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Modeling Craftsmanship: Identifying and Growing Talent

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ABSTRACT

Model-Based Systems Engineering (MBSE) has grown in popularity since the introduction of SysML a decade ago. Pockets of modeling excellence have developed within many government, industrial, and educational organizations. Few, if any, have achieved "wall-to-wall" adoption.

This paper will focus on a key component of a successful system modeling efforts: the individuals who must translate sound systems engineering into robust, useful system models. The author routinely teaches systems architecture, systems engineering, and system modeling and will share methods and techniques for identifying and growing modeling talent.

Success depends as much upon mindset and approach as it does upon understanding tool user interfaces and modeling conventions. Published texts, class exercises, videos, and case studies can be used to shape engineers' problem-solving methods. In addition, a craft system (with apprentice, journeyman, and master modelers engaged in interlocking skill development and mentoring) has shown significant promise as a way to increase the number of competent modelers.

Best practices, high-value resources, and working groups (such as those organized by the International Council on Systems Engineering) will be highlighted.

INTRODUCTION

Systems Engineering is defined by the International Council on Systems Engineering (INCOSE) as:

> "Systems Engineering (SE) is an engineering discipline whose responsibility is creating and executing an interdisciplinary process to ensure that the customer and stakeholder's needs are satisfied in a high quality, trustworthy, cost efficient and schedule compliant manner throughout a system's entire life cycle. This process is usually comprised of the following seven tasks:
>
> 1. State the problem
> 2. Investigate alternatives
> 3. Model the system
> 4. Integrate
> 5. Launch the system
> 6. Assess performance
> 7. Re-evaluate.

> These functions can be summarized with the acronym SIMILAR: State, Investigate, Model, Integrate, Launch, Assess and Re-evaluate…It is important to note that the Systems Engineering Process is not sequential. The functions are performed in a parallel and iterative manner.” [1]

The modeling associated in step three of this process may take many forms, from functional flow models to rapid, informal physics or fundamental principles-based models, to formal systems architectures modeled in the Systems Modeling Language (SysML).

Since the launch of a SysML initiative in 2001, INCOSE and a variety of tool vendors have supported and promoted its evolution. The growing body of knowledge, experience, and case studies have demonstrated its utility in executing Model-Based Systems Engineering (MBSE). In INCOSE’s Vision 2025 statement, it describes a state transition within the discipline in which MBSE becomes SE:

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 enable highly efficient and shared human understanding of systems in a virtual environment that span the full life cycle from concept through development, manufacturing, operations, and support. [2]

The author has coined the term “Document-Intensive Systems Engineering” (DISE) to refer to “traditional” systems engineering and enable MBSE to assume the label of SE.[3]

Vision 2025 also discusses the need for changes in the roles and competencies for systems engineers:

From:	A typical systems engineering role varies from managing requirements to being the technical leader on a project.
To:	The roles and competencies of the systems engineer will broaden to address the increasing complexity and diversity of future systems. The technical leadership role of the systems engineer on a project will be well established as critical to the success of a project. The systems engineering role also supports and integrates a broader range of socio-technical disciplines, technologies, and stakeholder concerns in an increasingly diverse work environment. Systems engineers will integrate programmatic and sociotechnical concerns that span global and cultural boundaries as well as system-of-system boundaries. Systems engineers will understand systems of increasing complexity that include emergent behaviors associated with system interdependence and human interactions. Systems engineers will address concerns such as security, economic viability and sustainability that span broader disciplines, applications and technical domains.[4]

This paper will discuss a number of topics related to the INCOSE Vision 2025 statements quoted above.

Comparison with CAD

The comparison between the current state of MBSE and the early days of CAD/CAE is often made (it is even quoted in INCOSE Vision 2025). However, there are significant differences as well.

In the case of the transition between drafting boards to CAD there was less of a cognitive shift required by practitioners. The specialist draftsman was expert at transforming three-dimensional objects into two-dimensional representations. Although there were numerous rules and conventions that were required, one could look at a tangible object and see how it would appear in two dimensions. Learning techniques to represent three dimensional objects as three dimensional models was straightforward and direct comparisons between the model and an object were possible, intuitive, and direct. Finally, the desired outcome of many CAD efforts is still a two-dimensional drawing. In essence, all CAD has done is reduce the effort required to generate the same artifacts (albeit with improved accuracy and more potential for reuse).

In contract, the contents of a competently-executed system model do not have direct physical analogues. The representations used by SysML are more abstract and require a different mindset to conceive, execute, and assess. Determining that a given model accurately represents a system and its desired behavior and structure is less intuitive than reviewing a set of drawings. And although a system model can be used to generate numerous traditional systems engineering artifacts, it may also supplant them.

Seeing the System with SysML

One of the reasons that MBSE is growing in acceptance is that system complexity is outpacing the ability of DISE to keep pace. Mechanical and electrical systems have grown in the past century and new technologies and analyses have become possible; it is software and its integration, however, that pose the greatest challenges. Numerous studies have shown the exponential growth in lines of code (LOC) and the rapid increase in the number of functions delivered by software in modern systems. Ensuring that desired capabilities are delivered without unintended consequences requires a span of understanding and control impossible to achieve with DISE. Disconnected documents must be read and understood by individuals who then must make needed connections between relevant data elements. In addition, individuals must work to keep these disconnected elements synchronized and controlled.

In the end, there is too much information for individuals to manage, no matter how skilled. Consider John Moses Browning, arguably the most prolific and gifted firearms designer in history. He held 128 patents and designed numerous firearms still in widespread use a century after they were designed. The M1911 pistol, for example, is enjoying renewed popularity and has a thriving enthusiast community. It has fifty-two parts.[5] Browning knew and was intimately familiar with every part's function, interfaces, and properties. By comparison, modern airliners have millions of parts…a number impossible for any one individual to comprehend. Providing a means to manage this growth in complexity was one of the drivers behind the development of SysML.

Engineering as a Craft

Engineering has evolved from a monolithic discipline in antiquity into a collection of highly specialized fields of study (some may argue it has fragmented instead). This segmentation has led to individual practitioners focusing on their respective areas of interest to the detriment of cultivating broader knowledge. In addition, many curricula do not provide instruction in engineering methods or systems approaches (though the recent surges in popularity of design thinking and human-centered design show promise).

However, at its core, engineering still marries art and science; it requires judgment and skill in execution. Billy Vaughn Koen's *Discussion of the Method: Conducting the Engineer's Approach to Problem Solving* proposes the following definitions:

> "Engineering design is the use of *heuristics* to cause the best change in a poorly understood situation within the available resources."[6]

This definition captures two important concepts; first, *heuristics* are used by engineers. Second, engineering situations are poorly understood. Although abstractions, analysis, and other cognitive tools may be used, reality is, by its nature, too complex for full understanding. It is impossible to predict and assess every possible use case and situation for a system over its life cycle.

Koen describes heuristics in this way:

> "Although difficult to define, a heuristic has four definite signatures that make it easy to recognize:
>
> 1. A heuristic does not guarantee a solution,
> 2. It may contradict other heuristics,
> 3. It reduces the search time for solving a problem, and
> 4. Its acceptance depends on the immediate context instead of on an absolute standard."[7]

The dynamic nature and constant evolution of heuristics as engineering evolves requires practitioners to invest in continuous professional development.

Heuristics blend theory and pragmatism. Too much emphasis on theory leads to an "ivory tower" mentality; too much emphasis on pragmatics leads to blunders. Successful design requires both (but when in doubt, the author suggests that an emphasis on pragmatism increases the odds of success).

Systems Engineering as a Craft

Systems engineering as a profession lacks one critical element that other disciplines enjoy: prompt feedback. Many issues are detected in testing and integration and never become public. Visible failures, whether as singular as the collapse of the Tacoma Narrows Bridge or as widespread as the lithium battery failures in consumer electronics, are impossible to ignore. All of these may then be dissected at length and the lessons learned spawn an entirely new set of laws, design guidelines, or heuristics.

In contrast, systems engineering failures are slow to emerge and hard to detect. Did a project fail because of bad systems engineering or was it due to other factors? This inhibits the growth of the heuristics that fuel the discipline. This shortfall is particularly acute in MBSE since it is in its infancy and so few skilled practitioners and public case studies are available. There are very few expert practitioners qualified to dissect failures and provide root cause analysis.

Systems engineering, therefore, is particularly amenable to a time-honored practice for transferring skills and knowledge: guild progression.

A Progression of Mastery

As skilled trades emerged and individuals abandoned farming to take up these new professions to enable civilization to advance and thrive, some mechanism was needed to transfer skills from one generation to the next. By the Middle Ages, a stepwise progression from apprentice to journeyman to master became formalized and institutionalized. Although the guild system arguably had its drawbacks, it did serve to convey both theoretical and practical knowledge to new generations of practitioners and maintain quality.

The author has informally used this approach when mentoring new system modelers with an emphasis on growing responsibility and skill in tandem with certifications (such as INCOSE's Systems Engineering Professional progression and the Object Management Group's Certified System Modeling Professional). One key advantage of this approach is that it is scalable and expands the field more quickly; by requiring journeymen to mentor new apprentices as part of their progression to master, an organization can improve the speed and quality of skill diffusion.

Apprentices work under the direction and guidance of a journeyman or master; during this phase of the progression, an individual is focused on learning language fundamentals, tool user interface, and the methods used in the work environment to engage with subject matter experts (SMEs) and discipline-specific engineers. Extracting content from SMEs, inputting it into the model as directed by the senior modeler, and generating derived work products from standard templates make up the bulk of the work done by apprentices. Individuals at this level should complete the OMG Certified System Modeling Professional (OCSMP) Model User and Model Builder Fundamental certifications; INCOSE Associate Systems Engineering Professional (ASEP) is also desirable.

When an individual grows in skill and becomes a journeyman, he is expected to begin to share his expertise with apprentices, to take on more of a leadership role in engaging SMEs, and to begin to develop custom content (such as new derived work products, custom model queries, and other advanced modeling practices). Journeymen may be expected to lead smaller projects (such as modeling a subsystem independently) or to explore new techniques. They should also complete OCSMP Model Builder Intermediate certification (INCOSE Certified Systems Engineering Professional is also appropriate at this level).

Skilled journeymen should be assessed by master modelers to determine if they are ready to be considered masters themselves. It is strongly encouraged that a master candidate present a *masterwork* for review; it should showcase the individual's grasp of the modeling language, tool, and modeling methods used by this peer group. OCSMP Model Builder Advanced and INCOSE ESEP certifications are also appropriate for master modelers (the 20+ year experience required for ESEP may delay its completion). Available masters should form a consensus about the individual's readiness and share with appropriate management. At the master level, a system modeler/architect should be able to lead a modeling effort on a large-scale system, interface with SMEs, program management, and other stakeholders, and help drive the culture shift towards system modeling in addition to executing competently at the highest level of skill.

Identifying Modelers and Architects

Success at any level of modeling requires a broad set of skills. One must:

- Understand systems engineering
- Understand SysML
- Understand the modeling tool UI
- Understand *how* and *why* to model the system and its context

- Understand how the model can help the development effort
- See how the model as *alive* and not just as a static collection of diagrams
- Be willing to challenge the *status quo*
- Be able to communicate with SMEs, SEs, PMs, and other stakeholders
- Be able to orchestrate the modeling effort
- Deliver value at *every* step of model development (provide *lift* as well as *drag*).[8]

Relatively few individuals have the combination of ability, mindset, education, and drive to excel at each of these criteria; the author believes that less than 10% of the engineering population can excel at system modeling and architecture, with approximately 25% able to model adequately with some guidance. That suggests that nearly two-thirds of the engineering population are best-suited as model consumers and contributors. (Note: When the author discussed this with notable experts, they suggested that these estimates are generous, with the actual number of top-tier architects at <5% of the engineering population. Further research and study will be necessary; in any case, it is a relatively small fraction of the engineering population at large.)

Because of the relatively small number of individuals suited for dedicated modeling and architecture, organizations cannot simply declare individuals qualified and place them in these critical roles. System models, if relied upon by programs, can have enormous leverage and will disproportionally tip the scales towards success or failure (depending on their rigor and quality). For this reason, it is strongly encouraged that any architect or system modeler be selected on the basis of demonstrated ability. Organizations should conduct regular courses and informal information sessions to expose as many staff as possible to modeling techniques and to identify those that show promise for further development.

One potential screening tool is the use of short training sessions coupled with hands-on modeling exercises. Experience suggests that modeling classes are most successful when conducted in short bursts followed by downtime to allow concepts to be considered an internalized. Four hour sessions, conducted on Tuesday and Thursday mornings, for example, have worked well to expose SMEs to modeling while not overwhelming them and leading to a reduction in engagement. This cadence also allows individuals to reflect on teachings, practice modeling independently, and formulate questions for the next class session.

To develop a modeler, the following resources are recommended (Note: These recommendations are based solely on the author's teaching experience at the University of Detroit Mercy and do not reflect the opinions or positions of his employer or clients):

Systems Engineering:

- INCOSE Systems Engineering Handbook, 4th Edition, International Council on Systems Engineering, Wiley, 2015, ISBN: 978-1-118-99940-0
- *Systems Engineering Principles and Practice*, 2nd Edition, Alexander Kossiakoff, William N. Sweet, Samuel J. Seymour, Steven M. Biemer, Wiley, 2011, ISBN: 978-0-470-40548-2
- *How Do We Fix Systems Engineering?*, Michael Griffin, 61st International Astronautical Congress, 2010

SysML:

- *SysML Distilled: A Brief Guide to the Systems Modeling Language*, Lenny Delligatti, Addison-Wesley Professional, 2014, ISBN: 978-0-321-92786-6
- *A Practical Guide to SysML, The Systems Modeling Language*, 3rd Edition, Sanford

Friedenthal, Alan Moore, Rick Steiner, Morgan Kaufmann, 2014, ISBN: 978-0-128-00202-5

OCSMP Training

- OCSMP Accelerator™ SysML training course, Lenny Delligatti, www.delligattiassociates.com

How and Why to Model the System and its Context:

- *The Design of Design: Essays from a Computer Scientist*, Frederick P. Brooks, Jr., Pearson Education, 2010, ISBN: 978-0-201-36298-5
- *Discussion of the Method: Conducting the Engineer's Approach to Problem Solving*, Billy Vaughn Koen, Oxford University Press, 2003, ISBN: 978-0-195-15599-0
- *Inventive Engineering: Knowledge and Skills for Creative Engineers*, Tomasz Arciszewski, CRC Press, 2016, ISBN: 978-1-498-71124-1
- *The Simplicity Cycle: A Field Guide to Making Things Better Without Making Them Worse*, Dan Ward, Harper Business, 2015, ISBN: 978-0-062-30197-0

Leadership:

- *Five-Star Leadership: The Art and Strategy of Creating Leaders at Every Level*, Patrick L. Townshend, Joan E. Gebhardt, Wiley, 1999, ISBN: 978-0-471-32728-8
- *Against the Tide: Rickover's Leadership Principles and the Rise of the Nuclear Navy*, USN (Ret.) Rear Admiral Dave Oliver, Naval Institute Press, 2014, ISBN: 978-1-612-51797-1
- *Turn the Ship Around!: A True Story of Turning Followers into Leaders*, L. David Marquet, Portfolio, 2013, ISBN: 978-1-591-84640-6

Also highly recommended are Henry Petroski's works (a corpus that includes numerous texts on engineering design, failure, and history that have significantly enriched the discipline) and the emerging body of work focused on elegant design (Alejandro Salado, Ph.D, Azad M. Madni, Ph.D., and Michael J. Ryan, Ph.D. have written notable papers on this topic).

INCOSE has a number of working groups that would provide architects and modelers an opportunity to practice their skills with other individuals from across the globe. Some of the most relevant groups are:

Transformational Enablers:

- Agile Systems & SE
- Lean Systems Engineering
- MBSE Initiative
- MBSE Patterns
- Model Based Concept Design
- Object-Oriented SE Method
- Very Small Entities (VSE)
- Systems Science
- Tool Integration and Model Lifecycle Management
- INCOSE-NAFEMS Collaboration
- Ontology

Process Enablers:

- Architecture
- Enterprise Systems
- Knowledge Management
- Life Cycle Management
- Measurement
- Requirements
- Risk Management

Conclusion

This paper has shared the background and context for the emergence of system modeling, discussed an approach to identify, train, and grow modelers and architects, and shared resources that have been proven useful in developing system modelers as part of the MPD program at the University of Detroit Mercy.

DISCLAIMER

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