Interactive Model-Centric Systems Engineering (IMCSE)
Phase 6

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Contents

LIST OF FIGURES

LIST OF (TABLES, SEQUENCES)

EXECUTIVE SUMMARY

The Interactive Model-Centric Systems Engineering (IMCSE) research program arises from the unique opportunity to investigate the various aspects of humans interacting with models and model-generated data, in the context of systems engineering practice. This is an important problem because human effectiveness in performing digital engineering and human acceptance of model-centric practice will be essential detriments of success of future acquisition programs. This is a multi-faceted investigation that involves both technical and social facets. Evidence-based findings are not readily found; but this is necessary to avoid failures grounded in using incorrect assumptions and ignoring cognitive and perceptual limitations.

Areas of inquiry include: how individuals interact with models; how multiple stakeholders interact using models and model generated information; facets of human interaction with visualizations and large data sets; how trust in models is attained; and what human roles are needed for model-centric enterprises of the future. This project is based on a belief that improving human-model interaction and social dimensions of model-based environments will significantly improve the effectiveness of digital engineering practice, quality of model-decision making, and cultural acceptance of a digital future.

IMCSE has used a research approach (Figure 1) that has involved many different research methods and engagement with the stakeholder community through multiple means.

Figure 1. IMCSE Research Program Approach.
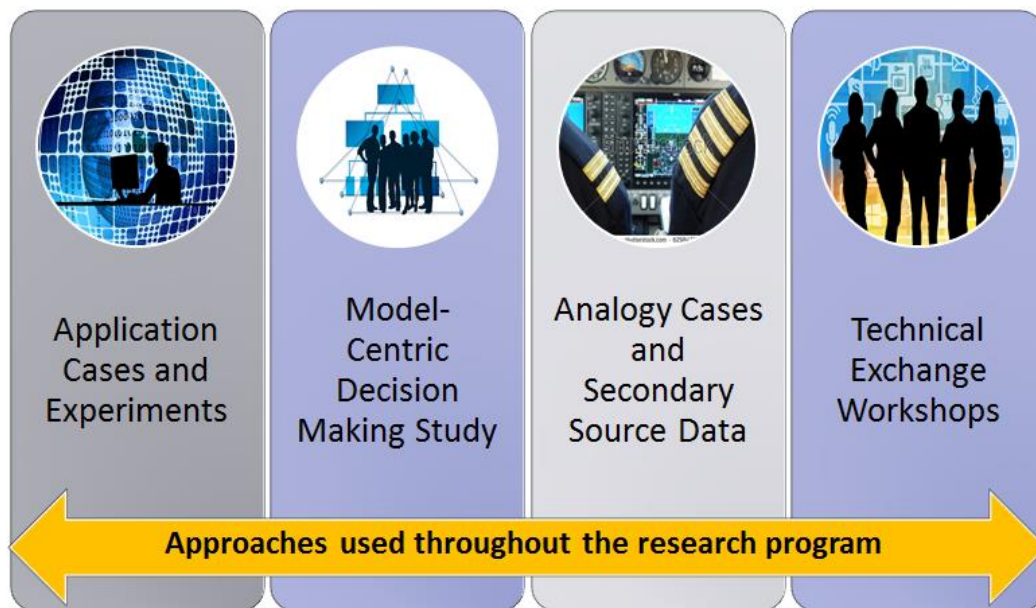
IMCSE Phase 6

IMCSE research generates knowledge impacting human effectiveness in model-centric environments of the future (Rhodes & Ross, 2016, Rhodes & Ross, 2017, Rhodes 2018). The Phase 6 research provided the opportunity to build on the research outcomes of prior phases.

This report discusses outcomes of Phase 6 of the IMCSE research program, in two areas:

Model Curation: Framework for Assessing Model-Centric Enterprise Capabilities. Prior phase research has identified sociotechnical leadership capabilities that provide enhanced ability to execute digital engineering at the program and enterprise levels. With a specific focus on model curation, a framework was generated that can serve to guide model curation in the digital engineering context. Evidence from other curation fields, expert knowledge and consideration of various situational perspectives was used to inform the formulation of a framework that enables assessment of curation capabilities respective to digital engineering implementation. The model-centric enterprise capabilities identified in prior phase research were further examined in context of model curation, including model composability, transparency, accession practices, model valuation practices, model trust and others. The resulting framework provides a structure for continuing SERC research on model curation practice and curator role, respective to state of transformation from traditional to digital engineering.

Guiding Principles and Patterns for Human-Model Interaction. Building on prior phases for research that generated expert-based interview findings and heuristics for human-model interaction and decision-making, this phase of research focused on converging on consensus-based principles. Various technical exchange meetings, feedback from practitioner community, and testing of heuristics were used to validate and adapt the prior phase work. This work resulted in a set of recommended guiding principles and application examples. A classroom experiment provided insights into the potential usage and usefulness of employing principles in a teaching module within an undergraduate leadership program. A model-based engineering program team launch module was designed and tested in a small project setting. Possible approaches for using patterns were furthered explored in this phase.

IMCSE research was presented and discussed with practitioners and sponsors in numerous research meetings and workshops throughout Phase 6, as well as presentations at government forums. These included SERC events, NDIA SE Conference, INCOSE International Workshop, INCOSE International Symposium, DoD Digital Engineering Work Group (DEWG), and various meetings at MIT and other research stakeholder locations. These interactions were invaluable in shaping research directions and outcomes, and identifying relevant research ongoing in the larger systems community.

MODEL CURATION

As engineering practice becomes increasingly model-centric, models are valuable assets for designing and evolving systems. Accordingly, enhanced practices and new leadership roles become necessary in model-centric enterprises.

BACKGROUND

Participants in the 2015 pathfinder workshop for IMCSE identified model curation as an important topic for investigation (Rhodes and Ross, 2015). Ongoing IMCSE research (Rhodes & Ross, 2016, Rhodes, 2017, Rhodes, 2018) has revealed a number of driving factors for model curation and a curation leadership role at the enterprise level. Rouse (2015) stresses that the wealth of existing models is often not used because of a lack of knowledge of these resources and the difficulty in accessing them. Although reuse of models can have benefits, the reality is that legacy models are not widely used beyond their original purpose. Lack of access to models, mistrust of models, and perception of legitimacy of models are all barriers in model reuse and longevity. According to Reymondet et al. (2016), model expertise is largely resident in individuals, and the ability to select and compose sets of models is typically limited to the original use. In many enterprises, modeling competency is distributed across individuals and organizations, but infrequently leveraged at the enterprise level. However, lack of a centralized leadership authority results in models being owned and managed at a "local" level. Modeling efforts are often duplicated across programs, and the individual programs may lack model experts preventing benefit from the collected wisdom of the enterprise.

A question arises as to whether a model curation function at the enterprise level could lead to more effective use of models and digital assets at all levels. Models exist at all levels of an enterprise (individual, program, business unit, enterprise) but rarely are these managed as an enterprise collection. Of course, there is a need to distinguish between the models that can be elevated to the enterprise collection (deemed of value and quality to be used across the enterprise) and worthy of distribution outside the enterprise (by exchange, loan, sale...), and those models that are suitable for use at a local level (highly specialized, insufficient maturity for reuse, designed to be used for quick studies, etc.). It is not expected that all models that are useful will be destined to become enterprise-level models. Further knowledge and specific criteria need to be developed to effectively determine which models will be most suitable for reuse across programs and of value at the enterprise level.

Reymondet et al. (2016) investigates considerations for curation in the engineering of complex socio-technical systems. As engineering practice becomes increasingly model-centric, models are valuable assets for designing and evolving systems, and continue to exist throughout the lifespan of a program, making the management and control of models and digital artifacts imperative. The investigation suggests maturing an approach for model curation in the systems engineering field can leverage curation practices from other fields.

RESEARCH APPROACH

Phase 6 research has focused on an organizing framework that can serve to guide model curation in the digital engineering context. Research evidence from other curation fields, expert knowledge and consideration of various situational perspectives was gathered for use in formulating a framework that enables assessment of availability of curation capabilities respective to digital engineering implementation. Prior phase work on model-centric enterprise capabilities was examined in context of model curation, including model composability, transparency, accession practices, model valuation practices, model trust and others. Technical exchanges and working groups were used to gather knowledge, test assumptions and validate interim research. A generalized framework was iteratively defined and refined for the objective of having a structure for continuing SERC research on model curation practice and curator role, respective to state of transformation from traditional to fully digital model-based engineering. Literature review and expert knowledge elicitation were used to gather knowledge from other fields of curation. Insights from the research were used to generate key research questions for a more extensive research project on model curation.

MODEL CURATION (MC) CAPABILITIES FRAMEWORK

Model curation is a complex subject to address, and therefore a capabilities framework has been generated to guide the definition and elaboration of model curation in the digital engineering context. Evidence from other curation fields, expert knowledge and consideration of various situational perspectives is used to inform the formulation of a framework. A framework structures the various capabilities respective to digital engineering implementation, and once elaborated can be used to assess implementation of the various facets involved. The model-centric enterprise capabilities identified in prior phase research were further examined in context of model curation, including model composability, transparency, accession practices, model valuation practices, model trust and others. The resulting framework may serve as structure for continuing SERC research on model curation practice and curator role, respective to state of transformation from traditional to fully digital model-based engineering.

The MC capabilities framework presented in this report includes six areas: (1) shared understanding of constructs and terminology; (2) model curation lifecycle; (3) model curation use cases; (4) model curation practices; (5) model curation enablers; and (6) model curation infrastructure and technology.

SHARED UNDERSTANDING OF CONSTRUCTS AND TERMINOLOGY

Evolving definitions, constructs and specific terminology for shared use in the digital engineering community is essential. This is a process that will occur over time, as this information needs to be vetted and discussed with the system community. This activity involves working with the Digital Engineering Information Exchange Working Group (DEIXWG), and its efforts to develop a Topical Encyclopedia for Digital Engineering Information Exchange,

referred to as DEIXPedia (OMG MBSE Wiki). An initial entry for Model Curation was developed and is under community review.

A draft definition for model curation is included in a Model Curation entry:

> *Model curation is the lifecycle management, control, preservation and active enhancement of models and associated information to ensure value for current and future use, as well as repurposing beyond initial purpose and context*

Table 1 shows a model curation lexicon, which is evolving through discussions with research stakeholders and investigation of other fields. Additional work is needed to complete and validate the usefulness of the terms.

Table 1 Model Curation Lexicon (continues to evolve)

Term	Definition (in development)
Model Accessioning	The formal process of accepting and recording a model as a collection object in the enterprise level model portfolio. Accessioning addresses the legal, IP and ethical issues in model acquisition and development.
Model Acquisition	The act of acquiring a model through an arrangement with the model owner (e.g., through purchase, trade, or other business transaction).
Model Cataloging	The formal process of making a model available for use through recording it in a catalog or directory, and tracking it throughout the model lifecycle.
Model Collection	The collection of model-based assets that is possessed by an enterprise, including those developed by the enterprise, acquired by the enterprise, and temporarily resident in the collection (e.g., leased, on loan).
Model Collection Object	A model or model-related object that is a unique asset in the enterprise's collection. An object is assigned a unique identifier.
Model Curator	A designated professional role entrusted with the ownership, tracking and use of model collection objects, and possessing designated authorities for managing and controlling models.
Model Composition	The process of composing models and model-related information that provides collective value beyond the individual models.
Model Composability	The characteristic of an interrelated set of models that enables them to be combined in accordance with given modeling formalisms.
Model De-accessioning	The formal process of removing a model as a collection object from the enterprise level model portfolio.
Model Demonstrator	A composed set of models with interactive interfaces for the purpose of demonstrating context-specific capability. Demonstrators enable the modeled system to be experienced by an individual through conveying cogent information.

Model Loan	The act of temporarily loaning a model through an agreement whereby the model owner agrees to share the model with the model acquirer for a specified time and specified terms (e.g., terms of use, remuneration, etc.).
Model Metadata	Descriptive metadata is contextual data about the model object(s). Metadata documents characteristics and used for indexing, discovering, identification. Provides user discovery of, access to, and management of an object.
Model Pedigree	Model-associated information that describes model origin, development process, originators and developers, assumptions, expert knowledge, model enhancements, investment costs, versions, change history, etc.

MODEL CURATION LIFECYCLE

Developing a model curation lifecycle is essential for digital engineering. The value of a lifecycle model has been demonstrated in the field of data curation, where the Digital Curation Centre (UK) has evolved the DCC Curation Lifecycle Model (DCC) as shown in Figure 2. According to the DCC website:

> *The DCC Curation Lifecycle Model provides a graphical, high level overview of the stages required for successful curation and preservation of data from initial conceptualisation through the iterative curation cycle. The model can be used to plan activities within a specific research project, organisation, or consortium to ensure all necessary stages are undertaken, each in the correct sequence. It is important to note that the description, preservation planning, community watch, and curate and preserve elements of the model should be considered at all stages of activity.*
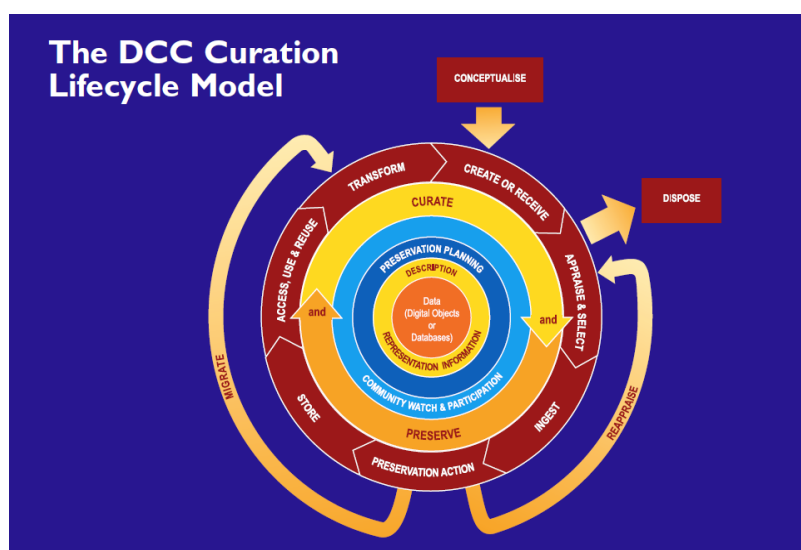

Figure 2. Digital Curation Centre (UK) Curation Lifecycle Model

The following is a description of benefits of the lifecycle model suggested by DCC (DCC, accessed 28 Feb 2019):

The Lifecycle model enables the mapping of granular functionality onto a series of practical activities which allows creators, curators, and re-users of data to identify where they themselves fit into the bigger picture. By applying the lifecycle model to your own working practices, you will be able to identify whether additional steps are required, if there are 'missing links' in your data curation processes, whether some steps can be eliminated for your particular working practices, and to define specific roles and responsibilities within your project/institution across the different stages. By separating discrete stages the model also supports the identification of collaborators in the process of curation (for example, allowing a data creator to work with a repository in order to design the most appropriate metadata for the data objects instead of 'going in blind'). The sequential stages encourage the documentation of processes and policies by and between different stakeholders, and also support the building of frameworks of standards and technologies, and identifies needs for particular tools and services to support data curators at every level.

DCC has developed a related reference manual, with successful practices and examples. Over time, model curation for digital engineering practice could be envisioned to have similar useful information developed through the systems community. Next phase research will further investigate the work of DCC and others to discover what is most useful for digital engineering.

MODEL CURATION USE CASES

Curation applies to longer duration models, rather than quick studies and models to work out a problem. Two broad categories of longer duration models (Figure 3) that necessitate model curation are: (1) models that will be used throughout the lifespan of a program; and (2) models that will be reused for other purposes and contexts.
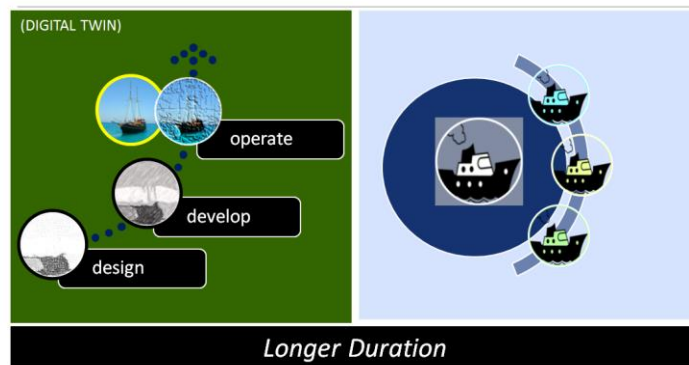

Figure 3. Longer Duration Models of Two Types

Model curation use cases need to be generated through investigating the myriad situations under which curation will be applicable. This will depend on enterprise and program characteristics and specialized circumstances.

MODEL CURATION PRACTICES

Maturing an approach for model curation for the engineering field can benefit from knowledge, practices and experiences from other fields of curation practice. Formalizing curation practice in context of digital engineering will require a significant effort and involvement of the broader community. There are practices from other fields that have similar characteristics (e.g., digital engineering as summarized in Figure 4).

Museum curation (or curation in similar cultural/heritage institution) is a mature profession, with formalized practices and many academic degree programs. Some new aspects of museum curation emerge with the increasing use of technology in the display and preservation of objects. And, digital object curation is now an extension of traditional museum curation, given the many digitized and digital artifacts that may now be found in institutional collections.

Digital curation was the subject of recent investigation by The National Academies. The resulting published report stressed the importance of "active management and enhancement" in digital curation, and discussed the importance of preparing the workforce (NAS, 2015). The study concluded that digital curation is unique in regard to "the immense and ever-increasing quantities of material to be curated, the need for active and ongoing management in a context of continually changing uses and technology, and the great diversity of organizational contexts in which curation occurs."
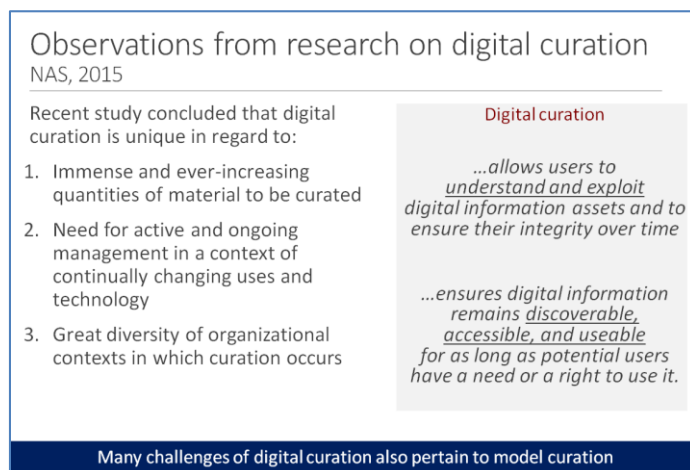
Figure 4. Digital Curation: observations from NAS study

Digital objects include such things as files, images, and video. Many of the challenges inherent in digital curation also pertain to model curation. Rusbridge et al. (2005) outlined a vision for digital curation that "embraces and goes beyond that of enhanced present-day re-use, and of archival responsibility, to embrace stewardship that adds value through the provision of context and linkage: placing emphasis on publishing data in ways that ease re-use and promoting accountability and integration."

Data curation is about the lifecycle maintenance of data, with the goal of preservation for use, for example, research data and census data. In particular, there is an emphasis on maintaining the value of data throughout its lifespan. With the rise of big data and data science the field takes on a greater importance in many different types of organizations. Data warehousing is an example of long-standing approach that falls under data curation. With increased digitization of objects such as paper-based reports, the lines between digital curation and data curation are less distinct. However, digital objects are not always data per se, and data curation may also deal with non-digitized data.

Social curation focuses on collaborative sharing of Web content organized around one or more particular themes or topics. Duh et al. (2012) define social curation as "the human process of remixing social media content for the purpose of further consumption." Potter and Gilje (2015) state curating (as a verb) suggests at least "… collecting, cataloguing, arranging and assembling for exhibition and displaying." Speaking to the act of curating at the individual, rather than institutional level, they note that verbs used to credit an author such as 'written', 'edited', or even 'created'… don't capture all the self-representational activities or practices in digital culture that the verb 'curated' does". Curating a digital space is "not only about writing or creating within it but also collecting, distributing, assembling, disassembling, and moving it across different stages." Social curation has implications for model curation, suggesting the importance of viewing curation at multiple levels from individual to enterprise. It also points out the importance of taking a situational viewpoint as part of curation activity.

In the field of engineering, Patel et al. (2009) examined curation of CAD engineering models, noting some specific challenges. The first is that "the information to be dealt with are diverse and particularly complex, including product geometry, finite element analysis models, manufacturing process models, etc." Another challenge is engineering organizations need to communicate that information to a wide range of different stakeholders, each with different information needs and access rights." They note that the purpose of the information may be varied. Their work primarily focuses on technical strategies for curation; but these authors also say "there is a need for best practice guidelines and cost-benefit models to aid in choosing appropriate curation strategies since the business of deciding a suitable path is non-trivial and contingent on many factors" (Patel et al., 2009).

MODEL CURATION ENABLERS

In support of model curation practice, various enablers have been have been identified. Subsequent research is needed to further identify, refine and develop these. Examples include model pedigree standards, data pedigree standards, model curation templates, model curator competencies profile, and model curator reference map for vulnerability assessment (Rhodes, 2019).

Model and data pedigree play a major role in model trust, as indicated in the empirical research studies under IMCSE. Interim research shows these as promising areas for future investigation for model curation as a practice.

Model Pedigree Standard. Model pedigree was first described as "model demographics" by Gass & Joel (1980), and the term pedigree was subsequently used by Gass. A pedigree contains all of the information about a model, its origins and use over time. As described by Gass & Joel (1980), the purpose is to "enable the decision maker to determine the model's status with respect to past achievements, theoretical and methodological state of the art, and the expert advice that went into its development." While model documentation is typically developed, the content of the pedigree may contain information not always included in engineering model documentation materials. Model pedigree provides non-technical information concerning the model origins, extensions and applications. Given that IMCSE research on model-centric decision making has shown that trust is a key determinant in use of models (German & Rhodes, 2017), a pedigree provides information that engenders trust. Model pedigree plays an important role in human trust and acceptance of models for decision-making and for potential reuse (Rhodes, 2018). Accordingly, a proposed enabler for model curation is a model pedigree standard. This standard would define the content and use of pedigrees, and specify how and when the pedigree is updated over time. Content creation and update authorities would be included in the standard.

Data Pedigree Standards. NASA has defined and uses data pedigree and input pedigree in Modeling & Simulations (M&S) efforts. NASA Standard 7009A (NASA, 2016) cites data pedigree and input pedigree as two of eight credibility factors for Modeling & Simulation. Data pedigree is defined in the standard as follows: "A record of traceability from the data's source through all aspects of its transmission, storage, and processing to its final form used in the development of an M&S." NASA associates data pedigree with M&S Development, and input pedigree with M&S Operations. Input pedigree is defined as "A record of traceability from the input data's source through all aspects of its transmission, storage, and processing to its final form when using an M&S." Further, the NASA Standard notes that "changes from real world source data may be of significance to its pedigree." The NASA standard specifies four levels for data/input pedigrees in terms of credibility assessment levels. A model pedigree standard may benefit from using a similar scale. While data pedigree and input pedigree share some common content with model pedigree, there are unique aspects to be addressed in each standard.

MODEL CURATION INFRASTRUCTURE AND TECHNOLOGY

Further research is needed to understand the infrastructure that will be needed to implement model curation. This may include the physical infrastructure, software toolsets, repositories, and other aspects of the necessary environment. Additionally, there are potentially many new technologies that can be applied to curation. These include machine learning, augmented intelligence, natural language processing and many others. These will be explored in follow-in research.

Managing the risks and vulnerabilities that arise though new digital environments, infrastructure and the digital engineering practice and culture is of key concern to model curation practice. While vulnerability analysis of products and systems is standard practice, examining vulnerabilities related to the enterprise itself is less common. Related ongoing research is investigating the use of Cause-Effect Mapping (CEM) as a mechanism for better

enabling program managers and system engineers to anticipate and respond to programmatic vulnerabilities as related to digital engineering practices and model-centric environments. A reference map resulting from the work shows promise for considering the cascading vulnerabilities and potential intervention options (Rhodes, 2018, Reid and Rhodes, 2018). A future goal is to develop such a reference map for the model curator role, providing visibility into enterprise-level vulnerabilities, especially cybersecurity vulnerabilities.

MODEL CURATOR ROLE & RESPONSIBILITIES

With the increasing use and reliance on models and digital artifacts (Zimmerman et al. 2017), enterprises need to re-examine the leadership that enables digital engineering effectiveness. The knowledge and expert insights on challenges and needs in model-centric enterprises, discovered in this research, have led to exploration of a model curation role appropriate to addressing these {Rhodes, 2019). Model curation (including curation of engineering data) is proposed as necessary at both the program level and the enterprise level.

 The DoD SE Digital Engineering Fundamentals (DoD DEWG, 2016) states "responsibility of planning and coordinating programs' use of models, simulations, tools, data, data rights, and the engineering environment belongs to the program manager; the performance of the actual tasks may be delegated to the program systems engineer and other program staff as appropriate." In addition to program-level curation, enterprises will benefit from an enterprise-level leadership role to enable strategic management and control of models and digital artifacts.

A study by the US Interagency Working Group describes seven challenges that organizations may encounter in infusing digital model-based engineering (IAWG, 2017). The challenges imply new or strengthened leadership capabilities, many that relate to a curation-type role, as well as re-examining basic leadership capabilities under the digital paradigm. These capabilities have potential to address many cited challenges related to organizational and cultural hurdles, contractual and data management practices, security for single source of truth, and others. And, the recently published DoD Digital Engineering Strategy (DoD, 2018) explicitly states model curation responsibilities as part of the digital engineering strategy.

Model curation involves complex practices and specialized situations in which it will be applied. It is useful to investigate other fields that have formal curator roles. Curation is practiced in a diversity of fields, and the role of a museum curator provides a useful analogy case to understand the benefits of a leadership role (Figure 5).
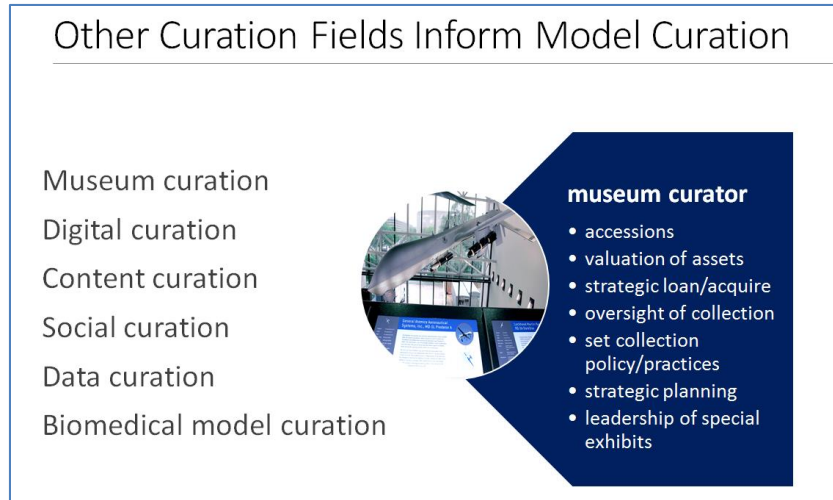
Figure 5. Curation Across Fields of Practice

Our research indicates that a unique enterprise-level role for model curation may be necessary in future digital engineering enterprises. The digital paradigm shift has led many enterprises to establish new leadership positions, such as a Chief Digital Officer (CDO). This role varies, but typically the CDO is a change agent for all things digital, with primary focus on creating business opportunities. These roles, however, are not sufficient for enterprises that depend upon digital engineering practice for designing, developing and operating engineered systems. As engineering enterprises undergo transformation, leadership roles can be expected to evolve over time respective to the extent to which models are central to the mission of the enterprise. Table 2 shows a notional description of leadership approach and enterprise characteristics respective to digital engineering transformation.

Table 2. Notional Transformation Stages and Leadership Approach

Transformation Stage	Leadership Approach	Enterprise characteristics include…
Model Use Throughout Program	"Local" model management	Limited reuse of models Organization embraces importance of models Models are primary artifacts replacing documentation
Model Reuse Across Programs	Enterprise model management	Model-centric enterprise culture Models are reused across programs Digital engineering as standard practice
Systems with "Digital Twin"	Enterprise-level curation role	Digital engineering culture throughout enterprise System "digital twin" maintained through lifecycle Enterprise practices for models (modularity, composability)
IP Inversion in Enterprises	Curator as top tier executive	Models/Digital Twins are key deliverables Model are valuable IP, sold, exchanged, loaned Innovations emerge from composability of models

Knowledge gathering and semi-structured interviews with executives have suggested seven proposed alternative forms for an enterprise to execute the role and responsibilities of an enterprise-level model curator. The seven organizational forms are briefly described in Table 3. In the future, studies are needed to evolve these forms and understand how effective they are for various enterprises, and under which conditions one might chose the form.

Table 3. Initial Investigation of Organizational Forms for Enterprise Curator Leadership Role

Form	Description	Chief Model Curation Office (CMCO) Organizational Form – under what conditions
Centralized – Top Tier	CMCO is a top tier exec reporting directly to CEO	High performing model-centric engineering enterprise or enterprise that has a very aggressive goal to become one. Culture has fully embraced model-centric engineering across entire enterprise, and enterprise believes model leadership is key to competitive advantage and innovation.
Centralized – Dotted Line	CMCO has "dotted line" reporting CEO	The enterprise is rapidly becoming a high performing digital engineering enterprise. The CMCO needs enterprise level authority to implement strategic decisions, but enterprise is not ready to make CMCO a full member of the executive management team.
Franchised	Enterprise units have CMCOs, with common policies	For very large enterprises with varied cultures within enterprise units, it can be difficult to have one top-tier CMCO. In a franchised form, CMCOs are appointed in each enterprise segment reporting to its top executive, conforming to enterprise defined policy and role.
Collaborative	Virtual CMCO role via collaborative committee	Enterprise does not wish to appoint a CMCO at this time, but recognizes need for model curation. An appointed collaborative committee is "virtual CMCO" as a strategy-setting and oversight body. May be preferred in enterprise comprised of newer acquisitions with strong heritage culture and processes.
Dual Hat	CMCO is one of two roles played by an executive	An enterprise that is working toward becoming a model-centric enterprise but still uses legacy approaches; not ready to appoint enterprise CMCO. A dual hat form, while challenging to perform, enables enterprise to allocate specific curation responsibilities to an existing leader (CIO, CTO, CDO).
Delegated	CMCO tasks delegated to one or more individuals	Similar to "dual hat" but role is not specifically delegated; responsibilities are delegated as add-ons to an existing role, or to the responsibilities of a standing committee. This implementation is weaker than dual hat, but does acknowledge these as MC responsibilities, as a precursor to a formal role.
Outsourced	CMCO role is performed by an external hire	Temporary hiring of an outside CMCO may be only option available to an enterprise that recognizes need for MC role but does not have expertise or capacity to staff from within. May also be a form used by an enterprise that is not convinced of value of CMCO, but wants to have trial implementation.

DISCUSSION AND FUTURE RESEARCH

Curation practices promote formalism and provide for the management and control of models (and digital artifacts). Examples of curation activities include model identification, acquisition, accession, composition, evaluation, valuation, presentation, preservation, and archiving. Models must be packaged with a complete set of information (or reference to that information), including model technical data, model metadata, and model pedigree. Models and the associated information must be actively managed and enhanced.

Five key points on curation emerging from the research are:

1. SERC's initial investigation of model curation has indicated the systems community will benefit from formal curation practices.

2. Lack of access to models, mistrust of models, and perception of legitimacy of models are barriers to reuse and longevity that are potentially mitigated through model curation.

3. There is potential to adapt practices from other fields once model curation-specific needs in the digital engineering context are clearly understood.

4. Enablers for implementation have potential to further enhance curation practice, including lexicon, pedigree standards, curation templates, and many others.

5. Model curation necessitates both curation practice and a curator role.

RESEARCH QUESTIONS FOR FOLLOW-ON RESEARCH

As Phase 6 comes to a close, the research team has defined three research questions to be investigated under a new SERC research project, entitled *Model Curation Innovation & Implementation* (SERC WRT-1009).

The first question is:

> *What is the lifecycle model and what are the fundamental practices for model curation?*

As previously discussed, there are useful models that exist in other fields of curation. The Digital Curation Centre's Curation Lifecycle Model (see Figure 2) is a promising model to consider as an exemplar of the type of lifecycle model that is needed for digital engineering. The follow-on research will investigate this lifecycle model, as well as others found in the literature and in the practitioner community.

The second question to be investigated in the follow-on project is:

> *What are the precursors, barriers and enablers for model curation?*

This is a rich area for exploration through empirical knowledge gathering around current practice, and through technical exchanges and collaboration. Interaction with stakeholders will explore various questions, such as:

- How are models presently managed and controlled?
- What roles/responsibilities exist within digital engineering programs
- How are models "certified"/evaluated for future use?
- What are the barriers to model throughout system lifespan?
- What issues impede model sharing between organizations?
- Can a model curator role benefit programs? Enterprises?
- What practices and templates can better enable model curation?
- How can technology help to make models discoverable?

The third area for future investigation is:

> *What innovations are emerging from other fields that may benefit model curation?*

Initial research will seek to discover promising innovation projects across various fields that leverage new sciences and technologies. Examples include: data science, visual analytics, machine learning, natural language processing, UX design, augmented intelligence, and lightweight formal methods.

HUMAN-MODEL INTERACTION

Digital engineering of complex engineering systems requires both human intelligence and the use of digital system models. Open areas of inquiry include: how individuals interact with models; how multiple stakeholders interact using models and model generated information; facets of human interaction with visualizations and large data sets; and underlying fundamentals such as model purpose and model handling. Given both social and technical dimensions of human-model interaction, heuristics and guiding principles are desired enablers.

BACKGROUND

IMCSE research is based on a belief that improving human-model interaction and social dimensions of model-based environments will significantly improve the effectiveness of digital engineering practice, quality of decision making, and cultural acceptance of a digital future. As discussed in prior phase reports, there is a need for the specific consideration of human-model interaction. The science of human-systems integration (HSI) has emerged, yet focus is on humans within operational systems, while models are abstractions of reality. The relatively mature field of human-computer interaction (HCI) offers valuable insights, however focus is on designing computer interfaces. A report of a recent workshop sponsored by the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), the Air Force Office of Scientific Research (AFOSR), and the National Modeling and Simulation Coalition (NMSC), highlights the need for understanding the individuals involved in the modeling process and how these individuals affect model development and usage (NSF, 2016).

Guiding principles for human-model interaction emerge from empirical investigation, iterative evaluation, refinement and testing of the initial heuristics that were identified through a variety of research activities. In this phase of research, the focus has been on validation with stakeholders and refinement of the initial heuristics into a set of guiding principles.

RESEARCH APPROACH

Throughout the multiple phases of IMCSE research, the research on human-model interaction has investigated the literature across various fields including cognitive science, decision analysis, organizational and human behavior, and systems science. Several secondary source research studies provided "analogy case" insights from situations having similarities to the transition from traditional engineering environments to model-centric engineering environments (German & Rhodes, 2016; German, 2017). Knowledge was also drawn from related fields of human-systems integration (HSI), human computer interaction (HCI), and Visual Analytics (VA), as relevant to the research. Key research themes emerged from these investigations, in addition to themes identified through a pathfinder research workshop involving expert practitioners and researchers (Rhodes & Ross, 2015). An exploratory interview-based study of model-centric decision making resulted in findings drawn from thirty subject matter experts (German & Rhodes, 2017, German 2017). Candidate heuristics were

derived primarily from the expert interviews, as supported by insights from the literature investigation and second source studies. A series of individual and group activities have been used for preliminary validation and refinement of heuristics, including classroom and practitioner interactions (Rhodes, 2018). Iterative vetting with stakeholders has been used to test and refine the heuristics, combined with continued investigation through the literature and technical reports.

In this phase, research focused on convergence toward consensus-based heuristics. Various technical exchange meetings, feedback from practitioner community, and testing of heuristics were used to validate and adapt the prior phase work to generate a set of recommended guiding principles and application examples. A classroom experiment was used to investigate potential usage and usefulness of employing principles in undergraduate engineering education (novices). A model-based engineering program team launch module was designed and tested in a small project setting, with a goal of using guiding principles with practitioners. Although the scope of the research did not enable extensive investigation, the research team continued to explore how using patterns and pattern languages could be of benefit.

MODEL-CENTRIC DECISION MAKING

Understanding the current state of the practice is an important step in model-centric enterprise transformation. The findings in our recent interview-based study involving 30 experts led to insights, along with information from literature and secondary source studies, have informed the derivation of heuristics for human-model interaction. A detailed discussion of the findings is presented in a recent paper (German & Rhodes, 2017) and in the IMCSE Phase 4 report (Rhodes & Ross, 2017). Some of the findings include:
- Three actor decision flow
- Understanding of assumptions and uncertainty
- Technological and social factors influencing trust
- Importance of documentation and model pedigree
- Using models as primary versus supplementary
- Model transparency and model trust
- Factors and biases limiting model-centric decisions
- Modes of interaction with models

HUMAN-MODEL INTERACTION HEURISTICS

The Human-Model Interaction heuristics generated in prior phase research have been further refined and shared with practitioners during this phase of the research. Appendix C includes the refined set of heuristics, as published in the prior phase report (Rhodes, 2018).

EDUCATING NOVICES

Recent research studies show benefit of using heuristics to assist novice engineers in early design activities (Yilmaz et al., 2016; Murphy, et al., 2017). Younger engineering students may learn to use model-based toolsets quickly (having grown up using software applications); however, they lack the foundational knowledge behind the use of models in engineering decisions. Use of heuristics in education modules and classroom exercises can amplify key learning points. Given that heuristics are concise statements, they have potential to make key points stick in the mind and are useful for triggering class discussion.

As an example, a teaching lesson on the importance of understanding context and assumptions could employ the following heuristic to initiate a discussion: **Models are created for specific reasons and context, and those assumptions fundamentally bound a model's applicability.** Discussion using this heuristic may revolve around a model as insightful and valuable within one problem context, but the assumptions built into the model may not be valid within some other context. A key point is that evaluating a model's applicability should not just consider whether it has been validated, but in what contexts the model has been validated. Another useful discussion point is that using a model outside of its inherent bounds leads to model results that are inappropriate for the problem under consideration. Specific case examples could be used to reinforce these points. Another use of a heuristic in education would be an assignment to write a short paper to elaborate on the heuristic.

During this phase of the research, a small experiment was conducted with undergraduate students in an engineering leadership program.   The experiment was performed as part of a teaching module on use of models in decision making. Four sessions with 20-22 students in each were taught the same material, and were asked to complete a questionnaire to rate their agreement/disagreement with statements related to the heuristics on decision making with models. Two of the groups were given the questionnaire before the lecture, and two groups following the lecture. Several of the heuristics that were used in the lecture showed impact on how the students answered the questionnaire, opening their thinking on the subject. The desired impact in the two instances shown below is that students understand that both technical and social factors play a major part in model-based decisions, and that models do not have agency, humans are ultimately responsible for decisions.

> *People decide whether to trust a model based on technical factors rather than social factors*. For the two groups who completed the questionnaire prior to the lecture 78% strongly agreed/agreed with the statement. For the two groups completing the questionnaire following the lecture, only 46% strongly agreed/agreed with the statement.

> *Some blame can be placed on the model itself, if it was used to make a decision that turned out to be a bad one.* For the two groups who completed the questionnaire prior to the lecture 78% strongly agreed/agreed with the statement. For the two groups

completing the questionnaire following the lecture, only 50% strongly agreed/agreed with the statement.

CONDUCTING PROGRAM TEAM LAUNCHES

A program team launch brings together the members of a team in a congenial forum to plan activities, assign responsibilities, and set team norms. Beyond practical planning, a team launch is meant to enhance trust and build collaborative spirit among team members. Using heuristics for launching a digital engineering program is supported by Maier & Rechtin (2009), who state they are "trusted, nonanalytic guidelines" and can be used "as aids in decision making, value judgements and assessments". Heuristics have potential to serve as a basis for an activity to set norms and team practices for the program. Younger engineers may quickly learn to use (or already know how to use) modeling toolsets, but lack the experiential knowledge. The members with years of experience, on the other hand, may find use of modeling software tools to be non-intuitive to the point where they spend more time on tool mechanics and less on decision making. Any discomfort and distrust of models and modeling toolsets (as our empirical research has shown exists) can have negative impacts on the engineering effort.

Using heuristics as "boundary objects" for team dialogue can enable discussion. An example of a useful heuristic for such a discussion is: **Models do not have agency – the ultimate responsibility for decisions must be upon the humans.** A team discussion on this heuristic could prompt discussion on the proper use of models in context of the specific program objectives, and how model-generated information is to be used by various team. Additionally, decision authorities and standard practices for documenting model-related decisions can be discussed and established. This heuristic can be used to invoke a discussion on what models will be used on the program, what decisions are expected to be informed by the model, and how model information is to be validated using expert review. Using a heuristic as boundary object encourages more open and non-confrontational discussion.

During this phase, the research team conducted a small trial use of the heuristics for launching a small academic research project. Although not a true test of the usefulness in the practitioner community, the participants in this small exercise felt that the heuristics prompted effective discussion, serving to organization discussion topics and to raise points of discussion that may otherwise have been sensitive points to bring up.

Future trial use in various settings is needed to assess the value of using the heuristics in program launch sessions and other team meetings.

Further investigation of the issues of models and trust during this phase has revealed some of the primary reasons why we trust (or distrust) models. Accordingly, the following are seven guiding principles for model trust:

1. ***Transparency should always be possible, but tailorable***.
   Our research shows that model transparency should always be available to the user, but tailorable to needs of the individual and situation. Individuals have been shown to desire different levels of transparency based on their role and personal preferences. Excess transparency may cause information overload that can obscure relevant information.

2. ***Model-context appropriateness is a key determinant of trust***.
   It has been found that model trust is not as much on the model entity itself, as the usefulness of the model for the situation at hand. The assumptions that are built into a model need to be acceptable for the context of use.

3. ***Real-time interaction with models has upsides and downsides.***
   On the positive side, real-time interaction enables asking "what if" questions to gain insights and establish trust. The downside of this is that gaining results very quickly may still lead to "making bad decisions real fast".

4. ***Trust may be implicitly on the models, but explicitly on people.***
   The research indicates that the ultimate decision maker often relies on a trusted individual in making model-centric decisions. The decision maker, lacking time and ability to fully investigate and understand the model, shift trust onto their trusted expert, who is like an interpreter of information from models and modeling experts.

5. ***Trust emerges from interaction between human actors, through models.***
   Our investigation suggests trust extends from the interaction between and across various actors (models, "interpreters", decision makers). Trust emerges more as a result of the human interactions through models, rather than direct model interaction.

6. ***Availability of model pedigree engenders trust.***
   Metadata and technical data are, of course, important. Our research shows that pedigree information is a major influence on judging trust (whereas integrity is judged with technical data). Pedigree tells the decision maker who originated the model, assumptions made, expert knowledge and investments, etc.

7. ***Trust is influenced by the entangled technological and social factors.*** The technological factors (e.g., model fidelity, data integrity, verified algorithms) and social factors (e.g., model originator, preferences, perceived modelers expertise) cannot truly be separated. It's important to be cognizant of how these interrelate and influence decisions.

CONCLUSION

Human-model interaction remains an open area for investigation as digital engineering practices and technologies advance. As this research concludes, next steps include additional publication of findings and continued collaboration with the INCOSE SE Principles working group activities. Although the scope of the research did not enable extensive investigation, the research team continued to explore how using patterns and pattern languages could be of benefit. This is a promising area for future work, in collaboration with the INCOSE Patterns Working Group.

APPENDIX A: LIST OF PUBLICATIONS RESULTED

The following publications were completed during Phase 6 of the research.

1. Rhodes, D.H., *Using Human-Model Interaction Heuristics to Enable Model-Centric Enterprise Transformation*, IEEE Systems Conference, Vancouver, CA., April 2018.

2. Rhodes, D.H., *Uncovering Cascading Vulnerabilities in Model-Centric Acqusition Programs* , NDIA SE Conference, 24 October 2018.

3. Rhodes, D.H., "Model Curation: Requisite Leadership and Practice in Digital Engineering Enterprises," 17th Conference on Systems Engineering Research, Washington, DC, April 2019.

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Duh, K., Hirao, T., Kimura, A., Ishiguro, K., Iwata, T., & Yeung, C. M. A. (2012, May). Creating Stories: Social Curation of Twitter Messages. *ICWSM*.

Gass, Saul I, & Lambert S Joel. (1980). Concepts of Model Confidence. *Computers and Operations Research*. 8, No. 4, 341-346.

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German, E.S. & Rhodes, D.H. (2017, May). Model-Centric Decision-Making: Exploring Decision-Maker Trust and Perception of Models. *15th Conf. on Systems Engineering Research*. Los Angeles, CA.

IAWG (2017, March). Digital Model-based Engineering: Expectations, Prerequisites, and Challenges of Infusion. Model-Based Systems Engineering (MBSE) Infusion Team. Interagency Working Group on Complex Systems.

Maier, M. & Rechtin, E. (2009). *The Art of Systems Architecting*. CRC Press.

Murphy, L. Daly.S, McKilligan, S. & Seifert, C. (2017). Supporting Novice Engineers in Ideal Generation Using Design Heuristics. *American Society for Engineering Education*.

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Potter, J. & Gilje, O. (2015). Curation as a New Literacy Practice. E-Learning and Digital Media. Volume: 12 issue: 2, page(s): 123-127.

Reid, J. and Rhodes, D.H. (2018, May). Applying Cause-Effect Mapping to Assess Cybersecurity Vulnerabilities in Model-Centric Acquisition Program Environments. 15th Annual Acquisition Research Symposium, Monterey, CA.

Reymondet, L., Rhodes, D.H., & Ross, A.M. (2016, April). Considerations for Model Curation in Model-Centric Systems Engineering. *10th Annual IEEE Systems Conference*. Orlando, FL.

Rhodes, D.H. (2019). "Model Curation: Requisite Leadership and Practice in Digital Engineering Enterprises. 17th Conference on Systems Engineering Research, Washington, DC.

Rhodes, D.H. (2018). Interactive Model-Centric Systems Engineering (IMCSE) Phase 5 Technical Report SERC-2018-TR-104.

Rhodes, D.H. & Ross, A. M. (2017). *Interactive Model-Centric Systems Engineering (IMCSE) Phase 4 Technical Report* SERC-2017-TR-103.

Rhodes, D. H., & Ross, A.M. (2016). A Vision for Human-Model Interaction in Interactive Model-Centric Systems Engineering. *INCOSE International Symposium*, Edinburgh, Scotland.

Rhodes, D.H. & Ross, A.M. (2015). *Interactive Model-Centric Systems Engineering Pathfinder Workshop Report*. MIT, Cambridge, MA.

Rhodes, D.H. (2019). Model Curation: Requisite Leadership and Practice in Digital Engineering Enterprises. 17th Conference on Systems Engineering Research, Washington, DC.

Rhodes, D.H. (2018). Using Human-Model Interaction Heuristics to Enable Model-Centric Enterprise Transformation, IEEE Systems Conference, Vancouver, CA.

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Yilmaz, S., Daly, S., Seifert, C., & Gonzalez, R. (2016). Evidence-based design heuristics for idea generation. *Des. Stud*. vol. 46. pp. 95–124.

Zimmerman, P., Gilbert, G., & Salvatore, F. (2017). Digital Engineering Transformation Across the Department of Defense, *The Journal of Defense Modeling and Simulation*.

Humans should not be forced to adapt to models, rather, models should be designed for humans.

Evolving technology enables more complex and capable models but may not increase effectiveness if humans are not appropriately considered. Humans have cognitive and perceptual limitations that limit the amount and type of information they can effectively comprehend and use to make decisions. Designing for humans requires understanding their capabilities and limitations so that the model intelligence can extend the overall system intelligence.

Model developers, model users, and organizations share responsibility for preventing improper model usage.

Model developers have the responsibility to make capabilities and limitations of a model salient and understandable, to enable decisions on proper use. Model users have the responsibility to obtain and use this information in determining use/reuse of a model, as well as documenting this decision with assumptions. Organizations have the responsibility to prevent the improper use of models in general, through effective policies, practices and controls.

Models do not have agency -- the ultimate responsibility for decisions must be upon humans.

Increasingly complex and automated modeling environments may make it easier to attribute agency and responsibility to models. The ultimate decision-making authorities are people and blame cannot be placed upon models for poor decisions. Individuals should be aware of the potential for improperly diffusing responsibilities for decisions upon models, and policies should clearly establish the responsibilities for which individuals are held accountable.

Before any model can be useful, its capabilities and limitations must be revealed and understood.

All models are inherently abstractions of reality that contain assumptions about the modeled system, and these assumptions limit the applicability of where and how the model can be used. Numerous empirical examples show that poorly understood and applied models have led to programmatic challenges and failures. An improper understanding of a model's limitations may lead to decision-makers inappropriately applying it beyond its limitations. Conversely, if a model's capabilities are not fully understood, decision-makers may not use the model to its fullest potential.

Models are created for specific reasons and contexts that fundamentally bound a model's applicability.

A model may be insightful and valuable within one problem context, but the assumptions built into the model may not be valid within some other contexts. Evaluating a model's applicability should not just consider whether it has been verified

and validated, but also under what conditions and in what contexts. Using a model outside of its inherent bounds may lead to model results that are inappropriate for the problem under consideration.

Model documentation should make the assumptions and limitations of a model explicit; otherwise it will not be usable by anyone other than the originator.

Model developers carry the most intimate understanding of a model's assumptions and limitations. If decision-makers are those other than the modelers, however, assumptions and limitations must be clearly documented so that others might calibrate an appropriate personal understanding of the model. Documentation should not only capture the assumptions built within the model, but the assumptions made about the model itself. Conceptual "white board" artifacts created early in a model's development can offer insight into decisions made about a model, including what problem contexts the model is designed for. With this line of thinking, both decisions made regarding assumptions within the model's code and the decisions made before the model was even designed should be documented. If these assumptions and limitations are not documented and accessible, users and decision-makers will not be able to appropriately calibrate their understanding and trust of the model, which makes it unusable.

Model trust is a sociotechnical construct: you must examine both technological and social factors to understand how individuals develop trust in models.

Individuals within the model-centric decision-making process rely upon various technological and social factors to develop trust in a model. Technological factors include technical information about a model, such as its transparency, uncertainty, and input data. Social factors include the people, organizations, and relationships that shape one's trust of a model. These social aspects could include factors such as the credibility of the people or organization developing the model, reliability of the relationship with individuals recommending a model, or word of mouth within a community concerning a model's performance. Different factors may play greater or lesser roles in developing an individual's model trust process; therefore, these factors should be understood to facilitate appropriate calibration of individual trust.

Models should have the capability to be as transparent as possible; however, not every user desires full transparency. Transparency should be tailored to the needs of the specific individual under consideration.

Transparency involves how clearly one might assess a model's functions and understand how and why it operates as it does. This allows individuals to determine if the operation is appropriate for a decision at hand. Full transparency would involve having complete access to a model's code and documentation of the assumptions built within it. While there should always be the opportunity for full transparency, individuals may desire different levels of transparency. For example, high-level decision-makers may only desire transparency concerning high-level model assumptions because they lack the time or training to effectively investigate a model's code. Too much transparency could cause an information overload that obscures the relevant information. Conversely,

others may desire the ability to be intimately acquainted with a model's workings. Transparency, therefore, should always be present, but should be tailored to the needs of the specific individual under consideration.

Appropriate model trust calibration includes sharing of mental models between actors in a decision-making flow.

A model is the explicit representation of the model developers' mental model of a situation. This mental model contains an implicit understanding of the capabilities and limitations of the model. The other individuals who interact with the model should calibrate their own mental models to that of the model developers, which includes developing an accurate understanding of the model's capabilities and limitations. Improperly calibrated mental models lead to inappropriate decisions on an individual basis, but as modeling is a sociotechnical process, improper mental models may also influence and hinder proper mental model development in other individuals within the flow of information.

Increasing the speed of decision-making implies a decrease in time spent analyzing a problem, which in turn increases the chance of biased judgments.

Humans excel at pattern recognition and efficiently jumping to conclusions in the presence of limited information. These intuitive capabilities prove effective for many day-to-day activities, but they can also lead to systematic biases in certain contexts. Model-centric environments may seek to provide a more intuitive environment that users and decision-makers can directly interact with to build intuition and speed decision-making. However, these environments may make biases more likely by allowing users to quickly match patterns and move forward with incomplete, and potentially biased, understandings of a situation. Complex problems may require focused attention and analysis that take time to fully understand in order to develop an accurate mental model of the situation. While faster decisions are desired if they are effective, the speed itself may set people up for failure by encouraging them to rely upon their fast and intuitive, yet bias-susceptible, judgment, rather than the more cognitively demanding rational and analytical thought processes.