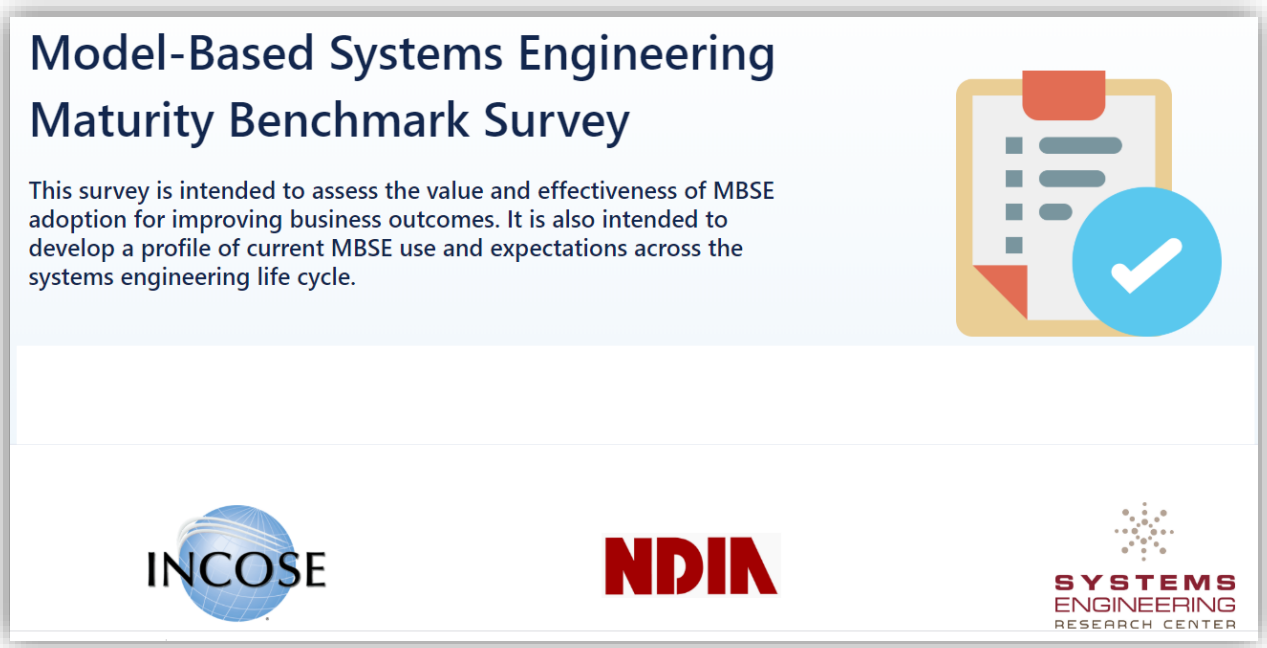
SYSTEMS ENGINEERING RESEARCH CENTER

Benchmarking the Benefits and Current Maturity of Model-Based Systems Engineering across the Enterprise

Results of the MBSE Maturity Survey
Part 1: Executive Summary

March 19, 2020

Technical Report SERC-2020-SR-001



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Part I: Executive Summary

This executive summary provides major survey findings in a summary form with references to more detailed analyses.

In 2019-2020, the National Defense Industrial Association Systems Engineering Division (NDIA-SED) and the International Council on Systems Engineering (INCOSE) collaborated with the Systems Engineering Research Center (SERC) at the Stevens Institute of Technology to benchmark the current state of Digital Engineering (DE) and Model-Based Systems Engineering (MBSE) across government, industry, and academia. The team developed and executed a survey of the systems engineering community to broadly assess the maturity of system engineering's "digital transformation", identify specific benefits of MBSE and associated metrics, identify enablers and obstacles to DE and MBSE adoption across the enterprise, and understand evolving and necessary shifts in the systems engineering (SE) workforce.

MBSE has been a popular topic in the SE community for over a decade, but the level of movement toward implementation has not always been clear. Differences in terminology and approaches sometimes make understanding the true state of MBSE or DE difficult. To address these issues and improve current insight to the community, as well as to enable understanding of changes related to DE/MBSE, the survey was developed around four sets of questions:

1. Where are we as organizations and as an industry in our progress to DE/MBSE capabilities, building and using models, and applying what we have learned?
2. Can we assess the value and effectiveness of DE/MBSE adoption for improving business outcomes? What are the benefits of DE/MBSE versus traditional SE methods? Can we infer profiles of DE/MBSE use and related outcomes across system lifecycles?
3. What are the obstacles, enablers, and needed changes to guide successful adoption of DE/MBSE? Can we help adopters to conduct a qualitative or quantitative assessment of their progress against MBSE best practices and provide guidance on developing an improvement roadmap?
4. What old and new roles and skills are being created, modified, or amplified in the adoption of DE/MBSE?

The survey was designed using the INCOSE Model-Based Enterprise Capability Matrix (now published as an INCOSE product and referred to simply as the "Capability Matrix" in this report).[1] The Capability Matrix was developed to help organizations that have already made the decision to implement DE/MBSE capabilities assess and grow these capabilities in a comprehensive and coherent manner. The matrix was developed by a team of individuals across various government and industry organizations and was socialized at five systems engineering community events in 2018 and 2019. The Capability Matrix is comprised of 42 individual capabilities across 8 areas with 5 different stages of maturity defined for each capability. This survey consisted of 23 rated questions linked to the 42 capabilities in the Capability Matrix, another 12 free-text questions, as well as a set of demographic questions. The 23 rated questions were scored by participants using a 4-point Likert agreement scale. The survey was fully anonymous, as no personal information from respondents was collected. A full list of survey questions and relevant Capability Matrix descriptions are included in section 2 of this report. A total of 240 respondents participated in the survey between 18 November 2019 and 31 January 2020. A summarization of the survey questions in Figure E-1.

[1] INCOSE Model-Based Enterprise Capability Matrix and User's Guide, Version 1.0, January 2020.

Topics	Summary of Survey Questions
1. MBSE Usage	1. MBSE strategy is integrated with product strategy at the enterprise level 2. MBSE processes & tools are integrated with product-level processes and tools *3. Most important reasons for integrating MBSE*
2. Model Management	4. Have a taxonomy for modeling across organization 5. Have defined processes/tools for model management 6. Have standard guidance for model management/tools *7. Identify business value from consistent model management*
3. Technical Management	8. Use modeling as the basis for technical processes 9. MBSE process supports our technical review process *10. Identify benefits or challenges of MBSE in technical reviews*
4. Metrics	11. Modeling provides measurable improvement across projects 12. Have consistent metrics across programs/enterprise *13. Identify any metrics that have proven useful*
5. Model Quality	14. Have defined processes/tools for V&V of models 15. Have defined processes/tools for data/model quality assurance
6. Data Management	16. Have effective approaches for managing the data interface between tools 17. Data is managed independent of tools for portability *18. Identify new data management roles/processes*
7. Model Sharing and Reuse	19. Support model libraries for reuse 20. Have interfaces around models for stakeholder use 21. Shared models are used to consistently manage programs across lifecycle *22. Identify practices for data/model discovery, reuse?*
8. Modeling Environments	23. Our modeling environment is secure 24. Our modeling environment protects IP 25. Have defined processes for tools, data interoperability *26. Identify benefits from collaborating on models across disciplines*
9. Organizational Implementation	*27. Identify most challenging org obstacles for MBSE* *28. Identify best organizational enablers for MBSE* *29. Identify biggest changes our org needs for MBSE*
10. Workforce	30. Have defined critical roles to support MBSE *31. Identify top MBSE roles in your organization* 32. Have sufficient staffing to fill MBSE-related roles
11. MBSE Skills	33. Have defined critical skills for MBSE *34. Identify the most critical skills for MBSE*
12. Demographics	Organizational size, domain, MBSE experience, role

**Questions in italics elicit free text responses*

Figure E-1. Summary of the survey questions.

The full report contains two major types of analyses: quantitative analysis of the scored questions and qualitative analysis of the responses to free-text questions. Section 3 of the full report provides the detailed analysis of all survey data and is divided into six subsections:

- **3.1 Survey Period and Responses** provides an overview of the survey.
- **3.2 Survey Demographic Information** provides a breakdown of the survey sample according to the reported demographic information.
- **3.3 Maturity Analysis, Participant Reported Ratings** provides the quantitative analysis of the Likert-scale responses to rated questions, including breakdown by demographics.
- **3.4 Analysis of Text Responses, MBSE Benefits and Metrics** provides a qualitative analysis of responses to free-text questions using a framework centered on value, benefits, and metrics.
- **3.5 Analysis of Text Responses, Enterprise Adoption** provides a qualitative analysis of responses to free-text questions using a framework centered on organizational performance excellence.
- **3.6 Analysis of Text Responses, Workforce Development** provides a qualitative analysis of responses to free-text questions using a framework centered on roles, skills, and associated processes.

The following executive summary represents key findings of the survey, with references to full report sections.

Survey Demographic Information

Section 3.2 presents the full survey demographic information.[2] Basic demographic information was collected from survey participants, to include organization type, size, and experience implementing DE/MBSE (in years), market segments of the participants (if reported), and the organizational role of

[2] Though 240 individuals started the survey, not all individuals completed the survey. The demographic information reflects the individuals who completed at least 70% of the survey questions.

participants. Survey participants included 109 from industry, 48 from government, and 11 from academia. With respect to organization size, 39 participants reported less than 500 employees, 21 reported 501-2,000, 48 reported 2001-10,000, and 62 reported greater than 10,000. For experience in using MBSE, 17 participants reported less than 1 year, 48 reported 1-3 years, 35 reported 4-6 years, and 63 reported greater than 6 years. Figure E-2 shows the demographic results by type, size and experience. Figure E-3 shows the survey respondents reported market areas and roles for those who provided this information.

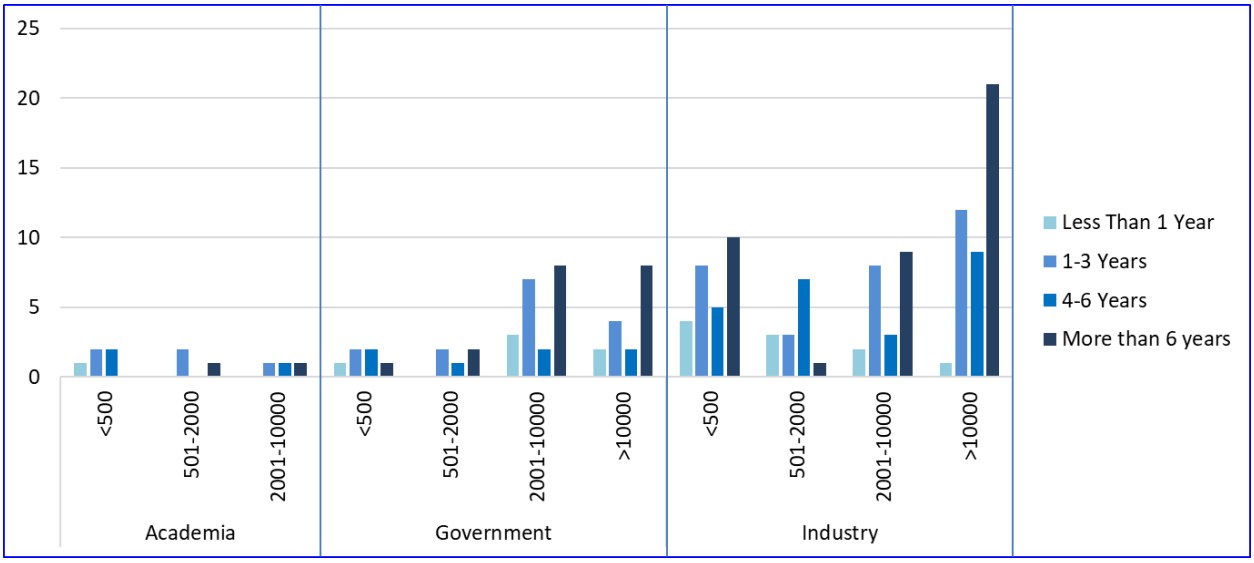

Figure E-2. Respondent's reported organizational type, size, and years' experience.

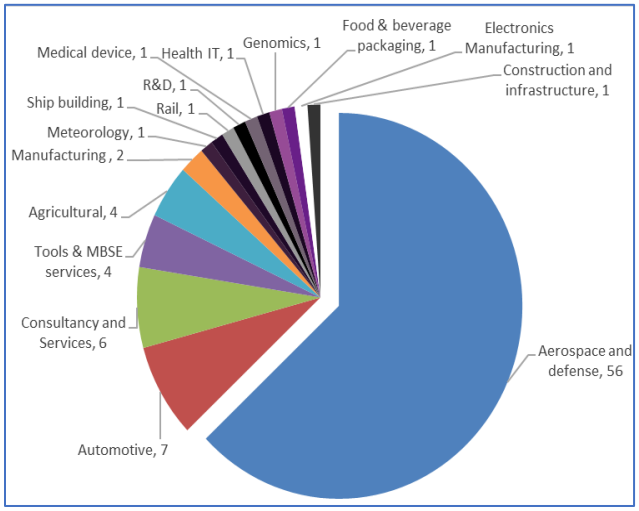

Figure E-3. Reported Market Areas for Industry Respondents.

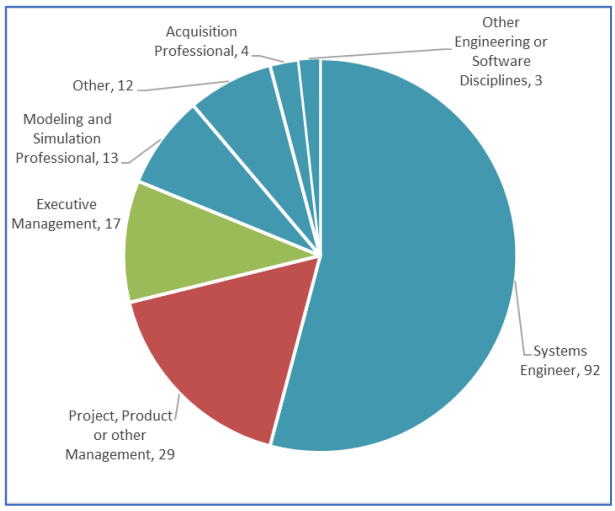

Figure E-4. Reported Respondent Organizational Roles.

The use of DE/MBSE continues to be dominated by the aerospace and defense community, but the survey responses also represented other industries. Reported participant roles included Executive Management (17 respondents), Project/Project/other Management (29 respondents), and Systems Engineering/Other related disciplines (124 respondents). Section 3.3 analyzes the demographic trends in

survey response data. Responses did vary by role – respondents identifying their role as Executive Management agree or strongly agree with 18 of the 23 Capability statements, while Program/Project/Other Management agree with 7 of the 23, and other System Engineering-related roles only agree with 5 of the 23 (this is discussed further in section 3.3 of the full report). There is a disagreement between Executive Management and other respondents on the relative maturity of their capabilities, which can be related to findings in the MBSE benefits and enterprise adoption analyses in sections 3.4 and 3.5.

Maturity Analysis, Participant Reported Ratings

Section 3.3 of the full report presents the quantitative analysis of responses to scored questions rated on a Likert-type agreement scale (strongly agree, agree, disagree, or strongly disagree). Participants were not given an option for a neutral response, forcing them to choose agreement or disagreement to some degree. The graph below summarizes a weighted scoring for each scored question. The positive (green) scores represent aggregate results in agreement with the Capability statement, while the negative (red) scores indicate disagreement. The responses to each statement are analyzed in detail in section 3.3.

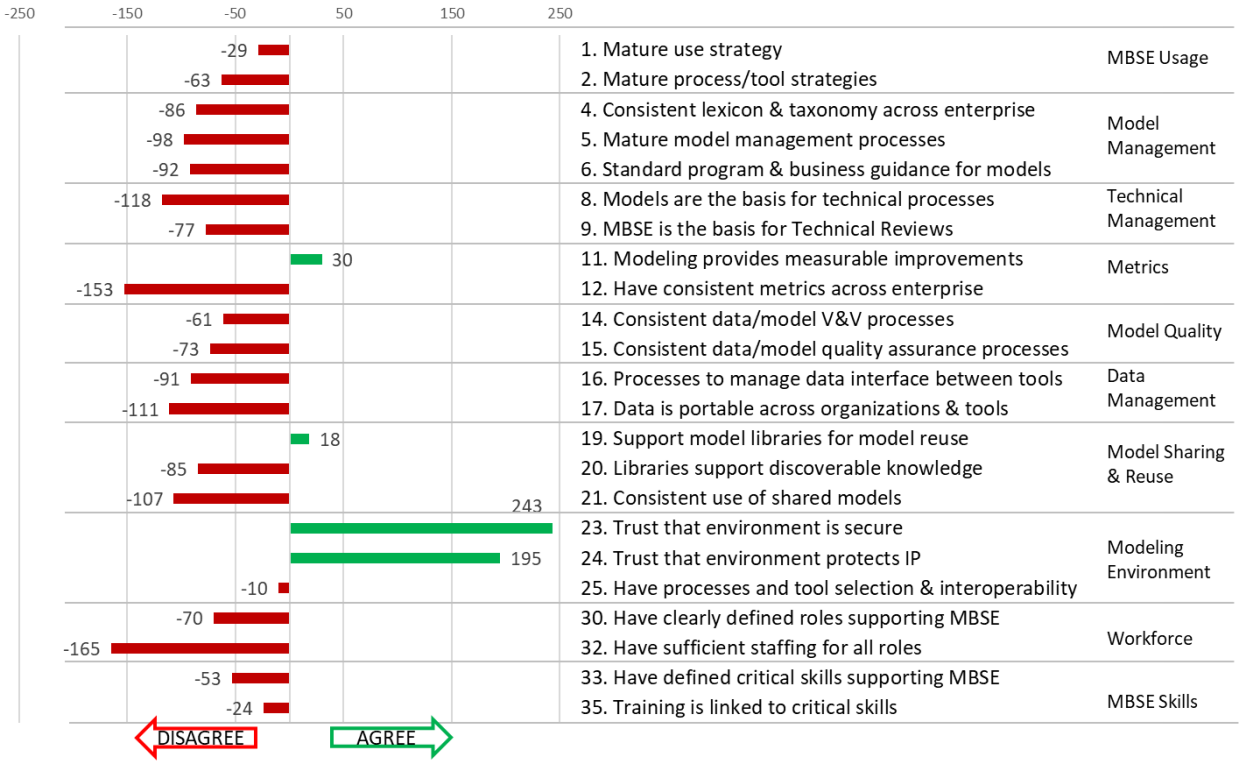

Figure E-5. Overall Capability Maturity Scorecard by Question.

As can be seen in Figure E-5, responses associated with maturity of their capabilities mostly disagreed with the statements, with a few exceptions. In most questions, government lagged industry and academia in their agreement scores. Also, organization size and years of experience had varying effect on the responses, as scores did not always improve with size of organization or years of experience with MBSE. In fact, there is evidence in the survey results from many of the question categories that smaller organizations are finding adoption to be easier than larger organizations, indicating cultural challenges

are at play. For a complete analysis see the detailed analyses of each question in section 3.3 of the full report. In the section "Analysis of Free-text Responses, Enterprise Adoption" free-text questions are used to infer enterprise enablers and obstacles to DE/MBSE adoption. This section provides additional insight on the likely reasons for organizational size and experience variations (refer to section 3.5 of the full report).

MBSE Usage, Model Management, and Technical Management relate to the enterprise-wide use of DE/MBSE methods, processes, and tools. Enterprise strategies for MBSE Usage are leading actual Model Management practices and associated Technical Management practices in capability maturity scores as might be expected. Overall, there was moderate disagreement from respondents that these capabilities are mature. There was agreement that the capabilities increase with years of experience. However, the survey results for each of these three areas indicate that smaller organizations have stronger agreement than larger organizations (see the detailed analyses of each question in section 3.3 of the full report). It is possible that smaller organizations are finding adoption to be easier than larger organizations, indicating leadership and cultural challenges are at play.

In the Technical Management area, additional concerns related to organization adoption were provided in the free-text question: "*Please identify any benefits or challenges your organization has found in the use of MBSE (or 'digital engineering') in the technical review process*." Section 3.4.6 of the full report discusses these findings in more detail. Figure E-6 provides a preview of the full analysis of benefits and adoption metrics in section 3.4 and 3.5, focused just on survey responses related to the technical review process. As can be seen in the figure, obstacles to adoption lead enablers to benefits by a large margin in survey responses. Also different factors can be both enablers and obstacles to DE/MBSE transformation.

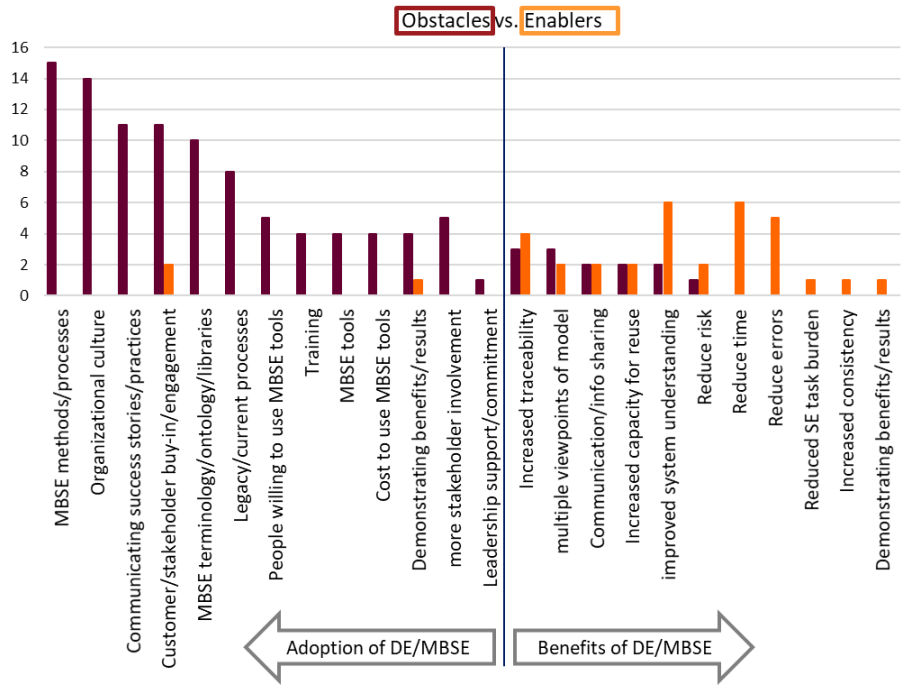

Figure E-6. Comparing Obstacles and Enablers in the Technical Review Process.

The Metrics category returned a dichotomy of scores from respondents. For detailed analysis refer to sections 3.3.4 and 3.4.4 of the full report. Respondents moderately agree that modeling provides measurable improvements, but looking more broadly across the DE enterprise, they strongly disagree that they have mature measurement capabilities. DE/MBSE benefits at this point are more perceived than measured. Organizations appear to be searching for guidance on measuring the value and benefits of DE/MBSE usage. In the section "Analysis of Free-text Responses, MBSE Benefits and Metrics" free-text questions are used to analyze top reported metrics.

Generally, agreement scores increased (i.e., higher levels of agreement) with years of experience. Most responses to the Likert scale questions showed a general increase in agree or strongly agree scores with increasing years of experience. Exception were the "Metrics" category (discussed in section 3.3.4), the "Data Management" category (discussed in section 3.3.6), the "Model Sharing and Reuse" category (discussed in section 3.3.7), and the "Workforce" category (discussed in section 3.3.10). These areas did not show much of an in agreement scores with years of experience. This may indicate there are some areas where the community is still not making much progress in maturing their capabilities. Analysis of free-text responses provides additional insight on the likely reasons for this (discussed in sections 3.4-3.6).

The Model Quality, Data Management, and Model Sharing and Reuse categories relate to enterprise management of data and models. Across these areas, respondents generally agree that they have enterprise capabilities for maintaining model libraries and achieving model reuse (a key value of DE/MBSE), but disagree or strongly disagree that other enterprise capabilities for managing, using, and validating data and models are mature. Most of these issues also appear to be related to workforce, culture, and change management concerns, which are further discussed in the enterprise adoption analysis in section 3.5 of the full report. In fact, responses from smaller organizations reflect more agreement than larger organizations on mature capabilities across these areas, likely because they are able to realize the necessary cultural changes more quickly.

The maturity of capabilities related to Modeling Environment was the only category to see broad agreement across the survey respondents, indicating that basic tools and processes are reaching a more mature state.

In the Workforce and Skills categories, responses reflected weak disagreement on effectiveness of training, moderate disagreement on maturity of organizational roles and skills, and strong disagreement with respect to availability of staffing. Roles, skills, and training are analyzed in section 3.6 of the full report.

Analysis of Text Responses, MBSE Benefits and Metrics

Section 3.4 of the full report provides a detailed analysis of free-text responses based on MBSE benefits and metrics. Per agreement with the survey sponsors, a separate SERC research project using literature review supported development of a framework for defining and categorizing metrics, which was used to analyze the survey results. This research identified 48 categories of benefits across 4 broad digital enterprise transformation categories. The survey results correlated closely to the literature review; survey participants cited 45 of the 48 benefit categories identified from literature review. This framework is shown in Table E-1.

Table E-1. List of DE/MBSE benefit categories from the literature review.

Category	List of Benefits		
Quality	Reduce errors/ defects	Improved risk analysis	Improved capability
	Improved traceability	Improved system design	More stakeholder involvement
	Improved system quality	Better requirements generation	Strengthened testing
	Reduce risk	Increased accuracy of estimates	Reduce cost
	Increased rigor	Improved predictive ability	Better analysis capability
	Increased effectiveness	Improved deliverable quality	
Velocity/ Agility	Improved consistency	Increased productivity	Higher level support for integration
	Increased capacity for reuse	Increased transparency	Increased uniformity
	Increased efficiency	Increased confidence	Increased precision
	Reduce rework	Increased flexibility	Early V&V
	Reduce time	Better requirements management	Reduce ambiguity
	Reduce waste	Ease of design customization	Easy to make changes
User Experience	Higher level support for automation	Improved system understanding	Reduce effort
	Reduce burden of SE tasks	Better data management/capture	
	Better manage complexity	Better decision making	
Knowledge Transfer	Better accessibility of info	Improved architecture	Improved collaboration
	Better knowledge management/ capture	Better communication/ info sharing	Multiple viewpoints of model

The three survey questions related to benefits are:

*Q3. What do you see as the most important **reasons** for **integrating** MBSE processes with program and business management processes*,

*Q7. Please provide one or more descriptions of the **business value** you are realizing from **consistent model management** processes and tools*, and

*Q26. Please identify any additional **benefits** you find from **collaborating** on models across disciplines*.

The three survey questions are categorized as relating to integration benefits, model management benefits, and collaboration benefits, as shown in Table E-2. The top 8 benefit categories based on frequency of citation in the free-text questions associated with benefits are shown below. Although the top 8 responses were consistent, they varied by type of benefit.

Table E-2. Top 8 stated benefits of DE/MBSE by question.

Q3 *Reason for Integrating MBSE*	**Q7 *Value from Consistent Model Management***	**Q26 *Benefit from Collaboration***
Reduce cost (17)	Increased capacity for reuse (18)	Better communication/ information sharing (13)
Reduce time (17)	Improved consistency (16)	Improved system understanding (10)
Better accessibility of info (16)	Improved system understanding (9)	Better accessibility of info (6)
Increased efficiency (14)	Reduce time (9)	Improved consistency (5)
Improved consistency (13)	Better communication/ information sharing (7)	Reduce errors (5)
Increased traceability (11)	Better accessibility of info (7)	Reduce time (5)
Improved system understanding (10)	Reduce cost (7)	Increased capacity for reuse (5)

An additional free-text question related to metrics was included to define specific metrics respondents have found useful in their organization: *Q13. Please identify any metrics that have proven to be useful for measuring the performance of your MBSE activities.* The literature review found that most benefits described in papers were either perceived to accrue with DE/MBSE or have been observed, versus being explicitly measured through formal metrics. The survey did not ask participants about specific measurement processes. As discussed previously, organizations appear to be searching for guidance on measuring the value and benefits of DE/MBSE usage. This may be due to the lack of a good measurement framework. Section 3.4 of this report provides a suggested framework for DE/MBSE metrics linked to the 48 benefit categories. Section 3.5 provides a framework additionally to assess enterprise adoption measures. The most frequently cited metrics from the survey were coded by our benefits framework and are listed in Table E-3 in the left-hand columns, with number of citations in parentheses. For comparison the related benefits total citation numbers are included in the right-hand columns.

Table E-3. Most cited benefits and adoption categories from survey data.

Top survey response metrics (Q13 only)		**Survey response benefits (Q3, Q7, and Q26)**	
Better requirements generation	7	Better requirements generation	7
Reduce errors	7	Reduce errors	19
Increased traceability	6	Increased traceability	17
Better requirements mgt.	6	Better requirements mgt.	3
Improved system design	5	Improved system design	9
Reduce cost	5	Reduce cost	25
Reduce time	5	Reduce time	31
Increased capacity for reuse	5	Increased capacity for reuse	30
Better analysis capability	4	Better analysis capability	6
Improved system quality	2	Improved system quality	14
Increased effectiveness	2	Increased effectiveness	6
Higher level support for automation	2	Higher level support for automation	3
Higher level support for integration	2	Higher level support for integration	14

The Quality, Velocity/Agility, User Experience, and Knowledge Transfer categories relate to the analysis of benefits in section 3.4. Figure E-7 shows the full survey result with respect to benefits.

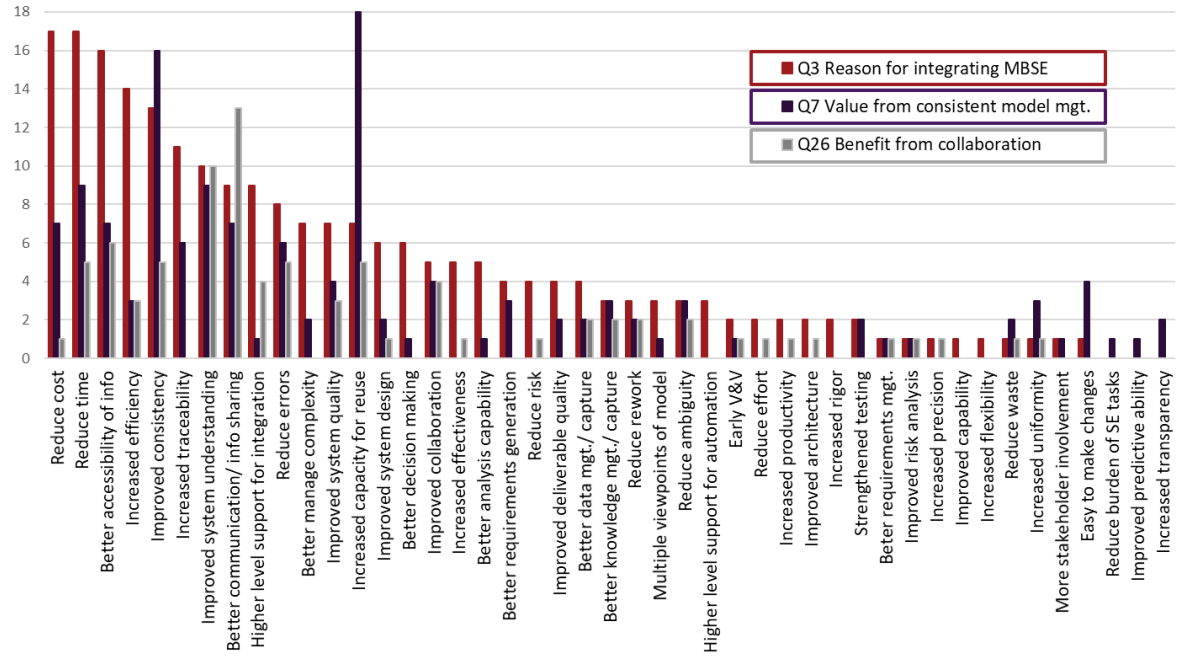

Figure E-7. Results for All Q3/Q7/Q26 Survey Questions on Benefits.

Respondents also cited numerous obstacles that have had a negative effect on successful enterprise adoption, related to the analysis of Enterprise Adoption in section 3.5. On the positive side, a number of enablers and changes to aid adoption were also cited by survey respondents.

Analysis of Text Responses, Enterprise Adoption

Section 3.5 of the full report analyzes three survey questions related to adoption:

Q27. The most challenging obstacles to implementing MBSE in our organization are:

Q28. The best enablers for MBSE in our organization are:

Q29. Going forward, the biggest changes our organization needs to make to improve our implementation of MBSE are:

Qualitative analysis of questions 27 and 28 examines MBSE adoption from the opposites of obstacles and enablers in order to identify a more robust and comprehensive list of "success factors" framed in a neutral way, i.e., regardless of whether they were experienced as an obstacle (barrier, impediment, etc.) or enabler. Analysis of question 29 explores changes needed within the organization to increase the likelihood of success. A total of 37 unique success factors were identified based on survey responses, which related to 8 categories: Leadership, Communication, Resources, Workforce, Change Processes, MBSE Processes, Organizational Environment, and External Environment. These are listed in Table E-4.

Table E-4. List of enterprise success factors from the survey analysis.

Category	List of Success Factors		
Leadership	Leadership support/commitment	Leadership understanding of MBSE	
Communication	Awareness of MBSE benefits/value	Communicating success stories/practices	Need for change
Resources	Cost to use MBSE tools	General resources for MBSE implementation	
Workforce	General MBSE awareness and knowledge	People willing to use MBSE tools	Teamwork
	MBSE learning curve	People in SE roles	Training
	Workforce knowledge/skills		
Change Processes	Champions	Competing priorities	Legacy/current processes
	Change management process design	Integration to support MBSE implementation	Vision and strategy for MBSE
	Community of practice	Demonstrating benefits/results	
MBSE Processes	MBSE methods/processes	MBSE tools	Security of data and IP
	MBSE terminology/ontology/libraries	Projects/programs to apply MBSE	
Organizational Environment	Alignment with business strategy	Organizational culture	Success metrics
	Organizational characteristics	Rewards/recognition	Supportive infrastructure
External Environment	Alignment with customer requirements	Customer/stakeholder buy-in/engagement	
	External regulations	Use in SE community	

These categories aid in examining MBSE adoption from the lens of the Baldrige Criteria for Performance Excellence (CPE)[3], which provides a comprehensive, holistic, systems view of an organization by identifying a set of management sub-systems an organization must purposefully design (or redesign) and monitor in order be high-performing[4]. Figure E-8 shows the full survey results for the most frequently-reported obstacles, enablers, and changes, with detailed analyses of each in section 3.5 of the full report.

[3] Baldrige Performance Excellence Program, 2019. 2019-2020 Baldrige Excellence Framework: Proven Leadership and Management Practices for High Performance. Gaithersburg, MD: U.S. Department of Commerce, National Institute of Standards and Technology. https://www.nist.gov/baldrige.

[4] Baldrige Performance Excellence Program, 2019. 2019-2020 Baldrige Excellence Framework: Proven Leadership and Management Practices for High Performance. Gaithersburg, MD: U.S. Department of Commerce, National Institute of Standards and Technology. https://www.nist.gov/baldrige.

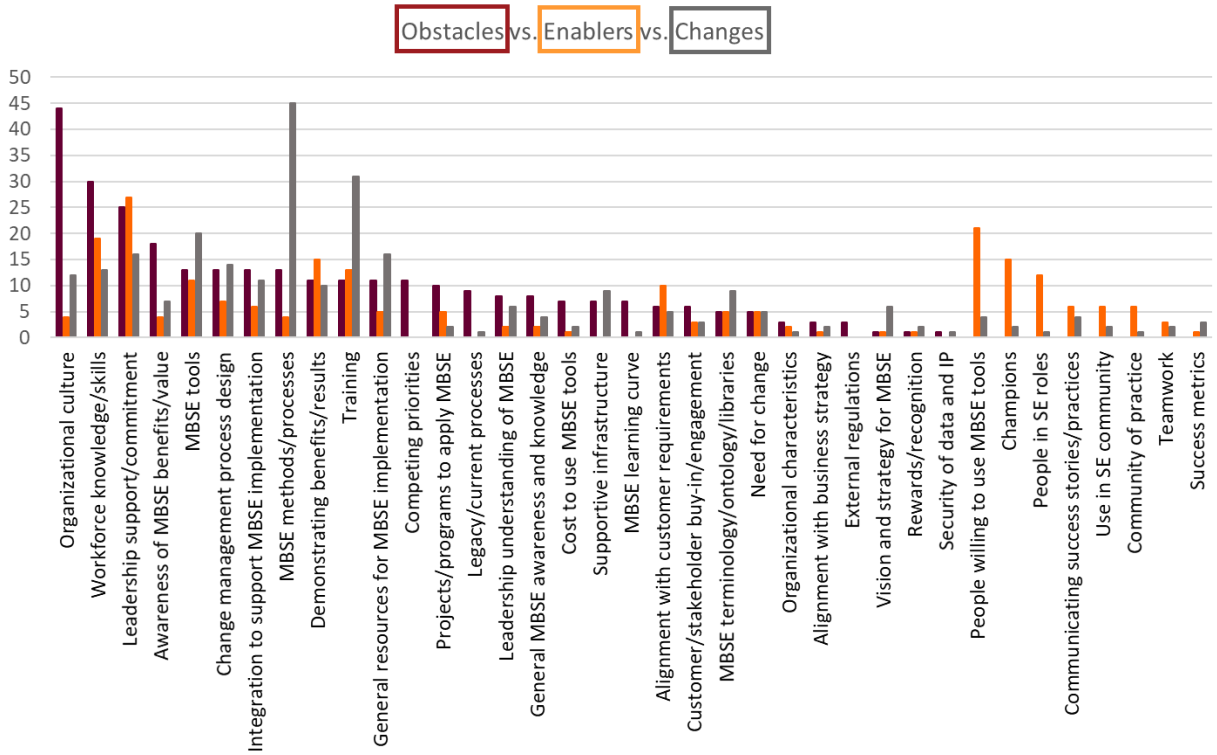

Figure E-8. Summary of Obstacles, Enablers, and Changes to DE/MBSE adoption.

The most frequently reported obstacles to MBSE adoption, as shown in the figure, were organizational culture, workforce knowledge/skills, leadership support/commitment, awareness of MBSE benefits and value, MBSE tools, and change management process design. The most frequently-reported enablers also included leadership support/commitment and workforce knowledge/skills, as well as people willing to use MBSE tools, champions, people in systems engineering roles, training, and demonstrating benefits and results. MBSE methods and processes, tools, training, resources, and leadership support and commitment were the most frequently reported changes necessary to improve MBSE implementation.

Insight from analysis of both obstacles and enablers, mapped to the Baldrige CPE, was used to define a preliminary set of adoption practices for achieving maturity in MBSE:

1. *Leaders communicate a clear reason and need for MBSE adoption*
2. *Leaders understand MBSE*
3. *Leaders support and are committed to MBSE*
4. *People understand the benefits of MBSE*
5. *MBSE is aligned with the overall business strategy*
6. *MBSE is used for the right projects/programs*
7. *MBSE adoption is aligned with what customers need/require*
8. *Customers and stakeholders buy-in to MBSE*
9. *Data management processes support MBSE*
10. *The IT infrastructure supports MBSE use*
11. *Clear metrics are defined to track results and progress of MBSE*
12. *Systems engineers have the skills needed to support MBSE use*
13. *Training is provided to develop needed skills*
14. *People are rewarded/recognized for using MBSE*
15. *The organizational culture is aligned with MBSE use*

Analysis of Text Responses, Workforce Development

Section 3.6 of the full report analyzes three survey questions related to the workforce:

Q18. Please identify any new data management roles and processes you have created.
Q31. The top MBSE role(s) in my organization are:
Q34. The most critical skills for MBSE are:

The workforce questions generally found that DE/MBSE was just an extension of existing systems engineering roles and skills. In other words, mature SE capabilities are essential to DE/MBSE success. Top DE/MBSE roles include SE, modeling, and organizational and technical leadership. Digital engineering presents newer roles related to the data science aspects of MBSE, particularly data management, data integration, and data analysis. Also, there is more emphasis on tool experts: roles focused exclusively on the use and maintenance of tools to support MBSE. Top DE related roles include data architect, data manager, model curator, and change manager.

The most critical skills for DE/MBSE favored system architecture and systems thinking, along with requirements engineering, domain knowledge, and SE process skills. Added to these were "digital skills" relating to modeling, data science, simulation, data/tools environment, and model governance.

The most commonly cited challenges were creation of DE/MBSE processes and issues with tool integration, along with staffing. The survey reinforces that the critical skills for a good systems engineer are the same as those for a good model-based systems engineer. The critical differences are the addition of the utilization of specific tools, an understanding of modeling language, and the "digital engineering" skills, which in this survey focus around the skillsets of data management and utilization and general modeling and simulation skills. These were linked in the section to the HELIX *Atlas* systems engineering proficiency model [5].

The remainder of the report provides the details of the survey method, results, and analyses. A key aspect of the survey details is the presentation of four frameworks related to DE/MBSE success:

- the INCOSE Capability Maturity Matrix which supports assessment of **enterprise-level capabilities**,
- a DE/MBSE Value/Benefits Framework developed from this survey and a literature review which defines four categories for DE metrics: **Quality, Velocity/Agility, User Experience,** and **Knowledge Transfer,**
- a DE/MBSE Adoption Framework developed from the Baldrige CPE Framework which addresses **organizational adoption** and **change management**, and
- a **workforce competency** framework linked to the HELIX *Atlas* model.

This completes the executive Summary portion of the report. The full survey methodology and analysis of survey results follows in Part 2.

[5] Hutchison et al. 2018

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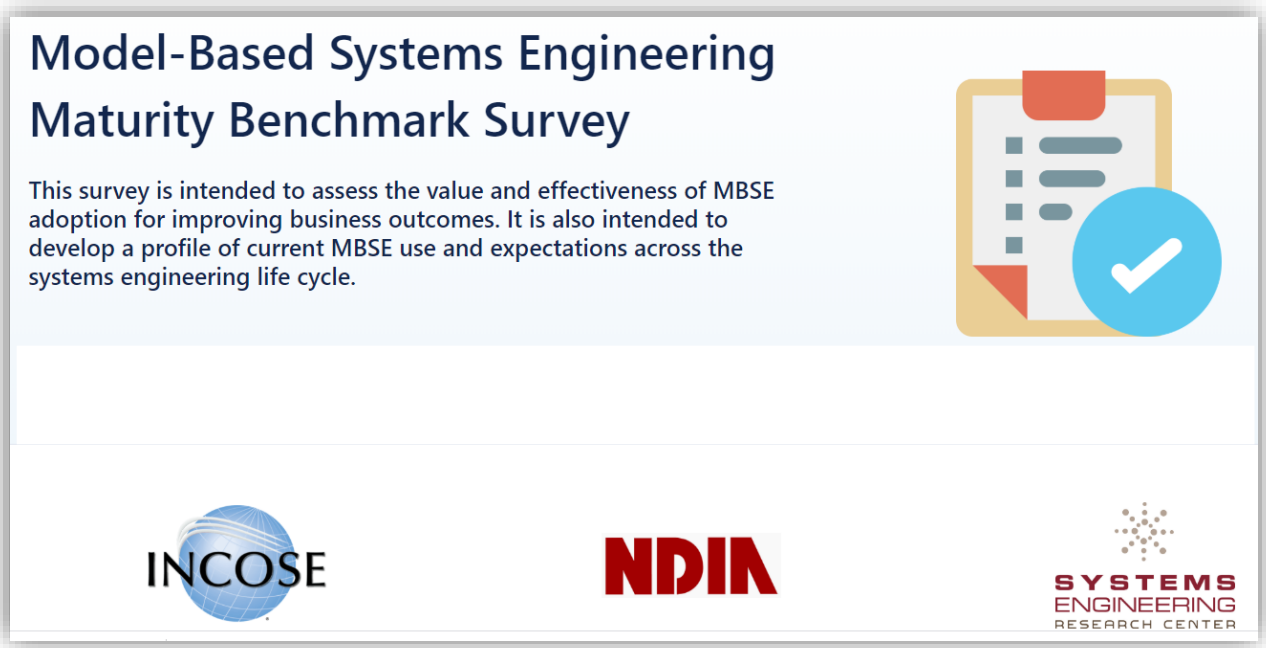

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Part II: Survey Methodology and Results

This section includes an introduction to the survey, the survey methodology, and all survey results.

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1. Introduction

Digital transformation is characterized by the integration of digital technology into all areas of a business, changing fundamental operations and how results are delivered in terms of new value to customers. It includes cultural change centered on alignment across leadership, strategy, customers, operations, and workforce evolution. Successful organizations include a strategy to measure and analyze enterprise change. This survey was conducted to broadly assess the value and effectiveness of DE and MBSE adoption for improving business outcomes. As DE is still in the early stages of adoption across industry, the survey also collected data to classify the benefits of DE versus traditional methods, as well as the enablers and obstacles to successful transformation.

DE is defined as ‘‘an integrated digital approach that uses authoritative sources of systems’ data and models as a continuum across disciplines to support lifecycle activities from concept through disposal. A DE ecosystem is an interconnected infrastructure, environment, and methodology that enables the exchange of digital artifacts from an authoritative source of truth.”[6] MBSE is a subset of DE, defined 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.”[7]

The International Council on Systems Engineering (INCOSE) and the National Defense Industrial Association Systems Engineering Division (NDIA SED) began discussing the need to examine the current baseline of DE/MBSE capabilities in organizations to understand how far implementation has come and to provide a basis for future comparison as DE/MBSE becomes a more common approach. INCOSE and NDIA SED leadership approached the Systems Engineering Research Center (SERC) regarding conducting a large-scale survey to address this need. The SERC, which was already conducting a research task around DE metrics, agreed to create the survey, conduct data collection, and analyze the results, which comprise this report.

Previously, Dr. Robert Cloutier had conducted three broad surveys around MBSE. Data for these surveys was collected in 2012, 2014, and 2018 and provided insights into the general adoption of MBSE in organizations as well as more specific questions such as the modeling languages in use, the level of formal training in MBSE implemented by organizations, and inhibitors to successful MBSE.[8,9] One key take away from the 2018 survey is the adoption of MBSE approaches outside of the defense and space domains, which had increased substantially since 2014. These surveys provided useful background and comparison for the current survey. However, INCOSE, NDIA SED, and the SERC wanted to conduct a more in-depth survey to explore more specifically the maturity of DE/MBSE efforts in organizations – the extent to which they have become integrated into the culture of doing business. That survey is reflected in this report.

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[6] Office of the Deputy Assistant Secretary of Defense (Systems Engineering) [ODASD (SE)], “DAU Glossary: Digital Engineering,” Defense Acquisition University (DAU), 2017.

[7] Systems Engineering Vision 2025 Project Team of INCOSE, “A World in Motion - Systems Engineering Vision 2025,” International Council of Systems Engineering (INCOSE), San Diego, CA, 2014.

[8] Cloutier, R. 2015. “MBSE Survey.” Hoboken, NJ: Stevens Institute of Technology. 12 August 2015.

[9] Cloutier, R. 2019. “2018 Model Based Systems Engineering Survey Conducted December 2018.” Mobile, Alabama: University of South Alabama. January 2019.

2. Developing the MBSE Maturity Survey

The survey was developed around four sets of questions:

1. Where are we as organizations and as an industry in our progress to DE and MBSE, building and using models, and applying what we have learned?
2. Can we assess the value and effectiveness of DE and MBSE adoption for improving business outcomes? What are the benefits versus traditional SE methods? Can we infer profiles of MBSE use and related outcomes across system lifecycles?
3. What old and new roles and skills are being created, modified, or amplified in the adoption of DE and MBSE?
4. What are the obstacles, enablers, and needed changes to guide successful adoption of DE and MBSE? Can we help adopters to conduct a qualitative or quantitative assessment of their progress against MBSE best practices and provide guidance on developing an improvement roadmap?

For the first question, an initial quantitative analysis was defined using the INCOSE Model-Based Enterprise Capability Matrix[10] (now published as an INCOSE product and referred to simply as the "Capability Matrix" below). These results are discussed in section 3.3. For the remaining three areas, survey questions were designed to elicit answers in the form of textual statements and phrases. These results and a description of the analysis methods are discussed in sections 3.4, 3.5, and 3.6.

The overall survey was defined using the INCOSE Capability Matrix as the guiding organizational structure. The Capability Matrix was developed to help organizations that have already made the decision to implement digital or model-based capabilities assess and grow these capabilities in a comprehensive and coherent manner. It was developed by a team of individuals across various government and industry organizations and was socialized at five systems engineering community events in 2018 and 2019. The Capability Matrix is comprised of 42 individual capabilities across 8 areas with 5 different stages of maturity (0-4) for each capability and, therefore, was too complex for a survey intended to be completed quickly by a large sample of individuals.

The survey team began by focusing on the Stage 4 (most mature) descriptions of each capability and crafting one or more statements that reflected this level of maturity, positing that "if my organization were capable, it would be doing this." Participants were asked their level of agreement with such statements as the mechanism to assess their organizations' maturity against these capabilities. For example, the first stage 4 description in the Capability Matrix: "*MBSE Use Strategy: Organization MBSE use strategy is documented as part of the organization's overall strategy at the enterprise level. The strategy is related to the overall risk strategy. Modeling is integrated with business information tools and results are used to inform systems engineers, program management, and all staff across the enterprise*"[11] became the first question in the survey: "*MBSE Usage: Our MBSE use strategy is integrated with our overall product strategy or strategies at the enterprise level."*

For each question, participants were asked to rate their agreement with each statement on a 4-point Likert-type scale (where 4=strongly agree, 3=agree, 2=disagree, and 1= strongly disagree). Participants were not given an option for a neutral response, forcing them to choose agreement or disagreement to

[10] INCOSE Model-Based Enterprise Capability Matrix and User's Guide, Version 1.0, January 2020.
[11] ibid.

some degree. Although there is some debate about this in the survey research community, many argue against using a middle point (or neutral option) on Likert-type scales such as used in this survey.

Table 1 maps the final survey to the Capability Matrix. Column 1 categorizes the Stage 4 descriptions according to the five strategic goals of the U.S. DoD Digital Engineering Strategy[12], and column 2 categorizes the Stage 4 descriptions as originally organized in the Capability Matrix. Column 3 is the verbatim description reflecting how a Stage 4, or "fully mature," organization might be characterized. Column 4 contains the derived survey questions that were developed through an iterative agreement process between the SERC researchers conducting the survey and the NDIA/INCOSE survey sponsors. In addition, the questions were organized into multiple sections, reflected by pages in the survey, to further categorize the results. These section categories were also developed as an agreement process between the SERC researchers conducting the survey and the NDIA/INCOSE survey sponsors. Note that items in blue in Table 1 are free-text questions rather than questions rated on a Likert-type agreement scale.

Table 1. Survey Question Design from the Maturity Matrix

DoD DE Strategic Goal	Model-Based Capability Name	Stage 4 Description	Survey Question
Section 1 – MBSE Usage			
Goal 1: Use of Models	MBSE Use Strategy	Organization MBSE use strategy is documented as part of the organization's overall strategy at the enterprise level. The strategy is related to the overall risk strategy. Modeling is integrated with business information tools and results are used to inform systems engineers, program management, and all staff across the enterprise to manage a full range of business concerns.	Q1: Our MBSE use strategy is integrated with our overall product strategy or strategies at the enterprise level.
Goal 1: Use of Models	MBSE Use Strategy	Organization MBSE use strategy is documented as part of the organization's overall strategy at the enterprise level. The strategy is related to the overall risk strategy. Modeling is integrated with business information tools and results are used to inform systems engineers, program management, and all staff across the enterprise to manage a full range of business concerns.	Q2: Our MBSE processes and tools are integrated with our overall product-level processes and tools.

[12] Department of Defense, Digital Engineering Strategy, June 2018.

DoD DE Strategic Goal	Model-Based Capability Name	Stage 4 Description	Survey Question
Goal 1: Use of Models	MBSE Use Strategy	Business value/benefits (free text question)	Q3: What do you see as the most important reasons for integrating MBSE processes with program and business management processes?
Section 2 – Model Management			
Goal 1: Use of Models	Common DE and MBSE Terminology	Common, tiered taxonomies are defined and consistent across enterprises and consistent with accepted community standards.	Q4: As part of our MBSE process, we have a clear taxonomy that we use consistently for modeling across our organization.
Goal 1: Use of Models	Model Management	Model management is applied to all models for an enterprise.	Q5: Our organization has well-defined processes and tools for managing models across a program lifecycle.
Goal 1: Use of Models	SE Agreement Process	Consistent model business case driven planning guidance is in place and is being practiced across an enterprise.	Q6: Our organization has standard business and program guidance that defines our model management processes and tools.
Goal 1: Use of Models	Model Management	Business value/benefits (free text question)	Q7: Please provide one or more descriptions of the business value you are realizing from consistent model management processes and tools.
Section 3 – Technical Management			
Goal 1: Use of Models	SE Technical Management Processes	Modeling is the basis for the processes and is used to optimize results across the enterprise.	Q8: Our organization uses modeling as the basis for our technical processes consistently across the enterprise.
Goal 1: Use of Models	Model Based Reviews and Audits	Enterprise organizations coordinate on common review criteria application, tailoring, and the use of specific digital artifacts to meet specific criteria. Models record the acceptance of criteria items. Rolling, frequent review of model contents, of identified "Knowledge Points" allow stakeholders to accept that the review is complete for that knowledge point whenever the exit criteria is met.	Q9: Our MBSE process fully supports our technical review process.

DoD DE Strategic Goal	Model-Based Capability Name	Stage 4 Description	Survey Question
Goal 1: Use of Models	Model Based Reviews and Audits	Business value/benefits (free text question)	Q10: Please identify any benefits or challenges your organization has found in the use of MBSE (or 'digital engineering') in the technical review process.
Section 4 – Metrics			
Goal 1: Use of Models	Modeling Process quality	Modeling processes re-engineered provides measurable improvements across the enterprise.	Q11: Modeling activities in our organization provide measurable improvements within and across projects.
Goal 1: Use of Models	Model Metrics	Consistent metrics are used across the enterprise to manage the model development, quality, or effectiveness with trend information kept and decision making thresholds established.	Q12: We have consistent metrics across our program(s)/enterprise that include our modeling activities.
Goal 1: Use of Models	Model Metrics	Digital Engineering Metrics (free text question)	Q13: Please identify any metrics that have proven to be useful for measuring the performance of your MBSE activities.
Section 5 – Model Quality			
Goal 1: Use of Models	Verification and Validation of Models	Modeling development processes have been established, modeling patterns, styles, and standards have been defined, and standard V&V procedures and programs have been formulated. (including associated automated scripts and tools). V&V of the models is performed and updates to the models made.	Q14: Our organization has defined processes and tools for verification and validation of models at appropriate levels and program phases.
Goal 1: Use of Models	Modeling Assurance	Model assurance measurement and corrective actions are conducted for the enterprise.	Q15: Our organization has defined processes and tools for data and model quality assurance.
Section 6 – Data Management			
Goal 1: Use of Models	Distributed Database/Tool Interoperability	Fully Federated w/ standard "plug-and-play" interfaces. Data is interchanged among tools.	Q16: Our organization has effective approaches for managing the data interface between tools.

DoD DE Strategic Goal	Model-Based Capability Name	Stage 4 Description	Survey Question
Goal 1: Use of Models	Model Based Data/Tool Independences	Data is independent of tools and allows for portability.	Q17: Data is managed independent of tools and allows for portability across different organizational structures and related disciplines.
Goal 1: Use of Models	Model Based Data/Tool Independences	Workforce (free text question)	Q18: Please identify any new data management roles and processes you have created.
Section 7 – Model Sharing and Reuse			
Goal 1: Use of Models	Model Libraries	Project model libraries are established and shared across an enterprise in a curated manner.	Q19: Our organization supports model libraries for the purpose of model reuse.
Goal 1: Use of Models	User Interface (UI), Viewpoint/ Views, and visualization	UI supports Interrogation across the federated enterprise Authoritative source of truth and provides visualizations for decision making.	Q20: Our organization has implemented an interface around our models that can be used and understood by a variety of stakeholders.
Goal 2: ASOT	Authoritative Source of Truth (ASOT)	Data and information are discoverable to provide knowledge to strategic to near real-time decision makers across the life cycle and across the enterprise	Q21: Shared models are being used to consistently manage systems across the lifecycle.
Goal 2: ASOT	Digital Artifacts	Enterprise decisions are based on tool and user defined digital artifacts to make decisions. (free text question)	Q22: Please identify any practices your organization has implemented to improve data and model discovery and reuse, either within or between teams. Include examples of appropriate model reuse if possible.
Section 8 – Modeling Environment			
Goal 4: Establish Environments	Modeling Tool Access	Model access permissions are shared within an enterprise.	Q23: Our organization takes steps to make sure our modeling environment is secure.
Goal 4: Establish Environments	Modeling Tool Access	Models across enterprises apply a common IP policy to model contents in the same way.	Q24: Our organization takes steps to make sure that our modeling environment protects our intellectual property.

DoD DE Strategic Goal	Model-Based Capability Name	Stage 4 Description	Survey Question
Goal 4: Establish Environments	Tool Governance	Program/projects across related enterprises consistency apply the same tool governance policy.	Q25: Our organization has defined processes and work instructions that cover tool selection, use, and related data interoperability concerns.
Goal 4: Establish Environments	Tool Governance	Business value/benefits (free text question)	Q26: Please identify any additional benefits you find from collaborating on models across disciplines.
Section 9 – Organizational Implementation			
Goal 4: Establish Environments		Enterprise Adoption (free text question)	Q27: The most challenging obstacles to implementing MBSE in our organization are:
Goal 4: Establish Environments		Enterprise Adoption (free text question)	Q28: The best enablers to for MBSE in our organization are:
Goal 4: Establish Environments		Enterprise Adoption (free text question)	Q29: Going forward, the biggest changes our organization needs to make to improve our implementation of MBSE are:
Section 10 – Workforce			
Goal 5: Workforce Transformation	Modeling Roles and Responsibilities	People who need to be active are identified and involved. Sufficient staffing and staffing plan ensure all roles are fulfilled.	Q30: Our organization has clearly defined the critical roles to support MBSE.
Goal 5: Workforce Transformation	Modeling Roles and Responsibilities	Workforce (free text question)	Q31: The top MBSE role(s) in my organization are:
Goal 5: Workforce Transformation	Modeling Roles and Responsibilities	People who need to be active are identified and involved. Sufficient staffing and staffing plan ensure all roles are fulfilled.	Q32: We have sufficient staffing in our organization to fill all MBSE-related roles.
Section 11 – MBSE Skills			
Goal 5: Workforce Transformation	Modeling-related Training/KSA development	People who need to be active are identified and involved. Sufficient staffing and staffing plan ensure all roles are fulfilled.	Q33: Our organization has clearly defined critical skills for MBSE.

DoD DE Strategic Goal	Model-Based Capability Name	Stage 4 Description	Survey Question
Goal 5: Workforce Transformation	Modeling-related Training/KSA development	Workforce (free text question)	Q34: The most critical skills for MBSE are:
Goal 5: Workforce Transformation	Modeling-related Training/KSA development	Provide leadership in proposing, designing, and delivering training that is appropriate for the modeling and user roles.	Q35: Our MBSE training is linked to the critical skills identified for MBSE.

In addition, the survey collected limited demographic information from each participant:

- My organization is in (select 1): Government, Industry, Academia
- Organization Size (select 1): <500, 501-2000, 2001-10000, >10000
- My primary role in my organization is (select 1): Executive management; Project/ product/ or other management; Systems Engineer; Information Technology professional; Modeling and Simulation professional; Acquisition professional; Other Engineering or Software discipline; Other
- Primary Market (free text question)
- How long has your organization been working toward MBSE (select 1): Less than 1 Year; 1-3 Years; 4-6 Years; More than 6 Years

The survey itself was delivered via a custom website created by researchers and students in the SERC and was designed to organize the questions into the sections (pages) that would be intuitive to participants. Survey analytics were built into the website to aid in publishing the results.

In addition, the following information was placed on the website entry page to provide clarity on the survey use and data collection approach:

- WHO IS RUNNING THE SURVEY?

  The survey is a joint effort of the International Council on Systems Engineering (INCOSE) and the National Defense Industrial Association (NDIA) Systems Engineering Division. The survey is supported by researchers at the Systems Engineering Research Center (SERC).

- WHO SHOULD PARTICIPATE?

  Individuals who are currently working on MBSE implementation in their organization and who have some knowledge of their organization's enterprise-level capabilities.

- WHY SHOULD I PARTICIPATE?

  The survey will provide a baseline assessment of the maturity of MBSE capabilities in your organization, based on the soon to be released INCOSE Model-Based Capabilities Matrix. Upon completion of the survey, you will be given an opportunity to download your survey responses as well as copies of the current Capabilities Matrix and Matrix User's Guide. These will not be published by INCOSE until 2020. In addition to getting these results, overall results will provide critical insights into the progress of MBSE activities in the broader systems engineering community. A final report

on the results will provide context for your organization and broad insights to support continuing MBSE maturity in the community.

- HOW LONG IS THE SURVEY?

The survey is intended to be comprehensive and capture critical thoughts from practitioners. It will take about 25 minutes. Respondents can complete a portion of a survey and return later to finish the rest. The incomplete survey will be shown on their dashboard.

- HOW WILL MY DATA BE USED?

Data from the survey will be stored by the SERC. The final anonymized dataset (no individually or organizationally identifying information) will be stored by the SERC. The SERC will analyze the data and this aggregated analysis will be provided to INCOSE and NDIA. In addition, a report on the results of the survey will be published by the professional organizations.

- HOW WILL MY DATA BE PROTECTED?

Protecting your data is important to the SERC. We do not share your data with third parties. We follow generally accepted standards to protect the data submitted to us, both during transmission and once it is received. Most common attacks such as XSS, SQL injection, and CSRF will be detected and handled. Your data will be stored in a private database that can only be accessed by authorized SERC researchers.

Survey requests for participation were published through direct solicitation of responses to the SERC, INCOSE MBSE Working Group, and NDIA Systems Division membership lists.

3. Complete Survey Results, by Section

There were two major types of analyses: quantitative analysis of the responses to scored questions and qualitative analysis of the responses to free-text questions. This section describes the detailed analysis of all survey data and is divided into six sections:

3.1 Survey Period and Responses provides an overview of the survey.

3.2 Survey Demographic Information provides a breakdown of the survey sample according to the reported demographics.

3.3 Maturity Analysis, Participant Reported Ratings provides quantitative analysis of the scored questions, including breakdown by demographics.

3.4 Analysis of Text Responses, MBSE Benefits and Metrics provides qualitative analysis of responses to free-text questions using a framework centered on value, benefits, and metrics.

3.5 Analysis of Text Responses, Enterprise Adoption provides qualitative analysis of responses to free-text questions on obstacles, enablers, and changes related to MBSE using an organizational performance excellence framework.

3.6 Analysis of Text Responses, Workforce Development provides qualitative analysis of responses to free-text questions on the workforce using a framework centered on roles, skills, and associated processes.

The order of the questions in the analysis is different from the order of questions found in Table 1. The order above groups questions by the type of analysis and better enables grouping similar threads from the qualitative analysis.

3.1 Survey Period and Responses

A total of 240 respondents participated in the survey between 18 November 2019 and 31 January 2020. Of these, 129 fully completed the survey, while 171 participants completed over 70% of the survey questions while making it through to the end, and the non-answered questions were sufficiently randomized. The survey team elected to base the quantitative aggregate results of scored questions on these 171 participants, termed “effective participants.” The remaining 69 participants clearly started the survey but did not complete it based on their answer trends. These responses were not used for the quantitative analyses. For qualitative analysis of free-text questions, responses from all 240 respondents were used.

3.2 Survey Demographic Information

Basic demographic information was collected from survey participants:

- Organization type, size, and experience implementing DE/MBSE (in years)
- Market segments of the participants (if reported)
- Organizational role of the participants

3.2.1 Organization Type, Size, and Experience

The survey requested organizational size data and data on experience using MBSE. Most of the participants reported they were in industry, although a significant number of government participants also responded. Effective participants included 109 from industry, 48 from government, and 11 from academia. For organization size, 39 participants reported less than 500 employees, 21 reported 501-2000, 48 reported 2001-10000, and 62 reported greater than 10,000. For experience in using MBSE, 17 participants reported less than 1 year, 48 reported 1-3 years, 35 reported 4-6 years, and 63 reported

greater than 6 years. Figure 1 reflects the effective responses combining type, size, and experience. On average, large industry participants are more mature in their MBSE experience.

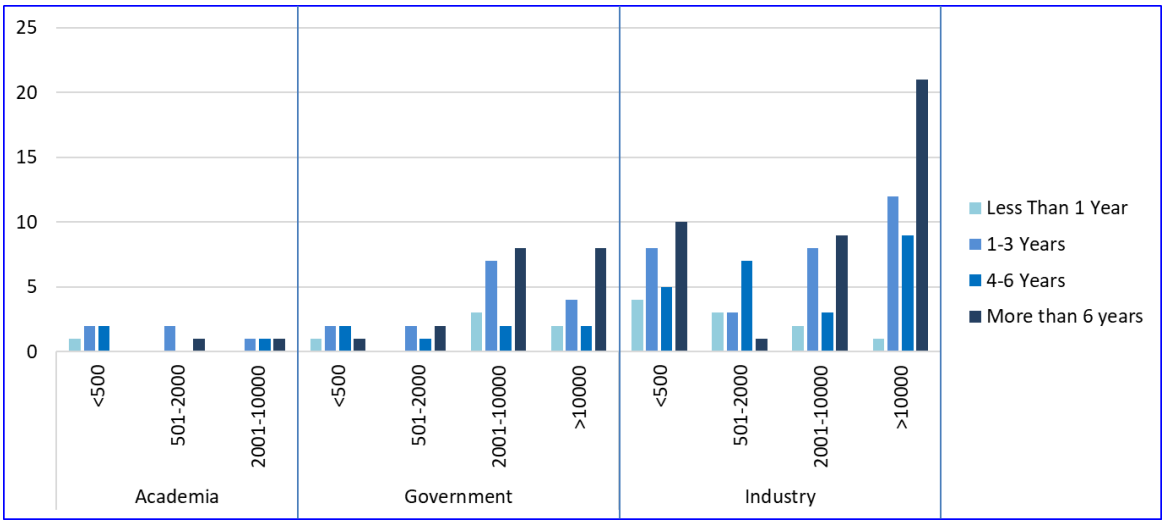

Figure 1. Organizational Demographic Data.

3.2.2 Organization Market Survey

Figure 2 represents the responses by organization type and by market area for industry. Participants were asked to provide an indication of the market segment of their organization via a text-based question. In total, 89 of the 109 industry participants provided answers to this question. Figure 2 reflects the responses only for participants indicating they were from industry. As expected, most of the respondents were in the defense and aerospace sectors, although a fair number of automotive and other industries were represented.

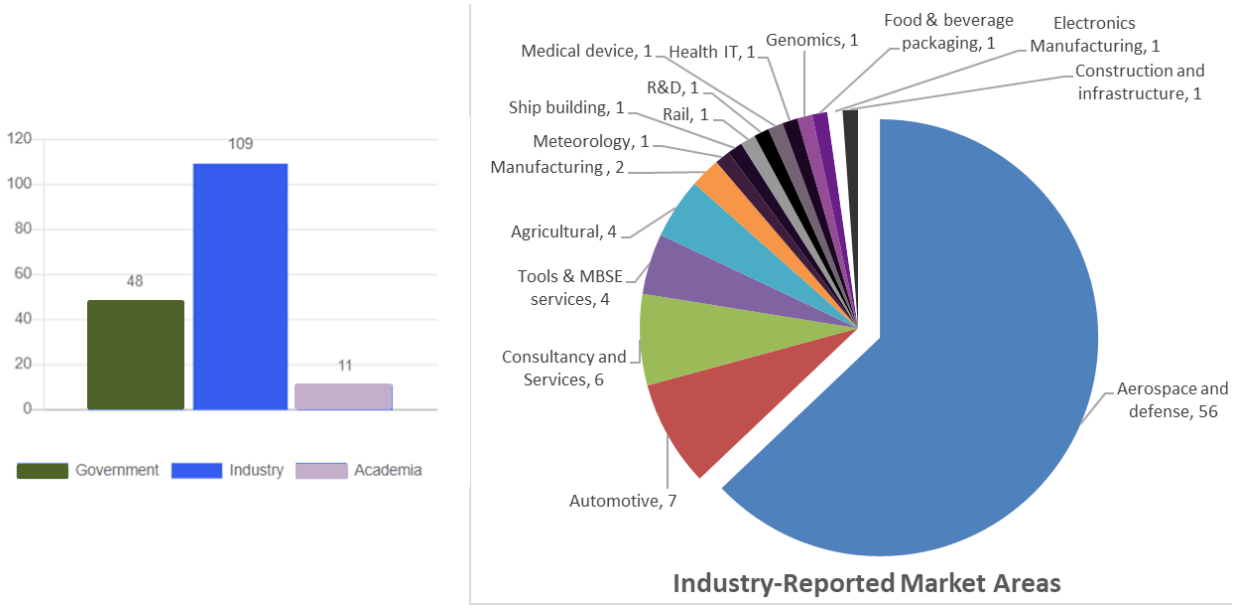

Figure 2. Organization Type and Industry Participant Reported Market Areas.

3.2.3 Organizational Roles

Participants were asked to identify their role in their organization. Figure 3 reflects the roles for participants who responded to this question. 46 respondents identified with Executive or Program level management roles and 124 with other program related and/or technical roles. Section 3.3 provides additional analysis on reported roles versus survey responses.

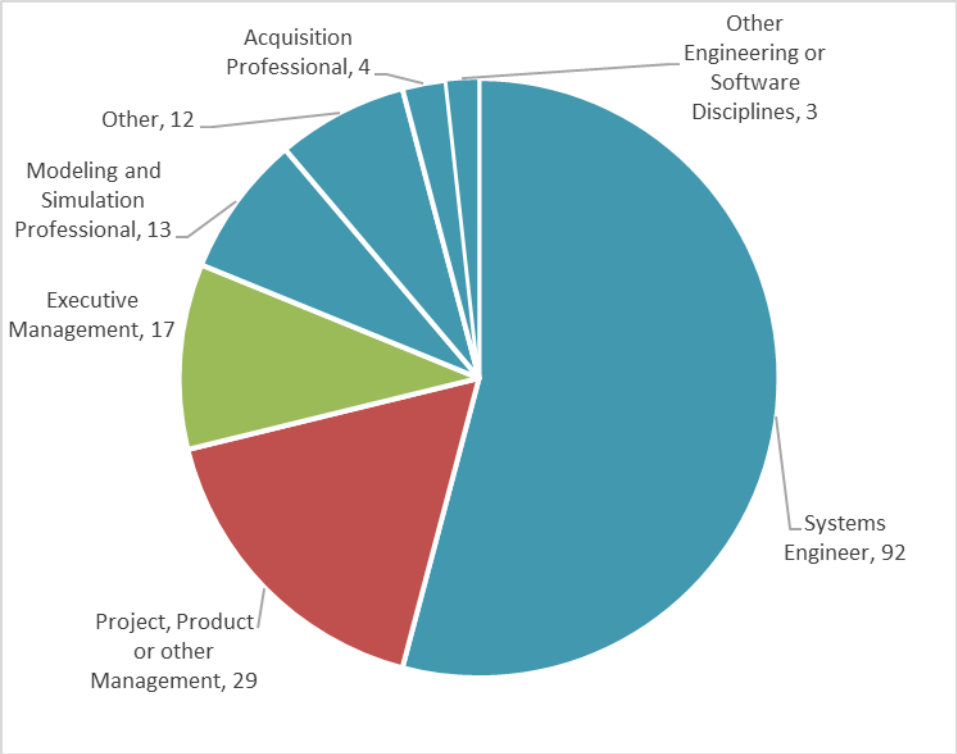

Figure 3. Participant Reported Organizational Roles.

3.3 Maturity Analysis, Participant Reported Ratings

Survey respondents rated their level of agreement with each scored question in the survey, representing statements, as described earlier (strongly agree, agree, disagree, and strongly disagree). For the purpose of this analysis reported here, overall scores for each question were calculated using the formula "strongly agree" = +3, "agree" = +1, "disagree" = -1, and "strongly disagree" = -3. The weightings are intended to create some distance between "agree/disagree" and "strongly agree/strongly disagree" responses and *should not be considered to reflect quantitative levels of agreement or disagreement*. A scorecard of all of the scores to survey questions of this type is shown in Figure 4. The figure refers to each Likert-type question in the survey using the question numbers from Table 1, a short summary of the question, and the related survey section title from Table 1. As can be seen in the graph, the respondent ratings to statements associated with maturity of their capabilities were mostly on the "disagree" side of the scale, with a few exceptions. The details for each question are discussed in the following sections, including total responses, and responses by organization type, size and years of experience.

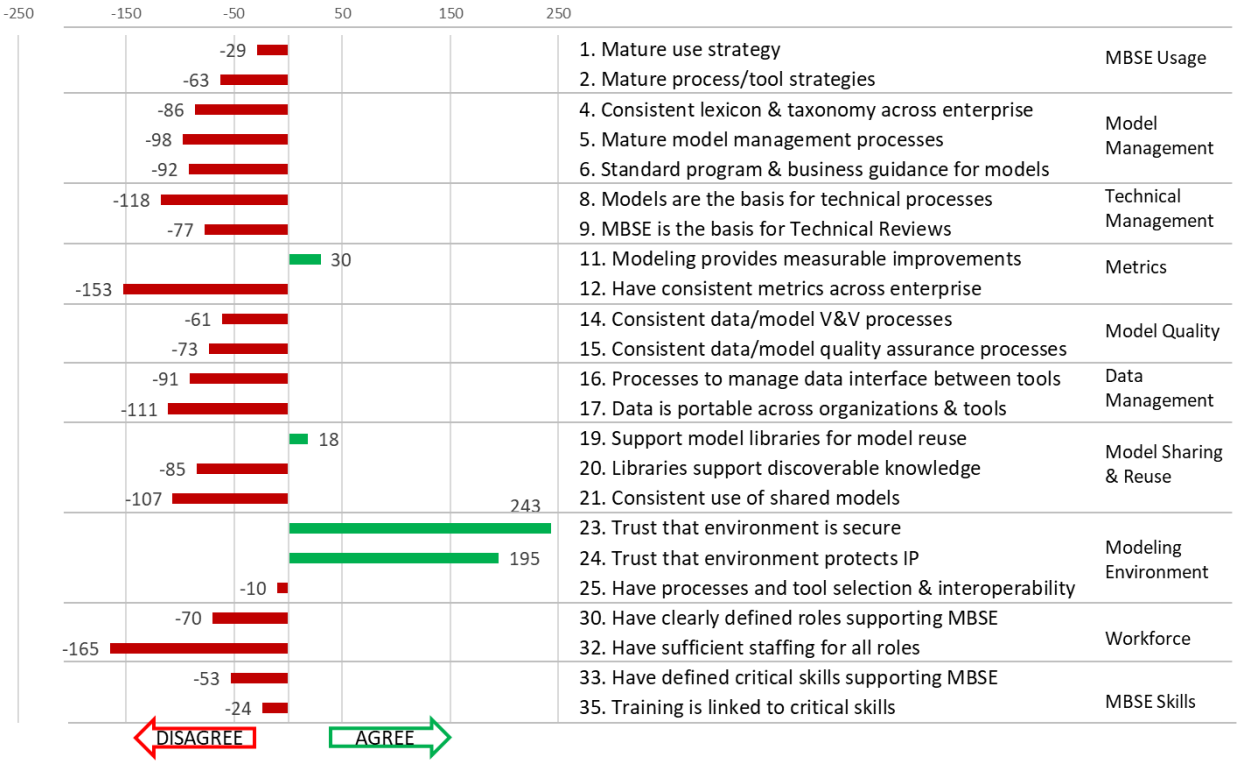

Figure 4. Overall Maturity Question Scorecard.

MBSE Usage, Model Management, and Technical Management relate to the enterprise-wide use of DE/MBSE methods, processes, and tools. Enterprise strategies for MBSE Usage are leading actual Model Management practices and associated Technical Management practices as might be expected. Overall, there was moderate disagreement from respondents that these capabilities are mature. In the Technical Management area, additional concerns related to organization adoption are discussed in section 3.4.6.

Use of Metrics in these processes turned up a dichotomy of scores that led to the analysis of benefits and metrics in section 3.4. Respondents moderately agree that modeling provides measurable improvements, but looking more broadly across the DE enterprise, they strongly disagree that they have mature measurement capabilities. Organizations appear to be searching for guidance on measuring the value and benefits of DE/MBSE usage.

Responses did vary by role – respondents identifying their role as Executive Management agree or strongly agree on 18 of the 23 Capability statements, while Program/Project/Other Management agree on 7 of the 23 and other Systems Engineering-related roles only showed agreement of 5 of the 23. Figure 5 lists responses to each question by reported role, in this figure response scores have been truncated at +40/-40 scales for readability. The sample size for each role was insufficient for quantitative analysis, only the relative differences in score should be used to interpret this data. There is a clear disagreement between Executive Management and other respondents on the relative maturity of their capabilities, which may be because Executive Management perceives benefits at the enterprise level that are not being measured at working levels. This is related to findings in the MBSE benefits and enterprise adoption analyses in sections 3.4 and 3.5.

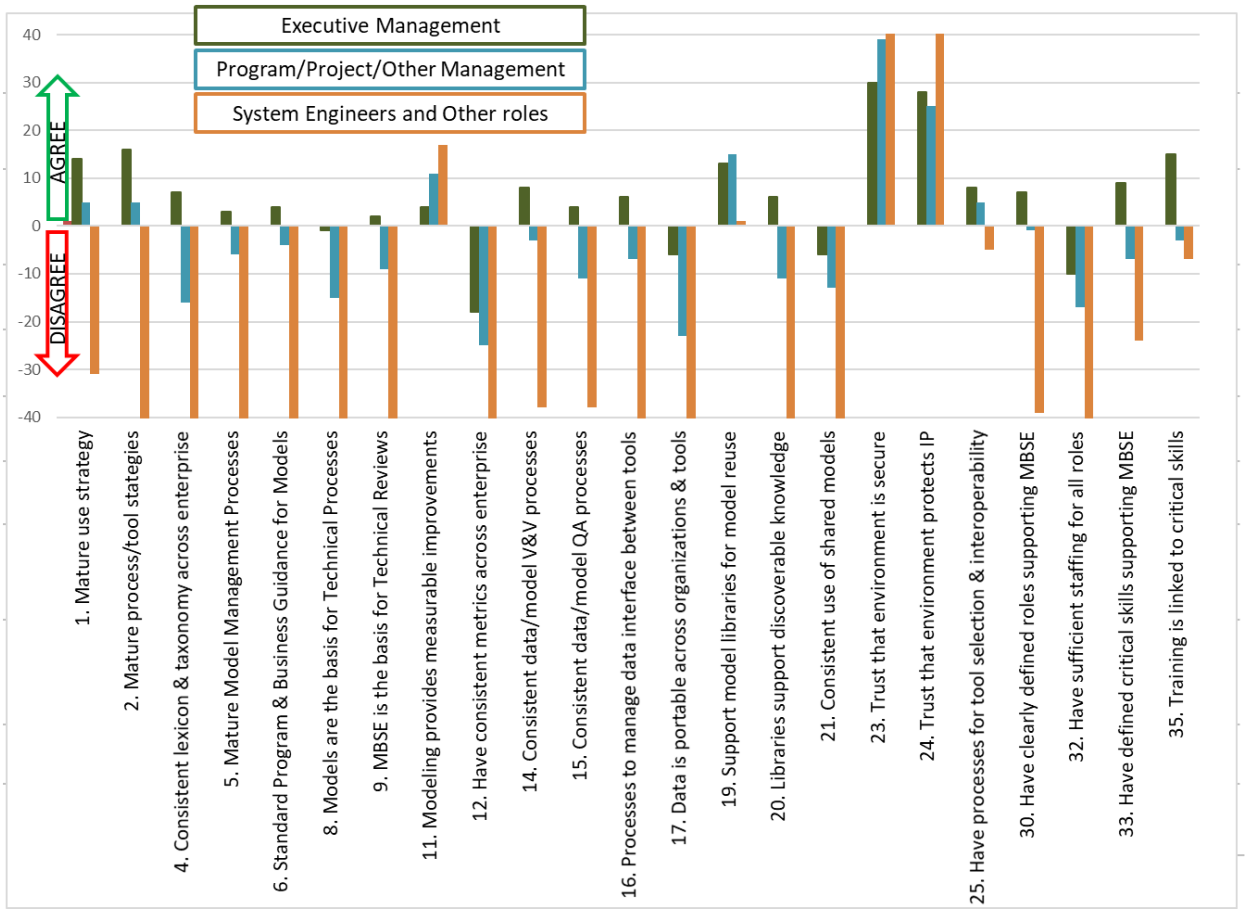

Figure 5. Scorecard by Role.

Model Quality, Data Management, and Model Sharing and Reuse relate to enterprise management of data and models. Across these areas, respondents generally agree that they have enterprise capabilities for maintaining model libraries and achieving model reuse (a key value of DE/MBSE), but disagree or strongly disagree that other enterprise capabilities for managing, using, and validating data and models are mature. Most of these issues appear to be related to workforce, culture, and change management concerns, leading to the enterprise adoption analysis in section 3.5. In fact, responses from smaller organizations reflect more agreement than larger organizations on mature capabilities across these areas, likely because they are able to realize the necessary cultural changes more quickly.

The maturity of capabilities related to Modeling Environment was the only category to see broad agreement across the survey respondents, indicating that basic tools and processes are reaching a more mature state.

In the Workforce and Skills categories, responses reflected neutral agreement on effectiveness of training, moderate disagreement on maturity of organizational roles and skills, and strong disagreement with respect to availability of staffing. Roles, skills, and training will be analyzed further in section 3.6. Trained staff remains an obstacle to DE/MBSE success as discussed further in section 3.5.

The following subsections analyze the survey results of each of the 23 capability statements individually.

3.3.1 MBSE Usage

A mature organization's MBSE use strategy is documented as part of the organization's overall strategy at the enterprise level. The strategy is related to the overall risk strategy, and the modeling is integrated with business information tools. The results are used to inform systems engineers, program management, and all staff across the enterprise. It relays a full range of business concerns. Statements were provided for survey participants for evaluation to help elucidate the maturity of MBSE use strategies within the organizations. Survey respondents moderately disagree with statements that reflect they are mature in this category. This survey section contained two capability related questions and one text question.

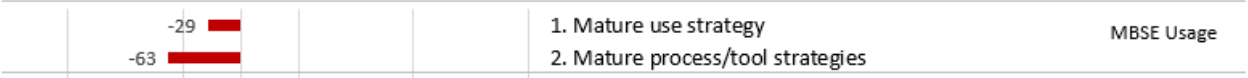

Figure 6. MBSE Usage Maturity Scorecard.

Participants were also asked in this section to respond to the question: *What do you see as the most important reasons for integrating MBSE processes with program and business management processes?* This question was designed to elicit responses discussing the value and benefits accrued from MBSE usage. These responses are analyzed in section 3.4.

Q1: Mature Use Strategy

Participants were asked to respond to the statement: *"Our MBSE use strategy is integrated with our overall product strategy or strategies at the enterprise level."* The maturity score on this question was slightly toward disagreement with the statement (-29). Government is slightly behind industry and academia in their reported agreement. In this area, the smallest organizations indicated highest agreement (likely related to ease of adoption), and agreement generally follows years of experience (i.e., higher levels of agreement with more years of MBSE experience).

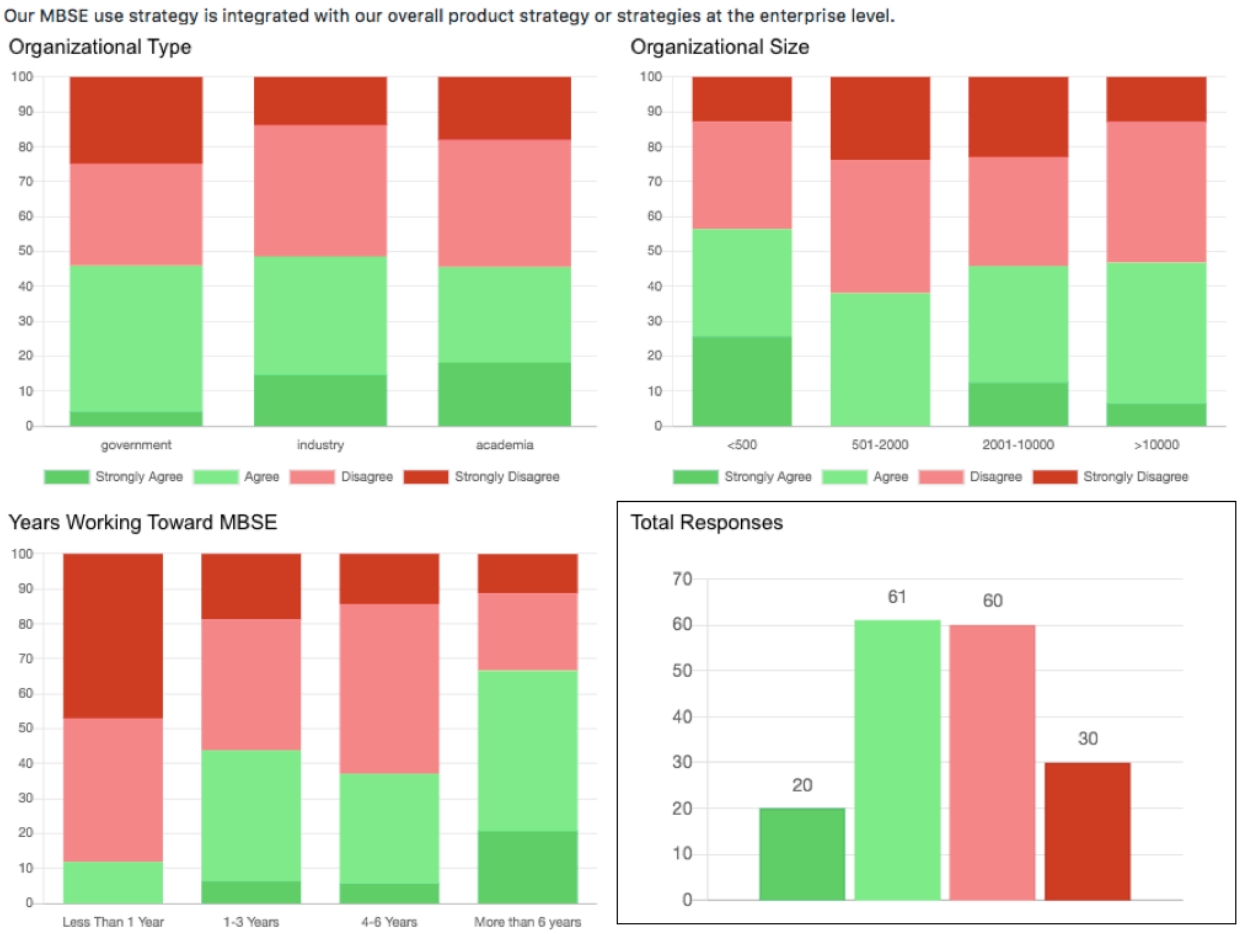

Figure 7. Mature Use Strategy.

Q2: Mature Process / Tool Strategies

Participants were asked to respond to the statement: *"Our MBSE processes and tools are integrated with our overall product-level processes and tools."* The maturity score on this question shows a greater level of disagreement with the statement (-63), indicating mature processes are lagging strategy. Again, the smallest organizations indicated highest agreement, and agreement generally follows years of experience.

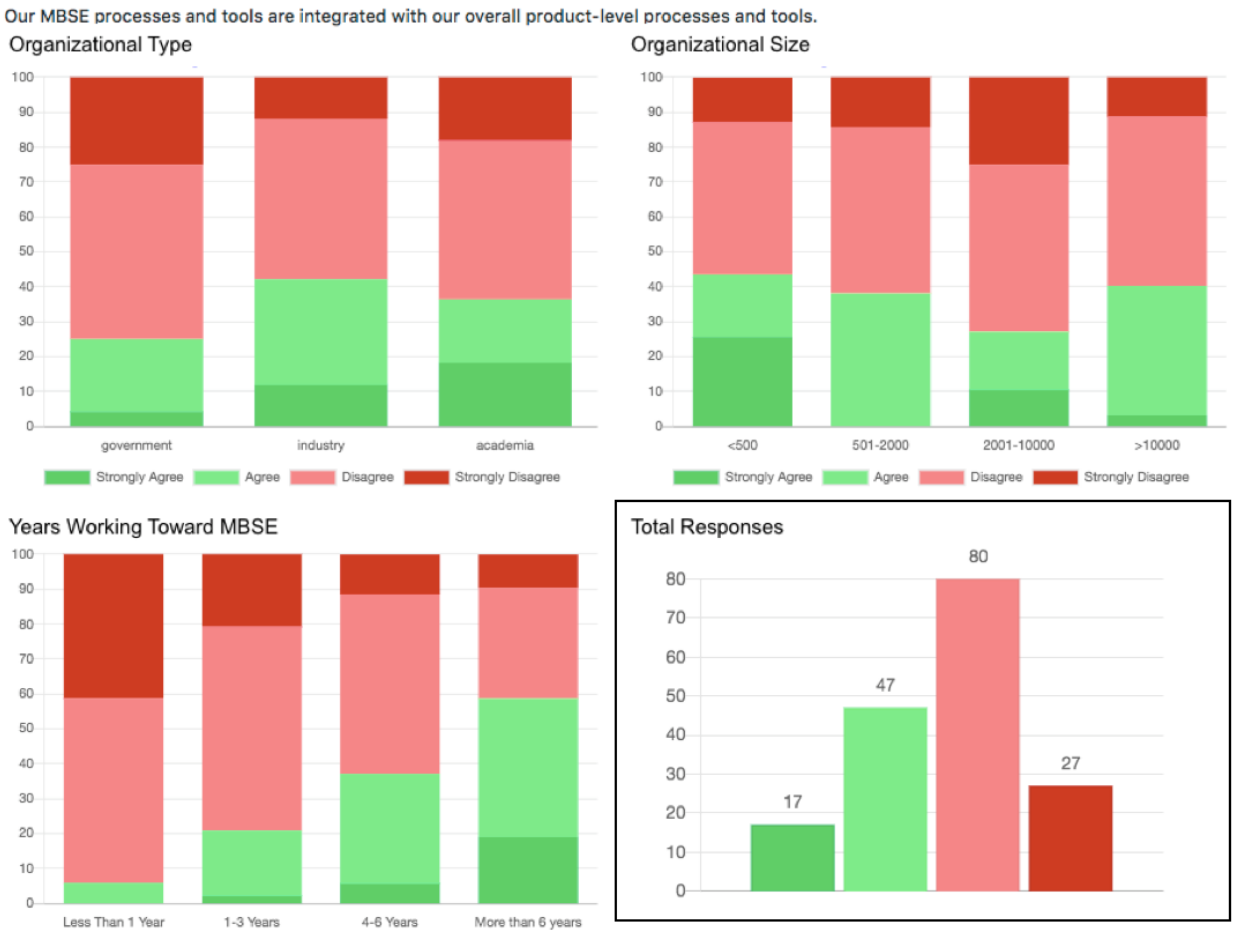

Figure 8. Mature Process/Tool Strategies.

3.3.2 Model Management

The model management section seeks to understand if there is a common, tiered taxonomy across the enterprise that is defined and consistent with accepted community standards, and also whether model management is applied to all models across the enterprise. It also seeks to comprehend if there is consistent modeling with business-driven planning guidance within organizations. Statements were provided for survey participants to assess the maturity of model management practices within the organization. Survey respondents moderately disagree with statements that reflect they are mature in this category. This survey section contained three capability related questions and one text question.

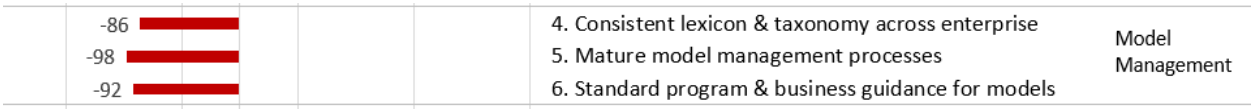

Figure 9. Model Management Practices Scorecard.

Participants were also asked to respond to the question: "*Please provide one or more descriptions of the business value you are realizing from consistent model management processes and tools."* This question was designed to elicit responses discussing the value and benefits accrued from consistent enterprise use of models. Analysis of responses to this question in described in Section 3.4.

Q4: Consistent lexicon & taxonomy across the enterprise

Participants were asked to respond to the statement: *"As part of our MBSE process, we have a clear taxonomy that we use consistently for modeling across our organization."* The maturity score on this question shows a high level of disagreement with the statement (-86). Government organizations had the highest level of disagreement. Again, the smallest organizations indicated highest agreement, and agreement generally follows years of experience.

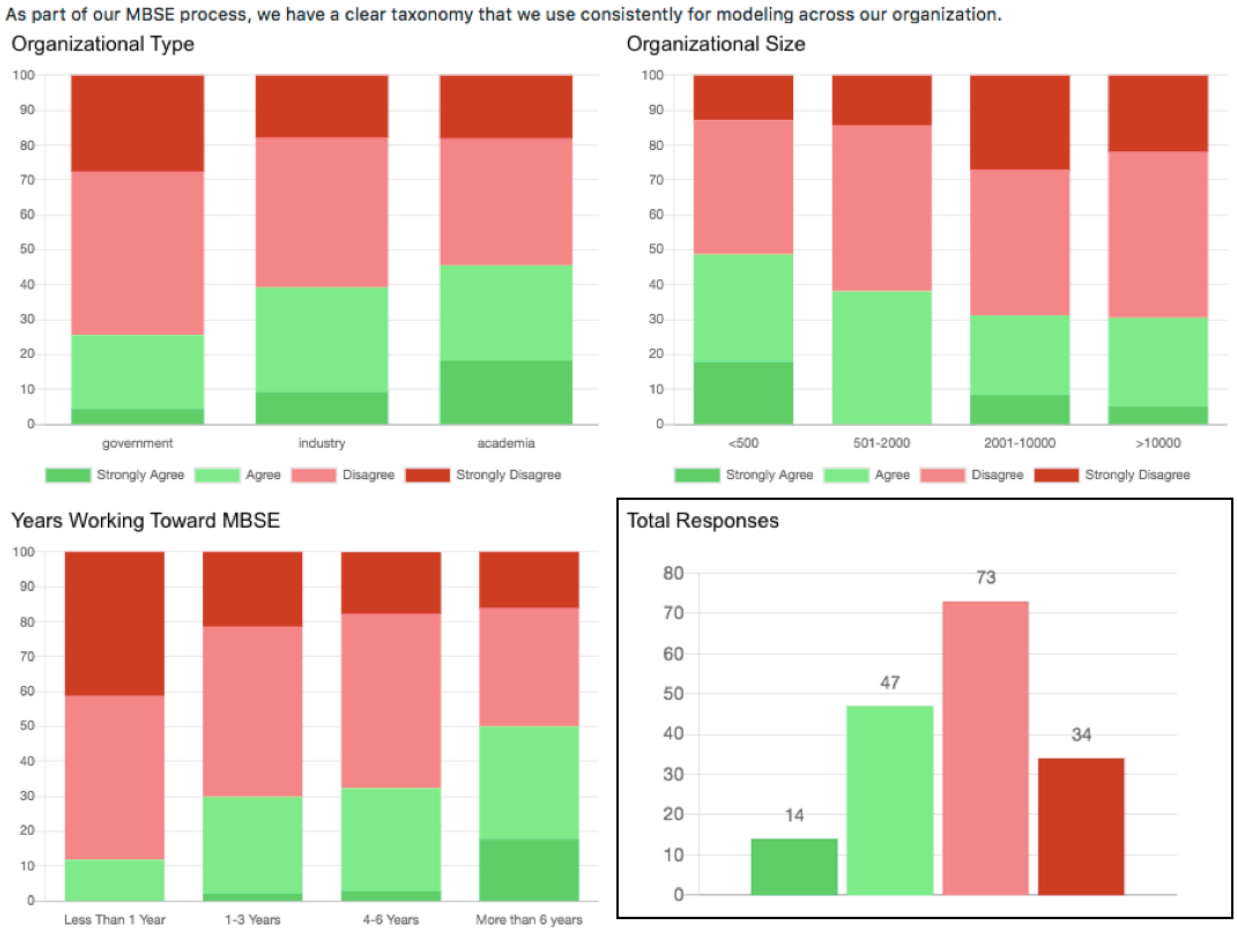

Figure 10. Consistent Lexicon & Taxonomy across the Enterprise.

Q5: Mature model management processes

Participants were asked to respond to the statement: *"Our organization has well-defined processes and tools for managing models across a program lifecycle."* The maturity score on this question shows a high level of disagreement with the statement (-98). For this statement, level of agreement was consistent across organizational demographics, and agreement generally follows years of experience.

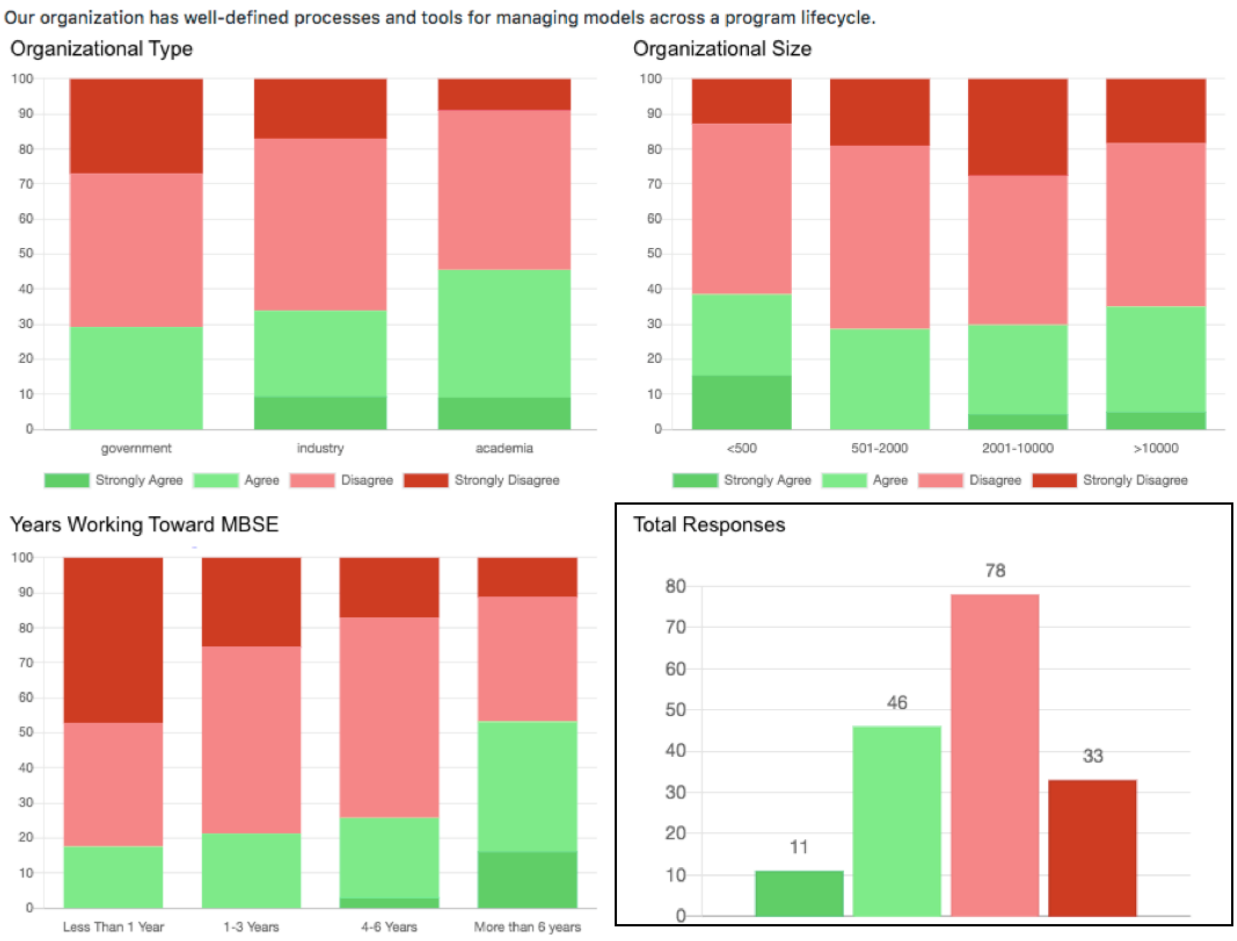

Figure 11. Mature Model Management Practices.

Q6: Standard program and business guidance for models

Participants were asked to respond to the statement: *"Our organization has standard business and program guidance that defines our model management processes and tools."* The maturity score on this question shows a high level of disagreement with the statement (-92). For this statement, level of agreement was consistent across organizational demographics and agreement generally follows years of experience.

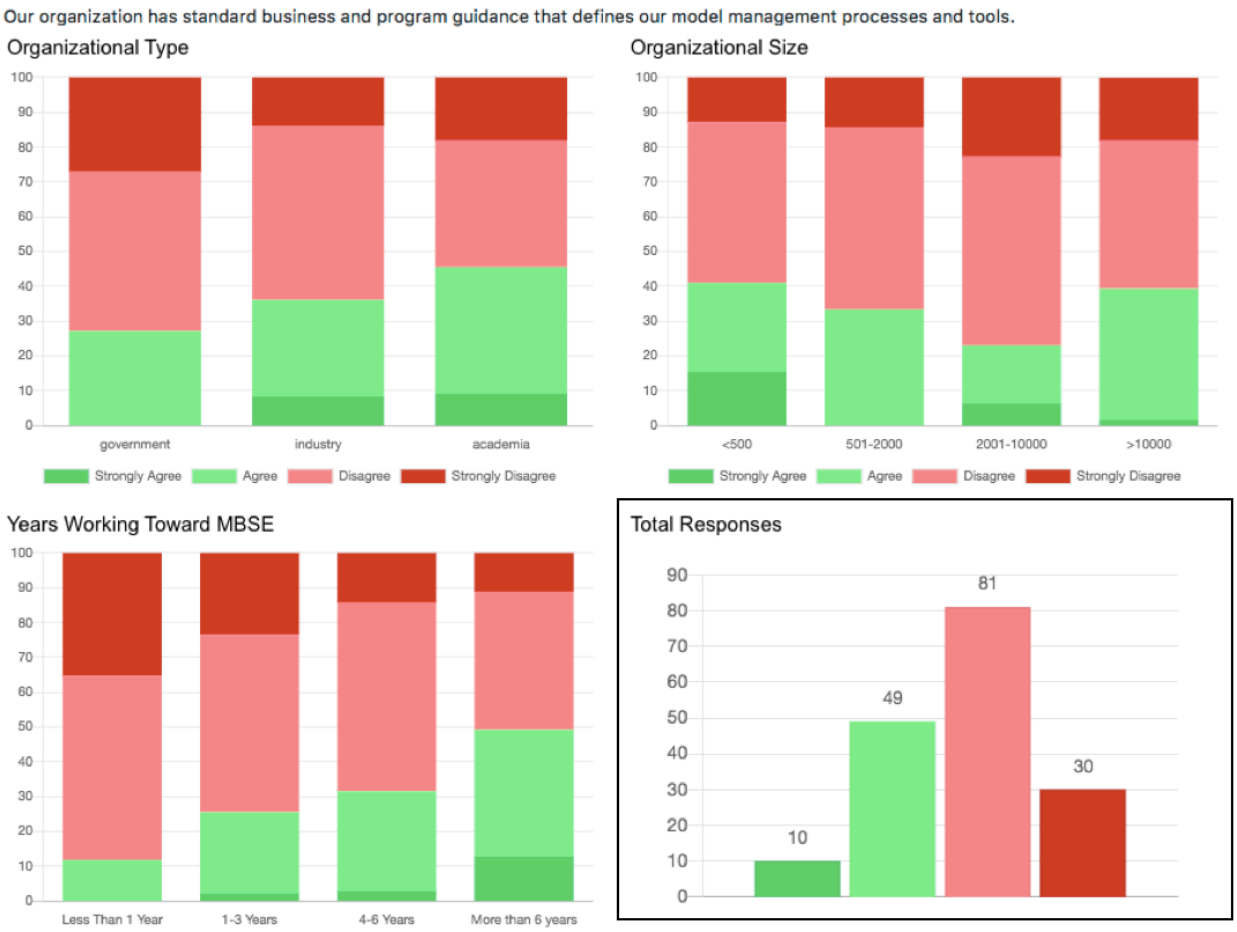

Figure 12. Standard program and business guidance for models.

3.3.3 Technical Management

The Technical Management section seeks to understand how well MBSE serves as a basis for technical practices across an organization. Mature enterprises coordinate on common review criteria for application, tailoring, and use of specific digital artifacts. The recorded acceptance of criteria items and critical technical data shows the rolling, frequent review of model contents. Accumulated knowledge allows stakeholders to accept that the review is complete whenever the exit criteria have been met. Statements were provided for survey participants for evaluation to help elucidate the integration of MBSE into technical management practices within the organizations. Survey respondents more strongly disagree with statements that reflect they are mature in this category. This survey section contained two scored maturity questions and one free-text question.

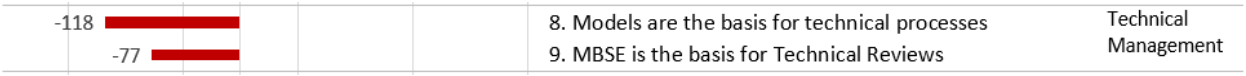

Figure 13. Technical Management Maturity Scorecard.

Participants were asked to respond to the prompt, "*Please identify any benefits or challenges your organization has found in the use of MBSE (or 'digital engineering') in the technical review process*."

Q8: Models are the basis for technical processes

Participants were asked to respond to the statement: *"Our organization uses modeling as the basis for our technical processes consistently across the enterprise."* The maturity score exhibits a high level of disagreement (-118). Of the participants, 78% either disagree or strongly disagree that their organization uses modeling as the basis for technical processes consistently across the enterprise. Again, responses from smaller organizations indicate higher maturity than larger organizations. The survey results indicate higher levels of maturity (i.e., agreement to scored questions) with years of experience.

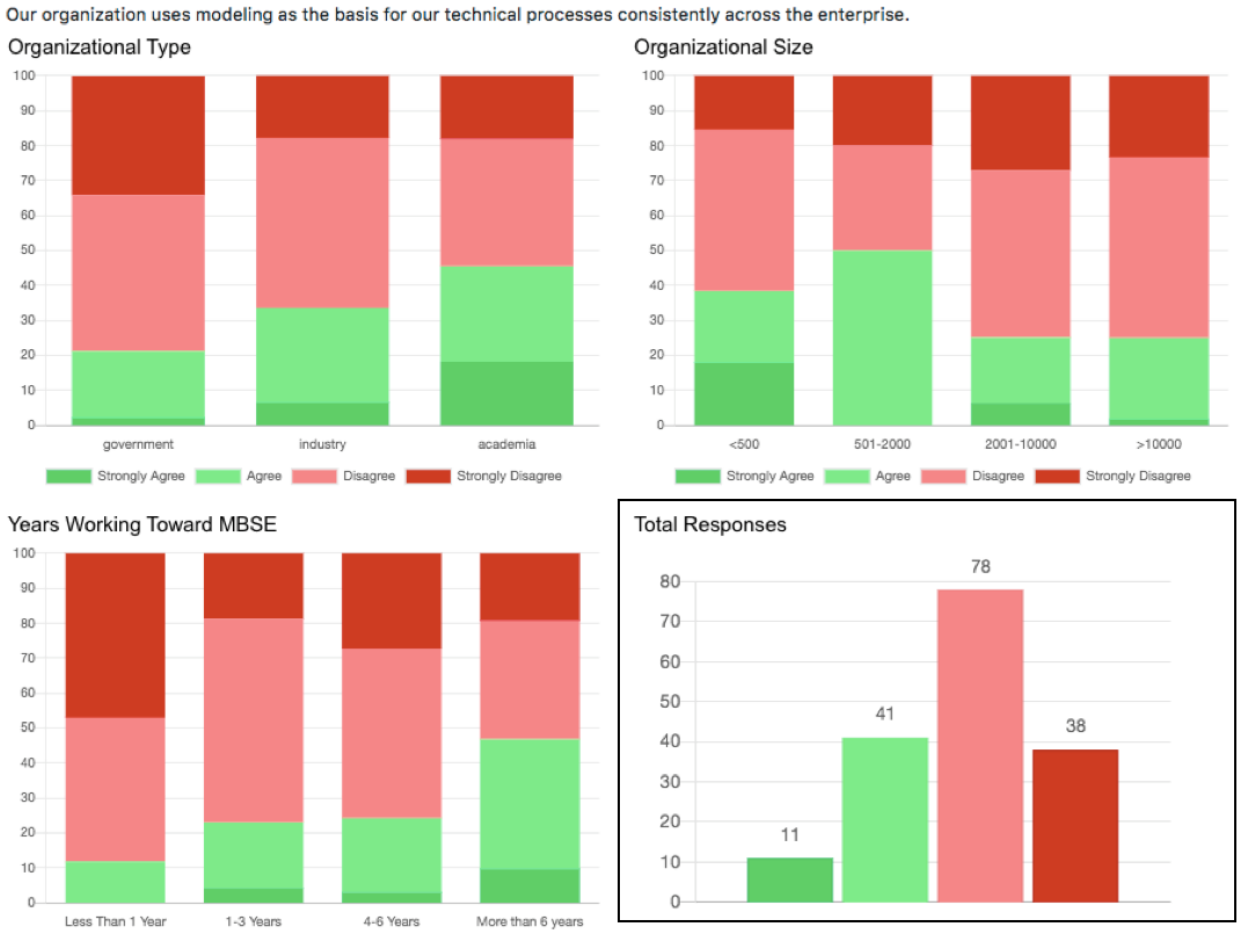

Figure 14. Models are the basis for technical processes

Q9: MBSE is the basis for Technical Reviews

Participants were asked to respond to the statement: *"Our MBSE process fully supports our technical review process."* The maturity score shows a moderate level of disagreement (-77), with 47% disagreeing that their MBSE process fully supports the technical review process. Each organizational type represented had over 50% of the responses as either disagree or strongly disagree. The answers were fairly consistent across organization type and size. For this statement, there were no responses reflecting agreement from any organization that has been working towards MBSE for less than a year, indicating there is a lengthy learning curve associated with DE/MBSE in the technical review process.

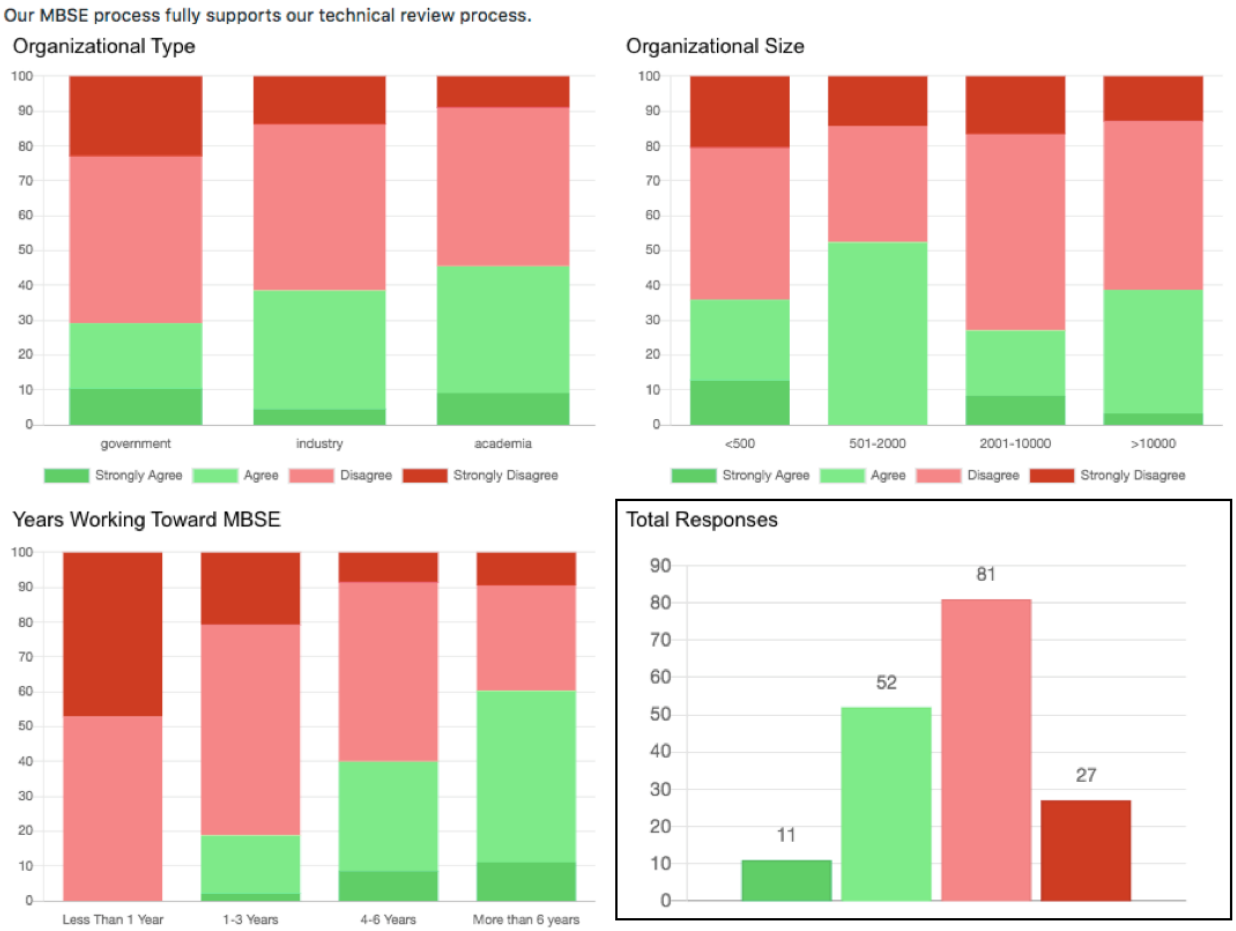

Figure 15. MBSE is the basis for Technical Reviews

Q10: Benefits or challenges with the technical review process

Participants were asked to respond to the prompt, "*Please identify any benefits or challenges your organization has found in the use of MBSE (or 'digital engineering') in the technical review process*." Of the 240 survey participants, 119 provided inputs to this question. Figure 16 shows the distribution of categories for the 146 analyzable responses in those inputs. 35 of the responses were categorized as Enablers to DE/MBSE while the other 111 were categorized as obstacles. As further discussed in sections 3.4 and 3.4, specific metrics of DE/MBSE transformation can be both enablers and obstacles. Figure 16 also shows a categorization of 45 responses that cite benefits from MBSE-based technical reviews while the other 101 responses address the adoption of DE/MBSE into the technical review process. A more detailed categorization of the specific responses is included in section 3.4.4. The data suggests at this point in time most organizations are struggling with adoption of DE/MBSE-based technical review processes. Based on questions 8 and 9, there is a significant experience curve associated with these processes. However, the data also suggests that those adopting DE/MBSE-based technical reviews are also seeing benefits – the most significant being increased system understanding, reduced time, and reduced errors.

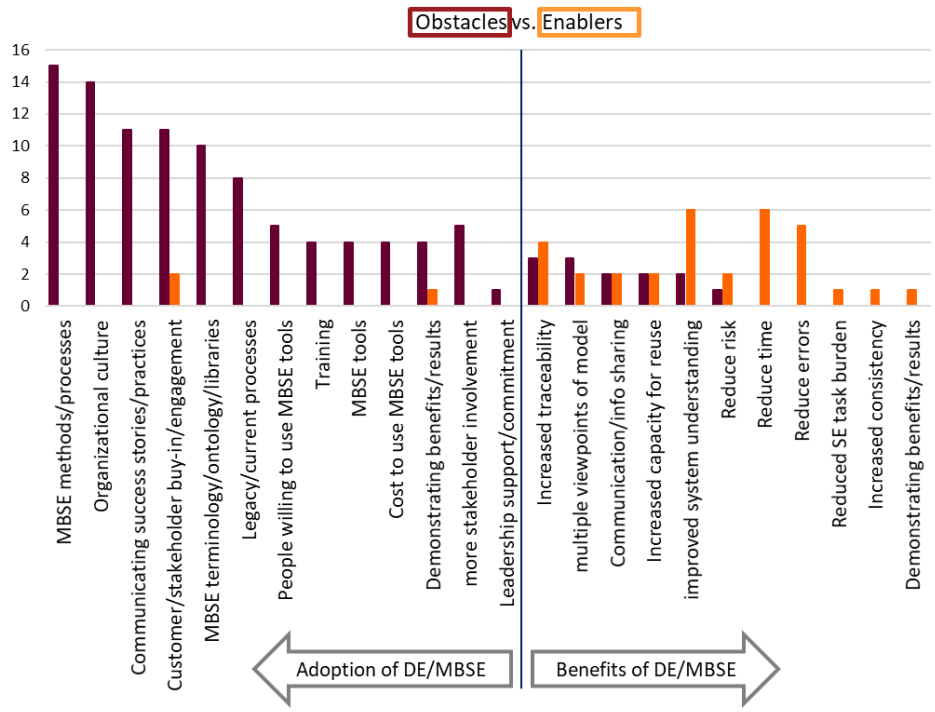

Figure 16. Comparing Enablers and Obstacles in the Tech Review Process.

3.3.4 Metrics

Enterprise performance metrics are of key importance. DE/MBSE processes should provide measurable improvements, and consistent metrics used across the enterprise to manage model development, quality, or effectiveness with trend information allowing for established decision-making thresholds. This section is intended to understand whether the organization has obtained measurable improvements within and across projects, and whether there are consistent metrics to evaluate benefits of modeling activities. As noted earlier, there was a disparity in level of agreement across these two statements focused on metrics.

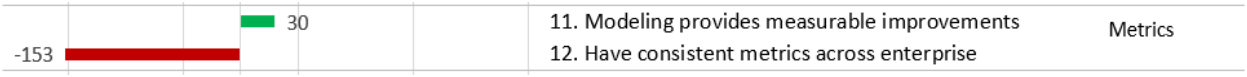

Figure 17. Metrics Scorecard

Participants were also asked to respond to the prompt, "*Please identify any metrics that have proven to be useful for measuring the performance of your MBSE activities*." These results are analyzed in section 3.4.3.

Q11: Modeling provides measurable improvements

Participants were asked to evaluate the statement: *"Modeling activities in our organization provide measurable improvements within and across projects."* The participants had a positive response to the statement (+30). The responses were consistent across respondents from industry, government, and academia, as well as respondents from different size organizations. Responses were also consistent no matter how many years the organization had been working toward MBSE, indicating that these improvements are either realized or perceived early in the DE/MBSE adoption process. Section 3.4.3

analyzes these data further via text responses and additional literature review. It appears the DE/MBSE adopters quickly realize improvements, but these are perceived and only partially observed and/or do not relate to outcomes typically measured through formal metrics. As noted in the next question, very few participants cite that they are actually measuring these results.

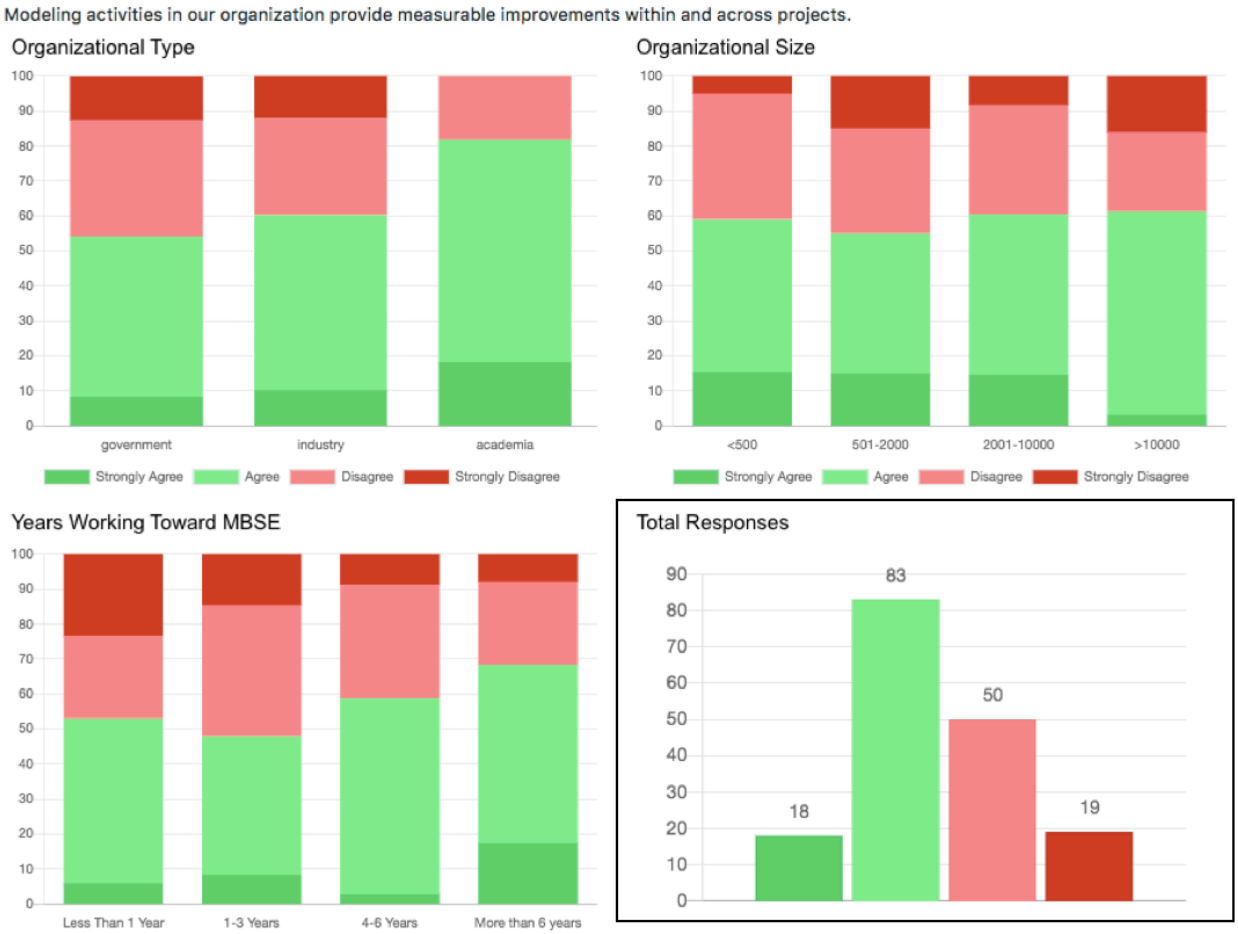

Figure 18. Modeling provides measurable improvements

Q12: Have consistent metrics across the Enterprise

Participants were asked to respond to the statement: *"We have consistent metrics across our program(s)/enterprise that include our modeling activities."* The maturity score for the question indicates very strong disagreement (-153), with 76% of participants rating this question as either disagree or strongly disagree. Participants affiliated with government saw the most negative responses with 87% disagreeing or strongly disagreeing. Section 3.4.3 analyzes this data further via text responses and additional literature review. At this point based on survey data, a framework for capturing metrics can be proposed, but very few organizations have the maturity in their measurement processes to be able to report actual results.

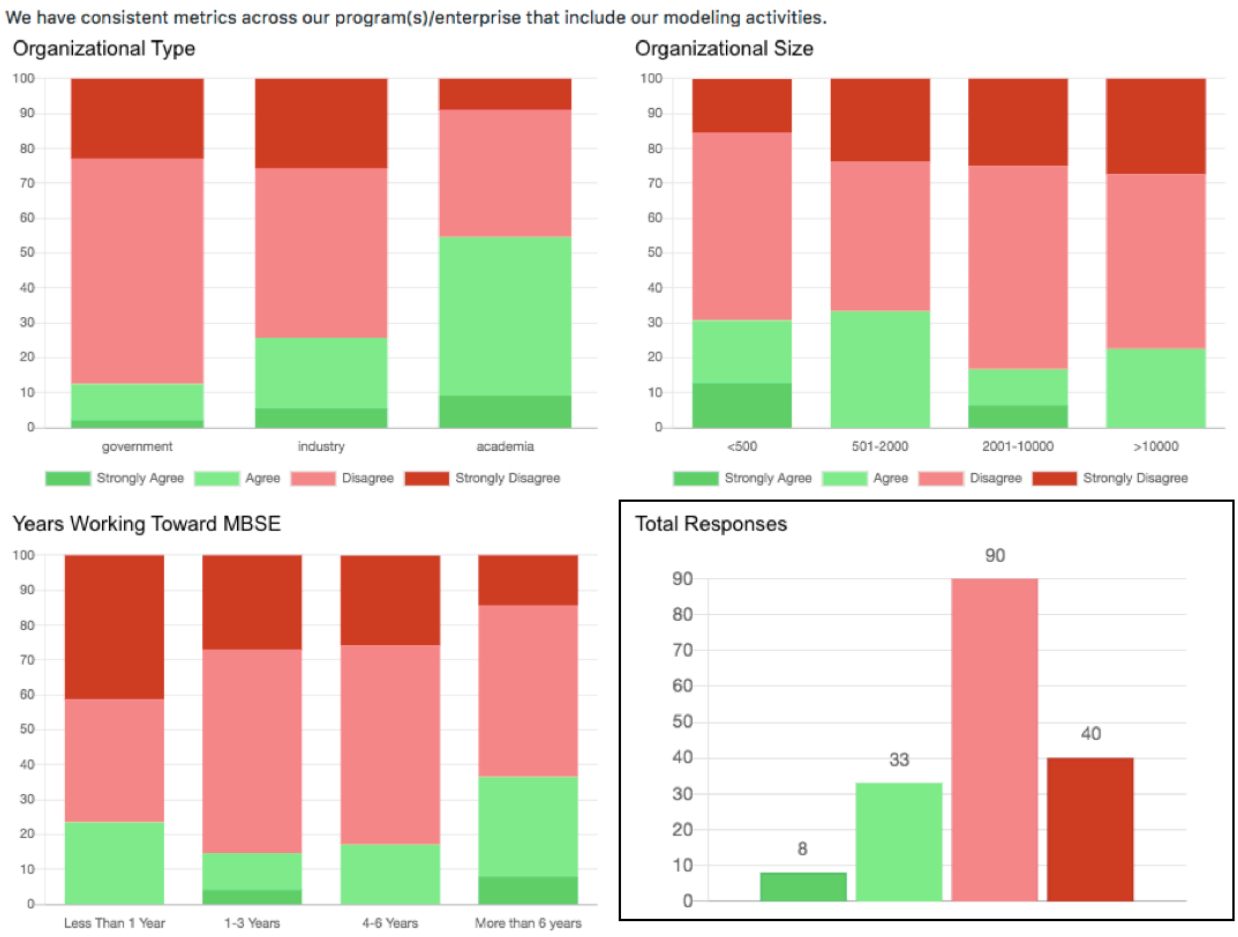

Figure 19. Have consistent metrics across the enterprise

3.3.5 Model Quality

This section seeks to understand if modeling development processes have been established, with defined modeling patterns, styles, and standards. As part of the standard, the verification and validation (V&V) procedures and programs have been formulated, including having associated automated scripts and tools to accompany V&V. The V&V of the models is performed and updates to the models are made accordingly. Another goal is to see whether the company employs model assurance measurements and corrective actions for the enterprise.

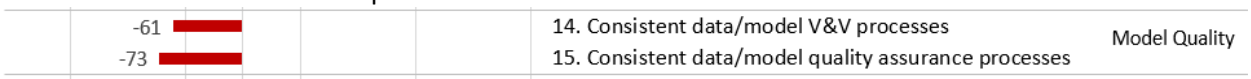

Figure 20. Model Quality Scorecard

Q14: Consistent data/model verification & validation processes

Participants were asked to rate their agreement with the statement: *"Our organization has defined processes and tools for verification and validation of models at appropriate levels and program phases."* According to the maturity score, there was moderate disagreement (-61) with 40% of responses being "disagree". The responses were reasonably uniform from organization type and size, and higher levels of agreement were associated with more years of MBSE experience.

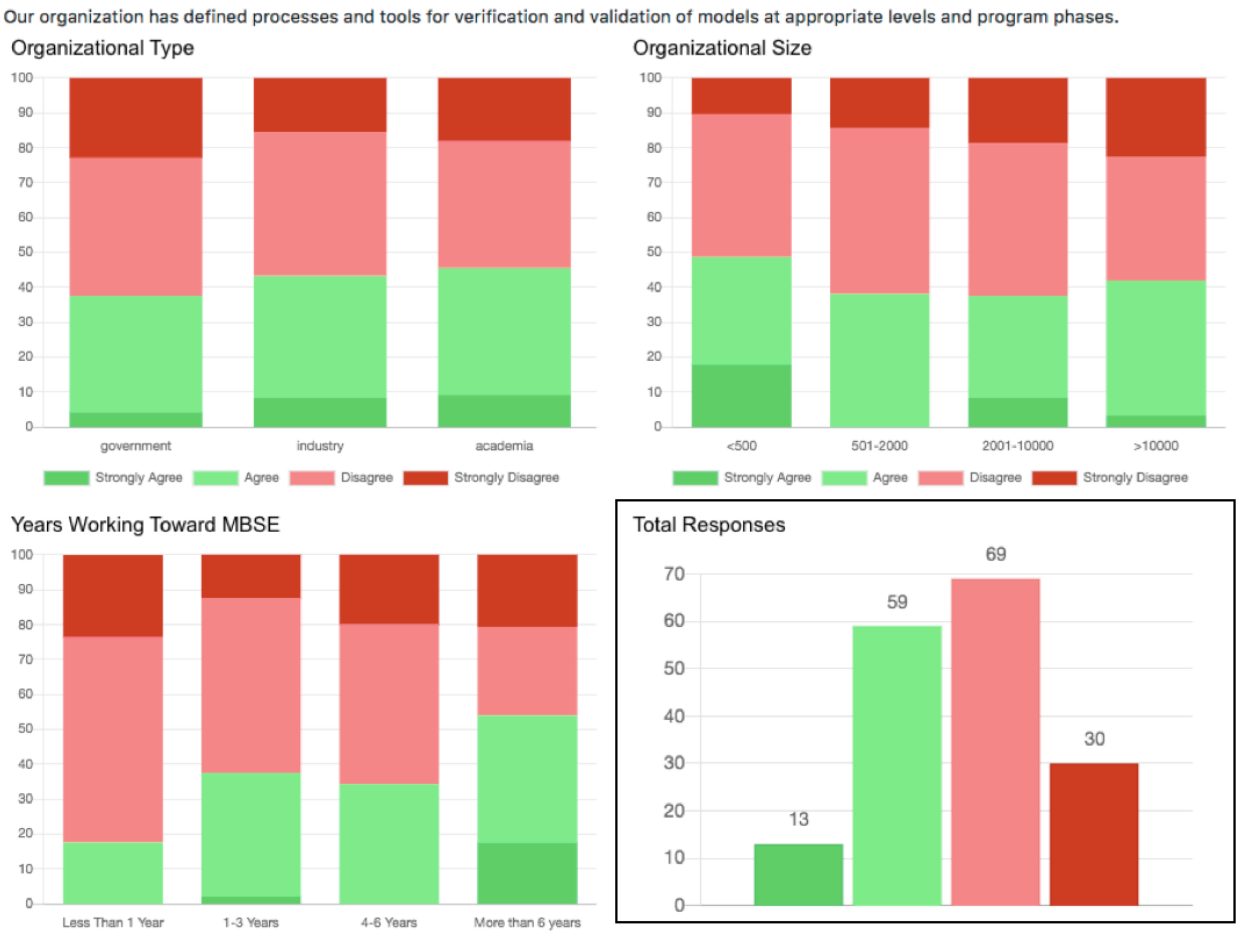

Figure 21. Consistent data/model verification and validation processes

Q15: Consistent data/model quality assurance processes

Participants were asked to respond to the statement: *"Our organization has defined processes and tools for data and model quality assurance."* According to the maturity score, there was moderate disagreement (-73) with 62% either disagreeing or strongly disagreeing. The responses were reasonably uniform from organization type and size, and higher levels of agreement were associated with more years of MBSE experience. However, the dip in the 4-6 years category suggests that there is a flat spot in this maturity category as the development of quality assurance processes start to become more mature. There is likely a need for earlier emphasis on these processes in the DE/MBSE transition.

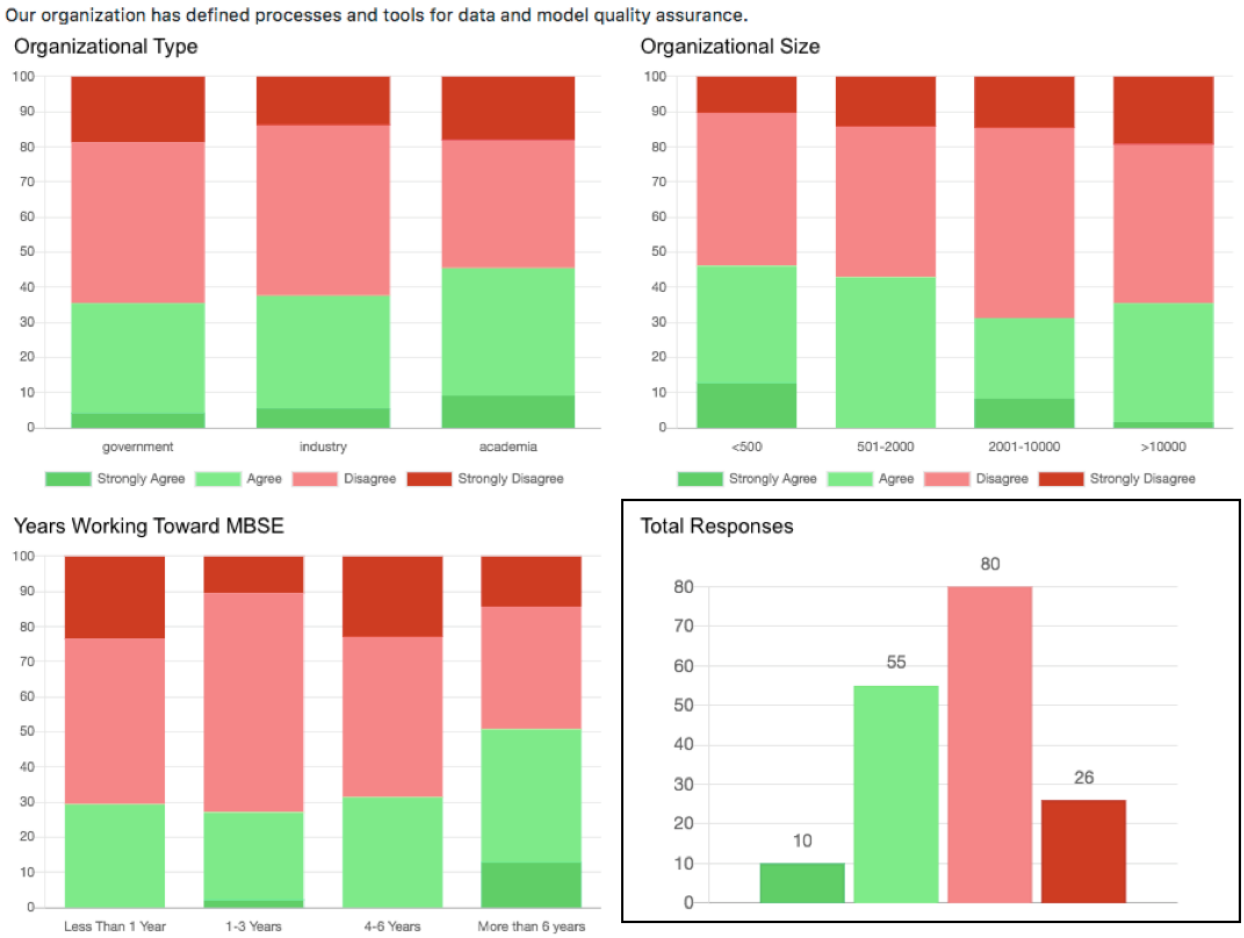

Figure 22. Consistent data/model quality assurance processes

3.3.6 Data Management

These questions reflect how well model data management is applied to all models for an enterprise, if data is independent of tools and allows for portability, if data is interchanged among tools, if there are standard plug-and-play interfaces for data across tools, and if associations among all data items are defined, captured, managed, and traceable where changes in one data source alerts owners of other data sources of intended updates. Respondents moderately to strongly disagreed with these statements, indicating a relatively low level of maturity. Maturity of data management processes is lagging maturity of model management processes, but only slightly.

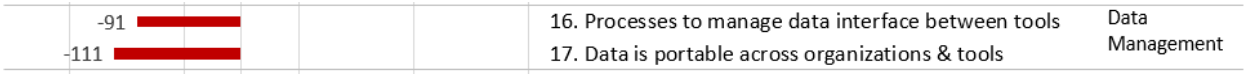

Figure 23. Data Management Scorecard

Participants were asked to respond to the free text question, "*Please identify any new data management roles and processes you have created*." Qualitative analysis of these responses can be found in the Workforce section 3.6.

Q16: Processes to manage data interface between tools

Participants were asked to respond to the statement: *"Our organization has effective approaches for managing the data interface between tools."* The maturity score shows that there was moderate to strong disagreement (-91). Over half (52%) of participants disagreed that their organization has effective approaches for managing the data interface between tools. The government respondents had the most participants strongly disagreeing (32%). The larger the company, the more participants either disagreed or strongly disagreed with the statement, indicating the move toward data-driven practices (as opposed to modeling itself) is much more advanced in smaller organizations. For this and the next statement, organizational size is a much larger determinant of DE/MBSE success than years of experience. This is likely due to the newness of DE/MBSE data management tools and processes (versus MBSE modeling tools), and the lower cultural obstacles to use in smaller organizations. At the time of this survey, MBSE experience seems to not be a determining factor, but that should change in the next few years.

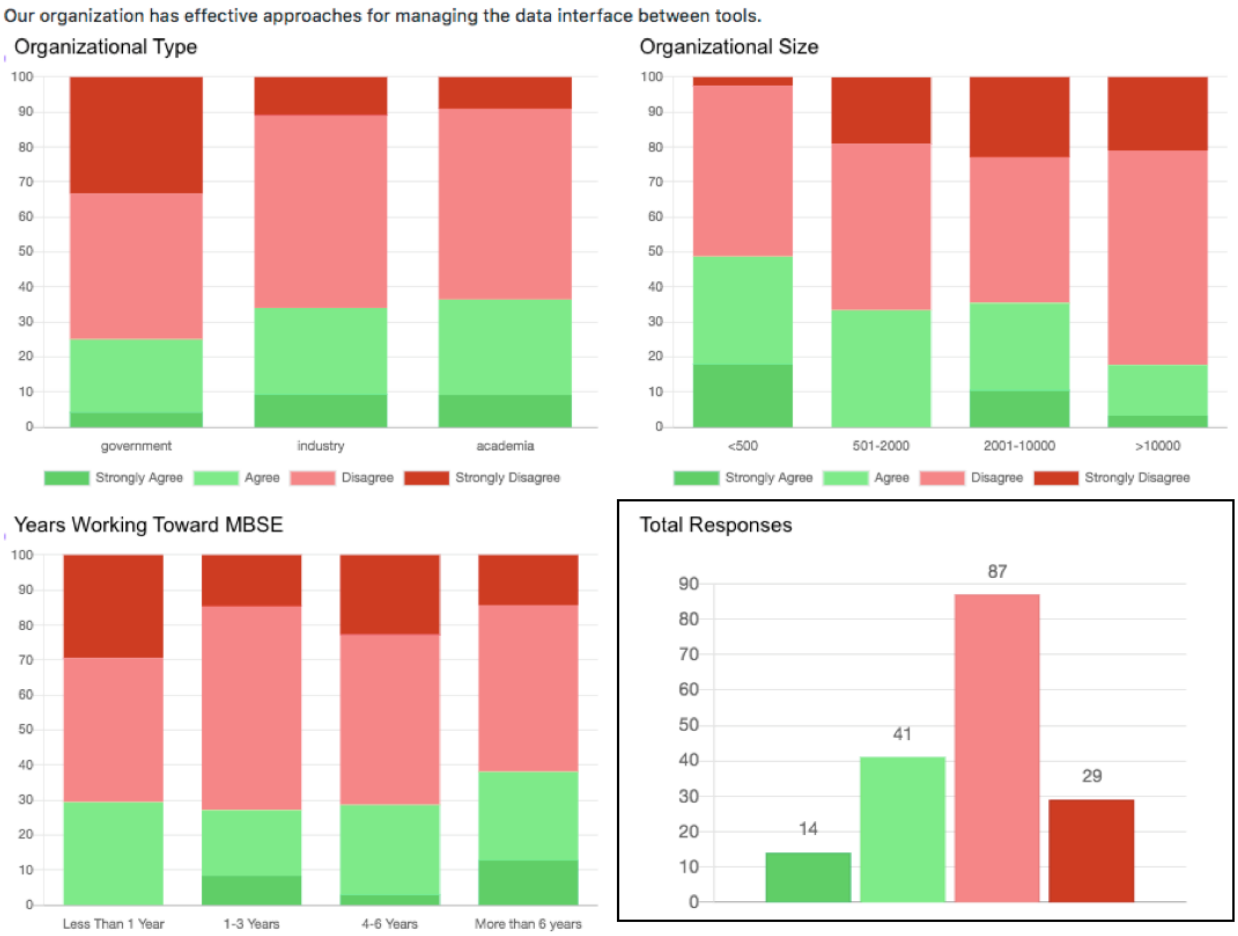

Figure 24. Processes to manage data interface between tools

Q17: Data is portable across organizations and tools

Participants were asked to evaluate the statement: *"Data is managed independent of tools and allows for portability across different organizational structures and related disciplines."* The maturity score shows that there was strong disagreement (-111). Organizational type/size and experience trends were similar to the previous survey statement. For responses from larger organizations, however, there was even more participants in strong disagreement than the previous survey statement. Overall, the two Data Management questions showed similar trends in response.

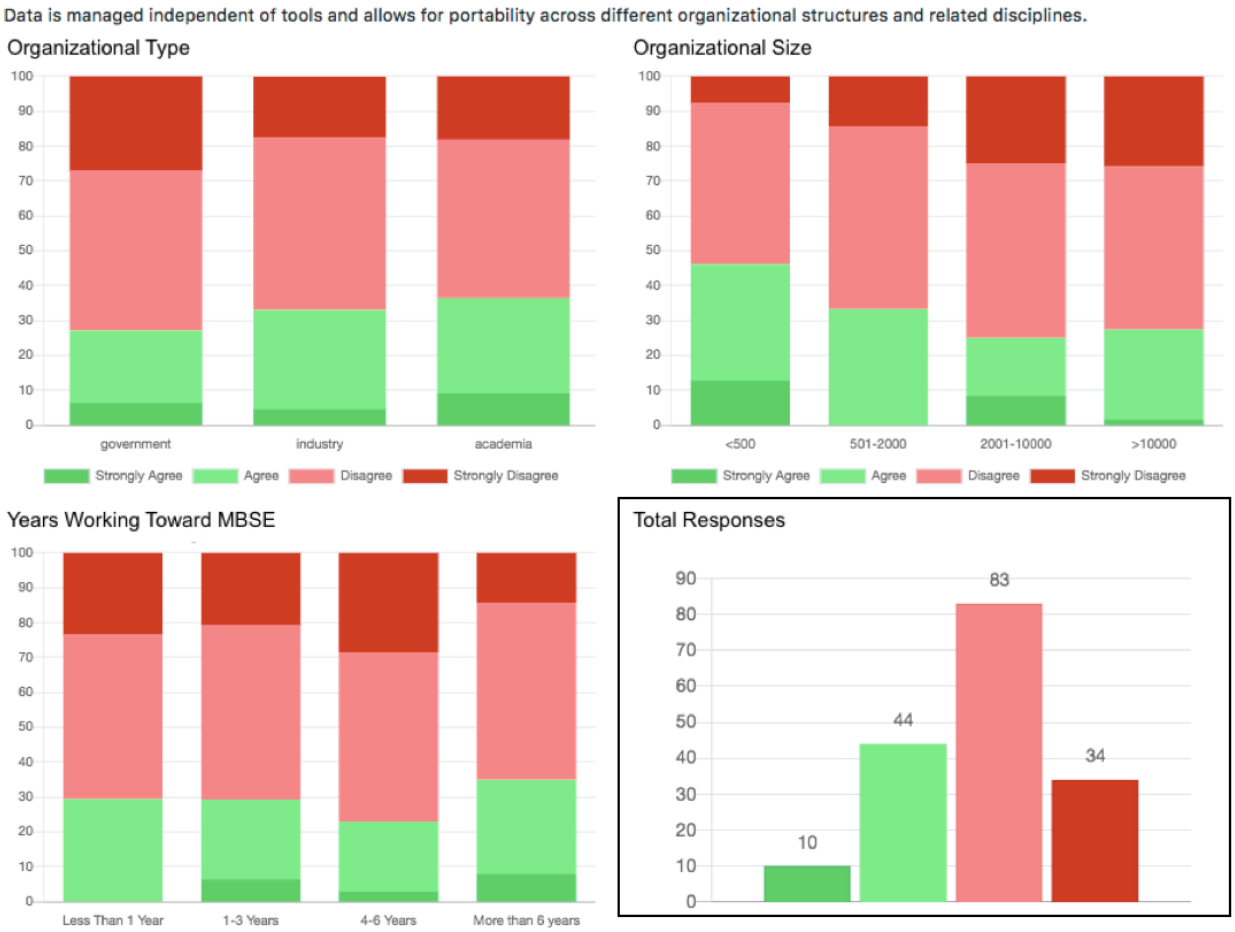

Figure 25. Data is portable across organizations and tools

3.3.7 Model Sharing and Reuse

This section was used to determine if project data and model libraries are established and shared across an enterprise in a curated manner. Tool interfaces should support interrogation of data and models across the federated enterprise and use of an authoritative source of truth allows the models to be scrutinized and have data and information discoverable. Data and model sharing provide knowledge to strategic real-time decision makers across the lifecycle and across the enterprise. However, data and model visualizations should be easily understood by a variety of stakeholders. For this area, respondents agree that their organizations support model libraries for reuse, but moderately to strongly disagree that they are consistently used or effectively support knowledge sharing for decision making. These trends are generally supported by the analysis of enterprise adoption and cultural obstacles in section 3.5: having people willing to use the data and models is as significant as the capabilities of the tools and skillsets.

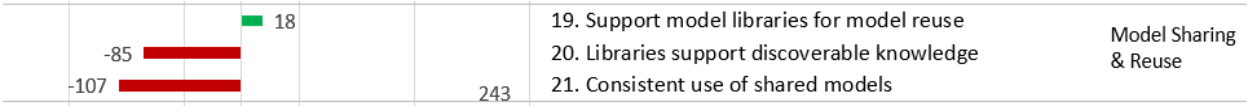

Figure 26. Model Sharing and Reuse Scorecard

Participants were also asked to respond to the free-text statement, "*Please identify any practices your organization has implemented to improve data and model discovery and reuse, either within or between teams. Include examples of appropriate model reuse if possible*."

Q19: Support model libraries for model reuse

The participants were asked to evaluate the statement: *"Our organization supports model libraries for the purpose of model reuse."* The maturity score shows that there was weak agreement (+18). Academia had stronger disagreement with this statement. Organization size was not a stronger determinant in the response, but participants indicating more than 6 years of experience had the highest agreement levels.

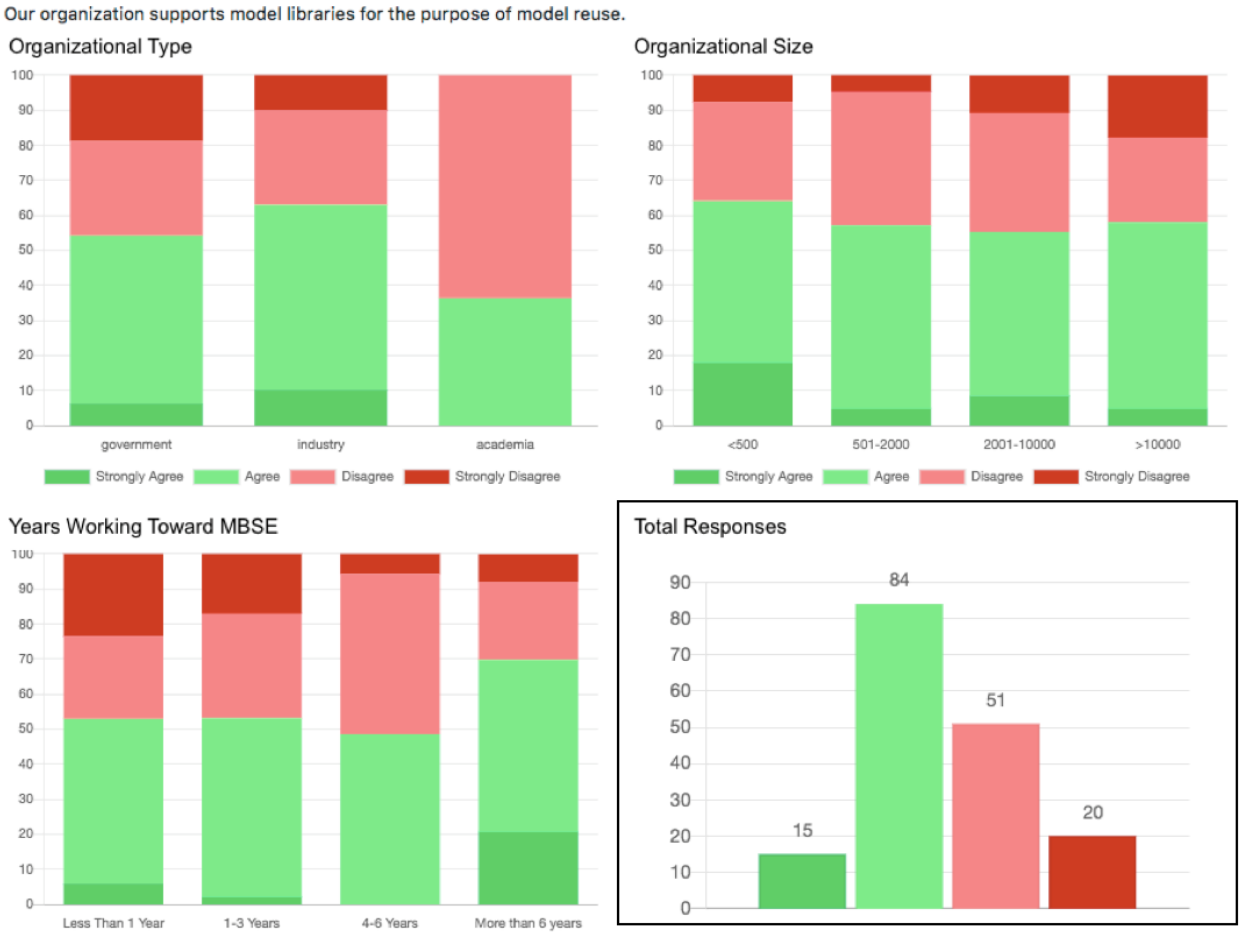

Figure 27. Support model libraries for model reuse

Q20: Libraries support discoverable knowledge

Participants were asked to respond to the statement: *"Our organization has implemented an interface around our models that can be used and understood by a variety of stakeholders."* The maturity score shows that there was moderate disagreement (-85). Half of participants (51%) disagreed with the sentiment, with an additional 15% strongly disagreeing. Academia saw the largest in disagreement at 62%, while the government sector had the most respondents strongly disagree with 24%. Companies under 500 employees saw the most in agreement (29% agree and 17% strongly agree). Years working towards MBSE for companies had mixed results. The organizations in the 'under a year' and 'more than six years' groups saw similarity, with 42% in agreement for under a year and 45% agreed and strongly agreed for companies over six years. Organizations that were between four and six years of working

towards MBSE saw the most disagreement, with 71% disagreed and 17% strongly disagreed. It is not clear why these experience trends are present, as they differ from general results across the other categories and statements.

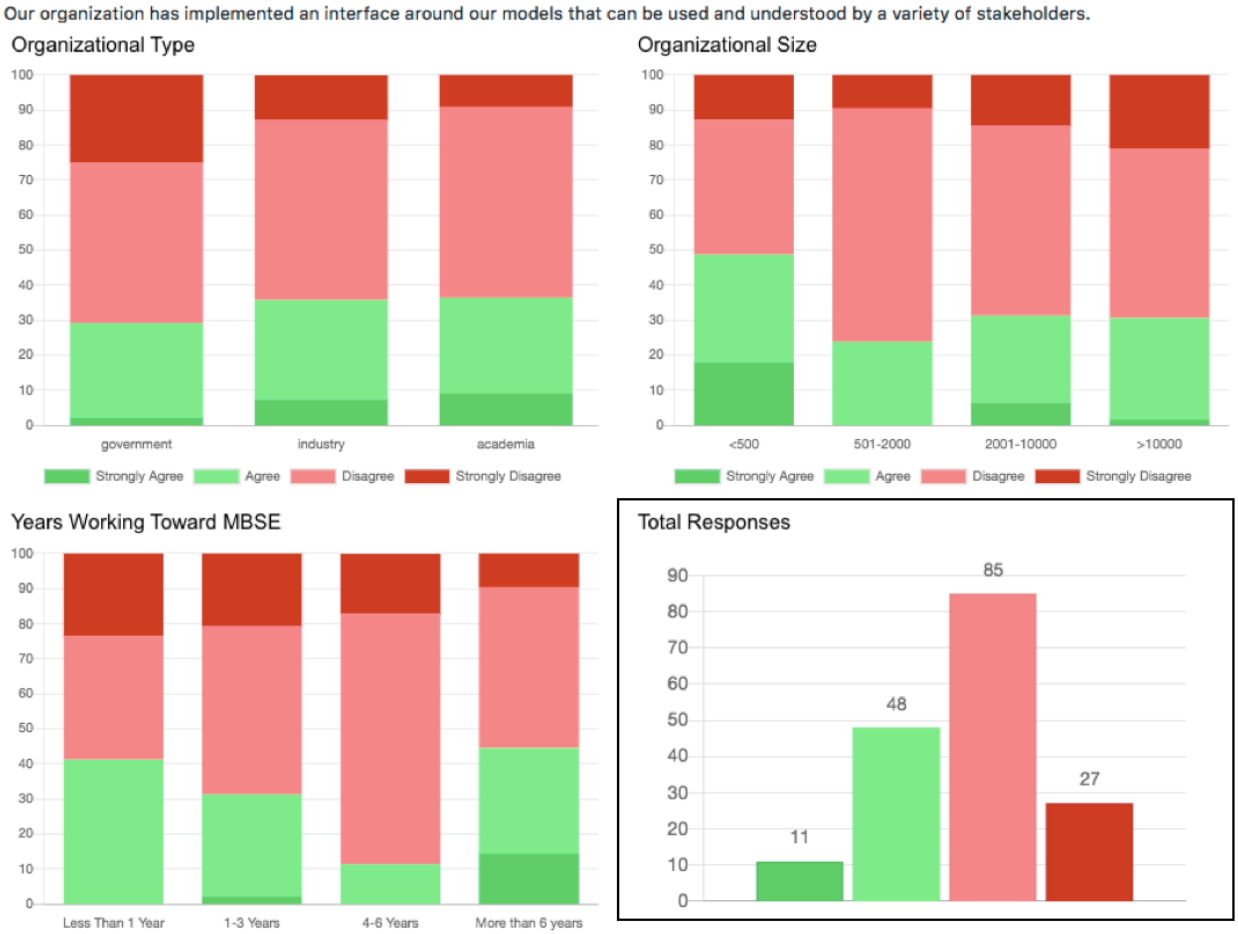

Figure 28. Libraries support discoverable knowledge

Q21: Consistent use of shared models

The participants were asked to evaluate the statement: *"Shared models are being used to consistently manage systems across the lifecycle."* The maturity score shows that there was strong disagreement (-107). Organization type had little effect on the responses. There was variation by organizational size. Smaller companies generally had stronger agreement, while larger companies generally had stronger disagreement. Organizations under 500 employees had the highest percentage of respondents in agreement. Organizations with less than a year of experience saw both the most respondents in agreement and the most strongly disagreeing. Organizations that have been working towards MBSE for 1-3 years had the most disagreement that their organization has shared models being used to consistently manage systems across the lifecycle at 62%. Again, it is not clear why these experience trends are present, as they differ from general results across the other categories and statements. This may be an area for further study.

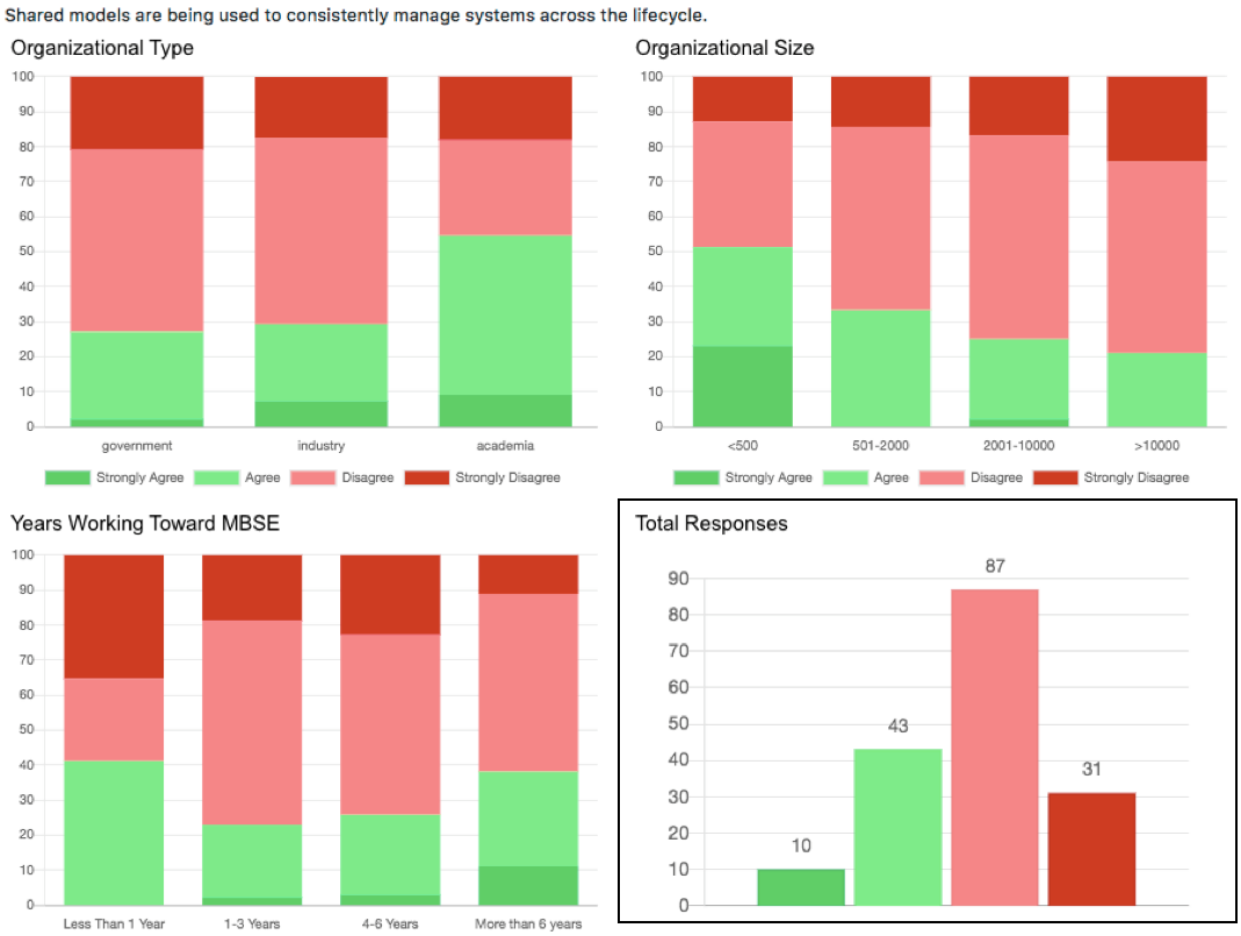

Figure 29. Consistent use of shared models

Q22: Practices to improve data and model discovery and reuse

Participants were asked to respond to the prompt, "Please identify any practices your organization has implemented to improve data and model discovery and reuse, either within or between teams. Include examples of appropriate model reuse if possible." Of the 240 survey participants, only 97 provided inputs to this question. Of these, 13 answers fell into the "none or not applicable" grouping. In addition, 26 were categorized as "TBD" or "too immature". This means that the participants indicated that their organizations are working on identifying what they will do but have not yet implemented these approaches. Examples of responses that fall into this category include, "Still fairly immature here. Re-use/sharing largely involves copying/comparison;" and, "Still in early adoption and definition." This left 58 responses that provided analyzable information.

Figure 30 shows the distribution of categories for the 58 analyzable responses. The most common approach provided was the creation of model or model element libraries. There were different ways that these were implemented (modules versus full models, reuse of wholesale models versus reuse of model elements), but 25 participants indicated that their organizations are taking this approach. Some responses (10) highlighted the ways their organizations have been focusing on tool-specific processes, highlighting the software tools that they are using. Challenges were highlighted by 10 of responses. Challenges included security restrictions that limit sharing and reuse, being able to share model data and reuse with non-MBSE stakeholders, getting buy-in from different parts of the organization on the value of MBSE, lacking clear understanding of how to guide reuse, and cultural resistance to changes in

approaches. Some participants (10) indicated that approaches are being implemented in individual projects or departments, but not holistically across their organization. A few other approaches were discussed by 2 participants each, as illustrated in Figure 30. The "other" categories were one-off responses provided by only a single participant. Examples include: "projects are required to create MBSE artifacts", "Search, User Experience, and graph database views have been developed to help with this purpose," or "Have a cross-company approach to Modularity and Reuse which utilizes models. An approach which is sponsored by the Executive and is gaining traction." Overall, the top three response categories can be considered foundational efforts to set up libraries, adapt to tool-specific reuse capabilities, and overcome adoption challenges. The rest of the response categories (except "others") can be considered more advanced efforts to build enterprise data and model reuse capabilities. Most organizations responding to this question remain in the foundational stages.

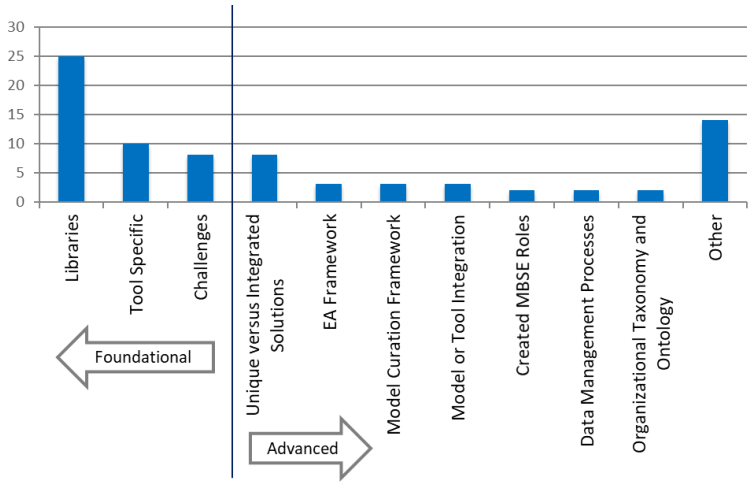

Figure 30. Free-text Responses: Data/Model Discovery and Reuse.

3.3.8 Modeling Environment

Enterprise capabilities require consistent and mature data and model infrastructure tools and processes. They have mature process to continuously examine and anticipate how technology can be used to solve problems. Model access permissions are shared within these enterprises, tool license counts are appropriate to the role, and access is controlled by role. Models across enterprises apply a common IP policy to model contents in the same way. Online, real-time collaboration among distributed teams is consistent across the enterprise and its customers and suppliers. Program and projects across related enterprises consistently apply the same tool governance policies. These combine to reflect a level of trust in the data and model infrastructure across levels of the enterprise. In general, respondents to the survey agreed or strongly agreed that such practices and trust is in place.

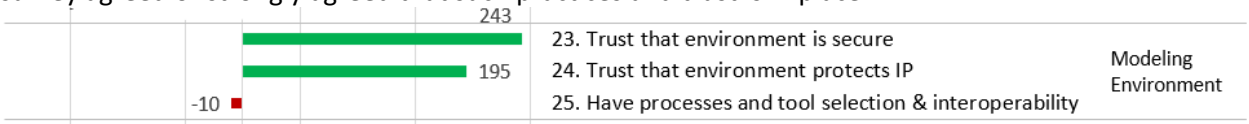

Figure 31. Modeling Environment Scorecard

Participants were also asked to respond to the free-text statement, *"Please identify any additional benefits you find from collaborating on models across disciplines."* These results are discussed in section 3.4.

Q23: Trust that environment is secure and Q24: Trust that environment protects intellectual property

Participants were asked to evaluate the statements: *"Our organization takes steps to make sure our modeling environment is secure,"* and *"Our organization takes steps to make sure that our modeling environment protects our intellectual property."* The analysis of these two statements is combined due to similarity of responses. These questions had the highest levels of agreement across all items in the survey (+243 and +195). A total of 58% of the respondents were in agreement that the organization takes steps to ensure the modeling environment is secure, and 56% that the organization takes steps to ensure the modeling environment protects intellectual property. Government respondents had the highest number of participants indicating strong agreement. The organizations that have been working toward MBSE for greater than six years had over half of the responses in strong agreement for both questions. These questions were included in the survey based on a DE/MBSE community concern at the time of the survey over security and protection of shared data and models in existing tool infrastructures. The survey responses appear to strongly counter those concerns, at least with respect to the steps that their organizations take to secure and protect data and models.

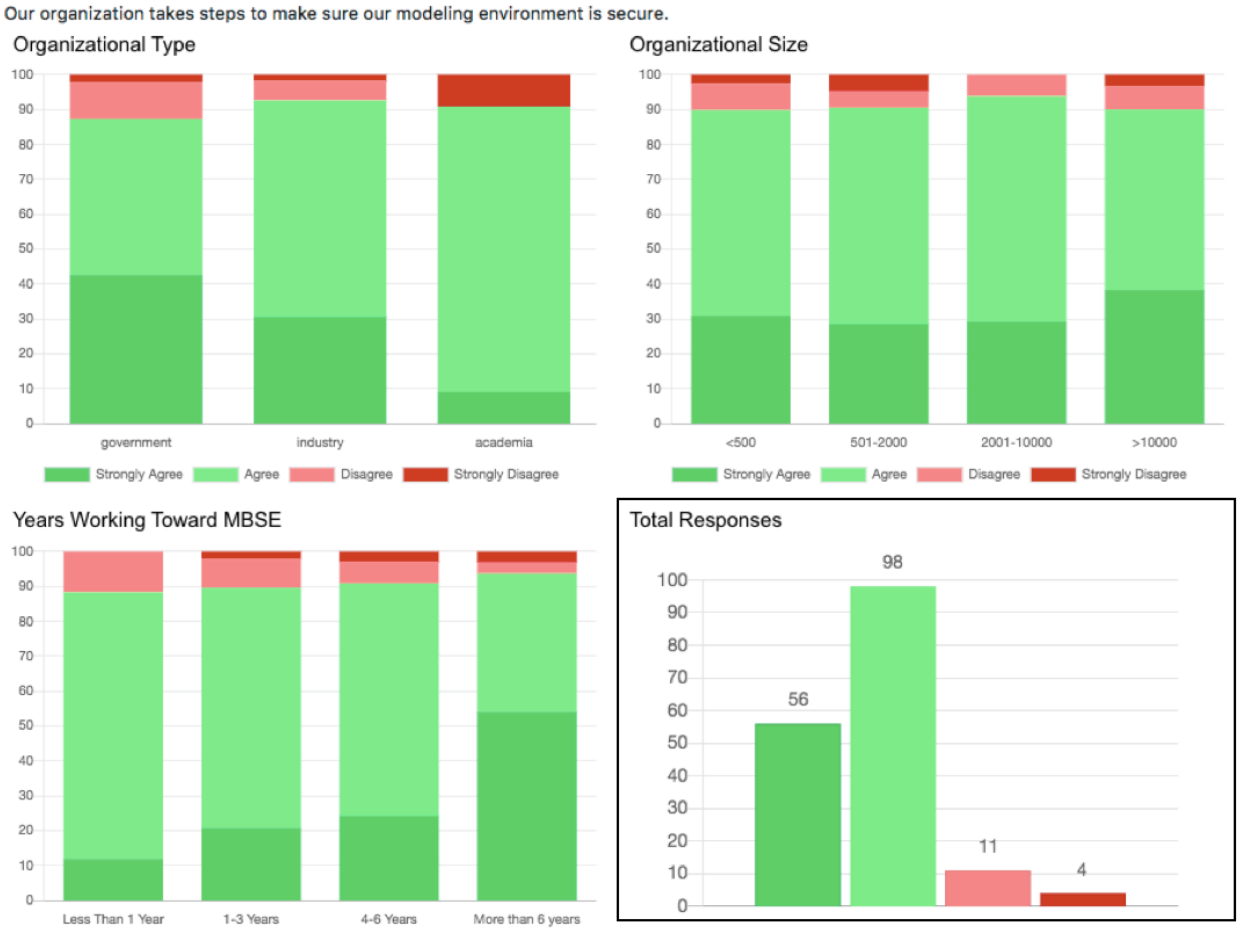

Figure 32. Trust that environment is secure

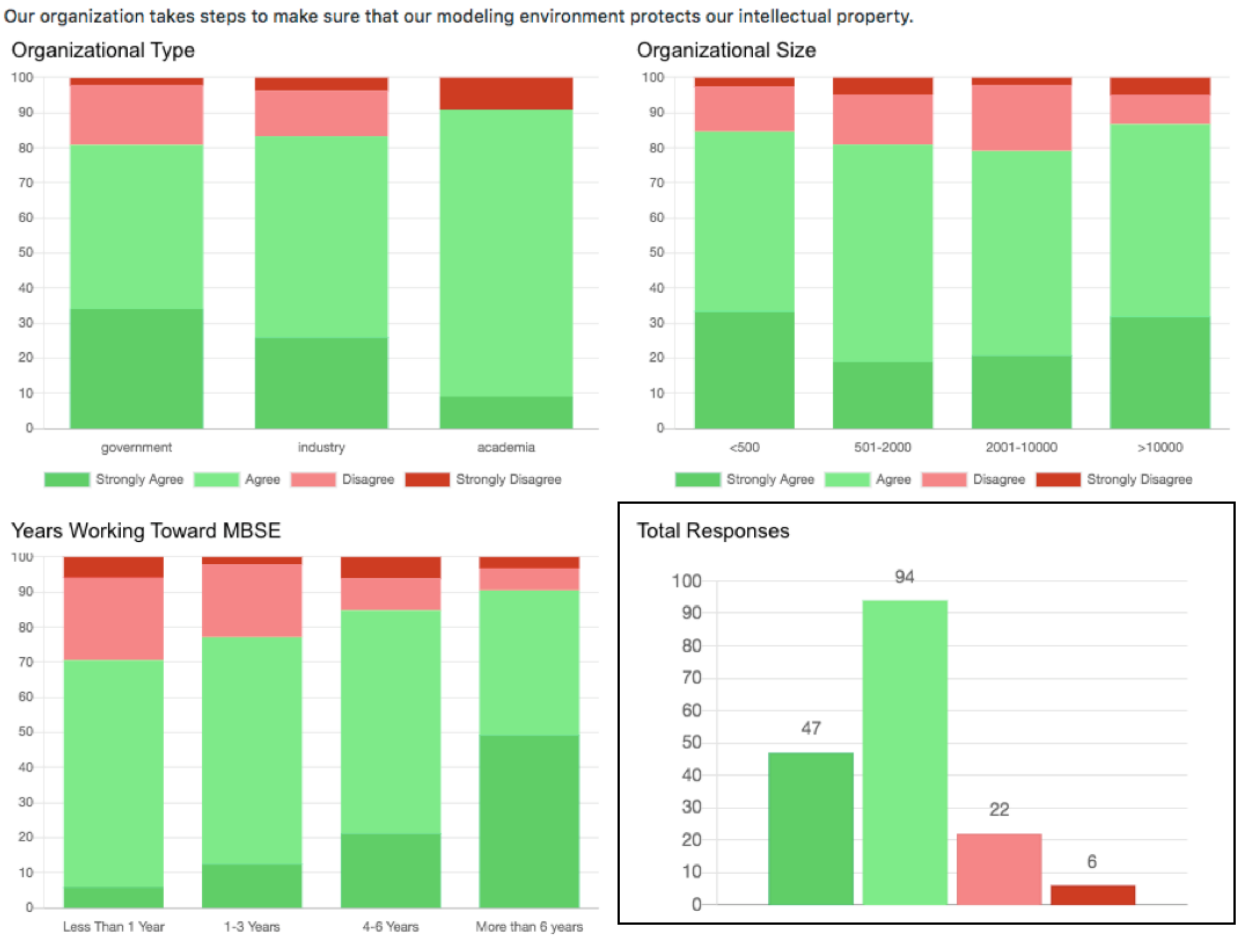

Figure 33. Trust that environment protects intellectual property

Q25: Have processes for tool selection and interoperability

The participants were asked to evaluate the statement: *"Our organization has defined processes and work instructions that cover tool selection, use, and related data interoperability concerns."* The maturity score shows that there was weak disagreement (-10). This particular statement had 39% in agreement and 11% strongly agree, with 37% disagreement and 14% strongly disagreeing. Results are evenly split, with responses from government, industry, and academia being relatively similar. Organizations that have been working toward MBSE for more than six years had the most agreement. This question can be interpreted to reflect the general trends for capability maturity across DE/MBSE tool and process infrastructures; it appears the community is in the mid-state of a long transition period.

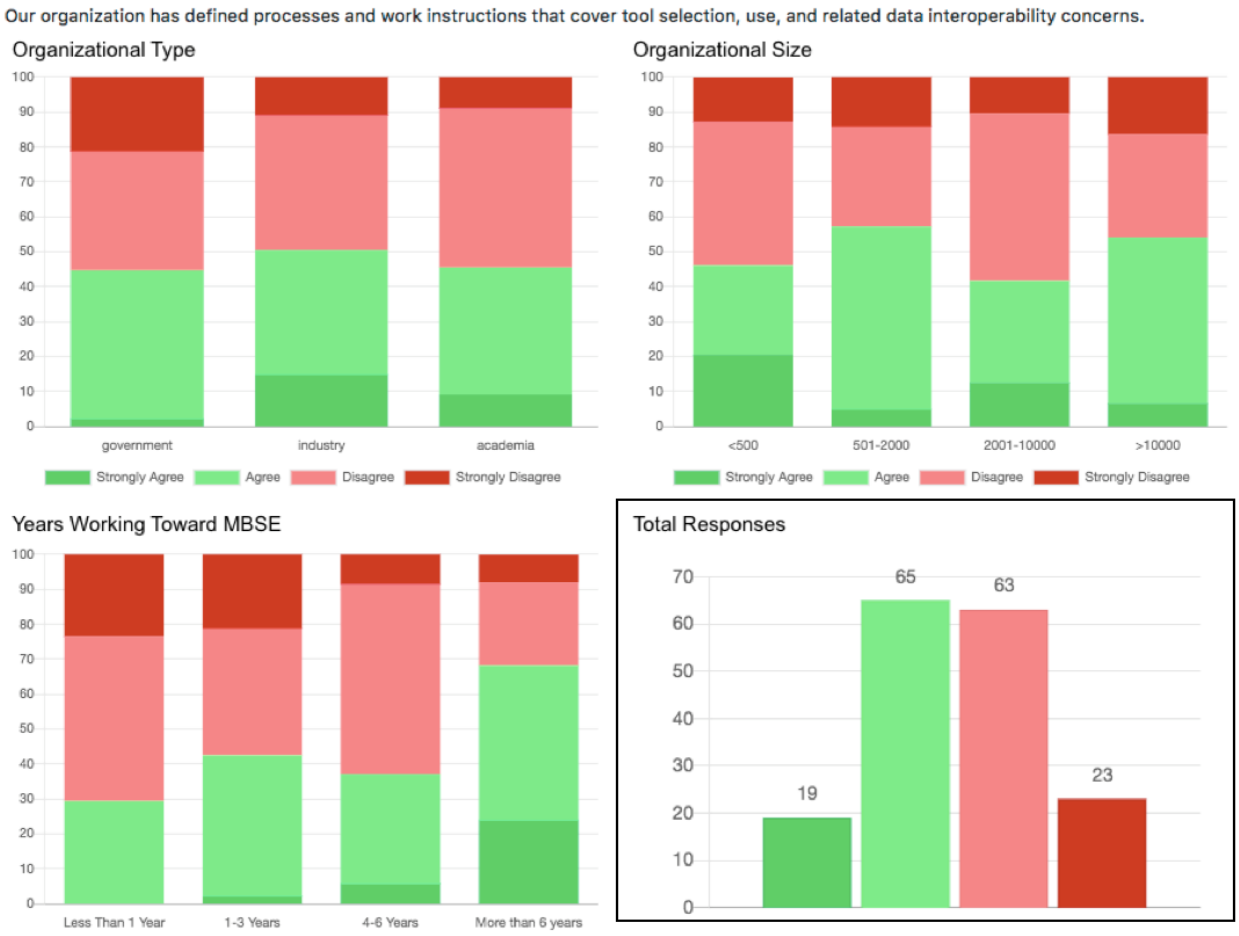

Figure 34. Have processes for tool section and interoperability

3.3.9 Organizational Implementation

The purpose of the organizational implementation section was to determine critical obstacles and enablers to implementing DE/MBSE. Specific questions asked included:

- Q27: *The most challenging obstacles to implementing MBSE in our organization are:*
- Q28: *The best enablers to MBSE in our organization are:*
- Q29: *Going forward, the biggest changes our organization needs to make to improve our implementation of MBSE are:*

In the organizational change literature, it is quite prevalent to study adoption/implementation of a particular change initiative from the perspective of *obstacles* (i.e., negative experiences) and *enablers* (i.e., positive experiences). This "polar opposite" approach involves asking respondents who have experienced a change initiative both questions in order to elicit a more comprehensive picture of the factors that may be associated with successful adoption. In this sense, one can identify a more robust and comprehensive list of success factors, regardless of whether they were experienced as an *obstacle* (or barrier, impediment, etc.) or *enabler*. An additional question focused on changes necessary provides another perspective to the responses for the *obstacles* and *enablers* questions – while the *obstacles* and *enablers* question asks respondents to reflect on their experience and perceptions to date, the question on *changes* asks them to think ahead in the future to what will increase the chances of success. These changes may represent things that will address problems/issues (*obstacles*) or will create success

conditions (*enablers*). Because answers were all free-text responses, the qualitative analysis is reported in section 3.4.

3.3.10 Workforce

The workforce of an organization must possess appropriate knowledge, skills, and abilities (KSAs) to perform the required activities. The workforce related questions of the survey explore workforce transition. This section asked participants to rate their level of agreement with whether there are clearly defined roles that support MBSE in their organizations as well as whether there is sufficient staffing for all the roles, particularly the critical positions. As shown below, participants generally disagreed that the roles for DE/MBSE were sufficiently well defined and even more strongly disagreed that there was sufficient staffing to support SE/MBSE activities.

In addition, a set of free text questions was used to gain more detailed information on the new roles and skills associated with DE and MBSE. Participants were asked to respond to the statements, *"The top MBSE role(s) in my organization are:"* and *"The most critical skills for MBSE are:".* The qualitative analysis results can be found in Section 3.6.

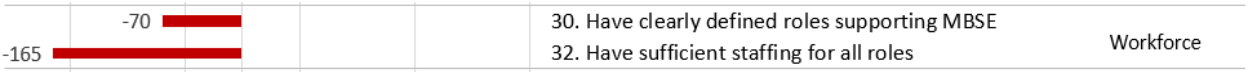

Figure 35. Workforce Scorecard

Q30: Have clearly defined roles supporting MBSE

Participants were asked to evaluate the statement: *"Our organization has clearly defined the critical roles to support MBSE."* The maturity score shows that there was moderate disagreement (-70). Over half of participants (53%) disagree that their organization has clearly defined roles to support MBSE. The most evident difference is within organizations that have been working towards MBSE. Those that have been working on implementation less than one year had 88% either disagree or strongly disagree. Organizations that had one to three years of working toward MBSE had 77% either disagree or strongly disagree. Neither had any participants strongly agree. For organizations with four to six years of working toward MBSE, nearly 6% of participants strongly agreed, 21% agreed, 62% disagreed, and 12% strongly disagreed. Participants from organizations who have been working toward MBSE for more than six years had 16% strongly agree, 37% agree, 41% disagree, and 6% strongly disagree. What these results may indicate is that organizations working on MBSE have been more focused on methods, processes, tools, and infrastructure and, overall, have not yet sufficiently considered workforce development considerations. However, it is worth noting that in small organizations particularly, qualitative responses indicated that "everyone" has responsibility for MBSE – which may mean that it has become part of the organizational culture in a way that does not result in clearly defined or separable roles.

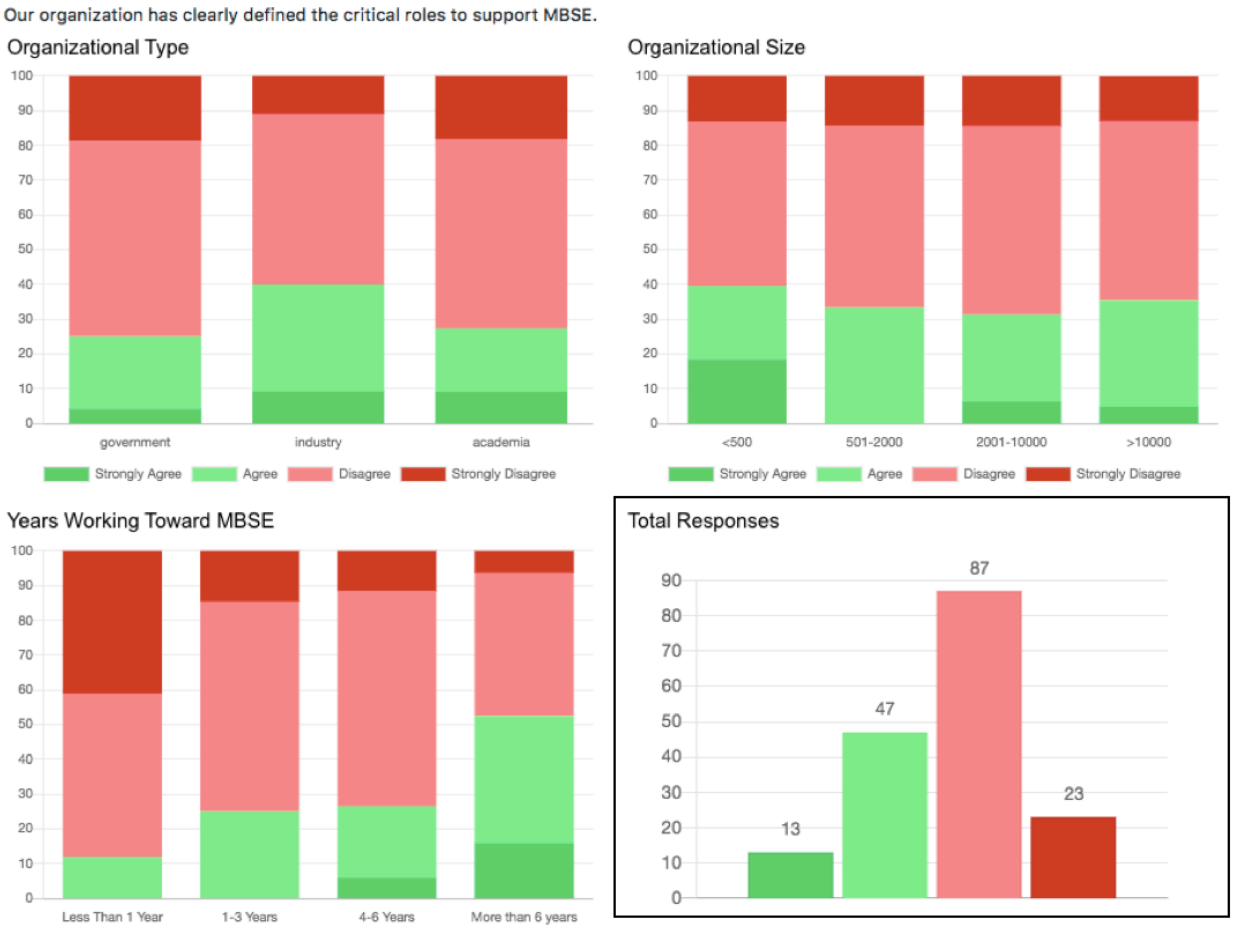

Figure 36. Have clearly defined roles supporting MBSE

Q32: Have sufficient staffing for all roles

Participants were asked to evaluate the sentence: *"We have sufficient staffing in our organization to fill all MBSE-related roles."* The maturity score shows very strong disagreement (-165). Over half of participants (53%) disagree that their organization has sufficient staffing to fill the MSBE-related roles. The government sector saw the most participants disagree and strongly disagree (54% and 34%, respectively). Industry had the most in agreement at 26%. There were higher levels of agreement with this question the longer an organization reported working towards MBSE.

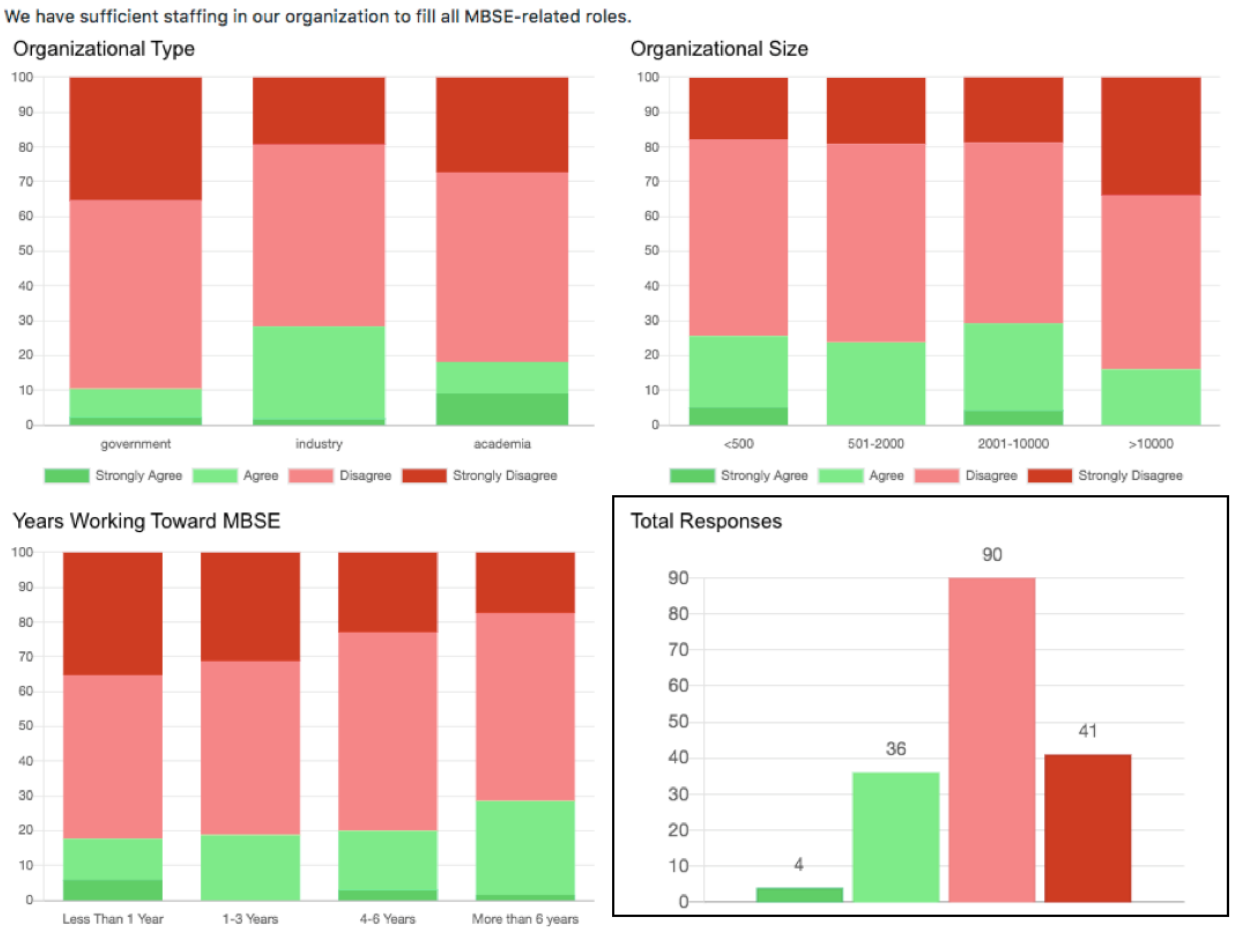

Figure 37. Have sufficient staffing for all roles

3.3.11 MBSE Skills

A part of integrating MBSE within an organization successfully is understanding and advocating for the specific skills needed for execution. This portion of the survey is to grasp whether organizations link training to critical skills, and if there are defined critical skills within the organization to support MBSE. Responses were fairly evenly split on whether training sufficiently linked to critical skills. Respondents disagreed that critical skills have been sufficiently identified; however, this disagreement is less strong than that seen regarding roles (as noted earlier). The focus on individual skills, rather than organizational implementation of those skills through roles, may be a useful indicator of maturity.

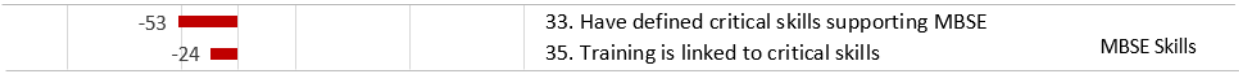

Figure 38. MBSE Skills Scorecard

Q33: Have defined critical skills supporting MBSE

Participants were asked to evaluate the statement: *"Our organization has clearly defined critical skills for MBSE."* The maturity score shows that there was moderate disagreement (-53). A little under half, 46%, of participants disagreed with the statement while 28% agreed. Industry had the most either agree or strongly agree, with 41%. However, government had 31% agree and 4% strongly agree. Nevertheless, the government sector had 28% of the participants strongly disagree that the organization has clearly

defined critical skills for MBSE. As expected, years of MBSE experience was associated with higher levels of agreement with the statement.

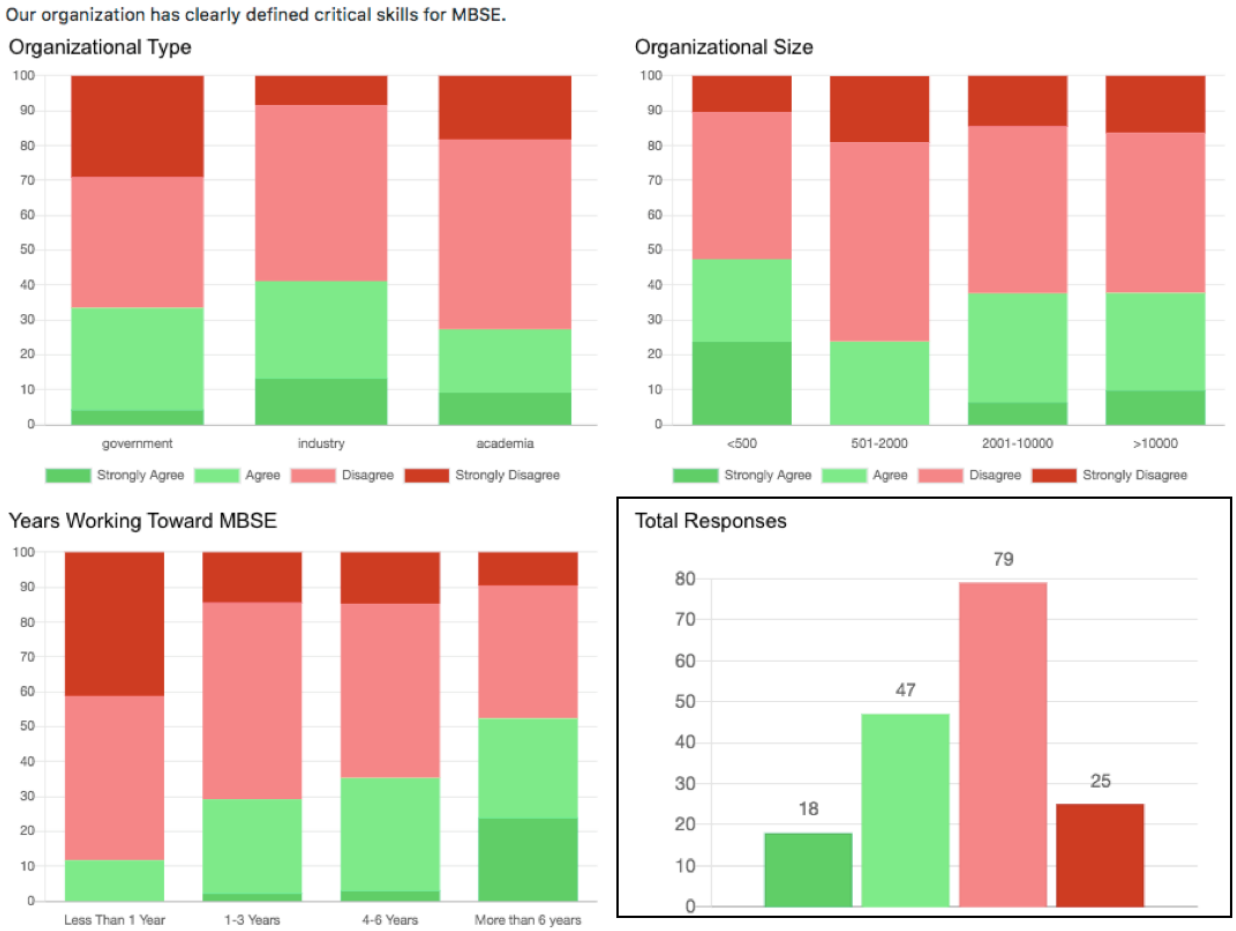

Figure 39. Have defined critical skills supporting MBSE

Q35: Training is linked to critical skills

The participants were asked to evaluate the statement: *"Our MBSE training is linked to the critical skills identified for MBSE."* The maturity score shows that there was weak disagreement (-24). Of the participants, 39% were in agreement and 36% of participants were in disagreement. The government had the most that strongly disagreed at 30%, and academia had the largest number of participants agreeing at 46%. Years of experience was less of a factor in responses to this question as the previous, but the trend still favors more experience.

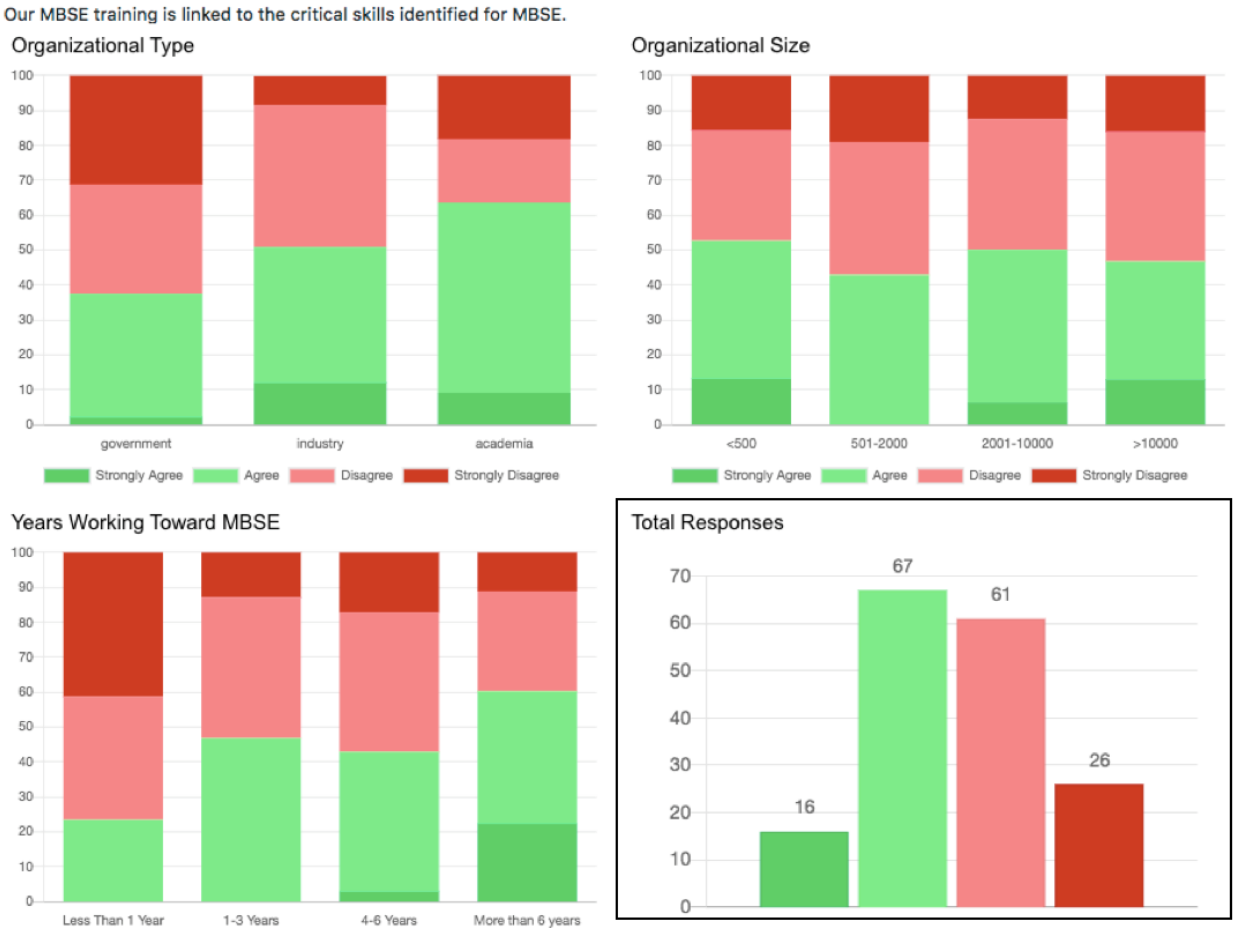

Figure 40. Training is linked to critical skills

3.4 Analysis of Text Responses, MBSE Benefits and Metrics

This section analyzes the free-text responses for those questions relating to MBSE benefits, value, and metrics. The section first discusses the analysis approach including the introduction of a framework linking value, benefits, and metrics. This framework was created from a literature review of publications citing MBSE benefits, along with a literature review of publications citing metrics for digital enterprise transformation. The actual text responses are then summarized quantitatively based on the framework.

3.4.1 Analysis Approach, MBSE Benefits Framework

Three survey questions related to benefits:

- *Q3. What do you see as the most important reasons for integrating MBSE processes with program and business management processes*,
- *Q7. Please provide one or more descriptions of the business value you are realizing from consistent model management processes and tools*, and
- *Q26. Please identify any additional benefits you find from collaborating on models across disciplines*.

While the three questions elicited responses indicating perceived or observed benefits of digital engineering and MBSE, there is a difference between the information elicited by Question 3 and by Questions 7 and 26. Answering Questions 7 and 26 required the respondent to have actually implemented MBSE in their organization and seen or experienced MBSE benefits directly. However, because Question 3 asked for reasons to integrate MBSE, it suffices for the responder to base their response on general knowledge, awareness, or even belief about how MBSE could benefit their organization.

Each of these three questions included some type of expected benefit of MBSE embedded within the statement (i.e., integration (Question 3), consistent model management (Question 7), and collaboration on models across disciplines (Question 26)). This structure may have led a respondent to report that particular benefit in their response. For the purpose of this analysis, all benefits were included in the analysis and summary of benefits reported for each question, even those that corresponded to the benefit explicitly mentioned in the statement itself, because respondents could have opted not to mention these benefits given the free-text nature of these questions.

Responses to the three questions were coded with the *a priori* "code list" representing benefits of MBSE shown in Table 2. The four general categories of Table 2 were developed from a literature review focused on digital enterprise transformation metrics, looking across similar digital enterprise transformation activities as well as agile software development activities and a previous SERC research report on digital engineering enabled transformation.[13] The Benefit Categories of Table 2 were developed as part of an independent literature review on MBSE benefits conducted in parallel with this survey.[14] They were used in this analysis in order to enable future research activities that explore the similarities and differences between the results of this survey and the evidence about the value and benefits of MBSE reported in existing literature. The list was deemed appropriate to use for the survey because survey questions 3, 7, and 26 had strong alignment with benefits of MBSE. Furthermore,

[13] Systems Engineering Research Center, Technical Report SERC-2018-TR-109, Enterprise System-of-Systems Model for Digital Thread Enabled Acquisition, July 13, 2018.
[14] Systems Engineering Research Center, Research Task WRT-1001, DE Metrics (ongoing).

because the literature review on benefits covered a large portion of the literature on MBSE, the benefits that emerged inductively from those papers was fairly comprehensive and probably covered most if not all of the benefits elicited through the survey. This was confirmed by an initial examination of the responses to these questions, which showed strong correlation with the codes elicited from the literature review. For context, the process to arrive at the list of benefits (and codes) as part of the literature review work is provided below.

Table 2. List of benefit categories used to analyze Questions 3, 7, and 26.

Category	Benefit Category	Sample Phrases from Literature
Quality	Improve system quality	higher quality, quality of design, increased system quality, first time quality, improve SE quality, improve specification quality
	Increased rigor	rigorous model, rigorous formalisms, more rigorous data
	Increased traceability	requirements/ design/ information traceability
	Reduce errors	reduce error rate, earlier error detection, reduction of failure corrections, limit human errors, early detection of issues, detect defects earlier, early detection of errors and omissions, reduced specification defects, reduce defects, remove human sources of errors, reduce requirements defects
	Reduce cost	cost effective, cost savings, save money, optimize cost
	Reduce risk	reduce development risk, reduce project risk, lower risk, reduce technology risk, reduced programmatic risk, mitigate risk, reduce design risk, reduce schedule risk, reduce risk in early design decisions
	Improved risk analysis	earlier/ improved risk identification, identify risk
	Improved system design	improved design completeness, design process, design integrity, design accuracy, streamline design process, system design maturity, design performance, better design outcomes, clarity of design
	Increased effectiveness	effectively perform SE work, improved representation effectiveness, increased effectiveness of model, more effective processes
	Improved deliverable quality	improve product quality, better engineering products
	Better requirements generation	requirements definition, streamlining process of requirements generation, requirements elicitation, well-defined set of requirements, multiple methods for requirements characterization, more explicit requirements, improved requirements
	Increased accuracy of estimates	confident estimates of accuracy
	Improved predictive ability	better predict behavior of system, predict dynamic behavior, predictive analytics
	Better analysis capability	better analysis of system, tradespace analytics, Perform tradeoffs and comparisons between alternative designs, simulation
	Improved capability	greater system capability
	More stakeholder involvement	easy way to present view of system to stakeholders, better engage stakeholders, quick answers to stakeholder's questions, share knowledge of system with stakeholders, stakeholder engagement, satisfy stakeholder needs
	Strengthened testing	model based test and evaluation, increased testability, improved developmental testing
Velocity/ Agility	Reduce time	shorter design cycles, time savings, faster time to market, ability to meet schedule, reduce development time, time to search for info reduced, reduce product cycle time, delays reduced

Category	Benefit Category	Sample Phrases from Literature
	Improved consistency	consistency of info, consistency of model, mitigate inconsistencies, consistent documentation, project activities consistent, data consistency, consistent between system artifacts
	Increased capacity for reuse	reusability of models, reuse of info/ designs
	Easy to make changes	easier to make design changes, increased agility in making changes, changes automatically across all items, increased changeability
	Reduce rework	reduce rework
	Reduce waste	reduce waste, save resources
	Increased productivity	gains in productivity
	Increased efficiency	efficient system development, higher design efficiency, more efficient product development process
	Increased transparency	transparent design
	Increased confidence	higher confidence in system solution, increased confidence in system validity
	Increased flexibility	flexibility in design changes, increase flexibility in which design architectures are considered
	Better requirements management	better meet requirements, provide insight into requirements, requirements explicitly associated with components, coordinate changes to requirements
	Ease of design customization	ease of design customization
	Higher level of support for integration	integration of information, providing a foundation to integrate diverse models, system design integration, support for virtual enterprise/ supply chain integration, integration as you go
	Increased uniformity	uniformity
	Increased precision	design precision, more precise data, correctness, mitigate redundancies, accuracy
	Early V&V	early verification and/or validation
	Reduce ambiguity	less ambiguous system representation, clarity, streamline content, unambiguous
User Experience	Higher level support for automation	automation of design process, automatic generation of system documents, automated model configuration management
	Reduce burden of SE tasks	reduce complexity of engineering process
	Better manage complexity	simplify/ reduce complexity, understand/ specify complex systems, manage complex information/ design
	Improved system understanding	reduce misunderstanding, common understanding of system, increased understanding between stakeholders, understanding of domain/ behavior/ system design/ requirements, early model understanding, increased readability, better insight of the problem, coherent
	Reduce effort	reduce cognitive load, reduction in engineering effort, reduce formal analysis effort, streamline effort of system architecture, reduce work effort, reduce amount of human input in test scoping
	Better data management/ capture	representation of data, enhanced ability to capture system design data, manage data
	Better decision making	make early decisions, enables effective decision making, make better informed decisions

Category	Benefit Category	Sample Phrases from Literature
Knowledge Transfer	Better accessibility of info	Ease of info availability, single source of truth, centralized/ unique/ single source of info, simpler access to info, synthesize info, unified coherent model, one complete model
	Better knowledge management/ capture	knowledge capture of process, better information capture, early knowledge capture, more effective knowledge management
	Improved architecture	help develop unambiguous architecture, rapidly define system architecture, faster architecture maturity, accurate architecture design
	Multiple viewpoints of model	shared view of system, more holistic representation of system/ models, dynamically generated system views
	Better communication/ info sharing	communication with stakeholders/ team/ designers/ developers/ different engineering disciplines, information sharing, knowledge sharing, exchange of information, knowledge transfer
	Improved collaboration	simplify collaboration within team

Twenty reputable journals and conferences known for publishing papers related to systems engineering were used in the literature review on MBSE benefits. These include the following:

- *From the field of systems engineering:* Systems Engineering, INSIGHT, INCOSE International Symposium, Systems, IEEE Systems Journal, IEEE Transactions on Systems, Man and Cybernetics, Conference on Systems Engineering Research, IEEE International Systems Conference, IEEE International Symposium in Systems Engineering;
- *From the field of engineering design:* Journal of Engineering Design, Design Science, Journal of Mechanical Design, Research in Engineering Design, International Conference on Engineering Design, ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference; and
- *From the field of space systems engineering:* Acta Astronautica, Journal of Spacecraft and Rockets, Journal of Aerospace Information Systems, AIAA Space, and IEEE Aerospace Conference.

The literature review initially identified 847 papers across all journals and conferences using "Model-Based Systems Engineering" OR "Model Based Systems Engineering" OR "MBSE" as search terms to identify relevant papers. Out of the 847 papers that mention MBSE, 360 (or 43%) cited one or more benefits of MBSE somewhere in the paper. These formed the final set from which the categories in Table 2 were obtained. The categories emerged inductively based on common occurrences in the literature. Each distinct benefit from each paper was counted as a unique occurrence. Slight aggregation of similar benefits was performed to account for the same meaning using different terms, as well as for handling complexity of the resulting set.

The digital enterprise transformation literature review created a categorization of Digital Engineering metrics. These were additionally used to provide the general category definitions in Table 2.

Gartner[15] reported four common characteristics for good digital transformation metrics:

- Measure people adoption, and enterprise process adoption (adoption)
- Analyze breadth of usability, and issues with usability (user experience)

[15] https://www.gartner.com/smarterwithgartner/how-to-measure-digital-transformation-progress/

- Measure productivity indicators (velocity/agility)
- Generate new value to the enterprise (quality and knowledge transfer)

To understand productivity indicators and areas of new value, a previous SERC study on digital enterprise transformation was used.[16] This study linked digital enterprise transformation to outcomes related to improved quality, improved velocity/agility, and better knowledge transfer. Knowledge transfer is a unique value of DE/MBSE that can be distinguished from other digital enterprise transformation metrics. This created a general categorization of DE/MBSE organizational change metrics linked to quality, velocity/agility, user experience, knowledge transfer, and adoption, as shown in Figure 41. Adoption metrics are discussed in section 3.5 of this report. Figure 41 only lists some of the top benefit categories in each metrics area; the full set of data is described in this section and section 3.5.

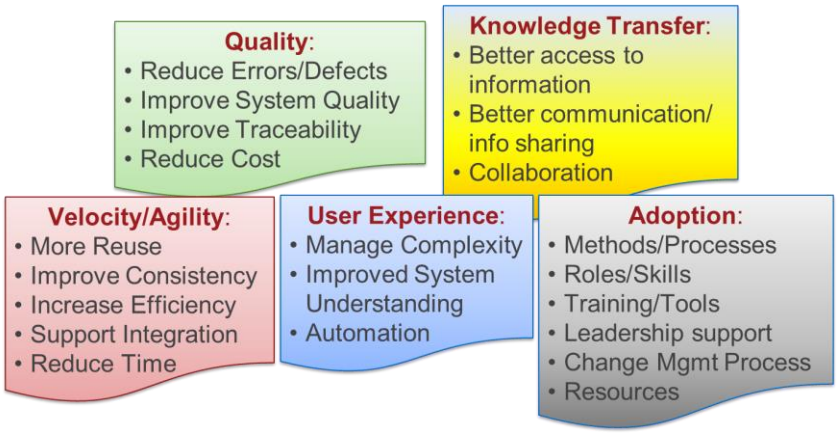

Figure 41. Metrics Framework for the Survey Analysis.

The initial list of benefit categories in Table 2 was developed from the literature review. In total, 45 of the 48 categories listed in Table 2 were cited in survey responses. The 3 that were not cited include "Increased accuracy of estimates," "Increased confidence," and "Ease of design customization." In addition, 2 additional categories that emerged during the analysis of the survey responses, were not in the baseline framework of Table 2. These include "Innovation" and "Continuous Improvement." Continuous Improvement was reported twice in response to question 7, which asked about business value from consistent model management processes and tools. It may also have replaced "Increased accuracy of estimates" and "Increased confidence" in the survey statements. Continuous Improvement could also have originated from "Better knowledge management/capture" and/or "Increased efficiency." Innovation was reported two times within question 26 responses about benefits from collaboration. Similarly, some "Better analysis capabilities" (e.g., the ability to do set-based design) are intimately related to higher levels of Innovation, as well as "Ease of design customization." As it could not be determined from the responses how these dependent benefits were realized and each was reported more than once, it was determined to keep these benefits defined as their own categories.

Responses were parsed into unique valid benefits comments. This means that one person's response to a question was parsed into unique statements that could correspond to different benefit categories. For example, the response "Opportunity for data analytics and visualization to shift burden of process

[16] Systems Engineering Research Center, Technical Report SERC-2018-TR-109, Enterprise System-of-Systems Model for Digital Thread Enabled Acquisition, July 13, 2018.

execution from people to machines in an effort to reduce cycle time and/or increase value (for a given cost)" was parsed into unique comments and assigned corresponding benefit categories as shown below in Table 3.

Table 3. Example of parsing a survey response to unique responses and allocation to benefit categories

"Opportunity for data analytics and visualization"	"shift burden of process execution from people to machines"	"reduce cycle time"	"increase value (for a given cost)"
Better analysis capability	*Reduce effort*	*Reduce time*	*Reduce cost*

The analysis framework was used to evaluate survey responses as discussed in the next section.

3.4.2 Evaluation of survey responses, MBSE Benefits Framework

A total of 338 responses was collected among the three questions. 88 responses either did not answer the question or provided an answer that was determined to not be an actual benefit. These responses were coded as Non-response. 24 responses indicated that no benefits or value had been achieved from the implementation of Digital Engineering or MBSE. In some cases, respondents indicated that although they had not yet achieved value, MBSE should provide value or they expect MBSE to benefit their organization in various ways. Thus, it was possible for a single response to be flagged both as no value achieved and as containing benefits. All other responses (226) were marked as containing benefits. A summary is provided in Table 4.

Table 4. Complete survey responses broken down by question.

	Non-response	**No value achieved**	**Response containing benefits**
Q3 Reason for integrating MBSE	41	N/A	104
Q7 Value from consistent model mgt.	23	18	70
Q26 Benefit from collaboration	24	6	52
Totals	**88**	**24**	**226**

Responses were coded to the benefit categories identified in the previous section. Across all three questions related to benefits, 566 unique valid benefits comments were recorded and analyzed against the codes in Table 5. As noted, none of the responses represented the literature cited benefits "Increased accuracy of estimates," "Increased confidence," and "Ease of design customization."

Table 5. Number of unique comments broken down by question

	Lit review benefits	**Unique survey benefits**	**Unable to categorize**
Q3 Reason for integrating MBSE	224	0	2
Q7 Value from consistent model mgt.	138	2	0
Q26 Benefit from collaboration	84	2	2
Totals	**446**	**4**	**4**

Figure 42 provides a summary of the data for all of the questions, representing the total number of times a benefit was cited for all of the 42 of the 45 benefit categories cited in the survey data.

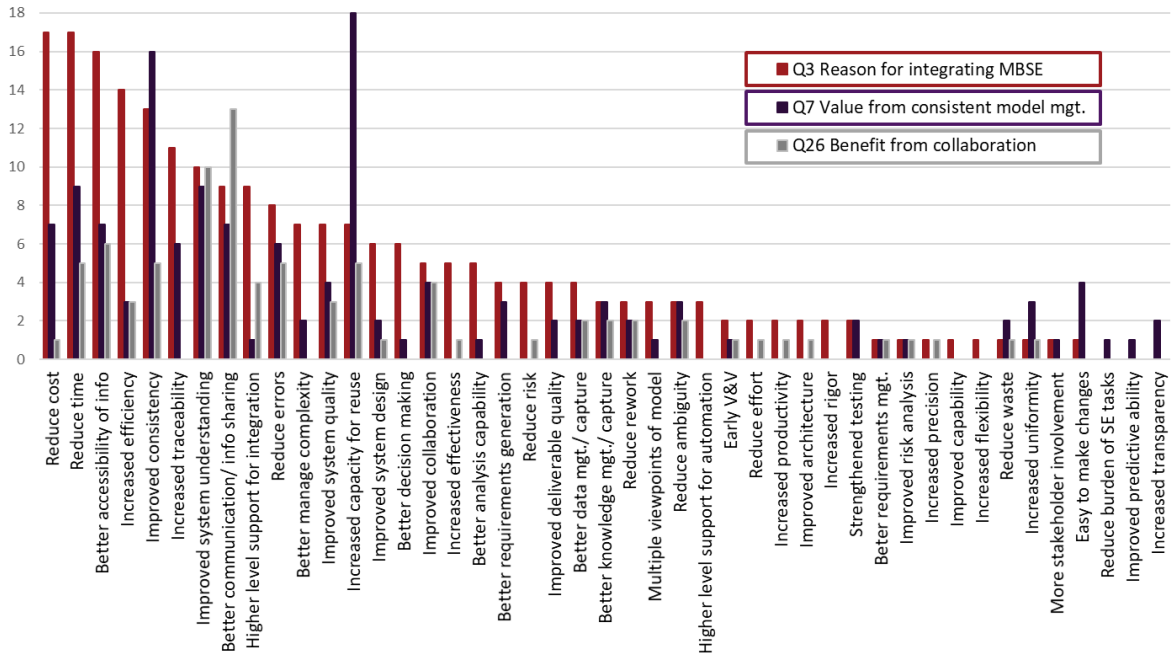

Figure 42. All Survey Questions on Benefits.

Figures 43-45 provide a summary of the data for each of the respective questions. For readability, the figures limit the benefit categories to those that had at least three cited responses.

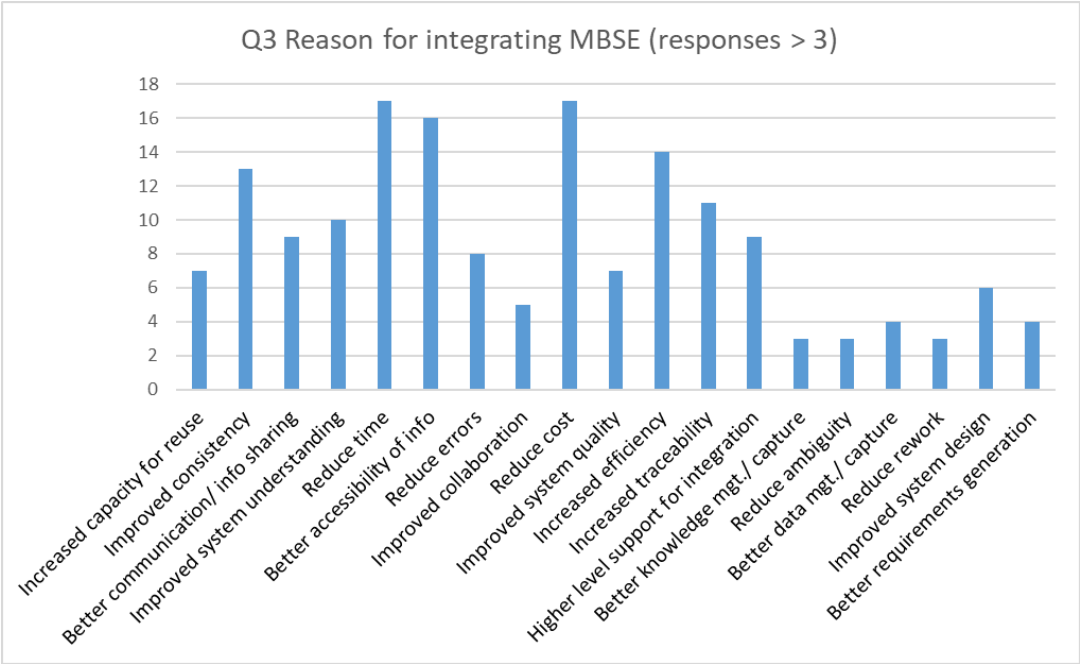

Figure 43. Reason for Integrating MBSE.

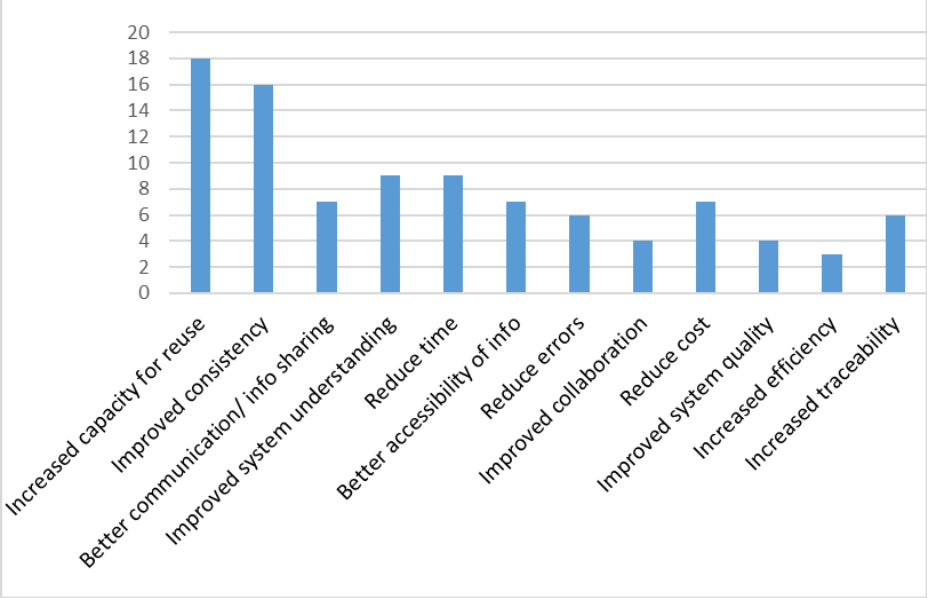

Figure 44. Q7: Value from Consistent Model Management.

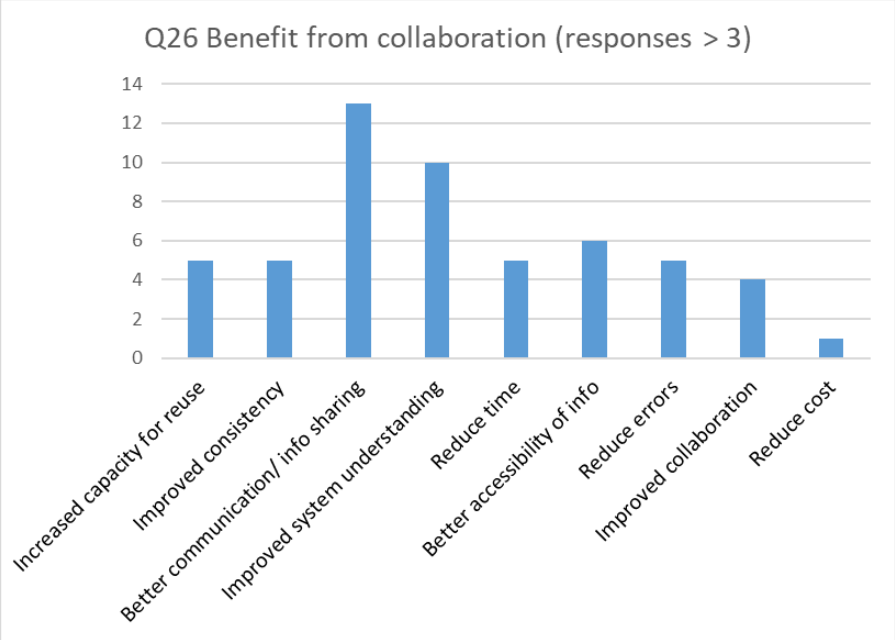

Figure 45. Benefit from Collaboration.

In general, the distribution of responses across the questions is fairly even, with a few outliers. Overall, because of its higher response rate (see Table 5), the number of benefits elicited through Question 3 (Figure 43) is higher than those elicited through the other questions. Yet, the results show that the highest benefits reported in Question 3 are closely aligned with those reported in the other questions. Three benefit categories that had a higher number of citations in Questions 7 and 26 than in Question 3. "Improved consistency" had a total of 16 responses in Question 7, "Better communication/ info sharing" had total of 13 responses in Question 26, and "Increased capacity for reuse" had a total of 18 responses in Question 7. "Increased capacity for reuse" had the highest number responses in any individual question.

Figure 46 summarizes the data by metrics category, showing overall that Velocity/Agility metrics are most cited overall, while improved Quality leads the "Reason for integrating MBSE" category. However, the spread of responses across all 4 categories indicates the need to broadly assess DE/MBSE benefits in enterprise transformation strategies.

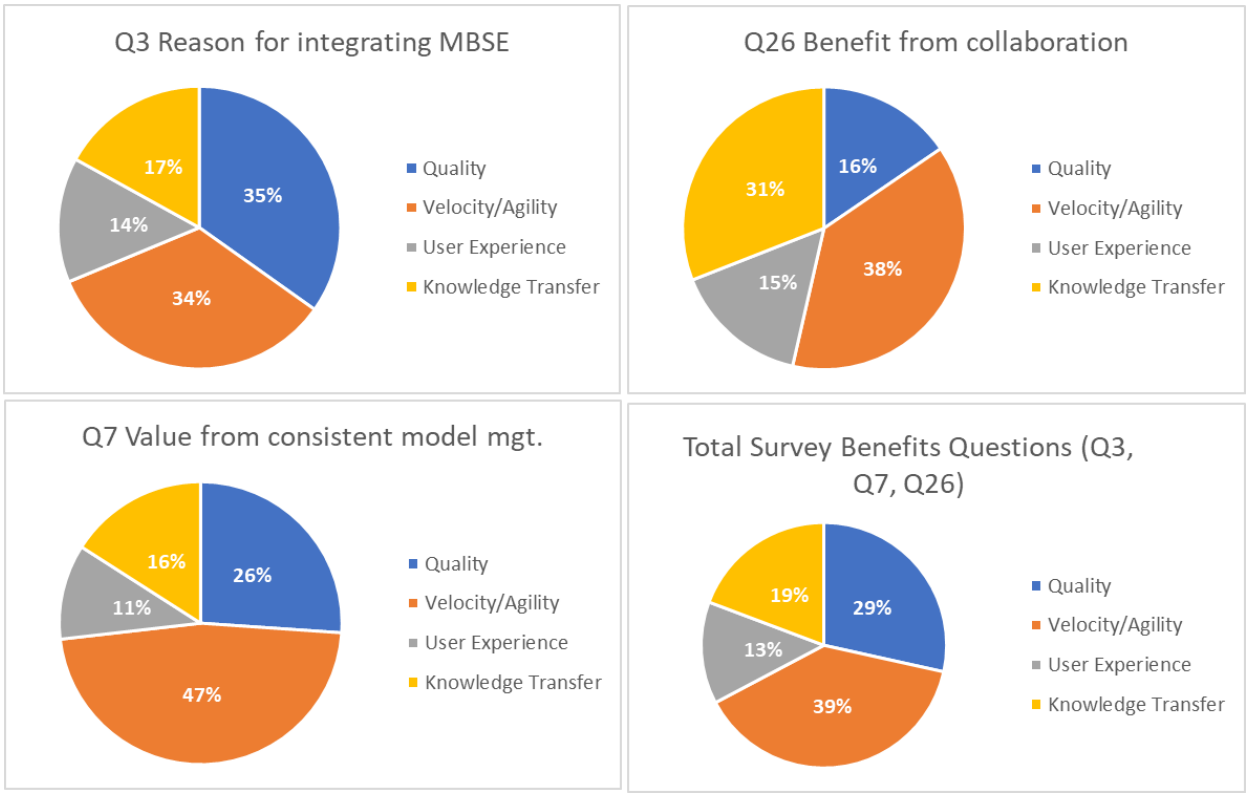

Figure 46. Survey Responses by Metrics Category.

3.4.3 Analysis Approach, MBSE Metrics Framework

Question 13, *Please identify any metrics that have proven to be useful for measuring the performance of your MBSE activities*, was also initially analyzed against the literature review benefit categories noted previously in Table 2. It was determined that the specification of metrics for measuring the performance of MBSE activities should lead to responses that show how valuable (or not valuable) MBSE activities are based on measurable performance. The potential value (or benefits) of MBSE are sufficiently covered with the benefit categories previously listed in Table 2. Using a similar classification system from the benefit questions, Non-response was used to designate responses that did not answer the question or were deemed to not be a metric. There were also some responses that were unable to be categorized. Table 6 provides some example quoted responses from the survey data for each benefit category.

Table 6. Example survey responses for metrics for each benefit category with a non-zero response

Category	Benefit Category	Example survey responses
Quality	Better requirements generation	Number of requirements we can assimilate or create, health (completeness) of technical requirements, developed system of system requirements, metrics that measure total requirements, additional requirements captured via MBSE vs Requirements captured via conventional requirements engineering.

Category	Benefit Category	Example survey responses
Quality	Reduce errors	Number of errors, number of mismatches, model defects found during detail design
Quality	Increased traceability	Reduced number of errors in traceability matrices, traceability matrix, traceability of emerging model elements to source (user or system) requirements
Velocity/ Agility	Better requirements mgt.	Requirements measurement, needs without requirements or vice-versa are examples of indicators for added focus, requirements validation, relations of technical requirements to other model elements
Quality	Improved system design	Completeness of interfaces, completeness of design, behavior and structure for decomposition to subsystem/component development at IPT / Subcontract level, with interface and SWAP identified at the boundaries
Quality	Reduce cost	Cost metrics comparing MBSE to traditional methods, cost savings, operating cost
Velocity/ Agility	Reduce time	Various time metrics, time it takes to accomplish standard SE/PM tasks, time to market, labor time, recorded time spent creating model based definition vs. 2D definition
Velocity/ Agility	Increased capacity for reuse	Reusability, reusable elements/components/objects, reuse of parts of models across projects
Quality	Better analysis capability	Number of documents we can incorporate in our analysis, ease of performance trade-offs and analyses, amount of simulation/ executions of models
Quality	Improved system quality	Quality improvement, 1st time quality improvement of SE and downstream disciplines
Quality	Increased effectiveness	Reduced number of RIDs (Review Item Discrepancies), number of revisions
User Experience	Higher level support for automation	Number of automations, quantity of documents/artifacts auto-generated from model
Velocity/ Agility	Higher level support for integration	Number of integrations, various interoperability
Knowledge Transfer	Better knowledge mgt./ capture	Populate metadata parameters
User Experience	Better manage complexity	Complexity
User Experience	Improved system understanding	measure aggregated lifecycle states across our modelled data to understand the state of development of all artefacts
Knowledge Transfer	Better accessibility of info	Availability of dedicated SE artifacts
Quality	Reduce risk	Risk
User Experience	Better decision making	Number of reports generated from the model on a monthly basis that are requested by and used by decision makers to make business decisions
User Experience	Reduce effort	Project effort
Knowledge Transfer	Multiple viewpoints of model	Number of links/ dependences
Quality	Improved deliverable quality	Quality of dedicated SE artifacts
Quality	Improved capability	Systems capabilities

Category	Benefit Category	Example survey responses
Velocity/ Agility	Reduce ambiguity	Rounds of confusion
Quality	Strengthened testing	Virtual optimization
Velocity/ Agility	Increased uniformity	Meeting best practices
User Experience	Better data mgt./ capture	Monitoring of system interfaces and data allocation to those interfaces

There was an emerging category that was unrelated to benefits and therefore not able to be coded against the categories from Table 2. This category was labeled Adoption metrics. These metrics were related to the successful adoption and implementation of MBSE instead of measuring the value of (or outcomes associated with) MBSE itself. Some examples that fell into this category were: "Number of projects using MBSE", "Leadership buy-in", and "Annual MBSE projects funding". Because these adoption metrics more closely relate to the Enterprise Adoption Framework used to categorize Questions 27 and 28 (obstacles and enablers to implementing MBSE), these responses were coded using the categories in section 3.5, Table 15.

3.4.4 Evaluation of survey responses, MBSE Metrics Framework

A total of 96 responses was collected from Question 13. Nineteen were marked as non-responses and 33 respondents indicated that they were not utilizing metrics, as summarized in Tables 7 and 8. While about half of the respondents did not provide any additional explanation about why they did not use metrics, the other half provided interesting insights. Table 9 shows the categories that emerged inductively by reviewing the responses. Sixteen respondents showed interest in developing metrics and two respondents indicated that their decision to use metrics was driven by customer requirements (and hence, we assume, not by a perceived value in using metrics).

Out of the 16 respondents that showed interest in using metrics, 3 indicated that they did not actually know how to develop them and 5 indicated that metrics were under development. The other 8 indicated that their implementation was too nascent for metrics to be put in place.

Table 7. Complete survey responses for metrics

	Non- response	No metrics	Response containing metrics
Q13 Metrics for MBSE	19	33	44

Table 8. Additional analysis of No metrics survey responses

"None" – no elaboration	Metrics in development	Too early in implementation/ immature	Need help developing/ no example metrics available	Customer doesn't prioritize metrics
15	5	8	3	2

Mapping between the survey response metrics and the categories in Table 6 is shown in Table 9. These would reflect general categories of adoption metrics and have been linked to additional codes that will be provided and discussed in Section 3.4.

Table 9. Unique comments categorized as Adoption metrics

Survey response metric	Code according to the Enterprise Adoption Framework
Authors	People willing to use MBSE tools
Licenses/ licenses per org	General resources for MBSE implementation
Un-modeled elements	MBSE methods/processes
Consumption	Project/ programs to apply MBSE
Management interventions	Leadership support/ commitment
Number of modeled projects	Project/ programs to apply MBSE
Number of engineers trained in model development using SysML tools	Training
Annual MBSE projects funding	General resources for MBSE implementation
Number of projects using MBSE	Projects/ programs to apply MBSE
People who have been through a MBSE or SysML training class	Training
Percent completion of plan vs. original plan	Change management process design
Leadership buy-in	Leadership support/commitment
Some areas use Number of Diagrams produced by type	MBSE methods/processes
Number MBSE practitioners	People willing to use MBSE tools
Number of engineers who participated in MBSE training	Training
Number of active Programs implementing MBSE	Projects/ program to apply MBSE
Disclosed value of Programs implementing MBSE	Demonstrating benefits/results

The remaining 44 responses were parsed into 100 unique statements. As shown in Table 10, unique statements were divided into those that reflected adoption metrics and those that reflected metrics to track business-focused outcomes from MBSE. In addition, 11 unique statements were left uncategorized because they contained metrics that did not address the question of measuring MBSE performance or fit into the emerged Adoption metrics category. As there was not a common thread emerging from these 11 statements they were left as Unable to categorize.

Table 10. Number of unique comments for metrics question

	Adoption metrics	Table 2 benefit metrics	Unable to categorize
Q13 Metrics for MBSE	17	72	11

Figure 47 shows the breakdown of metrics by the four top-level metrics categories discussed previously. In the Question 13 metrics related responses, quality metrics are most cited.

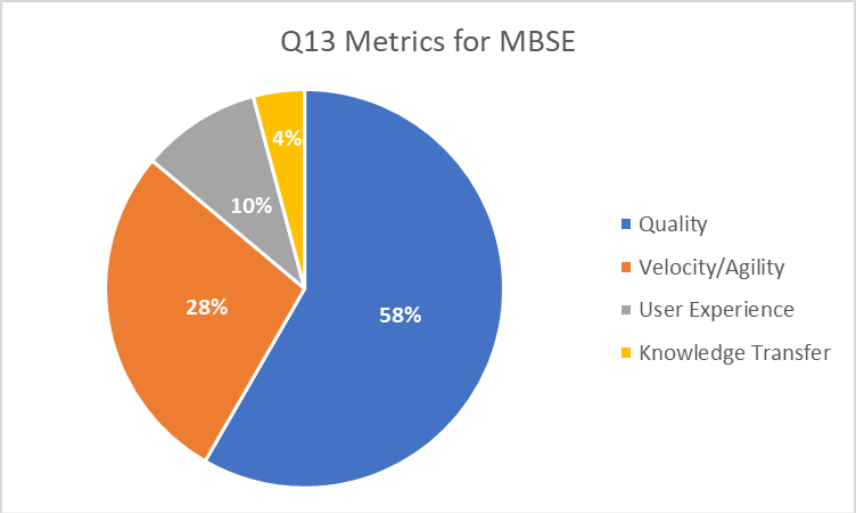

Figure 47. Metrics cited in free text responses by top-level metrics category.

Table 11 compares the top survey cited metrics from Q13, and the top benefits from the combined Q3, Q7, and Q26 that had at least 5 citations. The first section of the table is ranked according to the top metrics responses having at least 2 citations. There were 25 benefit categories in Table 2 that had greater than 5 citations, these are included in column 2. The second section of the table is ranked by the remaining benefit categories. There were overall 27 of the 48 benefit categories from Table 2 that were not cited in the free-text responses for the metrics question, including 6 of the top 25 benefit categories.

The distribution of responses seems reasonable at a conceptual level, since metrics related to Quality and Velocity/Agility are likely more straightforward to measure. However, many of the most commonly cited benefits also lie in the User Experience and Knowledge Transfer categories, which are significantly less represented in the survey responses. Therefore, there is an imbalance between the expected benefits of MBSE and the implementation of MBSE metrics to measure the achievement of those benefits.

Table 11. Top metrics to benefits comparison (part 1)

Top survey response metrics (Q13 only)		**Survey response benefits (Q3, Q7, and Q26)**	
Better requirements generation	7	Better requirements generation	7
Reduce errors	7	Reduce errors	19
Increased traceability	6	Increased traceability	17
Better requirements mgt.	6	Better requirements mgt.	3
Improved system design	5	Improved system design	9
Reduce cost	5	Reduce cost	25
Reduce time	5	Reduce time	31
Increased capacity for reuse	5	Increased capacity for reuse	30
Better analysis capability	4	Better analysis capability	6
Improved system quality	2	Improved system quality	14
Increased effectiveness	2	Increased effectiveness	6
Higher level support for automation	2	Higher level support for automation	3
Higher level support for integration	2	Higher level support for integration	14

Table 11 (continued). Top metrics to benefits comparison (part 2)

Remaining survey response metrics (Q13 only)		Top Survey response benefits (Q3, Q7, and Q26)	
(not cited)	0	Improved consistency	34
(not cited)	0	Increased capacity for reuse	30
Better accessibility of info	1	Better accessibility of info	29
Improved system understanding	1	Improved system understanding	29
(not cited)	0	Better communication/ info sharing	29
(not cited)	0	Increased efficiency	20
(not cited)	0	Improved collaboration	13
Better knowledge mgt./ capture	1	Better knowledge mgt./ capture	8
Reduce ambiguity	1	Reduce ambiguity	8
Better manage complexity	1	Better manage complexity	7
Better decision making	1	Better decision making	7
(not cited)	0	Reduce rework	7
Improved deliverable quality	1	Improved deliverable quality	6
Better data mgt./ capture	1	Better data mgt./ capture	6
Reduce risk	1	Reduce risk	5
Increased uniformity	1	Increased uniformity	5
Multiple viewpoints of model	1	Multiple viewpoints of model	4
Strengthened testing	1	Strengthened testing	4
Reduce effort	1	Reduce effort	3
Improved capability	1	Improved capability	1

This table shows that the metrics reported and value/benefits reported by the same survey respondents do not always align. This most likely means that many of the responses to Questions 7 and 26 were based on an observation of benefits or even just the expectation of benefits instead of actual measured benefit. The DE/MBSE community should make effort to share experiences in measuring the value/benefit of DE/MBSE and to exchange approaches on most useful measurement strategies.

3.4.5 Analysis Approach, Technical Reviews

Question 10, *Please identify any benefits or challenges your organization has found in the use of MBSE (or digital engineering) in the technical review process*, was also initially analyzed against the literature review benefit categories noted previously in Table 2. Again, the potential value (or benefits) of MBSE are sufficiently covered with the benefit categories previously listed Table 2.

3.4.6 Evaluation of survey responses, Technical Reviews

A total of 146 individual responses were collected from Question 10. In this question, only 12 of the 48 benefits categories were represented in the responses. Example responses are listed in Table 12. Also, for this question, there were a number of responses coded as obstacles to these benefits, or as obstacles to enterprise adoption. These are not quantified in the Enterprise Adoption framework discussed in section 3.5 but are listed here as examples of obstacles to process level performance. Table 13 provides some example verbatim responses from the survey data for each obstacle.

Table 12. Example survey responses for tech reviews for each benefit category with a non-zero response.

Category	Benefit Category	Example survey responses on benefits
Quality	Reduce errors	"…using MBSE in the technical review process has helped avoid errors." "MBSE provides additional information about the interoperability between the different functions that are generally not clear in a requirement document or specification. This additional view on the product will provide the clarity needed for lower level requirement documentation."
Quality	Increased traceability	"The use of models helps traceability and coherency between different technical workstreams." "1. Requirements verification/validation is faster and more complete, 2. interpretation of requirements and solutions is less ambiguous."
Quality	Reduce risk	"One process: Risk management is made available throughout the company for all projects. A central library of all risks with causes and consequences and countermeasures."
Quality	Reduce cost	Cost metrics comparing MBSE to traditional methods, cost savings, operating cost
Velocity/ Agility	Reduce time	"…reduces the review time of both in-process reviews and major milestone reviews." "Quicker review process."
Velocity/ Agility	Increased capacity for reuse	"…reduced paper and common use of models that each domain can easily consume and provide input to, allowing for a higher degree of collaboration across the development life cycle."
Velocity/ Agility	Increased efficiency	"The document generation does provide quite a good check of the model." "Information-driven reviews, instead of document-driven."
Velocity/ Agility	Increased consistency	"The use of models helps traceability and coherency between different technical workstreams."
User Experience	Improved system understanding	"Benefits include a more technical deep dive and fundamental understanding of how a system meets the requirements, traces back to the users needs and how systems/subsystems interface." "A lot of the reviews are completely prior to the official review streamlining the knowledge of the technical data." "Systems Thinking instead of component Design, Frontloading and Review in early design stages…" "Animations of a model are very useful in showing a customer how the product performs."
User Experience	Reduce SE task burden	"…'living in the model' reduces the amount of clerical documentation (e.g. PowerPoint) required for technical reviews and improves agile response to customer needs."
Knowledge Transfer	Better accessibility of info	"Questions during a review can be visually addressed immediately because the all aspects of the system and associated mission are available in the model."
Knowledge Transfer	Communication/info sharing	"Reduced paper and common use of models that each domain can easily consume and provide input to, allowing for a higher degree of collaboration across the development life cycle."

Table 13. Example survey responses for tech reviews citing obstacles.

Category	Benefit Category	Example survey responses on obstacles
Quality	Increased traceability	"The gap between the model and the actual requirements. Whether the model is the right model is not clear by examining the model itself. It is necessary to bring in the context and the environment which unfortunately is not modeled appropriately." "Even though the Technical specifications can be modeled, there still remains room for non-functional requirements that needs to be addressed along with other soft concerns of client and project unique needs."
Quality	Reduce risk	"Drawing out risks is more difficult as it less obvious where issues may occur (i.e. the model shows a pristine view, not always reality - hard to express experiential learning in a model."
Quality	Reduce cost	"Cost of moving the paper record into a model. Managing model size." "If we want people to model, then we have to purchase the licenses to the tools..."
Quality	More stakeholder involvement	"There is a lack of acceptance of the model for use in technical reviews. Enough people have concerns accepting the model that traditional documents are still used for technical reviews." "One challenge will be, who's the expert in our organization to critique the quality of MBSE? The people using MBSE are few and far between. Are we to critique our own?"
Velocity/ Agility	Reduce time	"Lack of strategic planning that governs the intended uses of the model results in a lack of key model planning at the start of the MBSE effort which is very likely to result in confusion in the minds of people involved in a tech review." "It is difficult to get non-modelers to access and use the modeling tools to participate in reviews. Producing artifacts for use outside the modeling tool solely for the purpose of technical reviews is time-consuming and non-value-added."
Velocity/ Agility	Increased capacity for reuse	"Reusability of elements in models, but we are still struggling with our own libraries. How to make them available through the entire company."
Velocity/ Agility	Increased efficiency	"Lack of strategic planning that governs the intended uses of the model results in a lack of key model planning at the start of the MBSE effort which is very likely to result in confusion in the minds of people involved in a tech review."
User Experience	Improved system understanding	"MBSE ability to integrate architectural data exceeds our ability to comprehend of a fully integrated architect."
User Experience	Reduce SE task burden	"Need to integrate more formal review processes into tool (i.e. review statistics, start/end, reports, etc). Informal review works well."
Knowledge Transfer	Multiple viewpoints of model	"Visualization of the models, change control, and virtual collaboration around a set of views/viewpoints continue to be challenges within our organization." "Need to integrate more formal review processes into tool (i.e. review statistics, start/end, reports, etc). Informal review works well." "Most participants in a tech review want read-ahead materials tailored in a manner that they can rapidly digest...which some MBSE toolsets and/or modelers may not be readily able to achieve."
Knowledge Transfer	Communication/info sharing	"Technical experts and modeling experts are not well integrated." "Visualization of the models, change control, and virtual collaboration around a set of views/viewpoints continue to be challenges within our organization."

This question also had a category that was unrelated to benefits and therefore not able to be coded using the categories from Table 2. This category was labeled Adoption metrics. These metrics were related to the successful adoption and implementation of MBSE instead of measuring the value of (or outcomes associated with) MBSE itself. Because these adoption metrics more closely relate to the Enterprise Adoption Framework used to categorize Questions 27 and 28 (obstacles and enablers to implementing MBSE), these responses were coded using the categories in section 3.5, Table 15.

Table 14. Example survey responses for tech reviews citing obstacles to enterprise adoption.

Category	Example survey responses on obstacles to adoption
Leadership Support/ Commitment	"Lack of Understanding and support from executives."
Leadership Understanding of MBSE	"Leadership has a difficult time following along in reviews when the technical review is performed within the MBSE environment." "Getting more senior managers to understand and use the models."
Organizational Culture	"Drawing out risks is more difficult as it less obvious where issues may occur (i.e. the model shows a pristine view, not always reality - hard to express experiential learning in a model."
Legacy/Current Processes	"Challenge using MBSE model artifacts as a basis for gate reviews and peer reviews - due to both internal and customer cultures." "People are reluctant to move away from their legacy way to MBSE approach." "Legacy projects do not want MBSE for new updates."
Customer/Stakeholder Buy-in/Engagement	"the customer lacks model management and so far is not outsourcing it. Thus there are multiple technical review processes." "Many of our customers are not MBSE practitioners and thus we are required to develop traditional document artifacts."
Awareness of MBSE Benefits	"Resistance to use of models, fueled by a inappropriate use of models for review; inappropriate to stakeholder concerns and understanding of what MBSE is."
MBSE Terminology/ Ontology/ Libraries	"Non-MBSE personnel get confused during the review by certain symbology needed by modelers." "Learning a tool and a language are not enough - the process and methodology, and 'customizations' are huge barriers to fully integrated MBSE and technical review." "No clear way of explaining it to non-systems engineers." "We usually have to cut and paste diagrams into PowerPoint slides; the tools and model are too complicated to use directly in a meeting. Oftentimes the diagrams are too busy to support meetings. Very few engineers seem to know how to use a diagram to tell a simple story." "Non-MBSE personnel get confused during the review by certain symbology needed by modelers."
Training	"For us, the main challenge is the lack of training on MBSE, especially on the method side. Thus, it's almost impossible for people to read MBSE models as part of the technical review process." "Access to, costs of, and training on, MBSE software tools."
MBSE Tools	"SysML is not well supporting companies in mass production, high variant numbers and B2C business. Moreover SysML is hard to learn and additionally SysML tools are over complicated and poorly integrated in ALM landscapes."

This question highlights the conflicts between DE/MBSE benefits and the challenges of enterprise adoption. The next section creates a framework to evaluate enterprise adoption.

3.5 Analysis of Text Responses, Enterprise Adoption

This section addresses questions 27, 28 and 29 of the survey, designed to elicit responses related to enterprise adoption of MBSE. These relate to category 5 of the Digital Engineering benefits and metrics framework on measures of adoption. The following sections analyze obstacles, enablers, and changes needed based on the textual responses to the three questions. The section starts with a description of the analysis approach. All participant responses were considered in the analysis.

3.5.1 Analysis Approach, Enterprise Adoption Framework

Successful adoption of MBSE, like many other large-scale enterprise change initiatives, can present significant challenges for organizations. These types of initiatives require intentional focus on many aspects within an organization – more than just the technical details of processes and tools associated with a particular change initiative. The Digital Engineering Working Group is a US Defense Department activity that has reported on some of the most significant challenges (or "pain points") associated with implementing DE. Although these pain points do relate to technical aspects of DE such as tools, reference models, standards, and data, they also include other types of organization-level challenges such as implementation and deployment approach, IT infrastructure, and training/skills of the workforce. In the most recently conducted survey by Cloutier at the University of South Alabama, the top five inhibitors to successful adoption of MBSE were: *cultural and general resistance to change*, *availability of skills*, the *MBSE learning curve*, *lack of perceived value of MBSE*, and *lack of management support*.[17]

This breadth of factors demonstrates the importance of a holistic, enterprise-wide perspective in designing and implementing the approach to adopt MBSE. Examining MBSE adoption from the lens of the Baldrige Criteria for Performance Excellence (CPE) can generate insight to increasing the understanding of MBSE adoption – its success or lack thereof. The CPE (Baldrige Performance Excellence Program, 2019) provide a comprehensive, holistic, systems view of an organization by identifying a set of management sub-systems an organization must purposefully design (or redesign) and monitor in order be a high-performing organization.[18] The CPE prescribe *what* key management sub-systems and processes must be in place for an effective organization but do not prescribe *how* they must be designed, as this must fit a given organization's context and environment (see below). The Baldrige CPE and framework are commonly used by organizations for assessing and diagnosing the maturity of their management sub-systems and processes (although this framework is also used to evaluate and determine formal awards for organizations). A brief summary of the overall categories is provided below, along with the key questions associated with each:

1. Leadership: How do you share your vision and lead your organization? How do you ensure good governance?
2. Strategy: How do you prepare for the future?
3. Customers: How do you listen to, satisfy, and engage your customers?
4. Measurement, analysis, and knowledge management: How do you use reliable data and information to make decisions?

[17] Cloutier, R. (2019). Model Based Systems Engineering Survey, conducted December 2018, presented January 2019.

[18] Baldrige Performance Excellence Program, 2019. 2019-2020 Baldrige Excellence Framework: Proven Leadership and Management Practices for High Performance. Gaithersburg, MD: U.S. Department of Commerce, National Institute of Standards and Technology. https://www.nist.gov/baldrige.

5. Workforce: How do you engage and empower your people?
6. Operations: How do you ensure efficient and effective operations that deliver customer value?
7. Results: How well are you doing?

Core Values and Concepts underlie the management sub-systems in the CPE categories and reflect the organizational culture. The Organizational Profile defines key characteristics of the organization's environment (such as customers, regulatory environment, competitors, etc.). Within the Baldrige CPE, the seven categories are broken down into more specific items and areas.

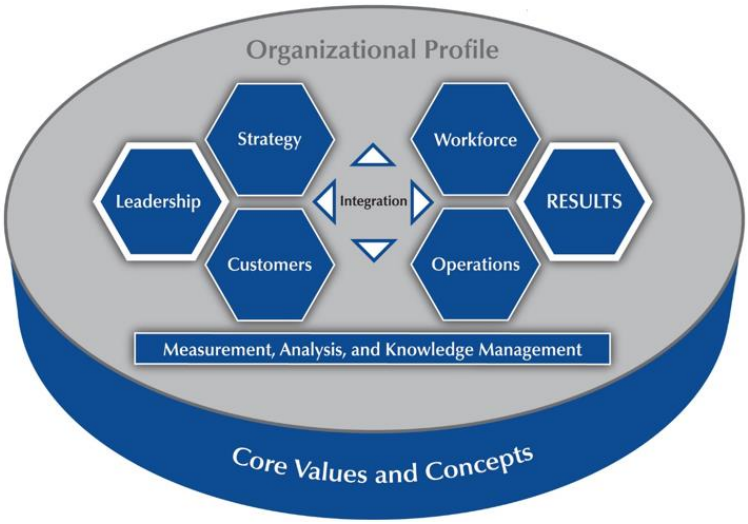

Figure 48. Baldrige Criteria for Performance Excellence (Baldrige Performance Excellence Program, 2019).

In addition to serving as a diagnostic framework for assessing an organization's current state, the Baldrige CPE can also serve as a useful framework within the context of enterprise-wide change initiatives, such as the adoption of MBSE, to proactively design a change initiative more likely to be successful (because it doesn't neglect any key management sub-system) or to assess current progress in implementing a change initiative. The Baldrige CPE do not represent a change initiative in and of itself – rather, it can inform the design or assessment of any major change initiative by identifying key factors to pay attention to in an implementation and deployment approach to the initiative. In this sense, the CPE could be adapted to develop a set of practices associated with a particular change initiative that reflects not only the common issues experienced in any large-scale change initiative (such as leadership support, organizational culture, etc.) but also the ones specific to a particular change initiative (such as user-friendliness of MBSE tools). Thus, the team has adopted the Baldrige CPE as an enterprise framework in this work to analyze and interpret the responses in the survey associated with the adoption of MBSE. Results reported here ultimately can be used to define potential practices for more successful MBSE adoption that are aligned with the Baldrige CPE, for example:

- Leaders communicate a clear reason and need for MBSE adoption
- Leaders understand MBSE
- Leaders support and are committed to MBSE
- People understand the benefits of MBSE
- MBSE is aligned with the overall business strategy
- MBSE is used for the right projects/programs
- MBSE adoption is aligned with what customers need/require

- Customers and stakeholders buy-in to MBSE
- Data management processes support MBSE
- The IT infrastructure supports MBSE use
- Clear metrics are defined to track results and progress of MBSE
- Systems engineers have the skills needed to support MBSE use
- Training is provided to develop needed skills
- People are rewarded/recognized for using MBSE
- The organizational culture is aligned with MBSE use

As described earlier in this report, Part 9 of the survey (Organizational Implementation) had free-text response questions relating to enterprise adoption of MBSE:

- Question 27: *The most challenging obstacles to implementing MBSE in our organization are:*
- Question 28: *The best enablers for MBSE in our organization are:*

In the organizational change literature, it is quite prevalent to study adoption/implementation of a particular change initiative from the perspective of *obstacles* (i.e., negative experiences) and *enablers* (i.e., positive experiences). This "polar opposite" approach involves asking respondents who have experienced a change initiative both questions in order to elicit a more comprehensive picture of the factors that may be associated with successful adoption. In this sense, one can identify a more robust and comprehensive list of success factors, regardless of whether they were experienced as an *obstacle* (or barrier, impediment, etc.) or *enabler*.

In this survey, an additional question relating to *changes* needed within the organization to increase the likelihood of success was asked:

- Question 29: *Going forward, the biggest changes our organization needs to make to improve our implementation of MBSE are:*

This question provides another perspective to the responses for the *obstacles* and *enablers* questions – while the *obstacles* and *enablers* question asks respondents to reflect on their experience and perceptions to date, the question on *changes* asks them to think ahead in the future to what will increase the chances of success. These changes may represent things that will address problems/issues (*obstacles*) or will create success conditions (*enablers*).

All responses to each of these three questions focused on adoption were coded inductively, without an *a priori* code list; rather, codes were identified based on themes emerging from the data. An initial set of codes was defined based on analysis of responses to the first question (*obstacles*) and was then refined iteratively based on analysis of the additional two questions (*enablers* and *changes*). Refinement and finalization of the codes, including definitions of each code, was informed by the Baldrige categories (e.g., Leadership, Workforce, Customers, etc.) to ensure that responses were interpreted comprehensively based on respondents' own experiences. Codes were framed and labeled as neutral success factors, regardless of whether they were identified as *obstacles*, *enablers*, or *changes*. This was done so that the same code list could be used to analyze each of the three questions, given that all three questions relate to factors associated with successful adoption, and so that comparisons could be made across questions about the prevalence of success factors.

For a given respondent, the response was separated into "unique response comments" so that each response comment was a distinct concept for the purpose of coding and analysis. Thus, each response

comment was only tagged with one unique code. A given respondent might provide a response that only resulted in one response comment or multiple response comments. The coding of response comments for each of the three questions was reviewed by a second member of the research team and any discrepancies were agreed upon.

A total of 37 codes was identified and used for analysis. The codes and code definitions are shown in Table 15, along with the higher-level code categories for each code. These eight code categories are aligned with the Baldrige CPE but do not map one for one, as they were defined based on empirical results from this survey.

Table 15. Code Definitions for Analysis of Obstacles, Enablers, and Changes

Code Category	Code	Code definition and potential practices
Change Processes	Champions	Defining and creating the role of champion to advocate for and, using their expertise, to encourage others to use MBSE.
	Change management process design	Defining and implementing a systematic change approach to implement MBSE, with clear actions, timeline, roles, resources needed, staged deployment steps/phases for experimentation (where relevant), and outcomes expected.
	Community of practice	Creating a community of practice within the organization to provide guidance, expertise, and other resources as MBSE is deployed.
	Competing priorities	Developing clear solutions for how to address other priorities within the organization that compete with MBSE adoption for time, funding, and other resources.
	Demonstrating benefits/results	Creating "quick wins" to demonstrate results (benefits and outcomes) from applying MBSE.
	Integration to support MBSE implementation	Integrating MBSE processes across disciplines, units, systems, models, tools, and data.
	Legacy/current processes	Identifying the extent to which legacy (current) processes for engineering design/development are aligned with MBSE, and may exert inertia to impede adoption, and addressing this in implementation processes.
	Vision and strategy for MBSE	Creating a clear vision and strategy, including roadmap for implementing MBSE.
Communication	Awareness of MBSE benefits/value	Creating a common understanding throughout the organization to communicate the value and benefits associated with MBSE so that it's clear why the organization is implementing it and how it is expected to produce positive outcomes.
	Communicating success stories/practices	Communicating success stories, use cases, and best practices to others within the organization.
	Need for change	Clearly identifying and communicating the compelling need for change within the organization, with emphasis on performance outcomes/metrics.
External Environment	Alignment with customer requirements	Identifying how MBSE adoption supports meeting customer needs and requirements.

Code Category	Code	Code definition and potential practices
	Customer/stakeholder buy-in/engagement	Ensuring that customers and other stakeholders are aware of MBSE, buy-in to its adoption, and are engaged as appropriate in its use.
	External regulations	Identifying any aspects of external regulations and requirements that may be misaligned with MBSE adoption and taking these into consideration in planning implementation processes.
	Use in SE community	Leveraging the momentum gained through increased use in the general SE community, external to the organization.
Leadership	Leadership support/commitment	Demonstrating commitment and general support for MBSE implementation by senior leaders through communication, actions, and priorities.
	Leadership understanding of MBSE	Creating understanding and knowledge within senior leaders about why MBSE is being implemented, how it will impact the organization, and how it will be implemented.
MBSE Processes	MBSE methods/processes	Developing and deploying consistent, systematic, and documented processes for MBSE throughout the relevant parts of the organization, including steps/phases, outputs, and roles/responsibilities.
	MBSE terminology/ontology/libraries	Clearly identifying a common terminology, ontology, and libraries to support MBSE adoption.
	MBSE tools	Ensuring MBSE tools have sufficient quality, have sufficient maturity, are available, and are common.
	Projects/programs to apply MBSE	Identifying the most appropriate types and quantity of projects/programs within the organization to target for MBSE, considering complexity, scope, and size of project/program.
	Security of data and IP	Identifying and mitigating any risks to data/information security, including intellectual property, associated with MBSE implementation.
Organizational Environment	Alignment with business strategy	Ensuring that MBSE adoption is aligned with the organization's overall business strategy and communicating this clearly and systematically throughout the organization.
	Organizational characteristics	Identifying the extent to which key organizational characteristics (e.g., size, products/services, sector, etc.) may limit the effective adoption of MBSE and ensuring this is addressed in planning implementation processes.
	Organizational culture	Creating shared values/beliefs and leadership expectations that support MBSE adoption such that resistance to change, fear of failure, and prevailing organizational practices do not impede adoption.
	Rewards/recognition	Identifying how people, teams, and units are rewarded/recognized for utilizing MBSE processes and tools, including formal and informal rewards/recognition.
	Success metrics	Defining and implementing performance metrics to track success and progress from MBSE activities.
	Supportive infrastructure	Ensuring that key aspects of the organizational infrastructure, including the IT infrastructure, are aligned with MBSE adoption.

Code Category	Code	Code definition and potential practices
Resources	Cost to use MBSE tools	Clearly defining the costs, including financial, to fully implement MBSE tools and ensuring that benefits outweigh costs.
	General resources for MBSE implementation	Ensuring financial and other resources are available to support MBSE implementation.
Workforce	General MBSE awareness and knowledge	Creating a widespread general awareness and understanding of MBSE within the workforce, including key differences to traditional processes.
	MBSE learning curve	Ensuring that the learning curve (time) associated with implementing MBSE is taken into consideration when planning training and implementation processes.
	People in SE roles	Quality of and support from people holding SE roles across the organization.
	People willing to use MBSE tools	People in SE roles across organization being willing and motivated to use MBSE tools.
	Teamwork	People working together harmoniously and collaboratively to use MBSE within and across project teams.
	Training	Investing in and providing the education/training required to develop the workforce knowledge/skills needed to support MBSE implementation.
	Workforce knowledge/skills	Developing a workforce having the knowledge, skills, and competencies needed to support MBSE adoption.

3.5.2 Analysis of Obstacles to MBSE Adoption

For Question 27 on *obstacles* to MBSE adoption, 166 respondents provided a response. Raw responses were parsed into 303 unique response comments. Thus, on average, respondents reported 1.8 distinct *obstacles* for this question. Examples of the verbatim response comments are shown in the Table 16. Inclusion of "…" in the table below indicates responses that were separated out because of containing a unique concept.

Table 16. Examples of Unique Response Comments for Obstacles

Code	Examples of unique response comment - ***Obstacles***
Alignment with business strategy	Lack of….strategy concerning model based design and digital continuity
	disconnect with business strategy and marketing
Alignment with customer requirements	Customers who require the use of old languages, tools and processes. They force poor practices due to their lack of understanding what real MBSE is.
	- if the customer isn't willing to pay for it, then it mostly will not get done since our corporate resources are so modest
	varying customer expectations has limited full, enterprise-wide adoption of MBSE
Awareness of MBSE benefits/value	understanding of the value of MBSE
	Uncertainty about….the potential benefits
	Communicating the value to be gained
	The lack of understanding of the real value that we can achieve by THIS program by implementing MBSE.

Code	Examples of unique response comment - *Obstacles*
	People are not convinced in the value of systems engineering, they believe systems engineering is creating documentation after the engineering is complete.
	and shown through stopping the incessant questioning "what's the value-added?"
	Understanding and believing the ROI from investing in MBSE Tools and practices
Change management process design	Uncertainty about the way to move forward
	Change management beyond engineering throughout the projects, management and sponsors
	Lack of a defined crawl-walk-run approach to applying MBSE.
	Lack of a defined, integrated paper-based and model-based approach as we work through how to implement MBSE for the first time.
Change management process design	Accepting sensible risk while focusing on immediate iterative MBSE execution
	Having opportunities to practice implementing MBSE approaches before having to deliver products for a customer. We often just have to quickly figure it out as we go.
	Change Management
Competing priorities	All the things I need to do myself.
	People in other discipline….are too time-challenged to learn something new.
	All this in parallel to the day - to - day work
	There is simply too much urgent work for individual projects and programs to feel justified in allocating resources to changing the status quo.
	Managing the pressure between adopting and exploiting MBSE and its benefits versus the pressure from project and program management to maintain schedule and deliver versus time and cost.
	Other digitization projects competing for funding and claiming same benefits (ignorant of difference between simply digitizing and MBSE).
	lack of time to implement use of tools and processes
Cost to use MBSE tools	...expensive MBSE tools limit its acceptance.
	Unable to use large set of tools, and development environments due to cost limitations
	Tool license (cost) and….
	cost of implementing before all of the tools and capabilities are defined
Customer/stakeholder buy-in/engagement	Lack of buy-in from my client.
	Full Stakeholder buy in
	Stakeholder engagement
	Conceptual distance amongst variety of stakeholders
	Lack of potential customer understanding of the MBSE potential
Demonstrating benefits/results	ability to demonstrate benefits in the short term.
	The organization has not done what is required... to provide results.
	The "payback" of MBSE, even if well-documented in other industries, is poorly defined for others.
	Programs still have a hard time quantifying ROE for MBSE use.
	we are very immature and we are struggling to show the ROI of doing MBSE
External regulations	Organizational inertia within DoD
	needs…. external support.
	severe regulatory oversight

Code	Examples of unique response comment - *Obstacles*
General MBSE awareness and knowledge	MBSE means different things to different people. Systems Engineers think it is just descriptive modeling. Executives think it is the holy grail vision of end to end digital transformation of product development, delivery, and sustainment.
	ability to explain to a non-technical audience
	Explaining to others what MBSE actually is…
	Understanding of what MBSE is
General resources for MBSE implementation	Organizational commitment (resources, funding, ...)
	… continued year-on-year commitment from management to fund MBSE adoption.
	resource constraints
	……upper management to fund and allocate resources to MBSE efforts within projects
	funding…. and dedicating resources to improving MBSE to improve development timescales.
Integration to support MBSE implementation	The biggest challenge to implement MBSE is fusing the modelers and the technical experts, either by teaching the technical experts to model, or embedding the modelers with the technical experts.
	The correct Interfaces between disciplines to reduce data copying
	Connecting across the enterprise organizational domains and related data silos
	model ownership conflicts across organizations
	Managing the tool interfaces to all other PLM or ALM tools
	The use of different modeling tools across different programs (often driven by the needs of different customers and/or preferences of different leaders) coupled with the inherent siloing of information that takes place when working on classified projects makes sharing models difficult or impossible.
	Lack of strong integration with external tools.
	lack of interoperability between MBSE tools
Leadership support/commitment	Management acceptance of MBSE, there is not a top down emphasis or push
	Fractured management
	Lack of a global leadership
	Lack of sponsor prioritization on MBSE
	Reluctance to mandate MBSE to all projects
	No commitment in upper mgmt.
	middle management resistance
	getting consistent support at management level
	leadership vision
	Management inertia associated with changing approaches associated with decades of non-model based systems development.
	The negative attitude of the management
	Lack of management support. Management like to "fly by the seat of their pants". A lot of inertia when trying to implement change.
Leadership understanding of MBSE	No knowledge in upper mgmt.
	Show the Value to C-Suite.
	Leadership buy-in is required to institutionalize MBSE, which may be difficult when leaders don't understand the MBSE value proposition
	Management understanding of MBSE to be fully bought in.
	lack of understanding by management about the effectiveness of MBSE

Code	Examples of unique response comment - *Obstacles*
	Convincing management that the value of having a dedicated, skilled team member to fulfill this role would outweigh the cost of having additional staff on the team.
Legacy/current processes	changing organization standard operations to accept MBSE
	Reliance on document-driven processes.
	Legacy process
	Many of our development processes are not currently model based.
	Additionally, Major Milestone Program Reviews do not require mature Systems Engineering artifacts as entrance or exit criteria
	The demand for SE artifacts to look the same as people are used to.
	Sticking to legacy process.
	hesitancy of engineering to use the system engineering artifacts as they are used to Power Point and Excel
MBSE learning curve	Steep Learning curve
	learning of new tools
	learning the method; learning formal or semi-formal modeling language (e. g. SysML); learning a tool using SysML
MBSE methods/processes	We are in the business of sustaining systems. Unless the MBSE is used at the onset (development), we have no models to use in our day-to-day operations.
	The organization has not done what is required to make MBSE projects repeatable with mature processes that….. are shown to provide results.
	lack of method…. to support "real-life" problems
	Setting up of processes as this is a new technique for us
	Consistent practices
MBSE terminology/ontology/libraries	Incomplete standard terminology
	lack of project-wide pattern/model libraries.
	Introducing, set up and maintain the type libraries: Object type library Activity type library
	lack of domain ontology shared between the stakeholders
MBSE tools	weak MBSE tools limit its acceptance. Analysis tools for HW, SW, FW and Mechanical disciplines are much more mature due to mandated use and better tool availability
	tool utility and functionality
	Lack of maturity of MBSE tools
	lack of uniformity of modeling features
	The Vendor tools are very incomplete and immature to support an enterprise level PLM capability
Need for change	The current processes have worked fine for the past 50 yrs, why should we change?
	The collection of metrics for specification exceptions that occur during acceptance testing are not well collected, or briefed to show a need for improvement by implementing MBSE.
	Thinking that the way we've done things for the last 50 years is fine.
Organizational characteristics	As an R&D organization our processes are continuously changing.
	Size of the organization
	diversity of products and disciplines
Organizational culture	Transitioning culture from documentation-based to model-based.
	Mentality
	resistance to change

Code	Examples of unique response comment - *Obstacles*
	Culture - New concept for a lot of the teams that would need to work with it, most of which are resistant to change
	Deeply entrenched traditional process
	Status quo does not revolve around the use of models.
	culture....it is not they don't want to do it...it is helping people understand to not just try and repeat traditional step and doing MBSE....which is actually doing more work.....you have to be willing to lean in to get the value
	The legacy systems that have been in production for decades have an ingrained "That's how we have always Done it" culture and are very resistant to change.
	People are worried about relying on something that they don't understand or aren't familiar with
	Our company culture has historically emphasized independence rather than common processes
Projects/programs to apply MBSE	Finding the 'right,' properly scoped problems that lend themselves to a bounded MBSE effort
	many believe it is only valuable for new starts
	applying it appropriately across the organization and projects.
	advocating for the additional cost and time of MBSE for smaller projects
	and that is only for a brand new programs with complete new design. The biggest challenge is showing value of MBSE for designs that are simply rollovers of previous designs with some modifications.
Rewards/recognition	...misalignment of incentive structures, where we do not reward the behaviors that would reinforce our MBSE implementation but rather reward (legacy) behavior which run counter to modern model-based practices.
Security of data and IP	Security and Intellectual Property
Supportive infrastructure	lack of support in IT organisation to install tools.
	Setting up the environment
	completely inadequate IT infrastructure and processes.
	We currently do not have the infrastructure to support MBSE the way that would be most effective.
	enterprise management support
	internal alignment
Training	There is no training for the people who need to be using the software.
	To aid in this, we need a robust training curriculum
	Getting sufficient training
	Inadequate Training!
	Lack of training opportunities…..
	No MBSE training
Vision and strategy for MBSE	We also need guidance and a strategy to move forward.
Workforce knowledge/skills	Workforce knowledge and skills
	Availability of trained staff remains the top bottleneck in implementation of model-based practices across our organization.
	MBSE and Systems Engineering bench strength (people with the correct skills and experience).
	Competency of the modelers; domain knowledge
	Finding engineers with modeling skills
	Building and retaining modeling talent is difficult
	MBSE knowledge base

Code	Examples of unique response comment - *Obstacles*
	Getting enough model expertise across the multiple system disciplines to include safety, certification, logistics and sustainment, costs, etc.
	shown through hiring,
	shallow knowledge of MBSE
	lack of people with the right skillset
	skills/in depth understanding

The frequency of *obstacles* reported is shown in Table 17 and Figure 49. It should be noted that there were eight codes for which there were no response comments for the question on *obstacles*, as shown in the table. For the sake of conciseness, these codes are not shown in the figure. It is instructive to note the categories represented by the most frequently reported *obstacles* – Organizational Environment (organizational culture), Workforce (workforce knowledge/skills), and Leadership (leadership support/commitment). Thus, the codes representing the top one-third of response comments do not represent specific technical details about MBSE processes and tools, but rather, represent factors often found as challenges in any type of large-scale change initiative. Thus, it seems that organizations would benefit from more systematic attention to MBSE as a change initiative, taking into account all aspects of the organization and the management sub-systems that can (or fail to) support and align with MBSE.

Table 17. Analysis of Responses to Questions on Obstacles *to MBSE Adoption*

Code Category	Code	Code label	# Comments Obstacles
Organizational Environment	Organizational culture**	CULTURE	44
Workforce	Workforce knowledge/skills**	SKILLS	30
Leadership	Leadership support/commitment**	LDR CMT	25
Communication	Awareness of MBSE benefits/value**	AWR BEN	18
Change Processes	Change management process design	CHANGE PROC	13
MBSE Processes	Integration to support MBSE implementation	INTEGRATION	13
MBSE Processes	MBSE methods/processes*	MBSE PROC	13
MBSE Processes	MBSE tools*	TOOLS	13
Change Processes	Competing priorities	COMP PRIOR	11
Change Processes	Demonstrating benefits/results	DEMON RES	11
Resources	General resources for MBSE implementation	RESOURCES	11
Workforce	Training*	TRAINING	11
MBSE Processes	Projects/programs to apply MBSE	WHERE APPLY	10
Change Processes	Legacy/current processes	LEGACY PROC	9
Workforce	General MBSE awareness and knowledge	GEN AWR	8
Leadership	Leadership understanding of MBSE	LDR UND	8
Resources	Cost to use MBSE tools	COST	7
Workforce	MBSE learning curve**	LRN CURVE	7
Organizational Environment	Supportive infrastructure	INFRA	7
External Environment	Alignment with customer requirements	CUST REQ	6
External Environment	Customer/stakeholder buy-in/engagement	CUST BUY-IN	6
MBSE Processes	MBSE terminology/ontology/libraries	TERM/ONTOL	5
Communication	Need for change	NEED	5

Organizational Environment	Alignment with business strategy	STRATEGY	3
External Environment	External regulations	EXT REG	3
Organizational Environment	Organizational characteristics	ORG CHAR	3
Organizational Environment	Rewards/recognition	REW/RECOG	1
MBSE Processes	Security of data and IP	SECURITY	1
Change Processes	Vision and strategy for MBSE	MBSE STRAT	1
Change Processes	Champions	CHAMPIONS	0
Communication	Communicating success stories/practices	COMM SUCC	0
Change Processes	Community of practice	COMM PRACT	0
Workforce	People in SE roles	SE ROLES	0
Workforce	People willing to use MBSE tools	WILLING	0
Organizational Environment	Success metrics	METRICS	0
Workforce	Teamwork	TEAM	0
External Environment	Use in SE community	USE SE COMM	0
Totals (n=166)	**37**		**303**

*** Related to one of the top five inhibitors in Cloutier's survey*

** Related to one of the inhibitors in Cloutier's survey*

These findings on obstacles can also be compared with Cloutier's survey of inhibitors. The four most frequently-reported obstacles in this work are also in the top set of Cloutier's inhibitors: organizational culture (*cultural and general resistance to change*, as labeled by Cloutier), workforce knowledge/skills (*availability of skills*), leadership support/commitment (*lack of management support*), and awareness of MBSE benefits/value (*lack of perceived value of MBSE*). One notable difference in this work as compared to Clouter's is *MBSE learning curve*, which had only 7 response comments (out of 303, tied for 17th in rank) but was reported by Cloutier as one of the top inhibitors. Other inhibitors found by Cloutier are also present in these findings, with varying level of frequency: MBSE methods/processes (relating to *method maturity*), MBSE tools (relating to both *availability of tools* and *tool maturity*), and training (*MBSE training*). This work identified a number of other obstacles, some of which were fairly frequently reported, that were not identified by Cloutier (i.e., change management process design, integration to support MBSE implementation, competing priorities, demonstrating benefits/results, and general resources for MBSE implementation). Lastly, there was one inhibitor defined by Cloutier (*risk associated with the adoption of MBSE*) that did not emerge as an obstacle reported by survey respondents in this work.

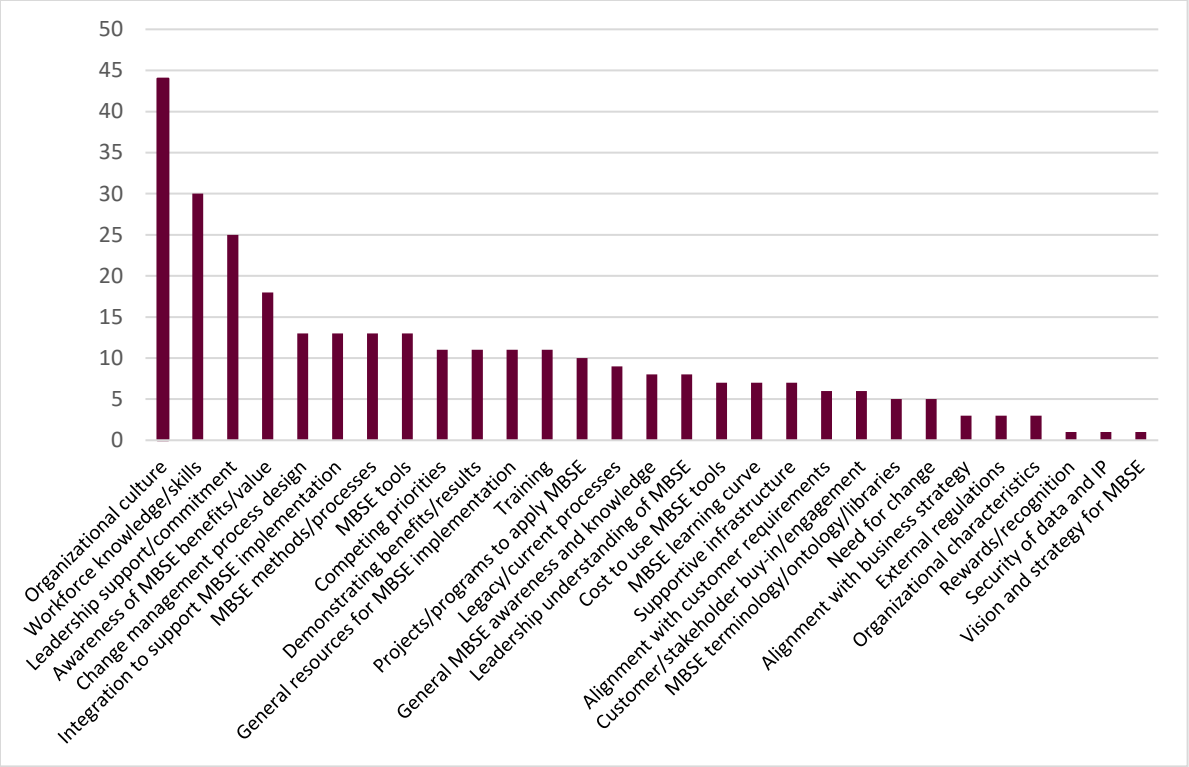

Figure 49. Obstacles to Implementing MBSE.

3.5.3 Analysis of Enablers to MBSE Adoption

For Question 28 on *enablers* to MBSE adoption, 156 respondents provided a response. Responses were parsed into 223 unique response comments. There were also 6 non-responses for a total of 229 response comments. Non-responses for this question included things like "we are not using MBSE" or responses mentioning specific individuals or groups. For the purpose of this analysis, the 223 response comments were used. On average, respondents reported 1.4 distinct *enablers* for this question. Examples of the verbatim response comments are shown in Table 18. Inclusion of "…" in the table below indicates responses that were separated out because of containing a unique concept.

Table 18. Examples of Unique Response Comments for Enablers

Code	Unique response comment- ***Enablers***
Alignment with business strategy	...with commonly shared goal
Alignment with customer requirements	….aligned with our customers' requests for digital engineering, which are very motivating top-down drivers for implementation…
	RFPs specifying Model-Based Engineering (MBE).
	customers asking for MBSE
	Our customers and competitors are starting to require it - this is extremely valuable in pressuring us to get moving.
	Our government customers are mandating MBSE on programs, which is driving our digital engineering transformation.
Awareness of MBSE	Advocacy and persistence in increasing awareness of benefits…

Code	Unique response comment- *Enablers*
benefits/value	Better access to information / guidance that can help "sell" MBSE to others (both within and outside of the Systems Engineering community).
	The belief that this is the right way to planning, designing, implementing and operational running the system.
Champions	Someone who is passionate about driving the organization to an intrinsic MBSE capability in all aspects of the technical approach.
	A set of modeling champions
	Low level champions for MBSE.
	champions at organization level and SME supporting modeling within projects
	A model champion senior manager.
	Champions / individuals in some projects that set the example of how it can be done effectively
	Our champions! A core set of people who believe and have the passion and staying power to support MBSE.
	MBSE evangelists in a central consulting group
	Individual champions trying to move MBSE ahead.
Change management process design	Pilot experiences
	... focus on iterative MBSE execution
	Small groups that effectively use MBSE
	Small groups of MBSE advocates are the primary force driving MBSE adoption.
	...from trial efforts.
	...Systematic Deployment.....
Communicating success stories/practices	Advocacy and persistence in increasing awareness of... MBSE adoptions
	sharing and providing solid good use cases to demonstrate the power of MBSE
	Group of folks consistently (using and) sharing MBSE best practices.
	...Success Stories…
Community of practice	we have established an MBSE Community of Interest
	Our Model-Based Engineering Community of Practice (CoP) provides programs and internal projects with access to resources and expertise.
	Support communities that meet regularly to help each other with MBSE work.
	...a team of people that can (train and) support the users.
	…and a part-time staffed MBSE Center of Excellence
Cost to use MBSE tools	improved pricing on tools that are associated with MBSE
Customer/stakeholder buy-in/engagement	Stakeholder buy-in.
	Customer... support.
	other stakeholders who desire to improve acquisition outcomes.
Demonstrating benefits/results	demonstrated success of projects with digestible items that can be reused
	Delivered business value. When non-modelers are able to more quickly make a business decision because a modeler had a useful answer ready in a prompt manner.
	Programs which benefited from developing models
	Results! showing actual data for improvements!
	Those who can show results quickly. Those that can quickly interpret and fix many poorly written and conflicting requirements.
	Business winning
	successful programs utilizing

Code	Unique response comment- *Enablers*
General MBSE awareness and knowledge	...awareness
	It brings together….believers in the concept…
General resources for MBSE implementation	... investment in staff resources…
	Investment….
	Engineering leaders giving budget line items to projects for establishing a model plan…
Integration to support MBSE implementation	…agreement to exchange models
	... with ability to refresh and maintain current information to all users.
	Inter-connected tools
	better way to be able to share data across companies and industry/USG
	SysML, Seamless integration with tools
Leadership support/commitment	Leadership enables MBSE in the organization, ….
	Top down management commitment to process change….
	Hiring new management
	Leadership being signed up to the idea.
	When senior and executive level leadership takes ownership.
	Leaders that "get" it and are willing to take a bet on MBSE even if the tactical aspects aren't 100% clear…
	Engineering leaders ... asking for MBSE to be used or for MBSE products.
	(Leadership with technical background and “systems thinking” mindset)…. intuitively know how to support MBSE.
	Managers that believe in connecting the data and digital engineering working together to determine how best to implement this for the team…
Leadership understanding of MBSE	Leadership with technical background and “systems thinking” mindset….
MBSE methods/processes	Our language (LML), ….well documented processes…available to all employees…..
	Good processes
	Built-in Object-Oriented concepts: inheritance, polymorphism and more.
MBSE terminology/ontology/libraries	Investment in …. standardized environment
	... reference architectures are the best enablers
	Digital technologies, Model Repositories, Reference architectures, Reference models
	model reuse library
MBSE tools	Technology maturity has finally reached a tipping point where the capabilities we've discussed for a number of years are sufficiently-mature to deploy on-program….
	...tools (Innoslate, primarily, but also GitHub, IntelliJ and other software engineering tools).....(processes available to all employees) through books.
	Common toolset,….
	At least the tools are available…
	Ready access to licensed tools….
	Good tools
	user friendly tools
	Own developed modeling tool with embedded architecture framework.
Need for change	Recognition of business need….
	Well defined business drivers….

Code	Unique response comment- *Enablers*
	There must be pain in the organization, otherwise there is no need for MBSE. If projects are running within time and budget, why shall I invest in MBSE?....
	willingness to be 'better in the future'
Organizational characteristics	... and inherent complexity of our products
	We are a smaller company…
Organizational culture	New thinkers…
	... cultural acceptance.
People in SE roles	Our systems engineers.
	System Engineers & project managers.
	Requirement analysts
	System analysts, system architects, quality engineers
	New systems engineers…
	Forward-Looking Systems Engineers!
	Systems engineers that lead the revolution
	Modelers and systems engineering.
	System's engineers who desire to improve acquisition outcomes.
People willing to use MBSE tools	….Widespread engineering grass-roots usage.
	Self-motivation
	Project/Program managers and key business personnel who are progressive and willing to take the risk to adopt.
	Enthusiastic people
	...people that have a passion to improve systems engineering.
	Peoples' ambition to learn.
	Our new professionals and some journeyman engineers are eager to utilize MBSE. We need to let them lead the effort and support them along the way.
	Group of folks consistently using... MBSE…
	Motivated employees and researchers
	Grass-roots users willing to try to implement MBSE where there might be opportunity to do so.
Projects/programs to apply MBSE	The complexity of the design…
	Small projects with resource constraints are actually the biggest drivers of successful implementation of MBSE.
	…Best enablers are complex topics, that cannot be approached with the existing methods and tools.
	New program upgrade start ups and…
	... It is easier for the staff to understand when and where MBSE provides the most value to the systems team.
Rewards/recognition	...incentive to adopt
Success metrics	... (well-defined) success metrics
Teamwork	Teamwork
	Team effort
	Good relationships with those who practise it.
Training	…(workforce) that has access to training and continuing education opportunities to learn and study MBSE.
	Workshops! Lots and lots of workshops in showing the benefits.
	... internal training geared to jump-start leaning and use

Code	Unique response comment- *Enablers*
	Engineering leaders (giving budget line items to projects for establishing)... training time to those who will be working in the model. Support communities that meet regularly to help each other with MBSE work.
	...MBSE training programs…
Use in SE community	...engineering community moving towards MBSE.
	We are telling our customers to use it so we should too.
	...collaborators/reviewers/vendors asking for MBSE to be used or for MBSE products…
	current digital continuity trend with MBSE moving to PLM
Vision and strategy for MBSE	....plus VISION, Strategy, Roadmap
Workforce knowledge/skills	Skilled and knowledgeable people….
	We have a talented workforce…
	... hiring of modern MBSE practitioners.
	engineers intelligence
	We have many experienced users…in this organization….which is not commonly found in other organizations….Many of these staff are also highly experienced and technically savvy designers from past systems.
	The Subject Matter Experts who will benefit from using MBSE data
	High level of MBSE experience and knowledge among the Systems Engineering team members.
	...with many young, talented employees.

The frequency of *enablers* reported is shown in Table 19 and Figure 50. There were six codes for which there were no response comments for the question on *enablers*, as shown in the table. For the sake of conciseness, these codes are not shown in the figure. Leadership support/commitment was the most frequently reported *enabler* and was prevalent as an *obstacle* (ranked third). Demonstrating benefits/value also appeared both as an *obstacle* and *enabler* – i.e., either difficulty in demonstrating (or proving) results from actual applications of MBSE within the organization or the ability to do so. There are several most frequently reported *enablers* that were either not reported at all as *obstacles* or in a different relative frequency, such as people willing to use MBSE tools and champions.

Table 19. Analysis of Responses to Question on Enablers *to MBSE Adoption*

Code Category	Code	Code label	# Comments Enablers
Leadership	Leadership support/commitment	LDR CMT	27
Workforce	People willing to use MBSE tools	WILLING	21
Workforce	Workforce knowledge/skills	SKILLS	19
Change Processes	Champions	CHAMPIONS	15
Change Processes	Demonstrating benefits/results	DEMON RES	15
Workforce	Training	TRAINING	13
Workforce	People in SE roles	SE ROLES	12
MBSE Processes	MBSE tools	TOOLS	11
External Environment	Alignment with customer requirements	CUST REQ	10
Change Processes	Change management process design	CHANGE PROC	7
Communication	Communicating success stories/practices	COMM SUCC	6

Code Category	Code	Code label	# Comments Enablers
Change Processes	Community of practice	COMM PRACT	6
MBSE Processes	Integration to support MBSE implementation	INTEGRATION	6
External Environment	Use in SE community	USE SE COMM	6
Resources	General resources for MBSE implementation	RESOURCES	5
MBSE Processes	MBSE terminology/ontology/libraries	TERM/ONTOL	5
Communication	Need for change	NEED	5
MBSE Processes	Projects/programs to apply MBSE	WHERE APPLY	5
Communication	Awareness of MBSE benefits/value	AWR BEN	4
MBSE Processes	MBSE methods/processes	MBSE PROC	4
Organizational Environment	Organizational culture	CULTURE	4
External Environment	Customer/stakeholder buy-in/engagement	CUST BUY-IN	3
Workforce	Teamwork	TEAM	3
Workforce	General MBSE awareness and knowledge	GEN AWR	2
Leadership	Leadership understanding of MBSE	LDR UND	2
Organizational Environment	Organizational characteristics	ORG CHAR	2
Organizational Environment	Alignment with business strategy	STRATEGY	1
Resources	Cost to use MBSE tools	COST	1
Organizational Environment	Rewards/recognition	REW/RECOG	1
Organizational Environment	Success metrics	METRICS	1
Change Processes	Vision and strategy for MBSE	MBSE STRAT	1
Change Processes	Competing priorities	COMP PRIOR	0
External Environment	External regulations	EXT REG	0
Change Processes	Legacy/current processes	LEGACY PROC	0
Workforce	MBSE learning curve	LRN CURVE	0
MBSE Processes	Security of data and IP	SECURITY	0
Organizational Environment	Supportive infrastructure	INFRA	0
Totals (n=156 respondents)	**37**		**223**

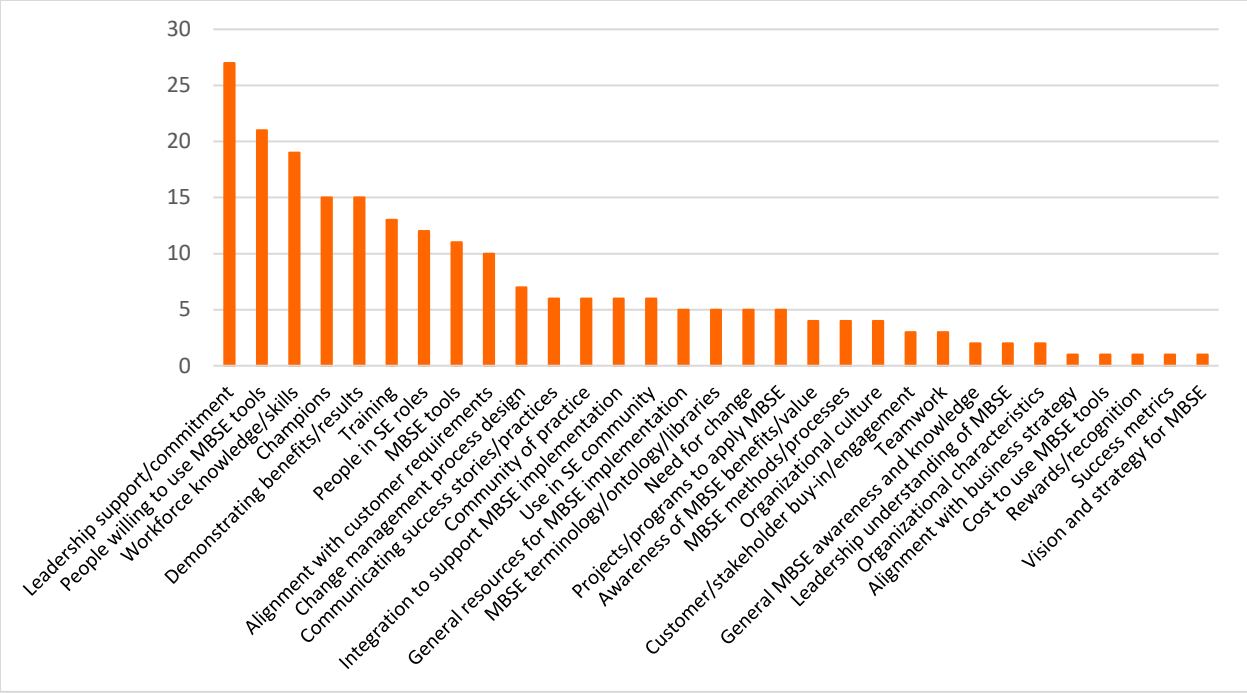

Figure 50. Enablers to Implementing MBSE.

3.5.4 Analysis of Changes to Improve Implementation of MBSE Adoption

For Question 29 on *changes* to improve implementation of MBSE adoption, 153 respondents provided a response. Responses were parsed into 273 unique response comments. There were also 5 non-responses for a total of 278 response comments. For the purpose of this analysis, the 273 response comments were used. On average, respondents reported 1.8 distinct *changes* for this question. Examples of the verbatim response comments are shown in the table below. Inclusion of "…" in Table 20 indicates responses that were separated out because of containing a unique concept.

Table 20. Examples of Unique Response Comments for Changes.

Code	Unique response comment- ***Changes***
Alignment with business strategy	Well defined business drivers…
	...singular front when it comes to outward facing marketing and business development
Alignment with customer requirements	We need new acquisitions of systems to include MBSE so that we can use them in sustainment.
	...Customers and project leads being supportive of MBSE and incorporating it into the project development. (Not just doing it on the side to see if it pans out)
	Gov should be leading this revolutionary change. For example: DAU doesn't even have a training course on MBSE!!!
	Leverage other tools based on needs of the customer or new ones developed to work certain challenges
Awareness of MBSE benefits/value	understanding the values of MBSE among all stakeholders
	(More communication and push from leadership on)... benefits of MBSE.
	More effort required to gain trust and recognition of model benefits.
	Better education about the value propositions of MBSE and benefits to all users.

Code	Unique response comment- *Changes*
	Providing training on the value ... of MBSE.
Champions	Hire and build a proper MBSE leadership team …
	Recruiting MBSE...experts
Change management process design	(Top down management commitment) to process change…
	Develop the models. Don't wait anymore for anyone to say 'go' because no one will say it.
	Accepting sensible risk...iterative MBSE execution
	Trial and error, understanding that not all models will provide the benefit that is desired but with multiple interactions can sure a useful purpose.
	intentional management of the transition to MBSE/MBE in a programmatic manner
	...MBSE adoption across enterprise
Communicating success stories/practices	Internal communication needs to be consistent and at a level that different layers of the organisation can understand it…
	...Show how we can make documents available online.
	... starter models that are to be used enterprise-wide and are accepted as best practice by engineering leadership from HQ to branches.
Community of practice	Getting hands-on in this area
Cost to use MBSE tools	Licensure for multiple users…
	Tool costs going up once there is increased traction on using MBSE
Customer/stakeholder buy-in/engagement	Improve collaboration with external partners/customers.
	Stakeholder buy-in…
	Increased potential customer understanding of the MBSE potential
Demonstrating benefits/results	Showing return on investment before management loses interest in systems engineering transformation.
	Demonstrate the ability to perform a standard design review without having to publish tons of paper documents…
	...demonstrate the difference of Systems Engineering abstract thinking/modeling and simple design activities.
	Prove the general value of systems engineering for rollover designs to upper level management.
	Successful projects demonstrating the efficacy of MBSE
	(Make it easier for existing systems engineers to ... link in with other engineering, program and business management processes) to show the benefits of doing it.
General MBSE awareness and knowledge	Increase in general understanding... of a common tool set.
	Having more people become aware of the MBSE feature
	Wider understanding of the non user base.
General resources for MBSE implementation	Time and resources to implement and use the model
	Providing the 'impulse' in resources (people & money) to break over the startup costs associated with changing process to MBSE
	2) Allocate resources to fuel change.
	Increase Funding and Resource Allocation
	Make existing resources available to pursue adoption and facilitate knowledge transfer.
	We need ... associated funding to grow our MBSE expertise.
	Hire and build ... with sufficient funding.

Code	Unique response comment- *Changes*
Integration to support MBSE implementation	…and embed the modelers with the technical experts
	(Continue to adopt new technologies and) integrate them into our processes and tools.
	Tool integration …
	Modification of the life cycle to incorporate model interoperability
	Ideally, these tools would knit together with our descriptive models to minimize manual labor required to manage our data inputs.
	Dream : Efficient interconnected... tools across the Life cycle from concept to disposal.
	(Make it easier for existing systems engineers to) ... link in with other engineering, program and business management processes to show the benefits of doing it.
	The opportunities for tool integration are few and far between.
Leadership support/commitment	More communication and push from leadership on implementing... MBSE.
	Top down management commitment…
	Hire new management
	Leaders MUST ... support the effort, else they undermine it if even unintentionally.
	A strong management team that... supports to the initiative.
Leadership understanding of MBSE	No leader with high level system design ability
	Leaders MUST understand ... the effort, else they undermine it if even unintentionally.
	Stop looking at a tool and what the tool can do, and start looking at ... what improvements can be made using MBSE.
	...leaders more a-tune to Model Based Engineering - not just MBSE.
	Upper management understanding of MBSE value…
	A strong management team that understands... the initiative.
Legacy/current processes	The new role of an architect is introduced and replaces some of the competences from project manager. This can lead to conflicts.
MBSE learning curve	... knowing that it will have a learning curve…
MBSE methods/processes	Standardization.
	Better definition of practices, processes…validating models.
	Clear organizational roles and responsibilities for developing & maintaining different aspects of system model/models.
	Common methods understood and implemented across organizations with the company.
	Identify and adopt a rigorous set of processes, products, and personnel to execute MBSE projects in a repeatable manner.
	...produce a streamlined process that produces the required information without creation of excess unused artifacts.
	... consistent implementation of methodology and technical review artifacts.
	Process definition and discipline
	Frontloading work in projects and execute problem prevention (hard to measure, needs lot of trust)
	Better documented processes for modeling interfaces…
	We need to develop a standardized process, document that process, and then follow that process. Our current SE environment is like the wild west.

Code	Unique response comment- *Changes*
	An implementation of … MBSE tools ... with clear access and use instructions …
	... ability to scale it
	Embed MBSE into standard processes.
MBSE terminology/ontology/libraries	...acceptance of libraries,…
	... and taxonomy for model reuse
	Keep a set of library of both levels as a repository.
	Libraries and profiles ... that are to be used enterprise-wide …
	Development of...a library of samples / templates
	Number/quality of enterprise MBSE artifacts/methods/playbooks, ….
MBSE tools	Increase in ... implementation of a common tool set.
	Accessibility to reliable database capability for collaborative MBSE tools
	... tools that help us to evaluate and optimize system trades.
	Dream: Efficient ... « light » tools across the Life cycle from concept to disposal.
	Growing the ... accessibility to the tools.
	Simplifying the tool UI and features.
	...scalable and easier to use tools.
	Can we achieve what we need, and meet our own expectations with the current state of the Vendor's tools. Their desire is to maintain a proprietary mindset.
	define ... standard tool configurations
Need for change	...with a "sense of urgency" focus…
	focus on why we are modeling…
	Consistent definition of the problem being solved by MBSE
	Challenge the status quo. The company has avoided several disasters, but the company's way of doing business will catch up with it as it grows.
Organizational characteristics	The diversity of the business portfolio.
Organizational culture	Cultural transition from traditional methods to a "prime system integrator" mentality.
	cultural change (document centric to model centric)
	Getting rid of the document based mindset
	Changing our mindset and way of doing business.
	Change the culture to be more collaborative and creative…
	Remove cultural obstacles (people included)
People in SE roles	Hiring of Systems Engineers on projects to....
People willing to use MBSE tools	getting Programs to use it and pay for it, with the return on investment coming later
	Identify... personnel to execute MBSE projects in a repeatable manner.
	Expect all Systems Engineers to use the modeling tools….
Projects/programs to apply MBSE	practice and policy fitting projects of various dimensions…
	focus on ... what needs to be modeled …
Rewards/recognition	(Acceptance of a holistic approach to model-based methods that includes)... incentive structure,…
Rewards/recognition	...Don't allow some to put their data in Word, PowerPoint, Visio, etc. while expecting someone else to translate it into a model. Stop enabling the behavior by providing reports in those tools instead of making them learn how to use the model.
Security of data and IP	An implementation of ... MBSE tools that balances security with user authority to

Code	Unique response comment- *Changes*
	manage projects...
Success metrics	Well defined and... success metrics
	Better definition of….providing metrics…
	Define master data and metrics to show MBSE delivered value to enterprise management.
Supportive infrastructure	...infrastructure changes…
	(Acceptance of a holistic approach to model-based methods) that includes infrastructure... technology development,...enterprise support,…
	3) fund major infrastructure IT and engineering hardware to use for model based engineering.
	An implementation of ... MBSE tools ... with ... full-time IT support.
	Organizational issues and IT Environment
Teamwork	... collaboration on consistent implementation of tools and design practices.
	Improved collaboration between teams and sites.
Training	Our organization needs to teach the technical experts to model...
	(Acceptance of a holistic approach to model-based methods) that includes...training,…
	Training!
	Training ... of methodology and technical review artifacts.
	Enhance internal training options…
	Train our engineers in details of modeling with SysML and developing/testing executable models
	We need MBSE training staff, courses (online and in-person), self-paced tutorials ... to grow our MBSE expertise.
	DAU should have three courses already being taught! 1. Intro to MBSE (four pillars, maturity of use, for PMs and SES, 0-6 and Flag level military) 2. Using MBSE tools (pick a tool and train how to add req, build bdd, ibd, state machines, simple simulations, using use cases). 3. Advanced MBSE tool use (expand on using the tool and run through an entire life cycle to include FRACAS, FMECA drills, QA, ECPs, CCB, etc.)
Use in SE community	Consistent adoption and acceptance by ... and partner-industries.
Vision and strategy for MBSE	Clear vision and strategy to move ahead,….
	Getting a global strategy and vision around model based design
	Revisit the goals of the process, what sorts of artifacts and information are actually needed by each consumer of information, and produce a streamlined process that produces the required information without creation of excess unused artifacts.
	Set the enterprise goals…
Workforce knowledge/skills	Especially the modeling tools are not for everyone. Mainly for persons outside the SW the usage of the tool is not easy.
	Education of non-modelers on what to demand of modelers.
	Understanding and implementing uncertainty quantification and stochastic methods
	... and upskilling our workforce.
	Finding people that can rapidly adjust to systems thinking (modeling is easy...)
	Skilled MBSE staff

The frequency of *changes* reported is shown in Table 21 and Figure 51. There were two codes for which there were no response comments for the question on *changes*, as shown in the table. For the sake of conciseness, these codes are not shown in the figure.

Table 21. Analysis of Responses to Question on Changes to Improve MBSE Implementation

Code Category	Code	Code label	# Comments Changes
MBSE Processes	MBSE methods/processes	MBSE PROC	45
Workforce	Training	TRAINING	31
MBSE Processes	MBSE tools	TOOLS	20
Resources	General resources for MBSE implementation	RESOURCES	16
Leadership	Leadership support/commitment	LDR CMT	16
Change Processes	Change management process design	CHANGE PROC	14
Workforce	Workforce knowledge/skills	SKILLS	13
Organizational Environment	Organizational culture	CULTURE	12
MBSE Processes	Integration to support MBSE implementation	INTEGRATION	11
Change Processes	Demonstrating benefits/results	DEMON RES	10
MBSE Processes	MBSE terminology/ontology/libraries	TERM/ONTOL	9
Organizational Environment	Supportive infrastructure	INFRA	9
Communication	Awareness of MBSE benefits/value	AWR BEN	7
Leadership	Leadership understanding of MBSE	LDR UND	6
Change Processes	Vision and strategy for MBSE	MBSE STRAT	6
External Environment	Alignment with customer requirements	CUST REQ	5
Communication	Need for change	NEED	5
Communication	Communicating success stories/practices	COMM SUCC	4
Workforce	General MBSE awareness and knowledge	GEN AWR	4
Workforce	People willing to use MBSE tools	WILLING	4
External Environment	Customer/stakeholder buy-in/engagement	CUST BUY-IN	3
Organizational Environment	Success metrics	METRICS	3
Organizational Environment	Alignment with business strategy	STRATEGY	2
Change Processes	Champions	CHAMPIONS	2
Resources	Cost to use MBSE tools	COST	2
MBSE Processes	Projects/programs to apply MBSE	WHERE APPLY	2
Organizational Environment	Rewards/recognition	REW/RECOG	2
Workforce	Teamwork	TEAM	2
External Environment	Use in SE community	USE SE COMM	2
Change Processes	Community of practice	COMM PRACT	1
Change Processes	Legacy/current processes	LEGACY PROC	1
Workforce	MBSE learning curve	LRN CURVE	1
Organizational Environment	Organizational characteristics	ORG CHAR	1
Workforce	People in SE roles	SE ROLES	1
MBSE Processes	Security of data and IP	SECURITY	1

Code Category	Code	Code label	# Comments Changes
Change Processes	Competing priorities	COMP PRIOR	0
External Environment	External regulations	EXT REG	0
Totals (n=153 respondents)	**37**		**273**

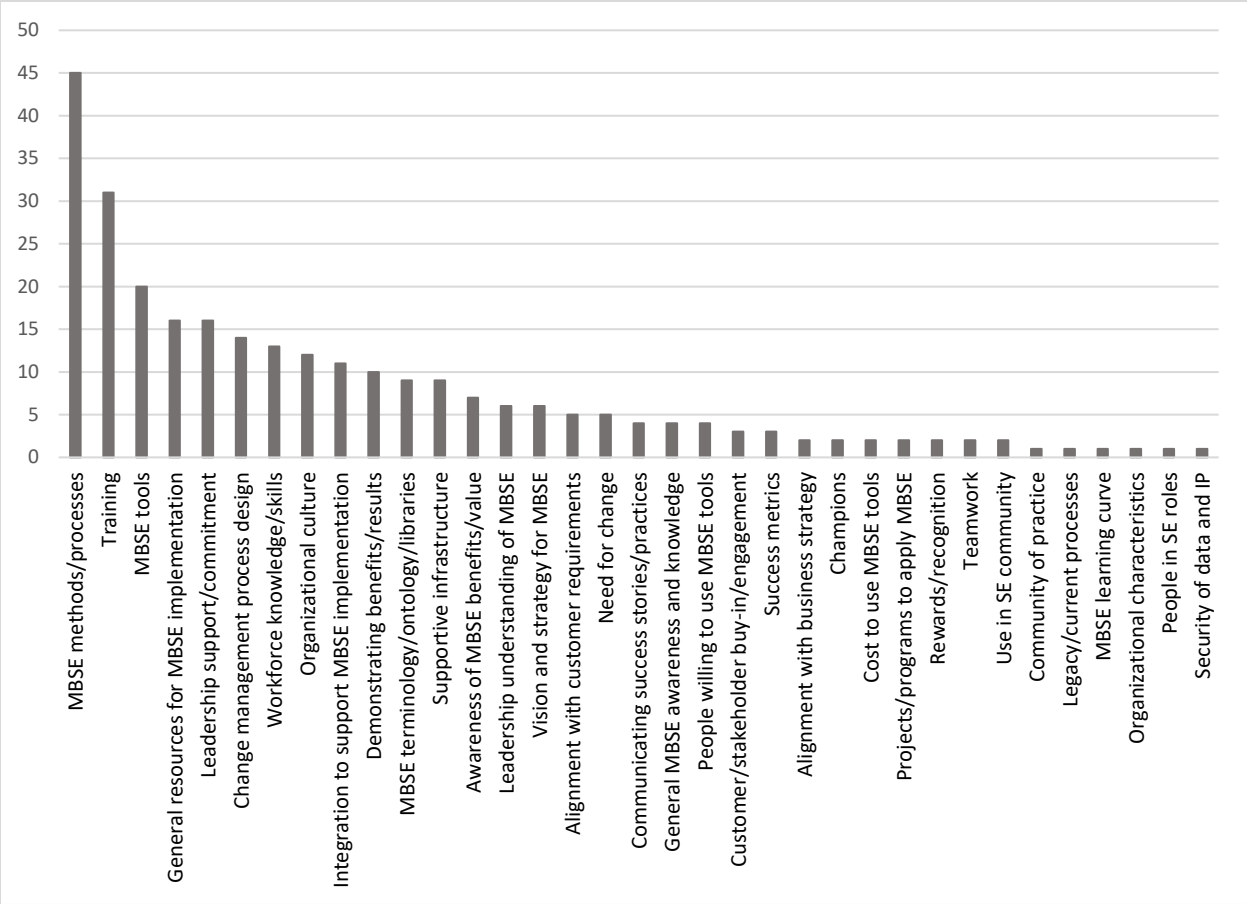

Figure 51. Changes to Improve MBSE Implementation.

It is useful to compare results for analyzing responses to *obstacles* and *enablers* (see Figure 52), as they represent two opposite perspectives of success of MBSE adoption, and thus, represent a more holistic picture of the success factors for adoption. The figure below combines these two. It is interesting to note the following:

- Factors reported frequently as *obstacles* but not *enablers* – i.e., organizational culture, awareness of MBSE benefits, competing priorities;
- Factors reported frequently as enablers but not obstacles – i.e., people willing to use MBSE, champions, people in SE roles;
- Factors reported frequently as both obstacles and enablers – i.e., workforce knowledge/skills, leadership support/commitment, and demonstrating benefits of MBSE. This category represents significant opportunity for organizations to proactively and intentionally manage MBSE implementation efforts to increase likelihood of success.

It is also useful to compare directly the most frequently reported *obstacles* and *changes*, as both represent opportunities for changing something about MBSE implementation efforts (see Figure 53). Interestingly, organizational culture is the most frequently reported *obstacle*, but not prevalent in *changes* needed, according to respondents. Rather, respondents focused on aspects of MBSE methods/processes and training in identifying future changes needed to improve implementation.

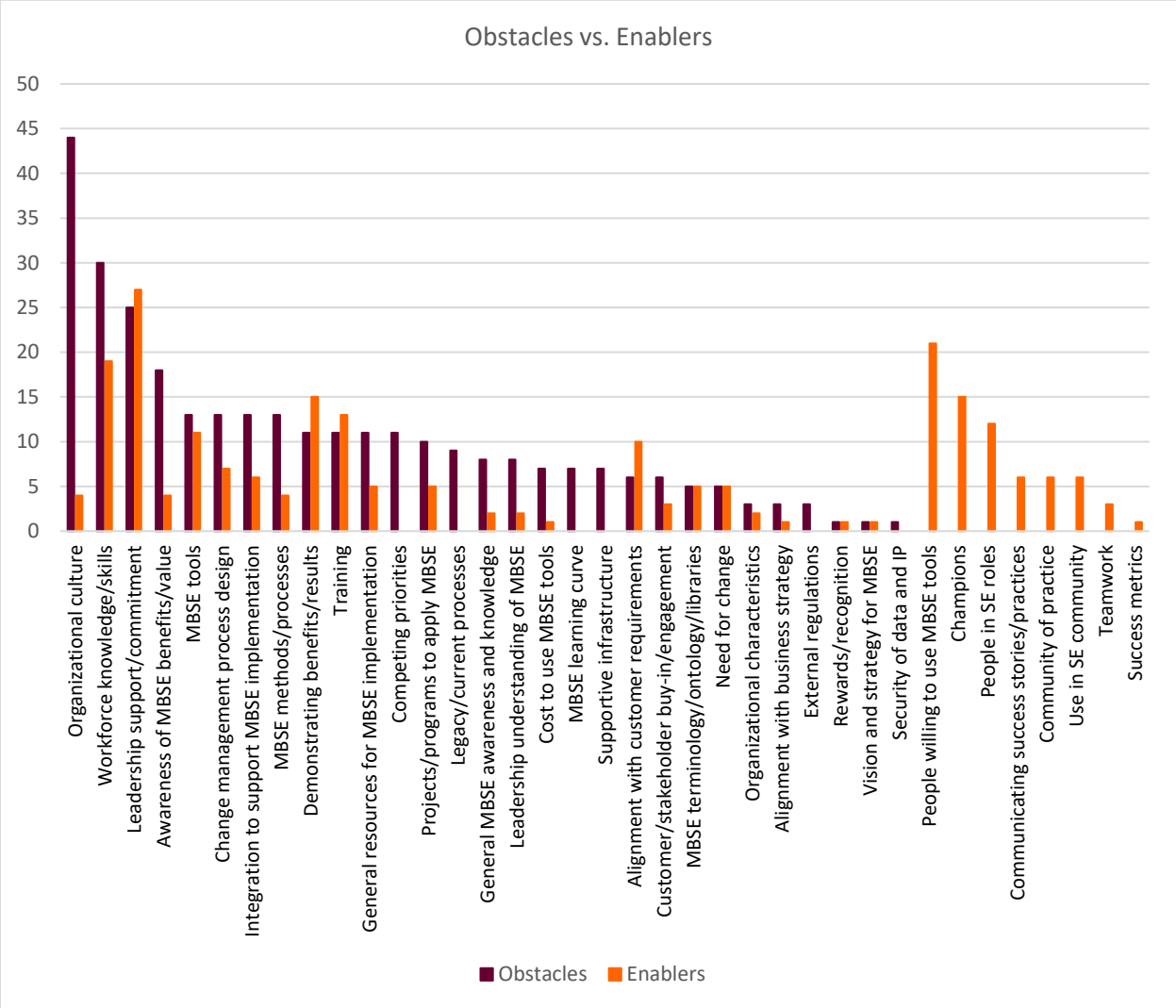

Figure 52. Obstacles versus Enablers.

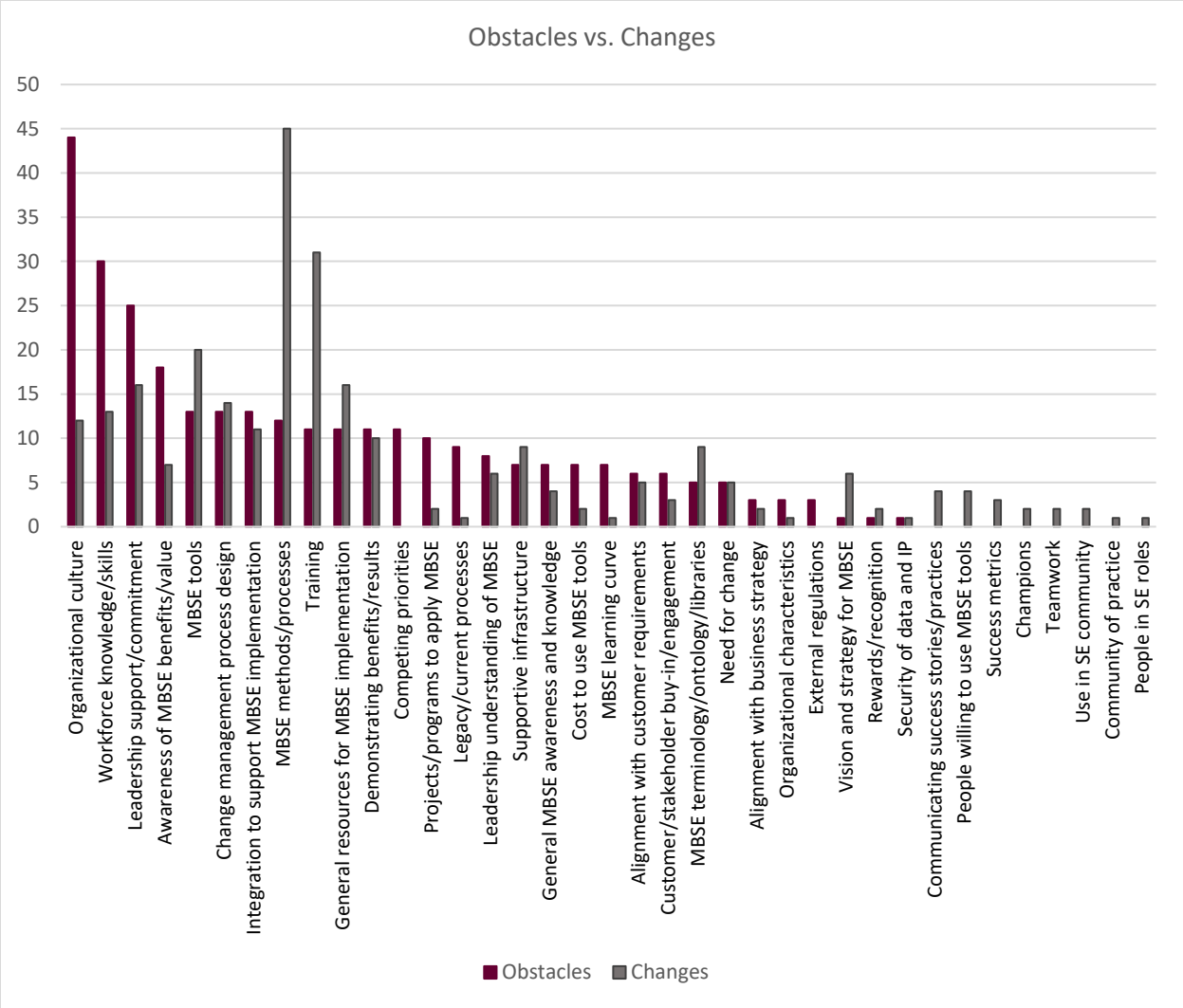

Figure 53. Obstacles versus Changes.

Overall, these results can be used to develop a set of practices, mapped to the Baldrige CPE, that organizations can consider in planning and deploying MBSE throughout the enterprise to increase the changes of successful adoption.

3.6 Analysis of Text Responses, Workforce Development

This section analyzes the free-text responses for those questions relating to workforce development. The section first discusses the analysis approach. The actual text responses are then summarized quantitatively based on the framework.

3.6.1 Analysis Method for Roles and Approaches

The workforce development-related questions of the survey specifically focused on the roles and skills identified and used by organizations as critical for DE/MBSE. Here, a "role" is category encompassing a set of specific, related activities and "skills" encompass the competencies required for DE/MBSE.

All text responses were included in this analysis, even if the individual did not fully complete the survey as comments are still considered valid. A total of 240 individuals started the survey. Table 22 shows the breakdown of the responses included in the analysis of the roles and skills questions. The actual text of the questions was:

> Question 18. *Please identify any new data management roles and processes you have created.*
> Question 31. *The top MBSE role(s) in my organization are:* and
> Question 34. *The most critical skills for MBSE are:*

Table 22. Overview of Responses Included in Analysis

	Non-response	"None" or "Not Applicable"	"TBD"	Analyzable Responses
Q18 Data Management Roles and Processes	161	25	6	65
Q31 MBSE Roles	136	18	5	98
Q34 Critical Skills for MBSE	143	2	4	108
Totals	**440**	**45**	**15**	**271**

Non-responses are individuals who did not provide any free text for the questions. "None" or "not applicable" answers are distinguished from "TBD" (to be determined) answers. Responses categorized as "TBD" indicated that the organizations are currently examining what appropriate roles or skills could be, but they have not yet been finalized.

Note that a single response could identify more than one role or skill, so the total number of items listed in each analysis below does not equal the total number of analyzable responses for a question. For example, "systems engineer, systems architect, and model manager", is a single response that highlights three individual roles.

3.6.2 Q18: New data management roles and processes

Participants were asked to identify any new data management roles or processes created in their organizations. The coding for Question 18 naturally divided into two main groups: data management roles and data management processes. These are shown in Figures 54 and 55, below.

Data Management roles were initially coded individually, then code categories were created to group these individual roles appropriately. In Figure 54, the "miscellaneous" category contains single instances of roles that did not readily group into other areas; these "one off" roles were common in the dataset and as most did not contain any explanatory text, there is no more rational way to group them. Examples of "miscellaneous" roles include: server support, product structure specialist, and chief engineer with digital responsibilities.

The common roles that emerged from the data are primarily focused around the different types of work that must occur in a DE/MBSE environment versus a traditional SE environment: namely around structured management and integration of data and use of modeling tools. Though "change management" is a traditional systems engineering process, the answers for Question 18 specifically centered on tracking changes in data. Because Question 18 asked for new roles established specifically around data management, it is not surprising that traditional SE roles are not reflected in this question as they are in Question 34 (next section).

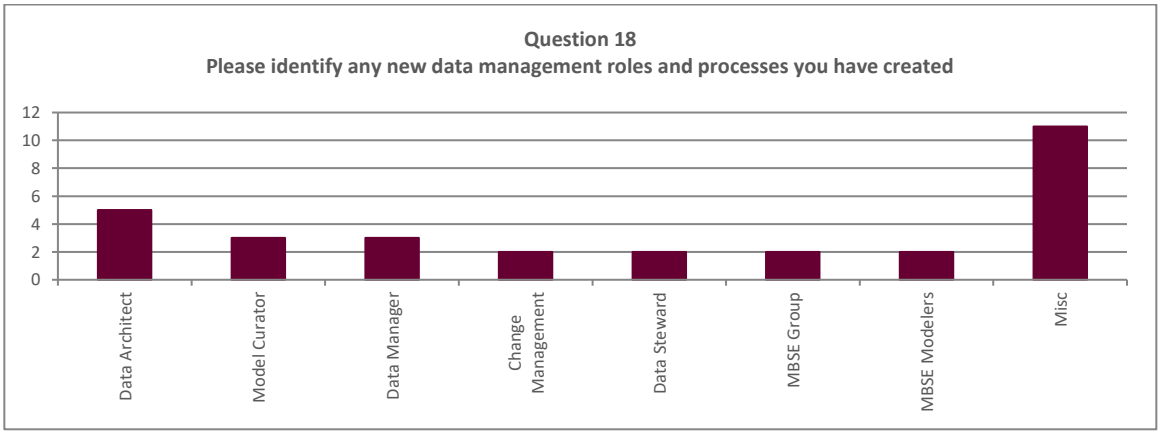

Figure 54. Data Management Roles

Figure 55 reflects the data management processes that have been established as a result of organizational implementation of DE/MBSE. As with the discussion of roles, traditional systems engineering processes are not reflected; the assumption is that SE processes are already established in these organizations. Also similarly to the roles discussion, the focus is around controlling data structure and creating an appropriate environment for tool use. Tool integration and data integration were often intertwined, with a respondent illustrating both integrating data from multiple sources as well as the need to "translate" data between different tool sets. These are not the same processes, but processes to handle two different aspects of the same issue and they were frequently co-occurring. The issue of data exchange across tools was also one of the more common "challenges" discussed in section 3.4. Implementation of open standards around DE/MBSE was mentioned, though the respondents cited different standards and guidance. The "Integrated Use of WBS" reflected the integration of project management Work Breakdown Schedules into the DE/MBSE environment in the respondents' organizations.

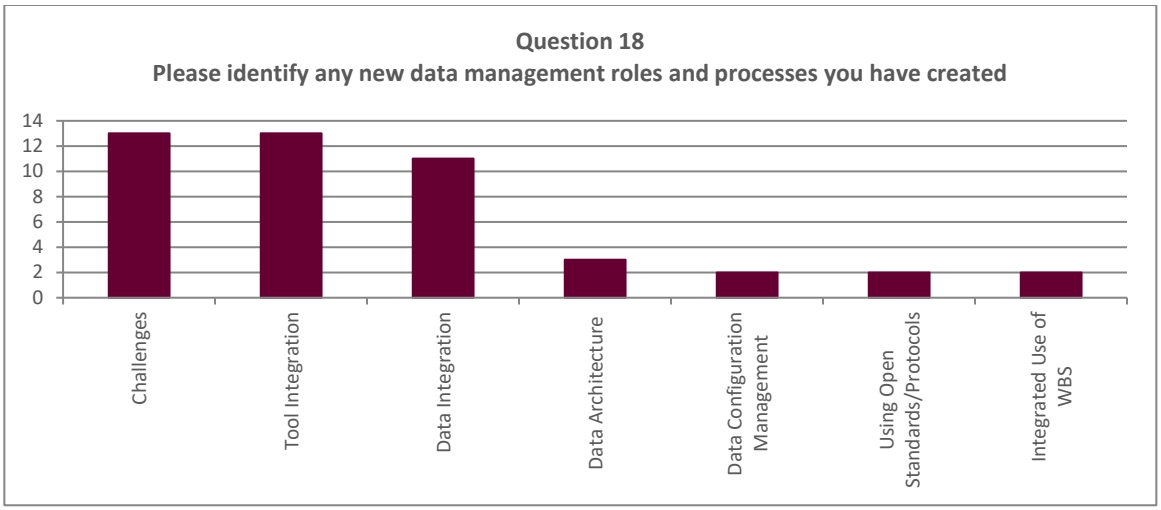

Figure 55. Data Management Processes

Challenges to creating DE/MBSE processes (or to MBSE in general) and issues with tool integration were the most commonly-cited challenges. The data management processes, roles, and skills described here align with the data management-focused responses received in Questions 31 and 34.

3.6.3 Question 31: Top MBSE Role(s)

Participants were asked to respond to the prompt, "The top BMSE role(s) in my organization are". The top MBSE roles reflected in Figure 56 are of two major flavors: roles required to perform DE/MBSE and roles that champion MBSE in the organization. In general, the Organizational Leadership and Project Leadership responses identified those who were champions in the organization; the rest were implementers of MBSE.

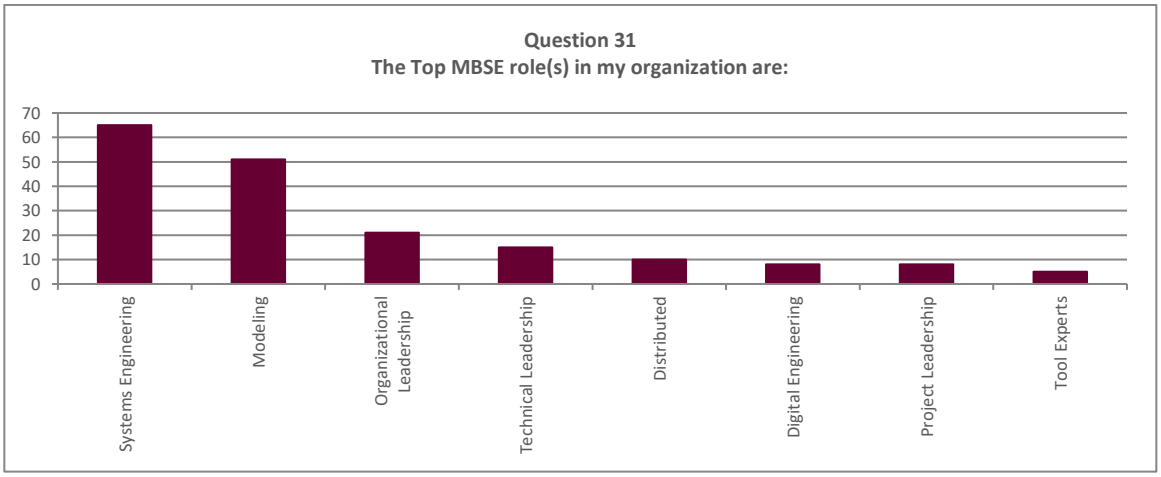

Figure 56. Top MBSE Roles

Table 20 provides the definitions of the code categories for MBSE highlighted in Figure 56. Similar to Question 18, the responses here highlight the importance of having individuals who focus on modeling, data, and the specific tools associated with them. However, they also highlight that systems engineering skills are critical important. Like with Question 34, responses indicated that the tools, digital environment, and modeling approach are not sufficient without a workforce skilled in SE.

Table 23. Definitions of Code Categories for MBSE Roles

Code Category	Definition
Systems Engineering	Recognized roles related to the systems engineering discipline (e.g., Atlas roles, updated from Sheard's "Twelve Systems Engineering Roles")[19]
Modeling	Roles focused specifically on the modeling that supports MBSE, including model development, maintenance, integration, and curation.
Organizational Leadership	Leadership roles that are focused on parts of an organization versus technical content, e.g., managers, directors, CTO.
Technical Leadership	Leadership roles that are focused on technical aspects, e.g., chief engineer, chief architect.
Distributed	These responses reflect an organizational view that everyone in the organization is a model-based systems engineer, e.g., "everyone!", "individual contributors", etc.
Digital Engineering	Roles related to the data science aspects of MBSE, particularly data management, data integration, and data analysis.
Project Leadership	Recognized project leadership roles, e.g., project manager, program manager.
Tool Experts	Roles focused exclusively on the use and maintenance of tools to support MBSE.

The "Distributed" code category was unexpected based on the existing roles framework, but reflects a culture in which DE/MBSE is "the way we do business here". DE/MBSE is integrated into all roles and is not an orthogonal approach in these organizations. For this question, "DE" code category reflected almost exclusively a digital architect role or a specific flavor of digital architect.

3.6.3.1 Question 31: Systems Engineering Roles Critical for MBSE

The "systems engineering" code category for Question 31 highlights the specific SE roles that are critical for DE/MBSE. These categories are shown in Figure 57 and defined in Table 25.

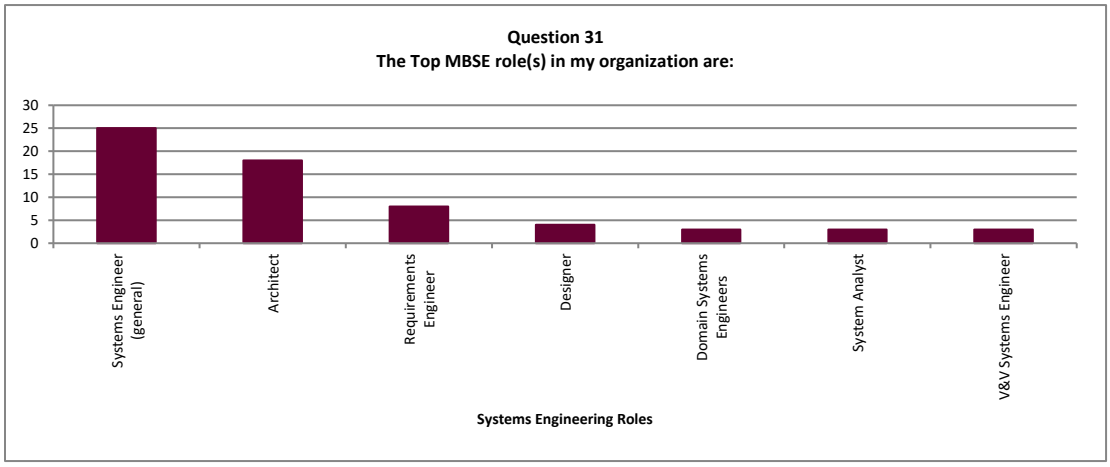

Figure 57. Top Systems Engineering Roles for MBSE

[19] Hutchison, N.A.C., D. Verma, P. Burke, M. Clifford, R. Giffin, S. Luna, M. Partacz. 2018. *Atlas 1.1: An Update to the Theory of Effective Systems Engineers*. Hoboken, NJ: Systems Engineering Research Center (SERC), Stevens Institute of Technology. SERC-2018-TR-101-A.

Table 24. Systems Engineering Role Definitions[20]

Code	Definition
Systems engineer (general)	Individuals whose primary responsibility it to conduct systems engineering activities.
Architect	Individual who owns or is responsible for the architectures of the system; this includes functional and physical architectures.
Requirements Engineer	Individual who is responsible for eliciting stakeholder requirements and translating them into system or sub-system requirements.
Designer	Individual who provides technical designs that match the system architecture; an individual contributor in any engineering discipline who provides part of the design for the overall system.
Domain Systems Engineer	Systems engineer focused on a specific application domain, e.g. automotive, space, energy.
System Analyst	Individual who provides modeling or analysis support to system development activities and helps to ensure that the system as designed meets the specification.
V&V Systems Engineer	Individual who plans, conducts, or oversees verification and validation activities such as testing, demonstration, and simulation.

Note that the "systems engineer (general)" code includes responses containing "systems engineer" or "SE" with no elaboration as well as recognized systems engineering roles like "process owner" or "systems engineering technical fellow", etc. that were only mentioned by a single respondent. This was the most common category. The code for "systems architect" was separated from "model architect" and "data architect", which were reflected in the "modeling" and "DE" code categories of Figure 57 (above), respectively. For most responses, the role was provided without any explanatory text. For the few responses that provided explanation, the theme was highlighting how these roles specifically utilize a DE/MBSE environment.

3.6.3.2 Question 31: Comparison to Existing Roles Framework

The INCOSE Capability Matrix does not have many specific roles called out; the focus is more on the fact that roles have been established. It is useful to compare the answers provided in Question 31 against an existing framework of systems engineering roles. The Helix *Atlas*[21] framework lays out the roles updated from Sheard's 1996 work "Twelve Systems Engineering Roles". An abbreviation of these roles is provided in Table 26. The detailed descriptions of this framework are provided in Appendix A.

Table 25. Comparison of SE Roles for MBSE with Atlas

SE Role Highlighted for MBSE	Helix/Atlas
Systems Engineer (general)	Information Manager Process Engineer
Architect	System Architect
Requirements Engineer	Requirements Owner
Designer	Detailed Designer
Domain Systems Engineers	
System Analyst	System Analyst
V&V Systems Engineer	V&V Engineer

[20] Adapted from ibid.
[21] ibid.

3.6.4 Q34: Most Critical Skills for MBSE

Participants were asked to respond to the prompt, “The most critical Skills for MBSE are”. In the responses to Question 33, just under two-thirds of the individuals responding indicated that their organizations had clearly identified critical skills for MBSE. Question 34 asked participants to identify, in free text, what critical skills had been identified. Of the 114 individuals who provided responses to this question, 5% indicated that they were unsure of which specific skills needed to be identified (2% indicated that their organizations were currently working on identifying these skills).

The code categories that emerged from this question are shown in Figure 58. The remainder of this section provides details on the first five code categories, which are the only categories with enough responses for details to be meaningful, and which are defined in Table 27. “Applied experience” is not about skills, per se, but the belief that individuals must have practical application of MBSE as well as theoretical knowledge. Software development included programming and software engineering.

“Challenges” around MBSE skills identified by respondents centered understanding the limitations of MBSE and training. As noted in Question 27, awareness of MBSE’s benefits is a key enabler; the responses under “challenges” highlight that for some respondents, the inverse is true: lack of awareness of key limitations is seen as an obstacle to success. Questions 27 and 28 highlighted the challenges and benefits around training. Here, responses highlight issues with existing training, specifically lack of training around MBSE, MBSE training not being integrated with other types of training offered, and a focus on “MBSE” training targeted exclusively on tools at the expensive of other critical skills. These align with the “MBSE learning curve” obstacle to adoption highlighted in the previous section.

A few respondents highlighted that MBSE – like systems engineering generally – should be multidisciplinary, though did not highlight specific disciplines. Organizational context as shown in Figure 1 focused on business analysis and organizational transformation and how insights from these areas should, in the respondents’ views, should be integrated into MBSE. Project management skills were also mentioned by a few of the respondents as being critical for MBSE to be successfully implemented.

Finally, there were a few codes that encompassed only 1-2 responses but did not fit into any of the other categories and are, therefore, not reflected in Figure 58. These included IT, marketing, roadmapping, value efficiency, and “technical” skills. In addition, the US Navy's Cross-SYSCOM Systems Engineering Transformation (SET) and the US Digital Warfare Office (DWO)/Digital Integrated Support Cell (DISC) guidance was mentioned.

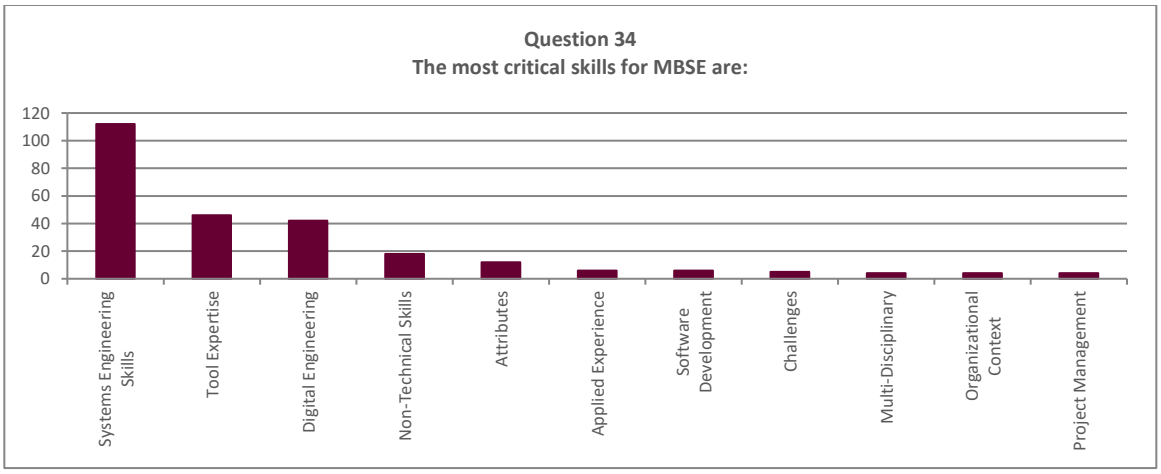

Figure 58. Themes around critical skills for MBSE.

Table 26. Code Category Definitions for MBSE Critical Skills

Code Category	Definition
Systems Engineering Skills	The specific skills required by systems engineers, in particular, the skills focused around the lifecycle activities of systems.[22]
Tool Expertise	The ability to successfully utilize critical toolsets – including understanding the underlying modeling languages – required in a model-based environment.
Digital Engineering	DE is defined as ‘‘an integrated digital approach that uses authoritative sources of systems’ data and models as a continuum across disciplines to support lifecycle activities from concept through disposal. A DE ecosystem is an interconnected infrastructure, environment, and methodology that enables the exchange of digital artifacts from an authoritative source of truth.”[23]
Non-Technical Skills	Skills associated with interpersonal or leadership capabilities that are critical to MBSE, but not considered to be technical.
Attributes	Characteristics of individuals who are viewed as successful at MBSE, attributes are differentiated from “skills”. Though they can grow and change over time, they are considered more inherent than learned, whereas skills are generally considered learned.

To be successful at MBSE, respondents stated that systems engineering skills were paramount, and must be supported by related but somewhat orthogonal skillsets around digital engineering and modeling tools.

3.6.4.1 Q34: Systems Engineering Skills

Forty-four percent of respondents provided details on the critical systems engineering skills that are required for MBSE. A total of 111 references to SE skills were recorded. These were grouped into the code categories shown in Figure 59. The key take-away from these responses is that good systems

[22] INCOSE defines systems engineering as, “A transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods.” (2019)

[23] Office of the Deputy Assistant Secretary of Defense (Systems Engineering) [ODASD (SE)], “DAU Glossary: Digital Engineering,” Defense Acquisition University (DAU), 2017.

engineering skills are critical for DE/MBSE; i.e., modeling and new tools will not make up for a lack of solid systems engineering skills in the workforce.

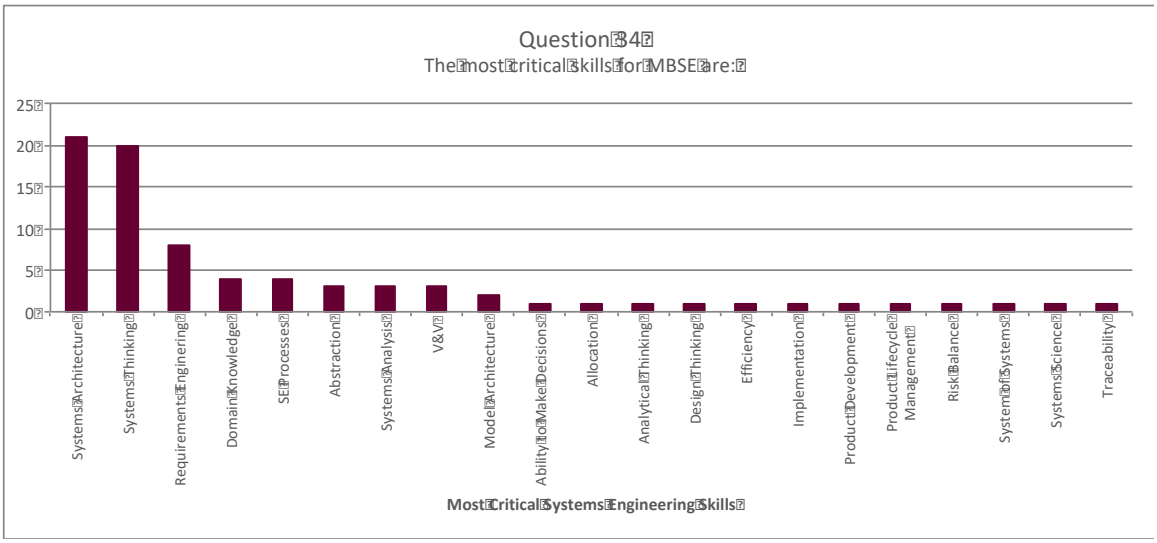

Figure 59. Systems Engineering Specific Skills for MBSE

Systems architecture was the most commonly cited area of skill required. Specifically, respondents discussed the relationship between the systems architecture and the model architecture. In addition, several specific architecture frameworks (e.g. DODAF, MODAF) were listed as critical in the respondents' organizations. Systems thinking was also top of mind among respondents. Interestingly, very little discussion was provided; there was a clear assumption that "systems thinking" was a well-understood term that did not require definition or elaboration. Codes under "Requirements" included not only the incorporation of requirements into system models, but specifically highlighted working with stakeholders for requirements elicitation and definition.

3.6.4.2 Q34: Tool-Related Skills

Tool expertise is ability to successfully utilize critical toolsets – including understanding the underlying modeling languages – required in a model-based environment. There were a total of 46 comments on this theme in the data, as shown in Figure 60.

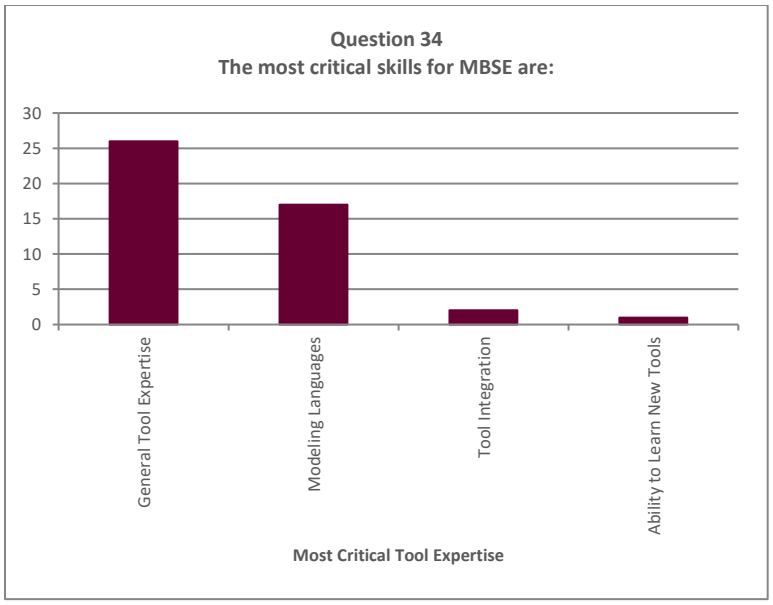

Figure 60. Most critical Tool-Related Skills

Most commonly, respondents discussed the need to understand and be able to learn tools in general terms, shown in Figure 60 as "general tool expertise". Closely related to this was the criticality of understanding the modeling language on which a given toolset is built. Note that most respondents did highlight a specific tool set or modeling language (SysML, for example, was cited in 14 of the 17 responses around modeling language). Mentioned less frequently, but important to highlight was the integration of different tools to better enable the "MBSE environment". This is a skill beyond simply using the tools and includes being able to appropriately maintain the tools as well. Respondents for tool integration listed this as both a critical skill and a current challenge. Finally, the ability to learn new tools was mentioned as a required meta skill.

3.6.4.3 Q34: Digital Engineering Skills

In the context of the survey, "digital engineering" skills specifically refer to the use and management of data, the creation of models, and their utilization to perform simulations. The major codes in this category are defined in Table 28 and the coding distribution is illustrated in Figure 61. In total, there were 42 separate instances of digital engineering skills reported in the survey.

Table 27. Code Definitions for "Digital Engineering" Skills

Code	Definition
Modeling	The act of creating and utilizing models (simplified versions of concepts, phenomena, relationships, structures, or systems) to facilitate understanding, aid in decision making, or explain, control, or predict events.[24]
Data Science	An inter-disciplinary field that uses scientific methods, processes, algorithms and systems to extract knowledge and insights from structured and unstructured data.[25]
Simulation	The process of developing or using a model to behave or operate like a given

[24] Hart, L. 2015. "Introduction to Model-Based Systems Engineering (MBSE) and SysML. Presented at the Delaware Valley INCOSE Chapter Meeting. 30 July 2015. Lockheed Martin Corporation.
[25] Dhar, V. 2013. "Data science and prediction". *Communications of the ACM*. 56(12): 64-73.

	system when provided a set of controlled inputs.[26]
MBSE Environment	The set of software tools and IT infrastructure that together enable MBSE activities.
Model Governance	Procedures to ensure that models are created and used consistently within an organization and achieve their intended purpose.[27] (Modified from US FDIC 2005)

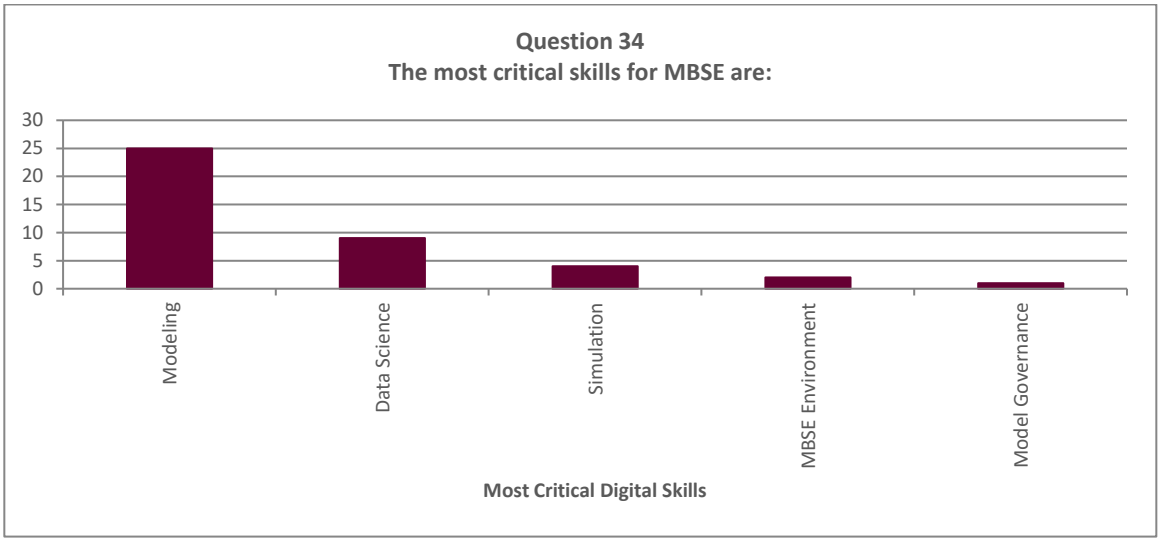

Figure 61. Critical digital engineering skills for MBSE

Not surprisingly general "modeling" skills were the most common highlighted. These skills were described as modeling "aptitude", "understanding", or "ability" and the types of models highlighted included architectural models (e.g., DoDAF), information models, system models, and business models. It is interesting that simulation was referenced far less frequently than modeling, though it is possible that "modeling and simulation" have become intertwined enough in the community that for most of the respondents, they were not separable.

Data science included reference to data analysis, data management, data sharing, data visualizations, and understanding and creating database structures. Respondents highlighted the importance of understanding how information is structured in and flows between different parts of a model.

MBSE environment here refers to the suite of tools required to enable system modeling. The inference is that the respondents were referencing the skills required not just to use the tools, but to set up these types of environments, including selecting the appropriate tools and ensuring appropriate integration between them, although this was not clearly stated.

Though it could have been included with modeling, a few respondents specifically highlighted the skill of model governance – ensuring that there is guidance on how models will be built and used as well as ensuring some quality control of the models themselves. Because this skillset is different than actually creating models, it was kept separate for this analysis.

[26] ISO/IEC/IEEE. 2010. *Systems and Software Engineering - System and Software Engineering Vocabulary*. Geneva, Switzerland: International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC)/ Institute of Electrical and Electronics Engineers (IEEE). ISO/IEC/IEEE 24765:2010.
[27] US FDIC. 2005. "Model Governance." *Supervisory Insights*. Winter 2005: 4-11.

3.6.4.4 Q34: Non-Technical Skills

In total, there were 19 references to non-technical skills in the dataset. The codes associated with this code category are shown in Figure 62.

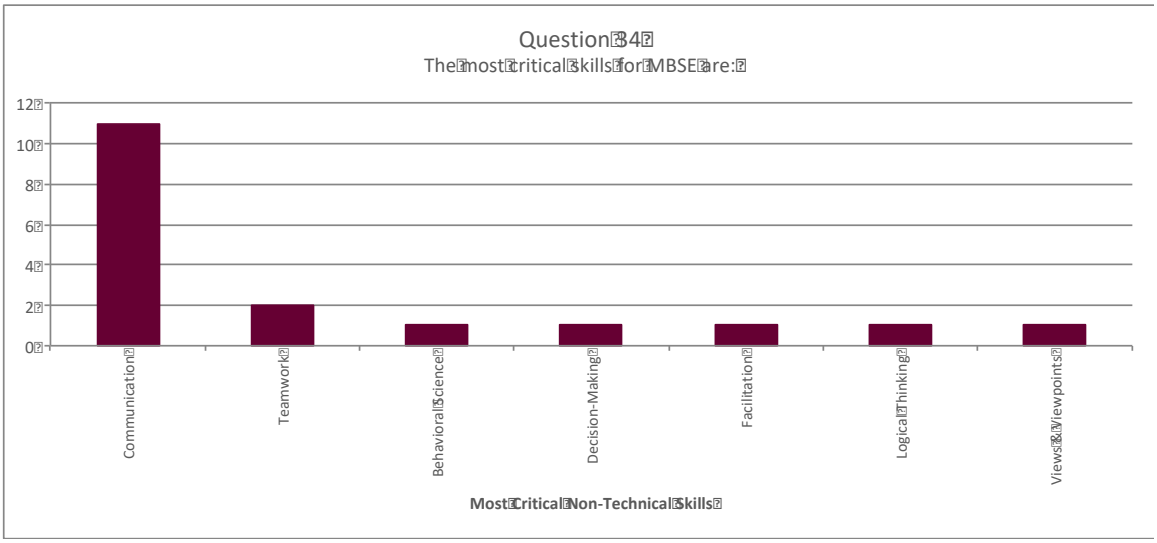

Figure 62. Critical Non-Technical Skills for MBSE

Communication was the most commonly cited skill with 11 references, though the types of communication highlighted varied between respondents. Oral communication (both formal presentation and general conversation) and written communication (from general correspondence to formal technical writing) were described as critical to ensuring that teams worked consistently together and to facilitating adoption of MBSE.

Teamwork referenced the role of a model-based systems engineer in coordination across different stakeholder groups. The other skills were mentioned only once by respondents. The main take-away here is that in MBSE, just as in systems engineering in general, these non-technical (or "professional") skills are viewed as important enablers.

3.6.4.5 Q34: Attributes

Though not "skills" per se, some respondents highlighted characteristics of individuals who are viewed as successful at MBSE. Though they can grow and change over time, attributes are considered more inherent than learned, whereas skills are generally considered learned. There were a total of 12 codes around attributes; only two attributes were cited more than once:

- Consistency (cited twice)
- Continuous Learning (cited twice)
- Adaptable
- Collaborative mindset
- Creative
- Detail-oriented
- Internally Motivated
- Open-minded
- Organized

3.6.5 Comparison of DE/MBSE Skills with Existing Frameworks

The skills highlighted in this section are commonly-understood systems engineering competencies and can be found in a number of competency frameworks such as the Helix *Atlas* model[28], the INCOSE Systems Engineering Competency Framework[29], or the MITRE Systems Engineering Competency Framework.[30] Because the *Atlas* framework was used for the roles discussion in Question 31, the comparison is continued in Figure 63 below. The bold text is the "proficiency areas" from the *Atlas* framework; the normal text is the list of skills codes from the MBSE maturity survey.

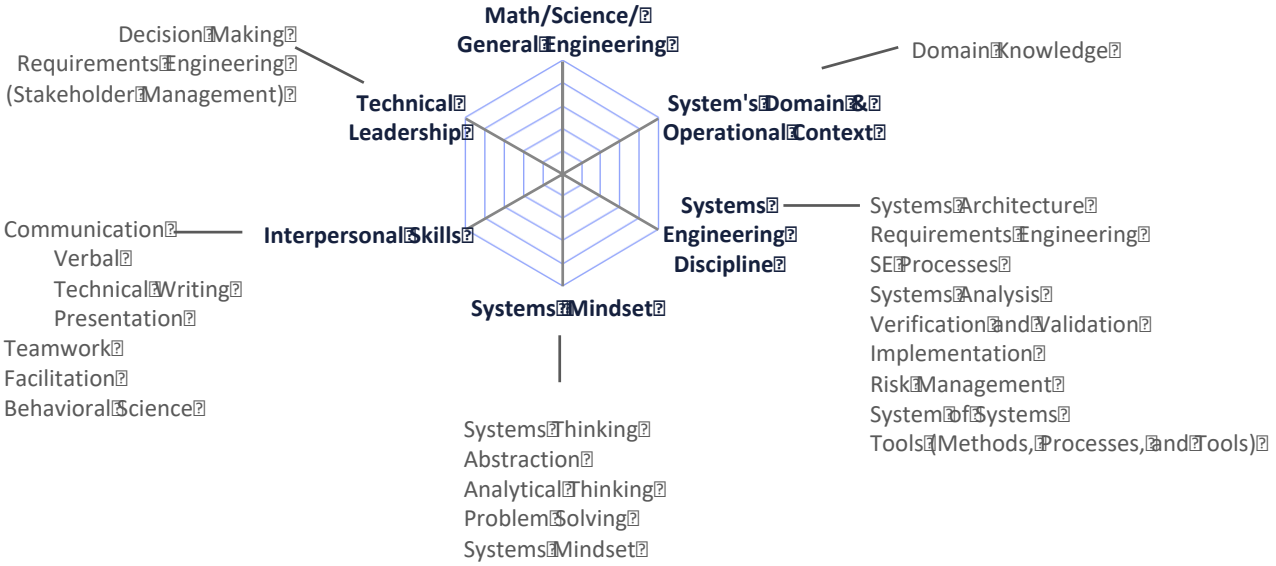

Figure 63. Mapping between MBSE Critical Skills and the Helix proficiency model.

Figure 63 reinforces that skills critical for a good systems engineer are the same skills that are required for a good model-based systems engineer. The critical differences are the addition of the utilization of specific tools, an understanding of modeling language, and the "digital engineering" skills, which in this survey focuses on the skillsets of data management and utilization and general modeling and simulation skills.

In addition to the skills, the attributes described above also align well with the "personal enabling characteristics" of systems engineers highlighted in *Atlas*, as shown in Table 29. Adaptability, though not reflected below, is reflected in the "systems mindset" of Atlas.

Table 28. Comparison of critical MBSE attributes with Atlas *personal enabling characteristics*

MBSE Survey: Critical Attributes	*Atlas* Personal Enabling Characteristics
Consistency (cited twice)	Persistence
Continuous Learning (cited twice)	Lifelong Learning
Adaptable	
Collaborative mindset	

[28] Hutchison et al. 2018

[29] INCOSE. 2018. *Systems Engineering Competency Framework.* San Diego, CA: International Council on Systems Engineering.

[30] MITRE. 2007. *Systems Engineering Competency Framework*. McLean, VA: MITRE Corporation.

MBSE Survey: Critical Attributes	*Atlas* Personal Enabling Characteristics
Creative	Creativity
Detail-oriented	
Internally Motivated	Ambition & Internal Motivation
Open-minded	Inquisitiveness
Organized	Professionalism & Respect

Because the dataset citing attributes was small, more detailed analysis is not appropriate.

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Appendix A: *Atlas* Systems Engineering Roles Framework

Atlas is the theory of effective systems engineers created by the Helix project.[31] The systems engineering roles framework from *Atlas* was used in the analysis of Questions 18 and 31. The following is the roles framework from *Atlas* (*used with permission*).

Tables 26-28 provide the roles of systems engineers and offers an explanation of how each role came to exist in the framework. For example, "System Integrator" is the role that was previously titled "Glue" in Sheard (1996), and the name change as well as the rationale for the change is captured below. Tables 2-4 also highlight the *roles* framework developed, consisting of three categories:

- ***Roles Focused on the System Being Developed*** – These roles are what may most quickly come to mind when describing a systems engineer. They align closely with the systems engineering lifecycle and the critical activities systems engineers must enable throughout the lifecycle.
- ***Roles Focused on SE Process and Organization*** – These roles focus on the organizational context in which systems engineering works and the critical role of systems engineers in providing guidance on how systems engineering should be used.
- ***Roles Focused on Teams that Build Systems*** – Systems engineering does not occur in a vacuum and is, instead, an intensely social activity. The roles in this category focus on enabling diverse, multi-disciplinary teams to be successful.

The categories help distinguish between the major types of activities that systems engineers provide.

*Table 29. Roles Focused on the Systems Being Developed (*Atlas*, Hutchison et al. 2018 used with permission)*

Role Name	Role Description
Concept Creator	Individual who holistically explores the problem or opportunity space and develops the overarching vision for a system(s) that can address this space. A major gap pointed out to the Helix team – particularly when working to implement the findings of Helix – has been that of the development of an overarching system vision. This is a critical first step in the systems lifecycle, and several organizations stated that they believed it needed to be separately called out. In addition, when looking to the future of what systems engineers need to do (e.g., INCOSE Vision 2025 (2015)), the focus on early engagement and setting the vision was deemed critical.
Requirements Owner	Individual who is responsible for translating customer requirements to system or sub-system requirements. **Note: This is updated from *Atlas* 1.0. Sheard (1996) also included the activities around functional architecture in this role. However, in working with the community, this has caused some confusion as to the differences between this role and that of "System Architect". The Helix team believes that grouping all architecture activities together will improve clarity on the roles.**
System Architect	Individual who owns or is responsible for the architectures of the system; this including functional and physical architectures. **Note: This is updated from *Atlas* 1.0. This is an update of Sheard's "System Designer" role (1996). There was concern both at community events and during later interviews that nowhere in the presented framework did the critical role of systems engineers in architecture come out clearly. Some also argued that "Design" gave the impression that this role focuses specifically on the details of systems design over architecture.**

[31] Hutchison et al 2018

Role Name	Role Description
System Integrator	Individual who provides a holistic perspective of the system; this may be the 'technical conscience' or 'seeker of issues that fall in the cracks' – particularly, someone who is concerned with interfaces. Likewise, there was concern over the word "Glue", which many expressed was not clearly descriptive enough.
System Analyst	Individual who provides modeling or analysis support to system development activities and helps to ensure that the system as designed meets he specification. This is unchanged from Sheard's roles (1996).
Detailed Designer	Individual who provides technical designs that match the system architecture; an individual contributor in any engineering discipline who provides part of the design for the overall system. This is an addition based on the Helix data. While systems engineers do not always get involved with detailed design, in smaller organizations or on smaller projects it is more common. Likewise, systems engineers who had played this role explained that it was critical in developing their own technical and domain expertise as well as in understanding the design approaches of classic engineers.
V&V Engineer	Individual who plans, conducts, or oversees verification and validation activities such as testing, demonstration, and simulation. This is unchanged from Sheard's roles (1996).
Support Engineer	Individual who performs the 'back end' of the systems lifecycle, who may operate the system, provide support during operation, provide guidance on maintenance, or help with disposal. This was previously titled "Logistics and Operations Engineer" in Sheard (1996). However, in interviews and at community events, the Helix team received feedback that using this title gave the impression that this role was limited and did not encompass the full spectrum of systems engineers' activities at system deployment or post-deployment. Likewise, in several organizations, "logistics" and "operations" were seen as separate disciplines from systems engineering, which caused some contention in discussions. The renaming of this category is intended to address these issues.

*Table 30. Roles Focused on Process and Organization (*Atlas*, Hutchison et al. 2018 used with permission)*

Role Name	Role Description
Systems Engineering Champion	Individual who promotes the value of systems engineering to individuals outside of the SE community – to project managers, other engineers, or management. This may happen at the strategic level or could involve looking for areas where systems activities can provide a direct or immediate benefit on existing projects. Sheard recommended that a role such as this, labeled in her work as "Systems Engineering Evangelist", be added in (2000).
Process Engineer	Individual who defines and maintains the systems engineering processes as a whole and who also likely has direct ties into the business. This individual provides critical guidance on how systems engineering should be conducted within an organization context. This is unchanged from Sheard's roles (1996).

*Table 31. Roles Focused on the Teams That Build Systems (*Atlas*, Hutchison et al. 2018 used with permission)*

Role Name	Role Description
Customer Interface	Individual who coordinates with the customer, particularly for ensuring that the customer understands critical technical detail and that a customer's desires are, in turn, communicated to the technical team. This is unchanged from Sheard's roles (1996).
Technical Manager	Individual who controls cost, schedule, and resources for the *technical* aspects of a system; often someone who works in coordination with an overall project or program manager. This is unchanged from Sheard's roles (1996).
Information Manager	Individual who is responsible for the flow of information during system development activities. This includes the systems management activities of configuration

Role Name	Role Description
	management, data management, or metrics. This is unchanged from Sheard's roles (1996).
Coordinator	Individual who brings together and brings to agreement a broad set of individuals or groups who help to resolve systems related issues. This is a critical aspect of the management of teams. This is unchanged from Sheard's roles (1996).
Instructor/Teacher	Individual who provides or oversees critical instruction on the systems engineering discipline, practices, processes, etc. This can include the development or delivery of training curriculum as well as academic instruction of formal university courses related to systems engineering. While any discipline could conceivably have an instructor role, this denotes a focus on systems and is a critical component in the development of an effective systems engineering workforce. This is an addition to the Sheard roles (1996 and 2000).