSE use on classified industries' clusters.
In your opinion, what stage(s) of a project has MBSE been most beneficial, and why?	Identify stages of projects that MBSE is most beneficial.
What do you (either individually or across your team) think are the advantages of using MBSE?	To ascertain similarities or contrasts of MBSE advantages according to the identified industry clusters.

Qualtrics and Nvivo 12 pro textual data analysis tools were employed to disseminate, evaluate, and interpret responses retrieved from 52 industry professionals over 6 weeks. Figure 1 illustrates the distribution of respondents according to their respective industries identified from survey responses. 81.2 % of the participants indicated that they have directly been involved with implementing MBSE at their respective organizations with familiarity with MBSE tools and techniques. Table II shows the system and environmental complexities of industry clusters [7] synchronized to the industry clusters identified in this survey.

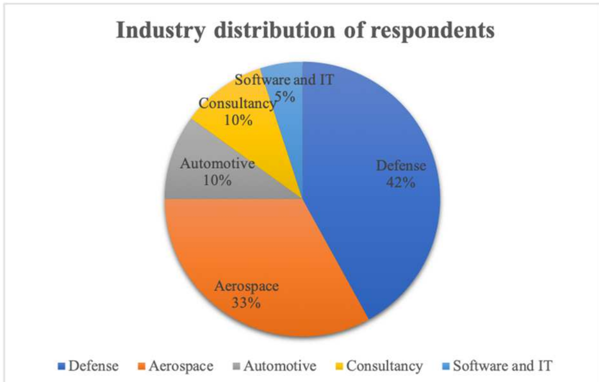

Fig. 1. Survey respondents across different industry clusters

TABLE II. INDUSTRY CLUSTERS OF SURVEY RESPONDENTS [7]

Industry	Respondent Industries in the study	System Complexity	Environment Complexity
Transportation & mobility	Automotive	high	high
Aerospace & defense	Aerospace, defense	high	high
High tech	Software & IT, Consultancy	medium	low

Survey respondents were asked to rate their technical knowledge and experience in using MBSE tools and techniques to understand the familiarity of the participants with MBSE. Table III illustrates the participant's familiarity with using MBSE tools and techniques. Most participants had

Basic or Proficient knowledge, understanding, and application of MBSE tools and used MBSE tools in at least two projects they have been involved with.

TABLE III. PARTICIPANT FAMILIARITY WITH MBSE TOOLS AND TECHNIQUES

Familiarity Scale	Participant Distribution
Limited competency (had limited or no opportunity to apply MBSE tools and techniques; limited understanding of the use of MBSE)	6.25%
Basic competency (Have a basic understanding of the knowledge needed to use MBSE tools; used MBSE in more than 2 projects you have been involved with)	37.50%
Proficient (Detailed knowledge, understanding, and application of MBSE; consistently use MBSE tools and techniques; assist others in your team or the organization in the application of MBSE)	31.25%
Expert (Authority level knowledge, understanding, and application of MBSE; recognized by others in your organization as an expert in MBSE; helped develop materials for application of MBSE in your organization)	25.00%

III. DATA ANALYSIS AND DISCUSSION

Findings of this survey on the existing perceptions of MBSE on the use, adoption, and implementation, are classified across different industry clusters with required varying levels of MBSE implementation efforts. The perceptions analyzed, are strictly based on the responses received by the survey respondents, including identifying how MBSE is defined, advantages on the use of MBSE, the effect of external stakeholders' sentiments on MBSE use, and impact on project success. In addition, the survey explored various project types and specific life cycle stages that respondents identified that MBSE is most often used for in their respective industry clusters. An analysis of the aspects listed above follows.

A. Definitions of MBSE as identified by survey respondents

This section sought to derive varying perceptions of MBSE identified from the survey. Moreover, the researchers compared different effort levels required to implement MBSE based on the system and environmental complexities of the different industry clusters. Three themes of MBSE definitions were identified from the textual responses of the survey participants:

1. MBSE as a document, information handling, and traceability tool,
2. MBSE as a design, conceptualization, creation, and communication tool, and
3. MBSE as a system/process development, support, and improvement tool.

Table IV shows the most often recurring keywords used to identify the themes. The three themes observed indicate MBSE as system development, support, and improvement tool, mostly used to run simulations, support system engineering activities, and improve requirements throughout process development - correlating with existing literature definitions credited to INCOSE i.e., "MBSE is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing through development and later life cycle phases" [1,3,8,9].

TABLE IV. KEYWORDS GATHERED FROM THE MBSE DEFINITIONS IDENTIFIED FROM THE SURVEY

Themes	MBSE definition - Keywords
Theme 1	Systems, Documentation, Information, Connected, Record, Traceable, Repository
Theme 2	Design, System, Conceptual, Model, Communicate, Abstract, Application, Definition, Create
Theme 3	Design, System, Support, Development, Verification, Validation, Process, Improve, Support

Figure 2 shows the percentage representation of how MBSE was defined by the industry personnel categorized based on the industry sector they belong to. Industry clusters such as automotive, aerospace, and defense are involved with developing complex systems and utilize MBSE as an information handling tool, design conceptualization, communication tool, system development, support, improvement, verification, and validation. In consultancy, software, and IT sectors that deal with systems with relatively medium and low levels of complexity, MBSE is perceived only as a process support and improvement tool. This reveals different views of what MBSE is and is used for, based on an increased level of implementation efforts and system complexities within the various industry clusters, and the extent to which MBSE is applied.

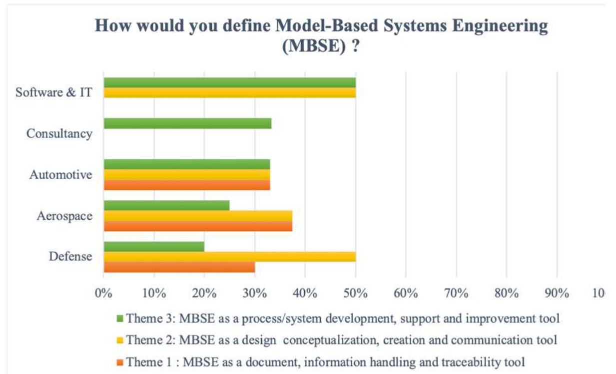

Fig. 2. Classification of MBSE definitions as reported by different industry clusters

B. Reported advantages of the use of MBSE

MBSE has several advantages [6]. In an extensive study of MBSE, Murray [10] listed improved communication, enhanced system management, and improved product quality as some of the MBSE advantages. Mazeika and Butleris [11] named increased system engineering efficiency, improved communication, managed complexity, and reduced risk as advantages of using MBSE. Regarding different levels of MBSE effort required across various industry clusters, the goal was to identify and classify the advantages of MBSE use according to the industries that deal with systems of high, medium, and low complexity. Textual responses from open-ended questions were gathered and analyzed. The reported advantages were classified into four themes based on the frequently occurring keywords from the responses:

1. Improved system communication, understanding, and productivity,
2. Ease and speed of work,

3. Enhanced documentation, record keeping, and traceability, and
4. Improved quality Analysis using verification and validation (V&V) and reduced number of defects.

The most often recurring keywords based on which the themes were classified are identified in Table V.

TABLE V. KEYWORDS GATHERED FROM THE MBSE ADVANTAGES REPORTED IN THE SURVEY

Themes	MBSE advantages - keywords
Theme 1	System, Understanding, Communication, Visual, Interactions, Analysis, Envision, Language, Pictures, Better, Modeling, Productivity, Diagram, Perspective
Theme 2	Easier, Better, Early, Increased, Agility, Faster, Speed, Flexibility, Cycle, Time
Theme 3	Record, Database, Information, Documentation, Repository, Traceability, Notation, Linkage, Centralized, Concise, Formalization, Linked, Source
Theme 4	Verification, Quality, Requirements, Assessment, Architecture, Analysis, Performance, Validation, Correcting, Defects, Impact, Function, Integration, Increase, Detect

Survey responses from Defense and Aerospace sectors dominantly represent all the four themes identified, with most respondents echoing themes 1 and 4. It is interesting to note that none of the other survey respondents reported the advantages of MBSE use reflecting all four themes. Considering the responses from the automotive industry cluster, 50 % reflects theme 3 that classified the advantages of MBSE use being enhanced documentation, records keeping, and traceability, and the remaining 50% echoing theme 4 with improved product quality and reduced defects.

The answers from the respondents who identified themselves with organizations that provide solutions to clients changing business i.e., Consultants, reflected only theme 4 that classified the advantages of MBSE use being improved product quality and reduced defects. The personnel belonging to software and IT industry clusters indicated that MBSE facilitates ease and speed of work (theme 2). Figure 3 illustrates the percentage representation of how the survey responses were classified across the themes identified and the respective industry clusters.

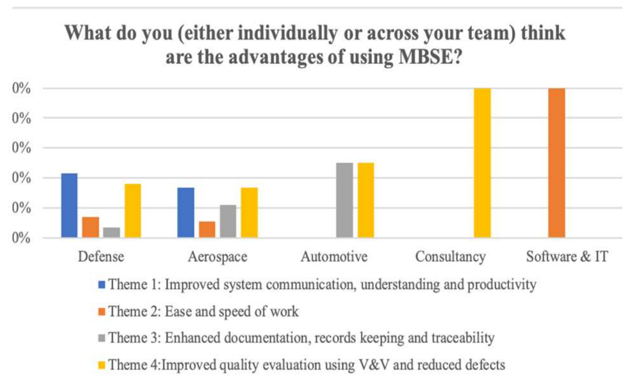

Fig. 3. Classification of advantages of MBSE use as reported by different industry clusters

The observed themes reporting the perceived benefits of MBSE use by the survey respondents indicate that the Aerospace and Defense industry clusters experience advantages at several fronts across the systems engineering lifecycle phases. These industries require high effort levels to implement MBSE and have both high system and environmental complexity. Yet, high-tech industries that require medium to low effort levels to implement MBSE indicated limited benefits on the use of MBSE.

C. *Exploring MBSE use in various types of projects and lifecycle stages*

In this section, the researchers aim to understand the impact and extent to which MBSE is used, and the type of projects MBSE is used for across industry clusters that deal with systems with both high and low levels of complexity. Based on the survey responses retrieved, MBSE is mostly used for system integration projects across industry clusters.

Although the use of MBSE for projects that deal with Systems integration is reported at least once by the participants from the industry clusters under analysis, it is not the most mentioned project type that utilizes MBSE. Projects that deal with Systems Architecture Development (SAD), represented by a 20% majority of overall responses across all industry clusters, are the most dominant that utilize MBSE, even though the use of MBSE is not reported for projects involving SAD in the Software and IT industry clusters.

Respondents from Defense and Aerospace industry clusters report the use of MBSE for all project types listed in Figure 4. However, the respondents from software and IT industry clusters did not report the use of MBSE for research and development, system of systems management (SSM), and systems architecture development projects. Moreover, consultancy-based industries indicated the use of MBSE for SAD, systems integration, systems simulation, and research and development projects.

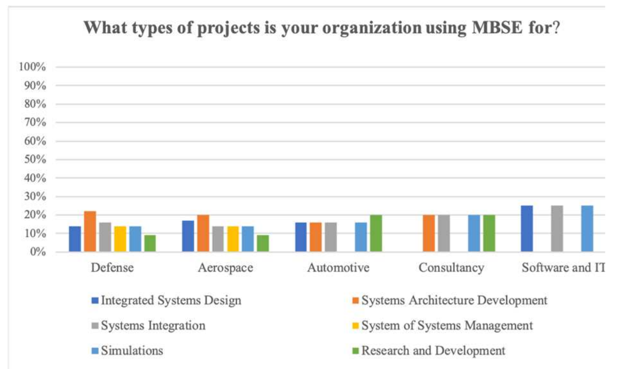

Fig. 4. Reported use of MBSE for different project types across industry clusters

Recurring use of MBSE for system architectural development (SAD) projects followed by systems of systems management (SOS) projects is vastly observed in the defense and aerospace industries. The observed use of MBSE limited to systems integration, systems architecture development, and systems simulation type of projects possibly reflects the scope of involvement and the type of systems the consultancy, software, and IT industries are involved with.

Figure 5 shows the responses identifying the specific lifecycle phases in which MBSE is used. Several commonalities are observed among all the industry clusters. Lu et., al [12] investigated the extent of MBSE use at the various phases of projects and found nearly all Chinese aviation and defense industry respondents use MBSE in all project phases with the top three phases being System architecture and system design, requirement management, and verification and validation.

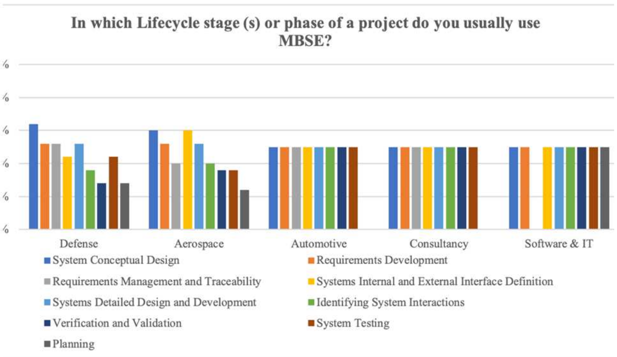

Fig. 5. Reported use of MBSE in specific project life cycle phases across industry clusters

An interesting observation for this survey data is that none of the respondents who associated with the Software and IT industry classification reported the use of MBSE for requirements management and traceability activities.

The extent of use of MBSE within project lifecycles stages among the industry clusters identified from the survey, not limited to aviation and defense, is investigated. Project lifecycle stages that use MBSE were analyzed to unearth the stages that benefit the most from MBSE use among industries.

Respondents from the defense and aerospace industry echoed that almost all the different project stages are usually benefited using MBSE, with systems conceptual design, requirements development, and requirements management and traceability stages being the ones most reported as shown in Figure 6. Respondents from the Automotive cluster report MBSE to be most beneficial in the initial systems engineering life cycles phases such as in requirements development, requirements management, traceability, system interactions, and V& V processes.

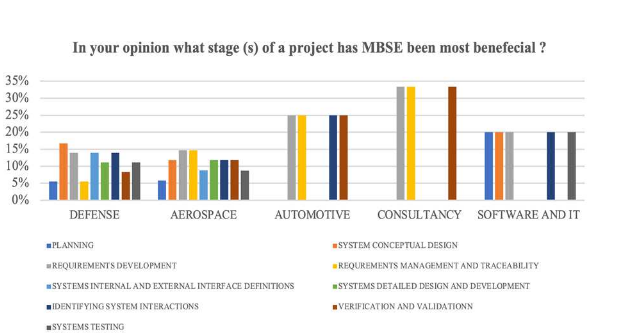

Fig. 6. Reported beneficial stages of project with MBSE

A similar trend is observed with respondents from consultancy cluster reporting MBSE to be most beneficial in both requirements development and management phases, and V&V activities of a project. Software and IT industry respondents reported that benefits with the use of MBSE include project planning, conceptual design, requirements development, systems interactions, and system testing phases.

Contrasting Figures 5 and 6, none of the respondents from software and IT industries responded to the use of MBSE for requirements management and traceability (see Figure 5), 20 % of them identified that the use of MBSE was more beneficial for the requirements development phase.

D. Impact of MBSE on organizational output and success

The perceptions on the impact of MBSE in the identified industry clusters output and success were identified. Using the textual responses of the participants, three themes were identified and classified:

1. Reduced risk, rework/defects, and cost,
2. Improved system quality, design, performance, and productivity, and
3. Customer satisfaction adds a better understanding of systems engineering principles.

Table VI lists the most often recurring keywords based on which the themes were classified.

TABLE VI. KEYWORDS IDENTIFYING THEMES FROM THE IMPACT MBSE HAD ON ORGANIZATIONS

Themes	MBSE impact on the organization - Keywords
Theme 1	Cost, Reduction, Risk, Defects, Detect, Labor, Errors, Correcting, Decreasing
Theme 2	System, Improved, Productivity, Design, Integration, Quality, Performance, Helped
Theme 3	Increased, Customer, Satisfaction, Requirements, Understanding, Systems, Engineering, Development

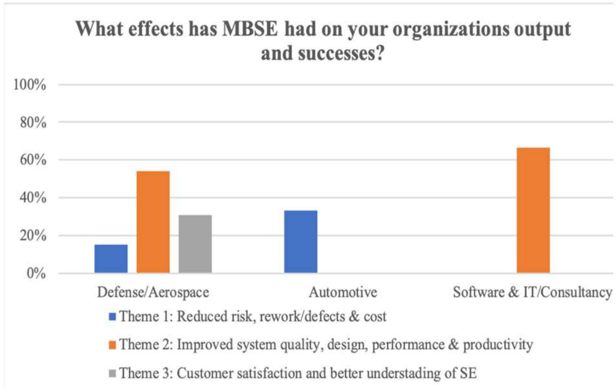

Fig. 7. MBSE effects on organizational output and success

The majority of respondents from the Defense and Aerospace cluster reported improved system design, quality, and performance as the positive effect MBSE has had on their respective organizational output, followed by the themes addressing increased customer satisfaction, and reduced both risk and rework. All the respondents from automotive industry clusters echoed only to Theme 1 addressing reduced risk, rework, and cost. Similarly, all the responses of the respondents from consultancy, software, and IT industry clusters reflected only Theme 2 addressing improved productivity, system quality, design, and performance. Figure 7 shows the survey responses and the distribution across industry clusters.

E. MBSE Adoption Challenges

System engineers have found MBSE to be a viable solution focused on the application of best practices to systems engineering (SE) activities throughout the product lifecycle. Addressing MBSE adoption challenges has been a topic of wide interest across several industries and research communities. The complexity of implementing MBSE practices poses the threat of jeopardizing its implementation in an organization. The goal here was to identify and categorize the adoption challenges as perceived by the industry professionals across various industry clusters characterized based on varying levels of system and environmental complexity.

Survey participants answered what challenges or obstacles their teams or they have come across for adopting MBSE in their projects. Four themes have been identified based on analyzing their textual responses. These include the survey responses classified based on:

1. Tools based,
2. Knowledge-based,
3. Cultural, Political and Cost related, and
4. Customer understanding and acceptance of MBSE practices.

Table VII lists the most often recurring keywords based on which the themes were classified.

TABLE VII. KEYWORDS IDENTIFYING THEMES OF MBSE ADOPTION CHALLENGES

Themes	MBSE adoption challenges - Keywords
Theme 1	Learning, Tools, Projects, Architecture, Approaches
Theme 2	Concepts, Diagrams, Knowledge, Learn, Accurate, Application
Theme 3	Adopting, Conflicts, Cultural, Convincing, Coworkers, Traditional, Revenue, Management
Theme 4	Customer, Language, Understanding

The majority of the respondents from Defense and Aerospace industry clusters identify tools-based obstacles in their organizations such as limited tool infrastructure in terms of the lack of architectural scalability in large projects, required learning of the tools to be used, lack of consistent toolset selection across teams in an organization, and limited tool capability to deal with the breath of models when dealing with complex systems.

Interestingly, one of the significant challenges echoed upon addressing this theme is the non-renewal of tool licenses every few years in an organization without any model transition guidelines provided for using a new tool. Figure 8

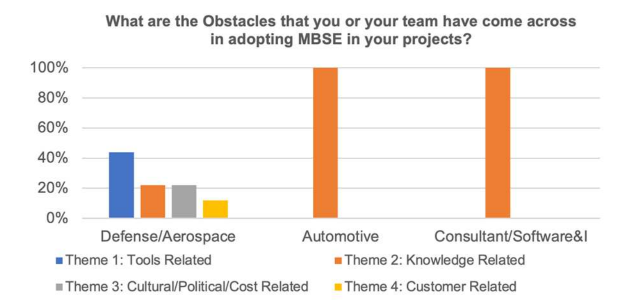

Fig. 8. MBSE adoption challenges in industries

illustrates the spread of the industry clusters and their reported MBSE adoption obstacles characterized into themes.

Theme 1 was followed by lack of MBSE knowledge in the new workforce, limited personnel with MBSE knowledge, cultural learning curves, lack of support from management for implementing MBSE, justifying the cost of MBSE implementation, and lack of compromise on the stakeholder's end for MBSE deliverables in the defense and aerospace industry clusters. This observation corroborates with [7], where Defense/Aerospace industry clusters require a higher level of MBSE implementation efforts. The responses from automotive, consultancy, software, and IT industry clusters when analyzed, echoed only to the theme addressing lack of MBSE knowledge, more specifically the difficulty in learning UML/SysML by non-object-oriented programmers.

IV. CONCLUSION

Considering the varying levels of effort required to implement Model-Based Systems Engineering in organizations classified based on varying levels of complexity, this paper aims to understand the varying perceptions of the use and advantages of MBSE across different industry clusters. Textual responses from a survey of professionals in several industry clusters were gathered and each response was categorized into themes for identifying overlaps in perceptions and use across the respondent industry clusters.

Exploring the definitions of MBSE provided in the survey, MBSE is perceived by respondents as an information handling tool, design conceptualization, communication, and system improvement – across the whole life cycle, whereas software and IT industries perceive MBSE strictly as process support and improvement tool. Further, researchers explored what the survey respondents perceive the advantages of using MBSE are. Respondents for aerospace and defense industry clusters identified experiencing the benefits of using MBSE at several fronts across the systems engineering lifecycle phases in contrast to other clusters that report the advantages limited to improved documentation and traceability.

Analyzing the survey responses for identifying the impact of MBSE on an organization's output and success across industry clusters, a concern on the lack of measurement and analysis tools to measure the impact of MBSE was identified. Nonetheless, it was noted MBSE has helped with increased reuse, improved customer satisfaction, cycle time reduction, and an increased number of solutions options analyzed in a project. Moreover, the responses related to the adoption challenges when characterized into themes, it is observed that defense and aerospace industry clusters echo all the four themes identified i.e., tools-based, knowledge-based, cultural and cost-related, and customer understanding and acceptance of MBSE practices. Whereas, automotive, consultant, software, and IT industries all reflect only the challenges of lack of both MBSE knowledge and the difficulty of non-object-oriented programmers in learning UML/SysML.

This work provides an insight on how the current perceptions on MBSE are related to its use, perceived advantages, and adoption challenges across aerospace, defense, automotive, software, and IT industries and further attempts to identify the commonalities and differences across the aforementioned industry clusters. This analysis could further act as a leeway in identifying strategies for addressing MBSE related challenges tailored to a specific industry type. It is to be noted that the analysis, results, and conclusions drawn upon in this paper are strictly based on the survey responses received and there is a scope for the change in the themes and observed industry response classification with an increase in respondent sample size.

ACKNOWLEDGMENT

This work was supported by the National Science Foundation under grant 1952634. The authors wish to express sincere gratitude for their financial support.

Disclaimer: "Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation."

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