

Modeling Beyond the V: Using Model-Based Systems Engineering (MBSE) as a Platform for Creativity in Systems Engineering Education

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Abstract

Traditionally, the educational process of systems engineering focuses on systematic methodologies, which is effective in terms of learning analytical competencies but does not encourage innovation, creativity and development of other necessary skills. As the engineering processes get more complex and require interaction between a variety of disciplines, this limitation becomes critical. This paper suggests a new approach to teaching systems engineering that combines it with the creative aspect and involves integration of systems engineering and STEAM education. Using concepts of systems engineering and design thinking as well as tools like SysML and MBSE, this paper discusses methods of using these methodologies and tools to foster classroom conceptual exploration. These methods involve modeling different architectures, exploring system behavior and incorporating non-functional requirements, including social, ethical and aesthetic ones, into the system model. The suggested instructional methods include stakeholder-centric modeling by means of use case and requirement diagrams, exploring the system functions using activity and block definition diagrams as well as validating the scenarios. Thus, by incorporating the STEAM values into the MBSE, the instructors can teach their students traditional skills of systems engineering, including requirements engineering, interfaces, lifecycle etc. and foster innovation and empathic abilities as well.

Keywords: MBSE, STEAM, Systems Engineering Education, SysML, Creativity

INTRODUCTION

Systems Engineering Education

Systems engineering education traditionally relies on the V-model in educating students about system definition, design, and validation (Forsberg et al., 2005). Rooted in the defense and aerospace fields, the V-model methodology stresses traceability and documentation and is characterized by fixed requirements (Pyster et al., 2012). Even though the approach is helpful in teaching discipline and structured thinking, it does not allow for flexibility and involvement of stakeholders (Sheard & Mosterman, 2009). Systems, however, become more and more interconnected and socio-technical in nature, and systems engineers face uncertainty and ethical dilemmas (Hess & Fore, 2018).

MBSE

Model-Based Systems Engineering (MBSE) is described as "the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities, beginning in the conceptual design phase and extending throughout the development process and other subsequent life-cycle phases" (INCOSE, 2007). There are three foundations of Model-Based Systems Engineering (MBSE): the modeling language, the modeling approach, and the modeling tool. MBSE is an alternative to the conventional paper-

based way, which uses digital models, mostly in SysML, as the definitive source of information about the system. These models provide structured and machine-interpretable representations of the system's structure, behavior, interfaces, and constraints. Figure 1 shows a taxonomy of SysML diagrams.

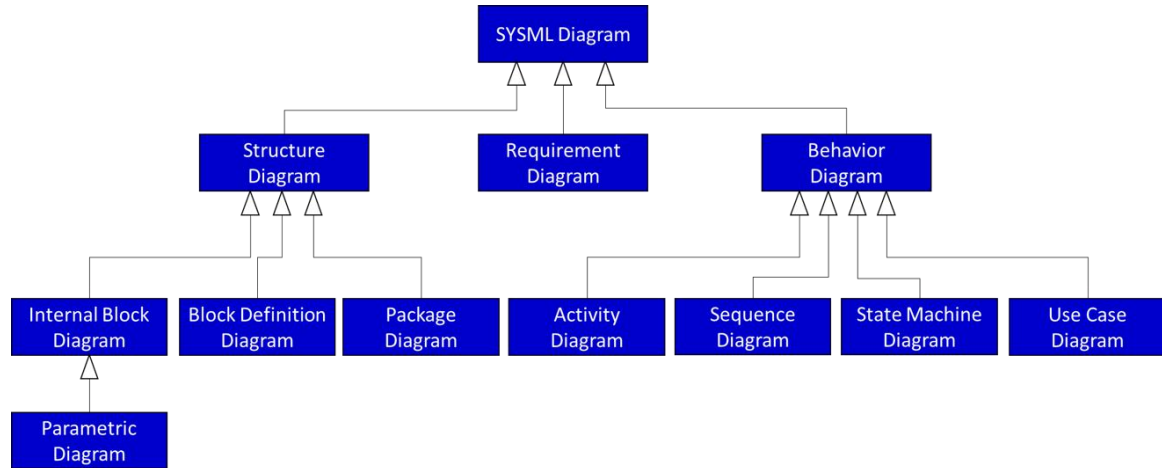


Figure 1. A Taxonomy of SysML Diagrams

Systems engineers utilize the MBSE approach to build, maintain, and query a system model within a common repository. Using MBSE provides systems engineers with opportunities to visualize their architecture early on, analyze change impact and evaluate alternative designs iteratively. Changes are propagated through the model, ensuring that all elements of the system are kept internally consistent and enabling the structured trade-off analysis. Using standardized modeling languages (such as SysML version 1 and SysML version 2), methods (such as OOSEM and SYSMOD), and tools (such as Cameo Systems Modeler and Capella) allows MBSE to ensure technical rigor and collaboration among different disciplines (Friedenthal et al., 2014; Weilkiens, 2016; Object Management Group, 2023).

Besides engineering applications, MBSE is also valuable in educational settings due to certain pedagogical aspects it has. When MBSE is used not just as a compliance tool but as a studio of simulation and discovery, MBSE can help students visualize the system, test assumptions and link their design decisions with constraints of reality.

When MBSE is integrated with STEAM concepts like creativity, ethics, human-centered design, and aesthetics, it turns into a tool that can facilitate education not only about technology but education itself (Yakman & Lee, 2012; Bequette & Bequette, 2012). Students learn not just how something works, but also its usability, fairness, sustainability, and social implications.

For example:

- Underserved or marginalized stakeholders can be included in Use Case Diagrams, which leads to inclusive design (Hess & Fore, 2018).
- Non-functional requirements such as accessibility, privacy, or emotional response can be included in Requirements Diagrams (Friedenthal et al., 2014).
- Activity and State Diagrams assist in examining behaviors of systems when they are under pressure, uncertainty, or failure.
- Parametric Diagrams represent trade-offs of values including safety and sustainability versus performance and cost.
- Rapid exploration of architectural alternatives is made possible by Internal Block Diagrams (IBDs).
- MBSE is not only a technique used for technical modeling but it is also an intellectual arena for values-based engineering. It allows students to not only learn how to create complex systems but also to critically analyze whose interests such systems are serving, under what conditions and at what cost.

STEAM

The acronym STEAM refers to Science, Technology, Engineering, the Arts, and Mathematics and is an expansion of STEM by incorporating the significance of human disciplines in technical learning processes. According to Georgette Yakman (2008, 2012), STEAM is not a case of adding art to science and engineering; rather, the STEAM learning approach is an integrated process where analysis, creativity, emotion, and design become intertwined aspects of education. Georgette Yakman was keen on the fact that literacy of the modern era demands knowledge about how various disciplines relate to each other.

Based on constructivism, the STEAM learning framework seeks to enable students to look at various problems in many different ways like the technical way, the moral way, the social way, and the artistic way. As mentioned by Georgette Yakman and Lee (2012), STEAM learning is a recursive model where engineering and the arts give structures to science and technology while mathematics provides logical grounding for the model.

STEAM education fosters empathy, creativity, and contextuality, skills which traditional STEM education fails to address adequately. STEAM education encourages an interdisciplinary outlook and demands that students consider the needs of stakeholders, cultural context, and value trade-offs during design. STEAM-oriented education equips engineering students to deal with the reality of complex systems, which never fit neatly into disciplinary categories. The following list includes non-technical STEAM values:

- 1) Creativity and Imagination:

- Encouraging novel approaches, original thinking, and artistic expression in problem-solving.
 - Valuing the process of ideation as much as the technical solution
- 2) Empathy and Human-Centered Design
 - Understanding the needs, emotions, and lived experiences of diverse stakeholders.
 - Designing with and for people, not just systems or specifications.
 - 3) Ethics and Social Responsibility
 - Addressing the ethical implications of engineering and technology.
 - Promoting justice, equity, and sustainability in innovation.
 - 4) Critical Thinking and Reflection
 - Questioning assumptions and examining broader consequences.
 - Reflecting on one's role in shaping society and technology.
 - 5) Collaboration and Interdisciplinary Thinking
 - Working across disciplinary boundaries and valuing diverse viewpoints.
 - Fostering teamwork among technical and non-technical contributors.
 - 6) Communication and Storytelling
 - Translating complex ideas for broad audiences.
 - Using narrative and visualization to build understanding and engagement.
 - 7) Cultural Awareness and Inclusion
 - Integrating cultural perspectives into design and learning processes.
 - Challenging dominant paradigms by valuing marginalized knowledge systems.
 - 8) Personal Growth and Well-being
 - Cultivating self-awareness, mindfulness, and resilience.
 - Balancing technical pursuits with mental, emotional, and social wellness.

The purpose of this paper is to present ways to unlock creativity in the learning of systems engineering. In STEAM education, both creativity and imagination are essential skills that need to be harnessed. Creativity and imagination enable learners to go above and beyond common practices, think about various options, and think about ways of doing things that are not bound by calculations and logic. Creativity is the ability to come up with new ideas, make new connections, and look at problems from different perspectives. On the other hand, imagination enables learners to imagine how certain things will happen and how certain systems will behave.

Design Thinking

INCOSE has come to see the benefits of Design Thinking in tandem with conventional Systems Engineering, especially in addressing complex, multifaceted and human-centered design problems (INCOSE, 2023). INCOSE does not propose any particular methodology but advocates for using Design Thinking in a well-thought-out way, combined with Model-Based Systems Engineering (MBSE), human-centered design approaches, and system architecture for more technically sound and user-relevant results (Madni & Sievers, 2018; INCOSE Vision 2035, 2022).

These are some of the themes in which Design Thinking influences INCOSE's evolving guidance:

Principle	Description	INCOSE Alignment
1. Empathize with Stakeholders	Understand user needs, values, and experience via interviews, observations, and personas.	Stakeholder analysis, elicitation of user needs, and operational environment modeling is encouraged by the INCOSE Systems Engineering Handbook (v5).
2. Define the Right Problem	Refine the problem statement based on the stakeholders' pain points as opposed to technical issues.	Concept exploration and scenario development during the process of needs and requirements definition is encouraged.
3. Ideate Multiple Solutions	Converge only after diverging via brainstorming across multiple disciplines.	Backed up by MBSE-supported trade study models, multiple architectural options, and design exploration models.
4. Prototype Early and Often	Consider different options through the use of low fidelity models (behavioral models, mockups, or SysML).	Iterative modeling in MBSE and rapid prototyping through digital twins or simulation is encouraged by INCOSE.
5. Test with Real Users	Assumptions should be validated via user interaction throughout the process.	Included in validation and verification planning and concept demonstration at an early stage.
6. Iterate and Learn	View failure as feedback. Employ systems thinking to develop the design further.	Encourages agile systems engineering, iterative baselining, and learning cycles in complex programs.

METHOD

Based on the knowledge gained through instruction designing practices, modeling, and literature review, an approach for integrating model-based systems engineering and STEAM education in engineering classrooms will be generated. This approach will not be based on any experimental research study but on actual hands-on experience and observations in the classroom, and systems modeling process.

1. Review of Relevant Literature

Upon an evaluation of the existing literature on systems engineering education, some recurring limitations of v-model based education were identified. More specifically, some emphasis was placed on criticisms regarding conventional teaching methods, changes that have occurred in MBSE education methods, and the use of STEAM approach in learning. Some important publications in the field include the work of Madni and Sievers on MBSE education and the book of Dym et al., 2005 on design thinking.

2. Development of Classroom Strategies

A total of ten instruction techniques were derived based on actual classroom experiences, workshops, and modelling sessions done by using SysML tools. Such techniques have been found to assist not only in the modelling process but also in non-modelling related skills, which include things like being creative, ethically aware, and system thinkers. The students improved their skills through iteration.

3. Linking Diagrams to Learning Goals

Specific SysML diagram types such as Use Case, Activity and State Machine diagrams were used for each instructional strategy to illustrate how the modeling directly demonstrates some of the key learning values. Abstraction was transformed into something concrete through modeling exercises in that the abstract aspects such as empathy and ethical reasoning became apparent.

4. Shaping Future Instruction

The methods and techniques presented in this paper could serve as guidelines for future curriculum pilot programs and classroom experiments and faculty training programs. It is an approach that is based on real-life experience of how to teach MBSE in such a manner as to go beyond compliance and technicality and towards thoughtfulness and human-centricity.

RESULTS AND DISCUSSION

The Case for Change: Limitations of Traditional SE Pedagogy

The systems engineering education field has traditionally been guided by the V-model, which stresses linear developmental phases from requirements elicitation to system verification (Forsberg et al., 2005). In this regard, this approach has created a sense of procedural rigor and strengthened good practices in terms of documentation, traceability, and lifecycle management. Nevertheless, this approach has shown some limitations in its ability to adapt to the new challenges of modern engineering (Madni & Sievers, 2018).

One of the main disadvantages of traditional pedagogy is the lack of balance between process-oriented approaches and creativity-based learning (Sheard & Mosterman, 2009). The

approach does not leave room for experimentation, modeling, failure, and divergent thinking, which are all essential for innovation processes (Dym et al., 2005). Moreover, a strong focus on delivering technical outputs may prevent students from thinking about such important issues as stakeholder diversity, ethics, and human-system interactions (Hess & Fore, 2018).

It also encourages disciplinary isolation. Engineering education often does not make it mandatory for engineering students to incorporate views from other disciplines such as humanities, social sciences, and arts, despite designing systems that have social implications (Yakman & Lee, 2012). This produces a technical education system that is efficient in providing technical skills but inefficient in dealing with uncertainty and values-based designs.

MBSE as a Platform for Creativity and Integration

Model-Based Systems Engineering (MBSE) is frequently introduced into academic programs as a technical means of dealing with the complexity of systems, tracing relationships, and performing structured analyses and design (Friedenthal et al., 2014). Standardized modeling languages, such as SysML, help represent system structure, behavior, requirements, and constraints through formal models (Object Management Group, 2023).

Unlike document-centric techniques, MBSE allows for exploring various designs iteratively. Students can experiment with different architectures, simulate system behavior, and explore different "what-if" situations using common modeling environment (Estefan, 2007). This capability helps validate ideas at an early stage and encourages experimentation, which is typically not encouraged in traditional engineering education. MBSE also makes it possible to perform conceptual integration by considering both technical aspects and objectives of stakeholders, operational context, and user experience, all of which are integral parts of STEAM approach (Bequette & Bequette, 2012).

Recent MBSE tools, including Cameo Systems Modeler, Capella, and OpenMBEE, provide means of collaborative modeling. These tools make it possible for students to develop and annotate models collaboratively and maintain traceability throughout system life cycle. Modeling together improves communication and promotes reaching agreements similarly to how professional engineers work (Weilkiens, 2016).

Furthermore, MBSE allows the representation of system characteristics that are hard to capture within traditional documentation. The parametric diagrams, behavioral models, and traceability views allow students to think through performance trade-offs, conflicts between stakeholders, and other design constraints, including ethical or sustainable ones (Madni & Sievers, 2018). Through the inclusion of both quantitative and qualitative aspects into one diagram, students get a much better sense of what systems are.

At the classroom level, MBSE transforms the goal of modeling from regulatory to insight-oriented. Insofar as it is used not just as an analytical tool, but as a design medium, it fosters creativity, systems thinking, and interdisciplinary reasoning. Such skills are critical for future engineers who will have to design socially and technically sustainable systems.

Embedding STEAM Values into MBSE Pedagogy

The STEAM approach promotes interdisciplinary thinking and human-centered design in addition to systems engineering education (Yakman & Lee, 2012). MBSE offers an integrated yet flexible modeling environment that realizes the stated goals.

Use cases diagrams help students describe a wide variety of participants, including disadvantaged or marginalized parties, encouraging empathy and design for inclusiveness (Hess & Fore, 2018). Systems engineers may expand the requirements diagram to account for non-functional constraints on privacy, sustainability, usability, and social responsibility of the system in question, thus emphasizing the importance of ethics in decision-making (Friedenthal et al., 2014).

Activity diagrams provide the means for creative exploration of interaction patterns between people and systems through visualization of logical processes, decision-making, and alternative behaviors. Block Definition Diagram (BDD) and Internal Block Diagram (IBD) serve as a canvas where alternative architectures of subsystems may be developed and compared (Object Management Group, 2023).

Sequence diagrams and state machines allow one to model temporal behaviors, emergent features, and interactive behavior sequences. Through such models, students may analyze responses of systems to changes in their environment or operation conditions (Weilkiens, 2016).

In conjunction with pedagogical approaches like stakeholder role-play, ethics mapping, and visual storytelling, these MBSE approaches contribute to designing systems with integrity both in technical and socio-cultural dimensions (Dym et al., 2005; Bequette & Bequette, 2012). Through such integration, MBSE can be not only an engineering framework but also a platform for designing values-based systems.

A holistic perspective on engineering is offered by the STEAM framework, which includes Science, Technology, Engineering, Arts, and Mathematics, and highlights the importance of such qualities as creativity and empathy together with analytical rigor in engineering education. The use of STEAM in systems engineering education supplements and enriches, rather than supplants, technical competences. STEAM enables modeling of systems that have both technical and aesthetic integrity.

- The use of case diagrams is a good way to begin stakeholder-oriented system design. In particular, the modeling of stakeholders like users, operators, regulators, or underserved populations helps students look at the behavior of systems from different angles.
- The requirement diagrams could include non-functional attributes such as accessibility, sustainability, equity, and privacy to make the model consistent with the social and ethical context of the project. Thus, the values-based requirement is legitimate for SysML.
- The use of activity diagrams allows visualizing behavioral logic and decision points. In this way, one can investigate alternative workflows, unpredictable results, and human interaction loops.
- BDDs and IBDs are helpful tools to develop and compare alternative architectures. This method is related to the concept of conceptual experiments and emphasizes the idea that most of the time, engineers improve systems through iterations.
- Sequence diagrams and state machines offer analysis tools for dynamic behavior and emergent phenomena. The artifacts enable students to simulate how a system behaves in different situations and analyze issues relating to usability, resilience, and ethics.
- Methods instructors can use to incorporate STEAM into education include:
 - Role-playing to gain perspectives from all stakeholders
 - Interdisciplinary design activities concerning public health, sustainability, and social justice; and
 - Diagramming to tell stories of ethical trade-offs and user experience
 - Constraint-driven design that regards beauty and society values as part of the system definition
- In this way, MBSE can be used as a medium of integrating values and, in turn, help educators to teach systems engineering as both a technical and social discipline. This way, STEAM instruction enhances engineering rather than undermining it because it expands the set of variables for students to model.

Instructional Techniques and Classroom Applications

In order to bring MBSE and STEAM together in actual classroom practice, teachers have to put aside theory and implement approaches that will link modeling to creative thinking, systems thinking, and human-centered design. Being structured – visual, iterative, and modular, MBSE offers a perfect way to engage in tasks that are beyond just checking boxes, but rather involve experimenting, reflecting, and collaborating. The following approaches are designed specifically for an MBSE context and aim at working with students' thinking, designing, and communication processes via modeling.

1. Early Concept Sketching and Informal Modeling

Prior to the implementation of MBSE in a formal way, students must begin by creating informal sketches using paper, boards, and sticky notes. These informal sketches will help in defining the system boundary, objective, and users. The stage is all about brainstorming and not making improvements on it. Eventually, the students convert these informal concepts into Block Definition Diagrams or Use Case Diagrams with the use of SysML.

2. Scenario-Based Design with Personas

Students create personas of the users such as emergency responders and people with disabilities so that they can analyze the system from varied angles. They will create user stories that they can convert into Use Cases and Activity Diagrams.

3. "What If?" Divergence Modeling

The students create the system in unexpected scenarios such as extreme weather and limited power. This activity will make the students reconsider the design assumptions as they design the model flexibly. They use Internal Block Diagrams, Parametric Diagrams, and State Machines for this process.

4. Parallel Architecture Modeling

The students develop models of various systems that perform the same basic function but have different architectures. These models are compared on the basis of the cost, complexity, and resilience using a matrix. SysML assists them in presenting and validating each architecture. This avoids tunnel vision in the design process at an early stage.

5. Model Jams and Design Sprints

Working together in groups with a set time limit, students have to create a model that solves the problem posed. Fast thinking, not perfection, is the aim. Use of lighter SysML diagrams like Use Case, Sequence or Package Diagrams enables them to express their ideas and get feedback.

6. STEAM Fusion Assignments

Students face technical problems that include creative or cultural constraints, such as aesthetics, emotional considerations, and social values. These students use SysML constraints and constraint notes to link the technical model with human considerations. This way of solving technical problems ensures that the designs created will not only satisfy the functional goals but also human values.

7. Human-System Interaction Modeling

The users simulate how people work with the system under actual conditions, such as stress, fatigue, or confusion. Activity Diagrams, Sequence Diagrams, and State Machines

show these interactions. The outcome is an enhanced understanding of system behavior, incorporating elements of human unreliability.

8. Unconventional System Design Challenges

The problem is modeled by the students and might include issues such as burnout prevention or restoring public trust. The Requirement and Parametric diagrams enable them to examine the connection between the design of the system and possible social and emotional results.

9. Design Journals and Reflection Logs

Through the entire project, students maintain a writing log describing their design process. They outline what they did, what was modified, and the reasoning behind their actions. In addition, students have to justify their decisions by making connections to the particular elements of the model.

10. Prompted Ideation with AI Tools

Students may take advantage of AI technologies in order to develop initial ideas, such as possible use cases or edge conditions. Students must analyze and criticize their ideas before modeling. Then, students employ MBSE technologies in order to further work on their concepts. AI acts as a supplementary technology here.

The methods described above not only show how to create MBSE diagrams. Moreover, they alter the way how students view systems thinking as a whole. In fact, every method encourages students to think about their assumptions, talk to actual users and scenarios, and view modeling as the design process, not merely as a reporting practice. The classroom becomes a place where both technical accuracy and creativity coexist. Students become able to combine structure and ambiguity when they model both for performance and meaning. Thus, by using these approaches as regular instructional practices, instructors turn MBSE into a technology that is not only an analytical but also an idea-generating one.

CONCLUSION

Systems engineering education based on traditional techniques requires change because of the growing complexity of socio-technical environment in which systems are being created. The V-model of systems engineering, being based on such concepts as traceability, discipline, and life cycle control, is very good; however, it is not enough. It does not provide students with skills to cope with ambiguity and to consider the needs of people or ethics of engineering.

The main idea of the current paper is that the combination of MBSE and STEAM principles does not mean ignoring technical principles but just the expansion of the concept of

engineering rigor. By using MBSE as a tool for investigation rather than the compliance tool only, students will have the opportunity to learn how to model uncertainty, evaluate conflicting requirements, and integrate ethical, aesthetic, and social considerations in their projects. Formal modeling languages such as SysML can provide structure and behavior but also the consideration of human factor if instructors use them in this way.

Modeling methods aid in this transition. From early sketching, through persona-driven modeling, design sprints, AI-enhanced brainstorming, and reflection logs, students can practice switching between divergent and convergent thought processes without losing focus on modeling itself. These approaches show that MBSE is not just about recording the reasoning processes, but also about influencing them.

Moving "beyond the V" is not about abandoning the structures of engineering education. It is about rethinking what engineering education entails. Such initiatives should incorporate piloting MBSE + STEAM courses, providing professional development for faculty members in creative teaching practices, and conducting studies about the relationship between modeling and socio-technical considerations. The advent of LLMs opens up possibilities to assist students in finding edge cases and generating alternatives earlier on in the design process through modeling. Creating an open-source repository of MBSE examples with a STEAM approach would be another promising step in this direction.

The future of systems engineering education belongs to engineers who not only know how to model their systems but also understand why they need to do it. This paradigm is formed by educators who equip students with proper methods, language, and independence to think through systems from multiple perspectives.

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