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DRIVING SYSTEMS ENGINEERING TRANSFORMATION

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ABSTRACT

While complex systems transform the landscape, the Systems Engineering discipline is also experiencing a transformation to a model-based discipline. In alignment with this, one of the International Council on Systems Engineering (INCOSE) strategic objectives is to accelerate this transformation. INCOSE is building a broad community that promotes and advances model based methods to manage the complexity of systems which seamlessly integrate computational algorithms and physical components across domains and traditional system boundaries. This paper covers contextual drivers for transformation as well as challenges, enablers, and INCOSE resources aligned with accelerating the transformation of Systems Engineering to a model-based discipline.

INTRODUCTION

Today's systems are more instrumented, interconnected and intelligent than ever before which is changing the way we develop, manage and interact with them. The number of internal and external interactions is growing at an increasing rate placing significant demands on organizations to improve system safety, security, and reliability. The challenges and opportunities of today's engineered systems which are built from, and depend upon, the seamless integration of computational algorithms and physical components[1] are both significant and far-reaching. To address the challenges presented by these systems, the Nation Science Foundation has called for methods to conceptualize and design for the deep interdependencies inherent in these systems within aerospace, automotive, energy, medical, manufacturing and other sectors.

While system complexity advances and transforms the landscape, the Systems Engineering discipline is also experiencing a transformation—moving from a document-based to a model-based approach. This transformation, led by the International Council on Systems Engineering (INCOSE), is necessary to advance the discipline, manage complex emergent behaviors and meet stakeholder needs.

CONTEXTUAL DRIVERS

Figure 1 below outlines internal and external drivers influencing systems and their context. Collectively these drivers influence both the discipline of Systems Engineering and the target systems, or systems of interest that Systems Engineering produces. Internally, both digital transformation and systems complexity have a significant influence on the need and ability to transform the discipline of Systems Engineering and delivery systems. Likewise, externally the market context is pushing for more customization and adopting technology more rapidly while connecting systems more readily as well. These interrelated systems and contextual influencers cut across all sectors, and they're driving profound change all around us.

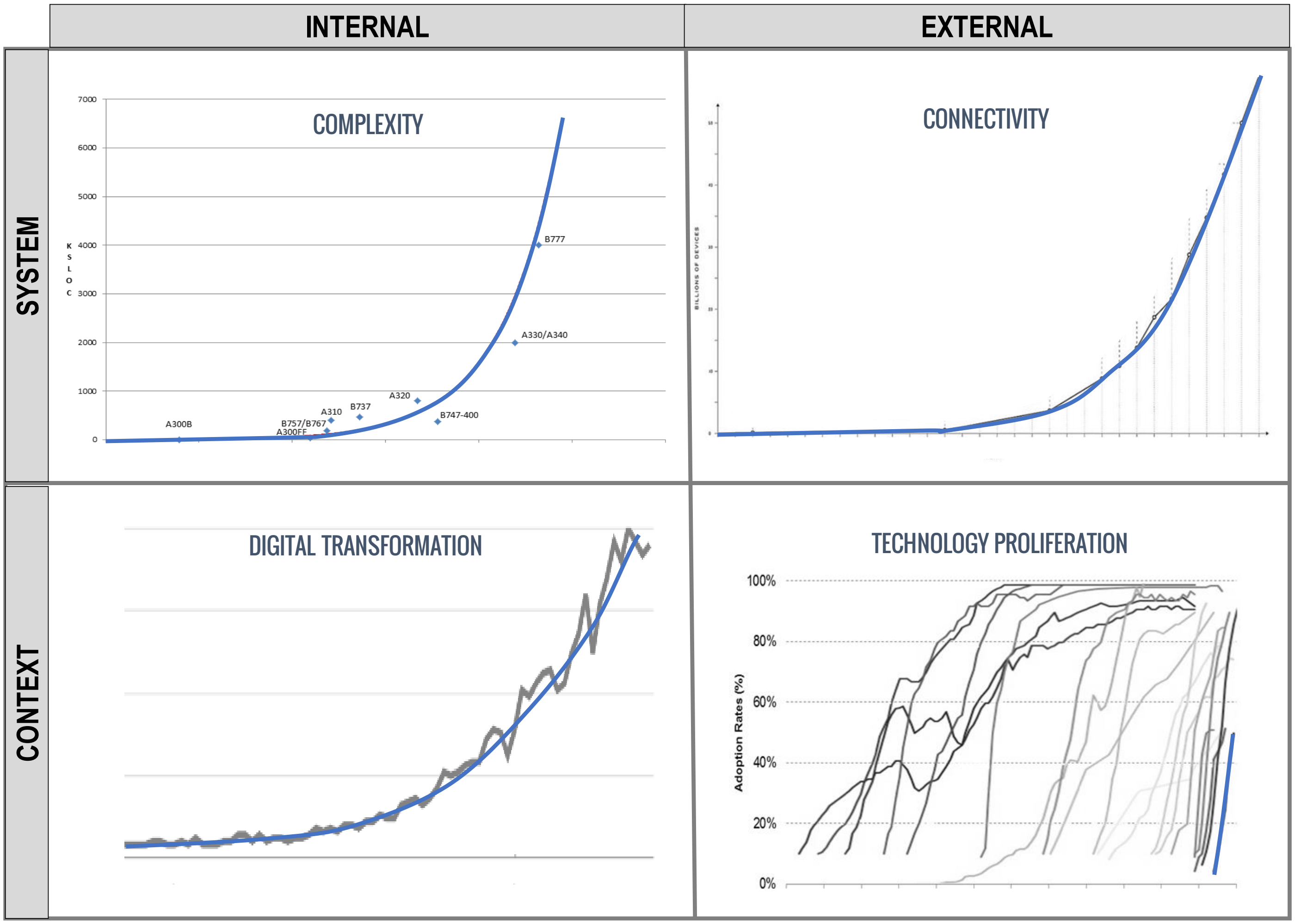

Figure 1: Growing internal and external system and contextual complexity and rate of Change.

Consider the following quotes which are put forward as appropriate descriptions of the challenges we experience with our programs and systems.

"Today more and more design problems
are reaching insoluble levels of complexity."

"At the same time that problems increase in
quantity, complexity, and difficulty,
they also change faster than before."

"Trial-and-error design is an admirable method.
But it is just real-world trial and error
which we are trying to replace by a symbolic method.
Because trial and error is too expensive and too slow."

These quotes nicely summarize our context today, yet they were expressed over 50 years ago by Christopher Alexander in his book *Notes on the Synthesis of Form*. These bullets are likely more applicable today than they were 50 years ago, and they will probably be even more applicable 50 years from now.

The Role of Digital Transformation

Digital Transformation is changing the fundamental nature of how organizations use and adopt digital technologies to create order of magnitude changes in value creation. This value can be expressed in more desirable products or in reduced resources such as time and cost to produce value. The lower left graphic of Figure 1 shows the rise in interest in Digital Transformation as given by Google Trends for the term "Digital Transformation." Given this dramatic growth and interest, there has been a similar growth in publications covering the topic. Many of the Digital Transformation publications, however, emphasize the anticipated impact of Digital Transformation on business systems such as corporate websites and marketing strategies, sales efficiencies, front office processes, and the customer experience as outlined in The Digital Imperative, Boston Consulting Group 2015[2][2]. In another publication, The Digital Business Imperative from Forrester, 401 global executives in companies with 250 or more employees identified e-commerce, marketing and IT as the top three functions to be impacted most by digital technologies[3][3]. This same report from Forrester charted insurance and retail as the most likely to have digital technology drive strategy and disrupt their business. It also mapped engineering as the least likely out of a dozen different sectors to have digital technology drive strategy and disrupt their business. Many publications also noted that the most significant impact of digital technologies is when they are leveraged within the most substantial value creation aspects of an enterprise i.e. when Digital Transformation impacts an institution's core capabilities. For many organizations, the most significant value creation area and core capability is new product development or Systems Engineering – the aspect of the business most directly impacting innovation. Unfortunately, the cited publications and many other articles and publications do not address the significant impact and value of a broader systems approach, and its effect on the innovation process and role of modeling and engineering. This paper proposes that transforming Systems Engineering and the application of systems modeling is the essential element to value creation and the area of necessary and revolutionary change in today's hyper-connected dynamic world.

To be at the heart of this revolution requires that organizations understand contextual drivers as well as leverage the major technological shifts as noted by INCOSE's Vision 2025, the World Economic Forum and other sources. System modeling provides a virtual system synthesis and an integrated view of how major digital technology trends impact designs. A model-based approach, however, requires a deep culture shift, and a new mindset to operate within a data-centric digital environment. The paper "Deep Shift from the World Economic Forum" highlights Six Megatrends affecting the global economy. It points out the convergence of IoT, AI, 3D printing, and other megatrends which are truly reshaping the industry. The trends identified by the World Economic Forum and others are supported and enabled through model-based systems engineering methods providing both new opportunities as well as ways to mitigate key risks. Below are a few example trend areas and associated challenges and opportunities for how model-based systems engineering methods can help.

Internet of Things (IoT) has created a rapid explosion of interrelated systems and is a significant contributor to the increase in interconnectedness and system complexity. IoT impacts are still only in the formative stages and it continues to have exponential growth. This hypoconnectivity is ubiquitous, occurring across domains and with systems we use every day. Systems Engineering is fundamentally about designing and managing interactions to drive state change and desired behaviors. IoT is driving up interactions, so the application of model-based systems engineering is a necessary and logical method to fully express and manage internal and external interactions and their potential risks and opportunities.

Data Science. The amount of data from instrumented and connected devices covers the full lifecycle from stakeholder needs to disposal. The amount of data organizations receive from systems is immense; in fact, it's often overwhelming. It's been said that many firms are drowning in data, and starving for information, knowledge and shared understanding. The use of systems models to put data in context, however, provides a great opportunity to improve engineering with robust feedback loops and ongoing learning and continual refinement of systems models and the overall systems engineering effort.

Cyber Security is another a rapidly growing need and trend. As our system boundaries expand and more and more systems and subsystems become interconnected - new vulnerabilities and failure modes are often introduced. Here multidisciplinary models that bridge the cyber and physical domains are essential. Cyber security is often viewed from an enterprise IT perspective rather than an engineering viewpoint of a Cyber-Physical System. As more and more elaborate systems models are produced integrating both the cyber and physical portion of a design a more complete understanding of Cyber Security and Safety is provided. System models can easily be traversed to assess vulnerabilities, propagation paths, identify broker components and more.

Artificial Intelligence (AI) may be the megatrend with the most hype given the strong movement toward autonomy. AI is being incorporated very rapidly into more and more domains and products. In 2009, Garry Kasparov concluded that "weak human + machine + better process was superior to a strong computer alone and, even more, remarkable, is that it's superior to a strong human + machine + inferior process." He also said that "Today, for $50 you can buy a home PC program that will crush most grandmasters." (2009). Design space, like chess, is a constrained space but rather than a limited board space, pieces, and rules - designs are often constrained by cost, schedule, technological advancements and existing assets. Formal systems models provide a way to enable the use of AI, and when combined with Human expert knowledge and robust systems engineering processes it can provide a significant competitive advantage in the development and quality of complex systems.

The Role of System Complexity and Rate of Change

Systems complexity is growing at an unsettling rate with the number and density of interactions increasing dramatically, especially in information exchanges. This increase is creating a web of interactions and related behaviors unlike what we have dealt with in the past. As an example, to demonstrate how interactions drive complexity consider Figure 2 which presents two basic systems represented by nodes (N) and links. The first system is the five-node system. To calculate how many unique configurations (UC) this system can have, we can use the equation provided in Figure 2 where N is the number of nodes representing system elements, i.e. subsystems or components, and the lines represent a simple connection or potential interaction without a type or direction. In comparing the 5-element system and 30 element system, one can see how quickly the number of Unique Configurations (UC) grows with the increase in system elements and interactions. Surprisingly, an

18-element system with a network density of one, where every node is connected to every other node, has more unique configurations than the number of known atoms in the universe. While a network density of one is highly unlikely this example does show how the rapid increase in instrumenting our systems and connecting them with external systems is impacting the complexity of systems management and engineering.

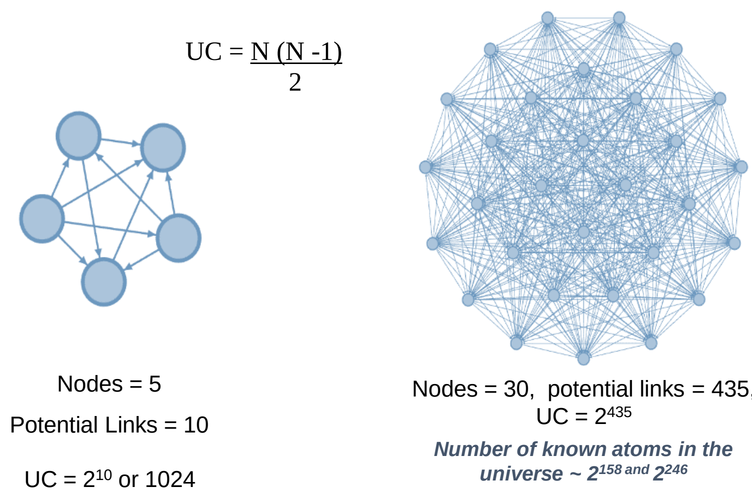

Figure 2: Example of how interactions density increases system complexity

Provided the significant shifts outlined, especially the contextual changes associated with digital transformation and systems complexity organizations are seeking approaches which leverage symbolic method, or formal models, to speed iterations, build in agility and ensure a holistic view when making decisions. Accelerating this approach is what INCOSE's transformation effort is directed toward.

SYSTEMS ENGINEERING TRANSFORMATION

INCOSE

"The International Council on Systems Engineering (INCOSE) is a not-for-profit membership organization founded to develop and disseminate the interdisciplinary principles and practices that enable the realization of successful systems."[4] [4] INCOSE's vision is "A better world through a systems approach." To meet this end, INCOSE produces state-of-the-art products that further the systems engineering discipline, leading to improvements in productivity, effectiveness and overall system performance and ultimately increased stakeholder value.

INCOSE Vision 2025

INCOSE's Vision 2025 addresses the movement to transform the practice of Systems Engineering to a model-based discipline. The vision states that "Systems Engineering will lead the effort to drive out unnecessary complexity through well-founded architecting and deeper system understanding; which can only be reasonably achieved through the use of models."[5] [5] The vision goes on to describe a virtual engineering environment that will incorporate modeling, simulation, and visualization to support all aspects of systems engineering by enabling improved prediction and analysis of complex emergent behaviors. It includes composable design methods in a virtual environment and supports rapid, agile and evolvable designs of families of products. It further proposes this will be accomplished by combining formal models from a library of component, reference architecture, and other context models so that different system alternatives can be quickly compared and probabilistically evaluated. The INCOSE Vision 2025 provides the following Systems Engineering "From" and "To" states:

> ***From:***
> *Model-based systems engineering has grown in popularity as a way to deal with the limitations of document-based approaches but is still in an early stage of maturity similar to the early days of CAD/CAE.*
>
> ***To:***
> *Formal systems modeling is standard practice for specifying, analyzing, designing, and verifying systems, and is fully integrated with other engineering models. System models are adapted to the application domain and include a broad spectrum of models for representing all aspects of systems. The use of internet-driven knowledge representation and immersive technologies enabled highly efficient and shared human understanding of systems in a virtual environment that spans the full life cycle from concept through development, manufacturing, operations, and support.*

INCOSE Systems Engineering Strategic Objective

The systemic complexity of systems today demands a systems engineering approach. It requires a systems paradigm which is interdisciplinary, leverages principals common to all complex systems, and applies the requisite physics-based and mathematical models to represent them. It also requires a model-based approach to manage the immense amount of interrelated engineering data, information, and knowledge. Model-Based Systems Engineering is the formalized application of modeling to support life cycle system engineering activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. INCOSE also notes that "Modeling has always been an important part of systems engineering to support functional, performance, and other types of engineering analysis."

Systems Engineering Transformation, one of INCOSE's seven strategic objectives[6] [6], is an essential objective for INCOSE and the systems engineering discipline. The INCOSE Systems Engineering Transformation strategic objective is provided below:

INCOSE accelerates the transformation
of systems engineering to a model-based discipline.

In alignment with this objective, the application of model-based methods have increased dramatically in recent years becoming a more standard practice for those who have established systems engineering capabilities. This shift in approach has been enabled by the continued maturity of standards for modeling languages, methodologies and related technologies to include capability advancements made by tool vendors.

Figure 3 below outlines a vision, mission areas, goals and objectives designed to help achieve INCOSE's strategic objective for transformation. The mission areas are targeted to #1 Infuse INCOSE with model-based methods, #2 Engage Stakeholders external to INCOSE to better understand and share what is practiced and needed, and #3 Advance the Practice and share with stakeholders what is possible through the application and transformation to a model-based approach.

Vision	**Systems Engineering is acknowledged as a model based discipline**		
Mission	**INCOSE accelerates the transformation of systems engineering to a model-based discipline**		
Mission Area #	**1**	**2**	**3**
Mission Area	**Infuse INCOSE**	**Engage Stakeholders**	**Advance Practice**
Mission Area	**What can INCOSE Do?**	**What is practiced and needed?**	**What is possible?**
Goals	Infuse model based methods throughout INCOSE products, activities and WGs	Engage stakeholders to assess the current state of practice, determine needs and values of model based methods	Advance stakeholder community model based application and advance model based methods.
Objective 1 Foundations	Inclusion of model based content in INCOSE existing/new products (Vision, Handbook, SEBoK, Certification, Competency Model, etc.)	Define scope of model based systems engineering with MBE practice and broader modeling needs	Advance foundational art and science of modeling from and best practices across academia, industry/gov. and non profit.
Objective 2 Expand Reach	Expand reach within INCOSE of MBSE Workshop; highlight and infuse tech ops activities with more model based content (products, WGs etc.)	Identify, categorize and engage stakeholders and characterize their current practices, enablers and obstacles	Increase awareness of and about stakeholders outside SE discipline of what is possible with model based methods across domains and disciplines (tech/mgmt)
Objective 3 Collaborate	Outreach: Leverage MOUs to infuse model based content into PMI, INFORMS, NAFEMS, BIM, ASME and others, sponsoring PhD Students, standardization bodies, ABET	Build a community of Stakeholder Representatives to infuse model based advances into organizations practicing systems engineering.	Initiate, identify and integrate research to advance systems engineering as a model based discipline
Objective 4 Assessment/ Roadmap	Assess INCOSE's efforts (WG, Objectives, Initiatives etc.) for inclusion of model based methods across the Systems Modeling Assessment/Roadmap	Engage stakeholder community with Systems Modeling Assessment/ Roadmap to better understand the state of the practice of MBSE. Push and pull content from stakeholders (change agents and the "to be convinced")	Provide baseline assessment framework, Systems Modeling Roadmap, to create a concrete measure of current state of the art of what's possible/what's the potential.

Figure 3: INCOSE Vision, Mission Areas, Goals, and Objective for Systems Engineering Transformation

The Challenges of Transformation

The focus of INCOSE's strategic objective is to accelerate the transformation already underway. However, transformation, let alone accelerating it, has many challenges. The consulting firm McKinsey has noted that over 70 percent of complex, large-scale change programs fail to achieve their goals[7] [7]. In their report on Transformation, McKinsey also found that this is primarily due to employee resistance and lack of management support. The Harvard Business Review (HBR) article notes similar challenges with Digital Transformation citing Organizational Silos, Legacy Processes and Cultural Resistance to Change as Key Barriers to Digital Business. The adjacent Figure 4 outlines the primary issues identified in the HBR article that tend to hold organizations back from achieving their transformation goals. Note also that these barriers apply to Digital Transformation leaders, followers, and laggards.

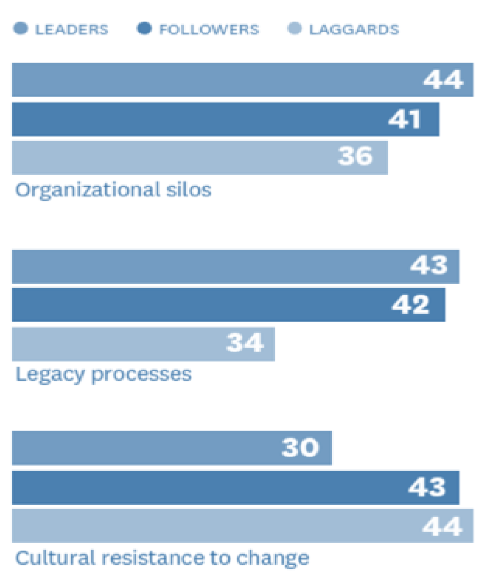

Figure 4: Barriers to Digital Transformation [viii]

Figure 5[8] [8] adjacent is an overlay of Gartner's Hype-Cycle[9] [9] and a graphic from Geoffrey Moore's Crossing the Chasm[10] [10], with adoption from Roger's Innovation cycle[11] [11]. These models frame the challenges of transformation well. They express the difficulty in managing expectations as shown in Gartner's Hype Cycle and its peak of inflated expectations and trough of disillusionment. Moore's Crossing, the Chasm graphic, identifies the roles in the transformation that stakeholders often take on, such as innovators, adopters, and laggards. The Transformation activities within INCOSE are aimed at supporting adoption and these transitions. This includes understanding and managing expectations as well as aiding those change agents who are navigating the chasm. INCOSE is working to produce products and communicate best practices and lessons learned to reduce inflated expectations, minimize the trough of disillusionment, and ultimately ramp up productivity in the application of systems engineering using formal models.

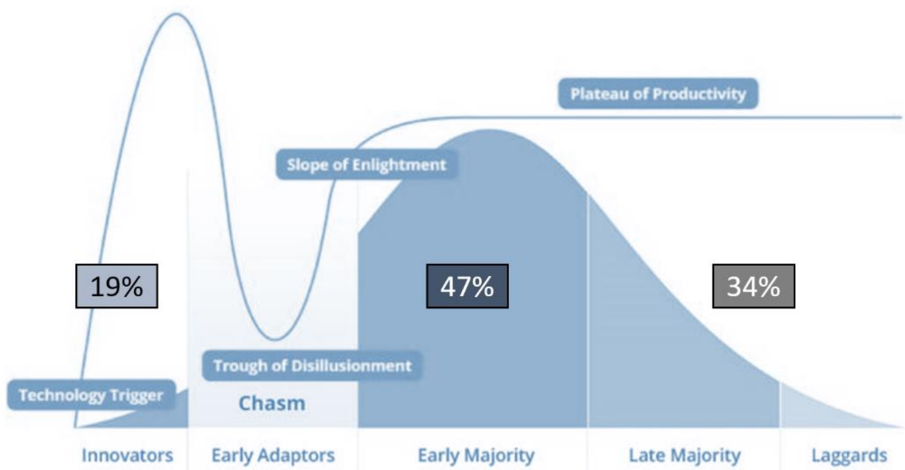

Figure 5: Gartner Hype-cycle and Moore/Rogers Crossing the Chasm

INCOSE and other sources have identified many enablers and barriers to transformation which are provided below. Figure 6 outlines enablers, needs, and obstacles by categorical area identified by INCOSE's Corporate Advisory Board (CAB). Table 1 outlines a summary of enablers for Digital Transformation from the Harvard Business Review Analytic Services Report titled "Driving Digital Transformation: New Skills for Leaders, New Role for the CIO[12] [12].

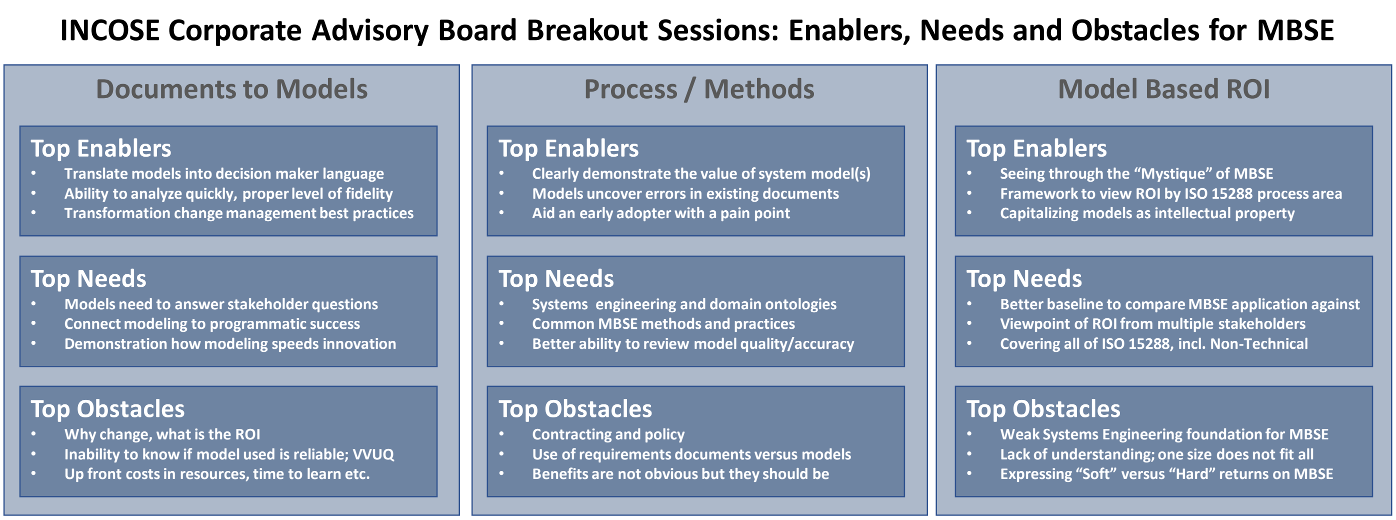

Figure 6: INCOSE Corporate Advisory Board Enablers, Needs and Obstacles for Model Based by categorical area

Table 1: Digital Transformation Enablers

Keys to Digital Transformation
Digital leadership starts at the top
Engage in a discussion of trends
Think about agile
Use examples to make it real
Need a foundation of trust
Use KPIs for sharing knowledge
Break down walls wherever possible
Need digital coaches or masters
Create appropriate learning forums

INCOSE Activities Aligned to Transformation

One of the key organizational elements that produce technical products are INCOSE's Working Groups (WG). INCOSE has nearly 50 working groups which are organized into Application Domains, Analytic Enablers, Process Enablers and Transformational Enablers. Several INCOSE Working Groups which have projects and products which are aligned with the Transformation Strategic Objective. Some of these WGs are noted in Table 2 below:

Table 2: Select INCOSE Working Groups

MBSE Initiative Challenge Team Name
Agile Systems & Systems Engineering
Lean Systems Engineering
Model-Based Concept Design
Object-Oriented SE Method
MBSE Patterns
System Science
Ontologies
Systems and Software Integration
Enterprise Systems
Tool Integration & Lifecycle Management
Digital Engineering Information Exchange
Very Small Entities (VSE)
Model Based Systems Engineering Initiative

The MBSE Initiative which resides within INCOSE's Transformational Enablers set of Working Groups is being used as an innovation incubator to kick-start innovative activities to advance the transformation of systems engineering and the application of model-based methods. Table 3 below outlines four new Challenge teams initiated by the efforts aligned with INCOSE's Systems Engineering Transformation strategic objective.

Table 3: Challenge Teams kicked off by INCOSE's Systems Engineering Strategic Objective

MBSE Initiative Challenge Team Name	Activities
Augmented Intelligence in Systems	How can machine learning and AI aid systems engineering and systems engineers in the innovation process
Digital Engineering Capabilities Assessment	Developing self-assessments and gap analysis, strategic planning, project progress aids aligned with the application of Digital Engineering
Production and Distribution Systems	Connecting models across the lifecycle to include production and logistics models and impacts of Industry 4.0, supply chain, logistics and more
VVUQ of models	Verification and Validation of Models – tied to ASME VV50 standards project is an essential element of trust in model and uncertainty quantification

Organizational Change Management

One of the most important areas in supporting the transformation of Systems Engineering to a model-based discipline is the need for organizational change management. As outlined under the subheading "The Challenges of Transformation" the ability to manage change within a project, program, enterprise or domain is the best predictor for a successful shift to a model-based paradigm. There are many references to aid change agents, teams and organizations and Figure 7 below provides one perspective of the many dimensions of change that must be considered to obtain the order of magnitude improvements required to manage the complexity of systems today.

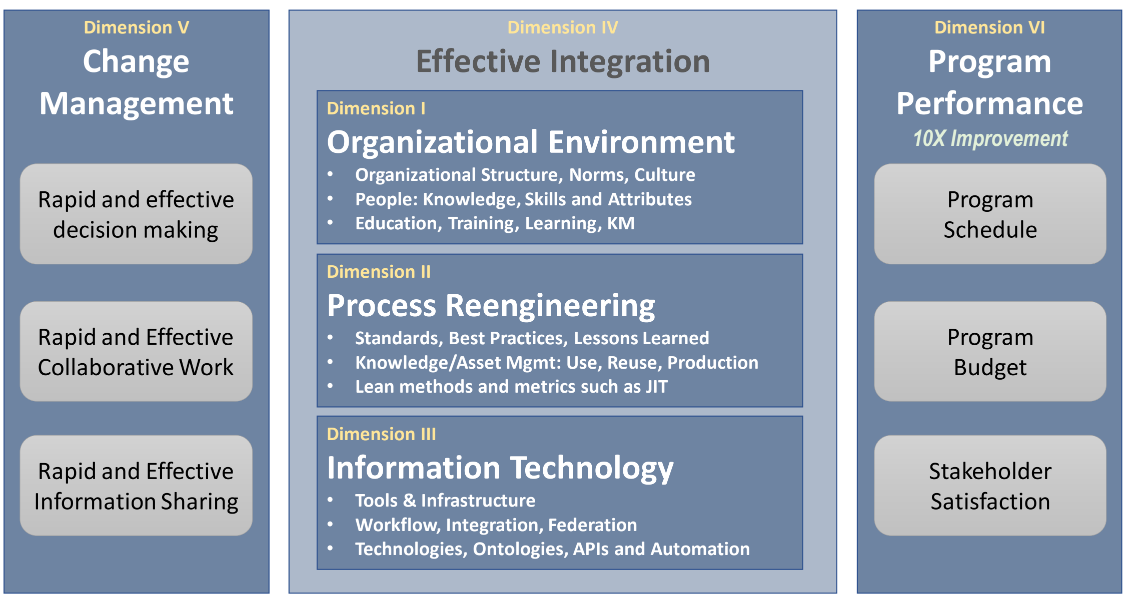

Figure 7: Factors to consider for transformation and organizational change management

John P. Kotter in his well-known book Leading Change[13] [13] provides an Eight-Step Process for Creating Major Change. These steps are also important factors to consider in the change management process:

1. Establishing A Sense of Urgency
2. Creating the Guiding Coalition
3. Developing a Vision and Strategy
4. Communicating the Change Vision
5. Empowering Broad-Based Action
6. Generating Short-Term Wins
7. Consolidating Gains and Producing More Change
8. Anchoring New Approaches in the Culture

CONCLUSIONS

INCOSE's Vision 2025 calls for Systems Engineering to lead the effort to drive out unnecessary complexity and to help stakeholders obtain a deeper system understanding. It calls for us to develop a virtual engineering environment with rich, dynamic visualization and analysis. It emphasizes the objective to obtain shared human understanding - an essential objective for transformation. INCOSE is building a broad community that promotes and advances model-based methods to manage the complexity of systems today across all domains.

For this transformation to occur the systems engineering effort must provide value within the business context of digital transformation and increasing complexity. Change agents must lead to help teams and enterprises leverage enablers and overcome identified obstacles - especially those associated with organizational change management.

It is an exciting time for systems engineers and the discipline of Systems Engineering - we've entered into the age of systems, a time when Systems Thinking, Systems Engineering and the ability to innovate and technically lead is essential. We are maturing model-based methods to help organizations address growing complexity, leveraging digital technologies and capitalizing on new and emerging trends. Systems Engineering Transformation, and INCOSE's role in it, is an essential element in the broader digital transformation and in providing stakeholder value through complex systems development.

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