The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
Paper ID #42593

Leveraging Active Learning Techniques to Teach Model-Based Systems Engineering

Dr. Joe Gregory, The University of Arizona

Dr. Joe Gregory is a postdoctoral research associate at the University of Arizona. His research interests include engineering education, digital engineering, model-based systems engineering, and the application of semantic web technologies to support engineering. In 2022, he received his PhD in Aerospace Engineering from the University of Bristol for his development of the SysML-based 'Spacecraft Early Analysis Model'. He is the co-chair of the Digital Engineering Information Exchange (DEIX) Taxonomy Working Group.

Rick Steiner, The University of Arizona

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Abstract

To be successful, Model Based Systems Engineering (MBSE) requires the coordinated application of an appropriate modeling language and methodology within a suitable tool. The language, methodology and tool chosen to support MBSE depends on the specific aims of the engineers. Teaching MBSE, therefore, presents the challenge of simultaneously instructing students in three distinct but interdependent concepts: the application of the systems engineering process, the expression of systems concepts in a rigorous modeling language, and the construction and analysis of system models using modeling tools. At the University of Arizona, MBSE is taught through the application of the Systems Modeling Language (SysML) v1.6 and a simplified version of the Object-Oriented Systems Engineering Methodology within the 'Magic System of Systems Architect' tool. Following recommendations from professional engineering associations, active learning practices are becoming increasingly applied to engineering education. Active learning refers to a teaching and learning approach where students actively engage in the learning process through various activities, discussions, and problem-solving tasks, rather than passively receiving information through lectures or traditional instruction. In this paper, we present various graduate-level approaches that leverage active learning techniques to support the teaching of MBSE. We highlight effective teaching approaches such as student modeling assignments, discussion sessions, adapting to online learning constraints, and emphasizing vendor-specific resources. We present a semi-flipped classroom teaching style, a closed-loop approach to feedback, and ways in which inherent motivation can be fostered by emphasizing authenticity, ownership, and community. The paper underscores the importance of fostering student engagement, critical thinking, and proficiency in MBSE practices. We also review the challenges of implementing these techniques in a hybrid classroom setting, present lessons learned based on feedback from the cohort, and discuss how the teaching of MBSE can be further improved using active learning techniques and modern technology. It is the authors' intention that other MBSE instructors may consider and implement some of the teaching techniques discussed in this paper.

1 Introduction

Model-Based Systems Engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, optimization, verification and validation[1,2]. It has often been claimed that successful adoption of MBSE within a complex systems engineering project can lead to benefits regarding schedule and cost - though the extent of these benefits can be difficult to quantify[3]. To be successful, MBSE requires the coordinated application of an appropriate modeling language and methodology within a suitable tool. The language, methodology and tool chosen to support MBSE depends on the specific aims of the engineers.

The most common language used by MBSE practitioners is the Systems Modeling Language (SysML)[4]. While incremental versions of the SysML v2 pilot implementation continue to be released[5], SysML v1.6 remains the de facto modeling language and is widely accepted and used in industry and academia for interdisciplinary modelling[6]. Unlike SysML v2, SysML v1 is based on the Unified Modeling Language (UML), and therefore requires an understanding of object-oriented modeling principles. Multiple software tools are available that support SysML v1, each with their own strengths and weaknesses[7].

In their 2018 review of the state of MBSE, Madni et al. claimed that "MBSE is still in the early stages" but acknowledged that "several ongoing research efforts in academia, government and industry are maturing the MBSE approach"[8]. Indeed, a 2020 study into the adoption of MBSE within Airbus Space highlighted multiple "cultural and technical hurdles" on the road to widespread MBSE adoption in industry[9]. As engineering technology continues to evolve and MBSE implementation strategies are refined, engineering education has a responsibility and an opportunity to evolve in parallel[10,11]. One of the main purposes of higher engineering education is to prepare engineering students for roles in industry[12]. It has been argued, however, that this is often not achieved[13,14]. A 2017 study claims that there has been a continuous background concern that "engineering programs inadequately prepare students for the professional world"[14]. This is particularly true for particular technical skills such as systems design[13] and non-technical skills such as communication and collaboration[14].

In order to address this, active learning practices are becoming increasingly applied to engineering education[15,16]. Active learning refers to a teaching and learning approach where students actively engage in the learning process through various activities, discussions, and problem-solving tasks, rather than passively receiving information through lectures or traditional instruction[17]. In particular, active learning techniques have been recommended by professional engineering associations such as the European Society for Engineering Education (SEFI) and the Active Learning in Engineering Education (ALE) network, political organisations like UNESCO, and national and international accreditation organisations of programmes like Accreditation Board for Engineering and Technology (ABET) and European Network for Accreditation of Engineering Education (ENAEE)[15].

In this paper, we present various graduate-level approaches that leverage active learning techniques to support the teaching of MBSE. We provide an overview of the content and structure of the 'Model-Based Systems Engineering' course offered at the University of Arizona (UA). We then highlight effective teaching approaches such as student modeling assignments, discussion sessions, adapting to online learning constraints, and emphasizing vendor-specific resources. We present a semi-flipped classroom teaching style, a closed-loop approach to feedback, and ways in which inherent motivation can be fostered by emphasizing authenticity, ownership, and community. We present feedback that has been gathered from the cohort, and review the challenges of implementing these techniques in a hybrid classroom setting. We also present

Table 1: ‘Model-Based Systems Engineering’ Learning Outcomes

No.	Learning Outcome
1	Identify how system engineering concepts can be expressed in a system model.
2	Describe how MBSE can both compliment and challenge the traditional systems engineering approach.
3	Choose an appropriate scope, define the purpose, and define the approach for a systems engineering project intended to leverage MBSE.
4	Describe the intent of SysML using the ‘4 Pillars’ rubric.
5	Construct and interpret semantically consistent SysML models.
6	Critique a project’s implementation of MBSE as captured in a SysML model.

lessons learned based on feedback from the cohort, and discuss how the teaching of MBSE can be further improved using active learning techniques and modern technology. The paper underscores the importance of fostering student engagement, critical thinking, and proficiency in MBSE practices.

2 ‘Model-Based Systems Engineering’ Course Overview

The ‘Model-Based Systems Engineering’ course takes place over 15 weeks and is split into three modules. There are two classes each week, and each class has a duration of 1h15m. The course learning outcomes are presented in Table 1 and the course structure is displayed in Table 2. The course is open to senior undergraduate and graduate students. This paper focuses on the delivery of the course during the spring semester of the 2023 academic year. In 2023, the course was offered as a hybrid course - students were able to attend in person (the class was hosted in a small classroom setting) or online over Zoom. There were 44 registered students, and attendance was split approximately equally between in-person and offline over the duration of the course.

To successfully apply MBSE, it is necessary to select an appropriate language, tool and methodology. In this course, students are taught to use SysML v1.6. Students are strongly encouraged to use the DS Catia product ‘Magic System of Systems Architect’, but they may use another appropriate tool if they have can provide a suitable reason (e.g., a student may use Enterprise Architect throughout the course if they have an internship at a company that uses Enterprise Architect). All 44 students registered for the 2023 offering of this course selected ‘Magic System of Systems Architect’. The course structure outlined in Table 2 approximately followed the Object-Oriented Systems Engineering Method (OOSEM) as outlined in[18].

Throughout the course, students are expected to apply what they are learning as they develop a model of a system of their choice. At the end of each module, students are required to submit a modeling assignment (MA) incorporating what they have learned. Each MA is to be completed individually and requires the submission of one SysML model to be graded against a set of predefined criteria (these criteria are made available to the students). MA2 and MA3 build on the previous MAs, and part of the students’ grade is dependent on how well they incorporate the feedback they have received in previous assignments. Over the course of these MAs, students work through a typical systems engineering process from needs and requirements elicitation, through functional and logical design, to analysis and verification.

Table 2: 'Model-Based Systems Engineering' Course Structure

Week	Module	Topic	Assignment Due
0		Course introduction and rationale	
1		SysML overview	
2	1	Establishing a system need	
3		Establishing a system context	
4		Elaborating stakeholder goals	Modeling Assignment 1
5		Modeling system structure	
6		Parametric modeling	
7	2	Modeling and allocation of activities	
8		Modeling states and state machines	
9		Modeling flow	Modeling Assignment 2
10		Modeling interconnection and interfaces	
11		Structuring a system model for useability	
12	3	Introduction to architecture and allocation	
13		Role of SysML in IDEs	
14		Transitioning to MBSE	
15		Extending SysML v1 (profiles)	Modeling Assignment 3

The purpose of Module 1 is to encourage students to consider the problem or need that their system will address, rather than the system itself (i.e., the solution), and to teach students how to model this information using SysML. This is not often taught in undergraduate engineering curricula. The key aspects of this module are concept/problem definition, system boundaries, and user goals. At the end of Module 1, students are expected to submit a proposed 'Mission Needs Statement' (MNS) to be approved by the instructor. This will provide the basis for the three MAs. The criteria against which MA1 is graded include model organization, system context (black box), mission needs statement, mission requirements, and mission level use case analysis.

The purpose of Module 2 is to teach students the distinction between functional and logical modeling, and the importance of both. For the submission of MA2, students are expected to have incorporated feedback received from MA1. As their models become increasingly complex, they are graded on continued model organization and consistency. They also need to demonstrate an understanding of activity modeling, state machine modeling, system structural modeling, parametric modeling, and traceability between the system and the requirements.

The purpose of Module 3 is to develop a more comprehensive understanding of system structure and how it can be modelled using internal block diagrams, ports and connectors. For MA3, students are expected to incorporate feedback from MA2 while demonstrating an understanding of requirement traceability and consistency, the relationship between state machines and activities, and interface management. To demonstrate the cohesive nature of their model, students must demonstrate at least one executable analysis that can be solved using the 'Cameo Simulation Toolkit' plugin.

Students are also expected to participate in discussions on an online discussion board. The instructor provides one prompt per module. Students have the option to start a new thread or respond to the responses of other students. An example of a prompt is as follows:

Please respond to both questions below. Feel free to build on other students responses, or start a new thread if necessary.

1. *Block definition diagrams (bdd) and internal block diagrams (ibd) seem to convey the same model information, and some critics of SysML have claimed that they are redundant. Do you agree or disagree? Please justify your answer.*
2. *Reference properties can be used to model cross-cutting hierarchies that correspond to specific subsystems, such as electrical (power), mechanical, security, etc. Discuss how you would organize a model to include these subsystem definitions.*

Students may also complete online quizzes throughout the course for extra credit. This provides the students with an opportunity to recover from a low grade on a modeling assignment. Students are free to retake these as many times as they like. Scoring 75% or greater on all quizzes before the final submission deadline earns the student an additional 15% on their grade. 37 of the 44 enrolled students were graduate students. Graduate students are required to complete an additional assignment in which they grade an anonymized MA3 submission from a previous cohort. A summary of the grading structure for this course is provided in Table 3.

Table 3: 'Model-Based Systems Engineering' Grading Structure

Assignment	Requirement	Total Points (Undergrad)	Total Points (Grad)
Mission Needs Statement	mandatory	10	10
Discussion	mandatory	40	40
MA1	mandatory	50	50
MA2	mandatory	50	50
MA3	mandatory	50	50
Model Review	mandatory (grad only)	0	30
Quizzes	optional	30	30
Total	(n/a)	200	230

3 Active Learning Techniques

Students benefit from a wide range of learning styles. Accordingly, it has been recommended that instructors incorporate a range of teaching styles in their classroom[19,20]. The 'Model-Based Systems Engineering' course offered by UA incorporates multiple teaching styles and techniques, including:

- Instructional: instructors present terms and concepts in a traditional classroom style
- Examples: instructors present examples of how these concept can be applied
- Interactive demonstrations: all member of the classroom work together to develop a model
- Discussions: students participate in discussion regarding a particular modeling topic

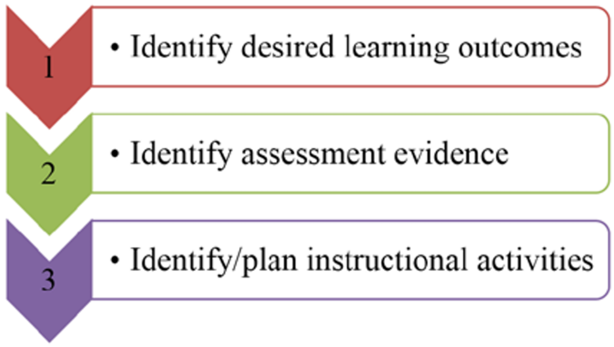

Figure 1: Backwards design approach, reproduced from[21]

- Independent study: students are encouraged to work outside of the classroom (alone or in groups)

In this section, we describe how we have structured the course to leverage these different teaching styles.

3.1 Backwards Design

The *Backwards Design* approach to teaching can be described as follows: "learning outcomes are identified first, the evidence of how achievement of the results will be assessed is determined second and, finally, the learning activities and instruction methods are planned, with the main priority being the students' engagement through active learning"[21]. This can be implemented in a classroom using the 'Understanding by Design' framework[22]. This approach has been summarized in Figure 1, reproduced from[21].

An abridged summary of the backwards design approach to the 'Model-Based Systems Engineering' course is presented in Table 4. The required learning outcomes of the course have informed the assessments, which have in turn have informed the instructional activities in terms of both content and learning style. One of the main benefits reported in the literature with regards to this approach is that the clear structure helps to motivate students[23]. Students are provided with a clear line-of-sight from the content they are being presented with, through the activities in which they are participating, to the ultimate goals of the course.

This approach is supported by clearly stating the expected learning outcomes of each class at the beginning of the session. Our aim for each week is to define three learning outcomes that span Bloom's taxonomy[20]. An example is provided below, where three learning outcomes have been defined for Module 2, Week 7:

- "Understand how activities use actions, nodes and flows to define behavior"
- "Apply swimlanes to allocate behavior"
- "Create an 'act' (schematic diagram) to model your system behavior"

Table 4: Summary of backwards design approach to MBSE course

Learning Outcome	Assessment	Content	Learning Style
Understand the value and limitations of MBSE	Discussion questions	Examples from industry and academia	Presentation, discussion
Practical application of MBSE to a project	Develop a requirements model	Requirements elicitation, modeling, traceability	Presentation, interactive demonstration, modeling assignment
	Develop a use case model	Use case elucidation and modeling	Presentation, interactive demonstration, modeling assignment
	Develop a structural model	Black box and white box, interactions and flows	Presentation, interactive demonstration, modeling assignment
	Develop a behavioral model	Activities, states, sequences	Presentation, interactive demonstration, modeling assignment

3.2 Flipped Classroom

The instructional activities defined to support the assessments and learning outcomes identified in the previous section can also be structured according to the *Flipped Classroom* approach. The flipped classroom approach advocates moving easier tasks that can be completed independently (e.g., introductory reading) outside of the classroom, saving class time to work on more challenging problems regarding the application of the knowledge. This contrasts with a traditional approach in which content is presented during the class, and students are expected to complete example problems as homework. The most frequently reported advantage of the flipped classroom is the improvement of student learning performance[24]. However, a major challenge of the flipped classroom approach is inadequate student preparation prior to class[24].

To address this challenge, a *semi-flipped* approach to class structure was adopted. This is presented in Table 5, where it is also compared to a traditional classroom setting and a fully flipped approach. This approach leverages the fact that there are two classes per week to overcome the issue of inadequate student preparation. The first class of each week focuses on the delivery of the relevant concepts in a presentation style. During this class, attention is also drawn to ‘real-world’ examples from industry and academia. The second then puts the relevant concepts into practice with a modeling demo that the students can follow along with. The demonstration is interactive, and students are encouraged to offer modeling suggestions. Often, there is no single ‘correct’ modeling solution. Students are encouraged to discuss and justify certain modeling decisions. The instructor is there to guide the modeling process and offer input only when required to keep the discussion and modeling process moving.

Table 5: Summary of semi-flipped classroom approach

Approach	Before Class	Class 1	Class 2	After Class
Traditional approach	n/a	Introduction to concepts		Problems (as homework)
Flipped approach	Introduction to concepts	Problems		Further exploration
Semi-flipped approach	Introduction to concepts (reading)	Introduction to concepts (examples)	Interactive demonstrations	Assignments

3.3 Fostering Motivation

One of the major considerations when structuring the 'Model-Based Systems Engineering' course was the fostering of student motivation. Student motivation can be extrinsic (e.g., reward-based) or intrinsic (from within)[25]. It has been reported that intrinsic motivation leads to better long-term learning than extrinsic motivation[26]. That is to say, fostering an inherent desire to learn the material is more effective than the promise of reward (e.g., a good grade) or the threat of penalty (e.g., extra homework). Multiple techniques have been identified that can be used to foster intrinsic motivation[27,28]. We list some of these below, and discuss how we have employed them in this course.

- Community (i.e., the classroom is treated as a learning community)
- Autonomy (i.e., students are allowed autonomy in their work)
- Authenticity (i.e., assignments are representative of how they might look in the 'real world')
- Purpose (i.e., the skills being developed are relevant and are required in potential future roles)
- Lower stakes (i.e., participation is encouraged with 'low-stakes' assignments)

We have attempted to foster a sense of *community* in multiple ways. The required Discussion posts provide a convenient way in which all students can introduce themselves and their projects. Students are also required to discuss statements, such as the example presented previously. As previously described, the interactive demonstrations that take place during the second class of the week are intended to be collaborative. Indeed, the instructor is there primarily to facilitate the discussion - the decision-making with regards to the modeling is led by the students through modeling suggestions and discussion. As defined in Table 2, graduate students are also required to grade models submitted by peers. The goal of these activities is to encourage an atmosphere of collaboration where students mutually benefit from feedback and discussions with their peers.

To create a sense of *autonomy*, students are free to choose the subject of their modeling assignments. The first assignment requires students to define a 'Mission Needs Statement' (MNS). This MNS is reviewed by the instructors to ensure it is a suitable foundation for the coming assignments, and therefore some modifications may be recommended, but ultimately students may are able to propose a problem (and thus develop a solution) that they are genuinely interested in and knowledgeable about. As all subsequent modeling assignments build on previous assignments, students are able to explore this area of interest in increasing detail throughout the course.

Authenticity and *purpose* have been demonstrated to the students through regular use of examples. In each module we include relevant examples of SysML models that have been developed to support real projects. Examples include the Large Synoptic Survey Telescope (LSST)[29] and the Radio Aurora Explorer (RAX) cubesat mission[30]. We show practical examples of recent work where the concepts that they are learning are being used. To further emphasise the importance of the subject and the need for skilled systems engineers, we also include examples of where systems engineering can go wrong. A typical example is the Mars Climate Orbiter[31], which ultimately crashed onto the surface of Mars in 1999 due to a mismatch of units between the contractor (NASA) and the supplier (Lockheed Martin). This example is particularly useful as Edward Weiler, NASA associate administrator for space science, was quoted as saying the following: "People sometimes make errors. The problem here was not the error; it was the failure of NASA's systems engineering, and the checks and balances in our processes, to detect the error. That's why we lost the spacecraft"[32]. Furthermore, all modeling assignments build on previous assignments in a way that more accurately reflects a typical systems engineering process than a collection of isolated tasks.

Lowering the stakes encourages student participation by providing a low-risk incentive to contribute to the learning environment. The Discussion posts are graded - but students need only contribute to a discussion to receive the full grade. The content of the discussion post itself is not graded. As the modeling assignments progressively build on the assignments that have gone before, students have the opportunity to correct previous mistakes for extra credit, thus lowering the stakes for each individual assignment. Students also have the opportunity to complete online quizzes to demonstrate understanding of the concepts being taught. These are optional, but students may attempt these as many times as they like.

3.4 Assessment and Formative Feedback

In this section, we consider the modeling assignments - and particularly the approach to assessment and feedback - in more detail. In[20], the following claim is made: "people learn new material most effectively when they perceive a clear need to know it in order to solve a problem or meet a challenge". Problem-based learning is an approach to leverage this by providing students with a significant problem that students gradually attempt to solve as they increase their knowledge of the relevant domain and improve their skills. Project-based learning is a similar but less instructional approach[33]. These approaches are particularly well-suited to engineering students[34,33], who tend to appreciate its emphasis on group work and problem solving[34]. Taking this a step further, the following claim is made in[35]: "the use of project-based learning as a key component of engineering programs should be promulgated as widely as possible, because it is certainly clear that [this] would be welcomed by students, industry and accreditors alike".

The progressive modeling assignments required of the students enrolled in the 'Model-Based Systems Engineering' course have aspects of both 'problem-based' and 'project-based' learning.

Students are presented with a significant problem at the beginning of the course - in fact, they choose it themselves in order to foster a sense of ownership and intrinsic motivation. As they progress through the course and learn new modeling concepts, they are able to do so with a particular problem in mind. In accordance with the claim made in[20], they have a "clear need to know it". Students will need to know incorporate all of the knowledge and skills they develop throughout the course to adequately address the problem they have identified.

With regards to *assessment*, students are provided with a SysML-based rubric that clearly states the modeling criteria that need to be met in order to achieve a particular grade for each modeling assignment. Students are encouraged to import these rubrics into their model as they progress through the course, and manually add ⟨⟨*satisfy*⟩⟩ relations between the criteria and relevant model elements as they develop their model. Not only does this provide a convenient table for instructors to reference during grading, it provides a way in which students can actively consider the criteria that their models must fulfill in order to receive the highest grades. This degree of transparency is a key aspect of the *Backwards Design* approach.

A crucial part of the assessment process is the provision of detailed feedback from the instructors. The benefits of formative feedback have been firmly established[36]. It has also been claimed in[37] that: "encouraging self-reflection on strengths and weaknesses is an essential factor in training reflective practitioners". By providing detailed feedback, students have the opportunity to reflect and implement changes based on the feedback they have received. This is explicitly encouraged as one of the criteria in each modeling assignment rubric is the "response to instructor feedback".

3.5 Mental Models

It has been shown that diagrams, and particularly simple diagrams, support students in factual learning[38]. This can be applied to a course syllabus - a visual representation of the course content and structure can help students to "grasp key information about a course"[39].

In this course, therefore, we use diagrams to support the textual syllabus. At the beginning of every class we present the diagram shown in Figure 2, but with the relevant models and diagrams highlighted. In the case shown in Figure 2, we are in Module 2, Week 7 (see Table 2), and are focused on the use of activity diagrams and block definition diagrams to visualize activity models.

4 Feedback from Students

At the end of the course, students were encouraged to submit an anonymous survey regarding their experience of the course. Students were asked to rate multiple statements related to their experience on a Likert scale of 1 to 5 (1 = strongly disagree, 5 = strongly agree). 14 of the 44 students enrolled in the class responded. Relevant statements and their scores are presented in Table 6.

The results of the survey indicate that the majority of students were satisfied with the way in which the course was delivered. The survey focused on ascertaining student satisfaction with

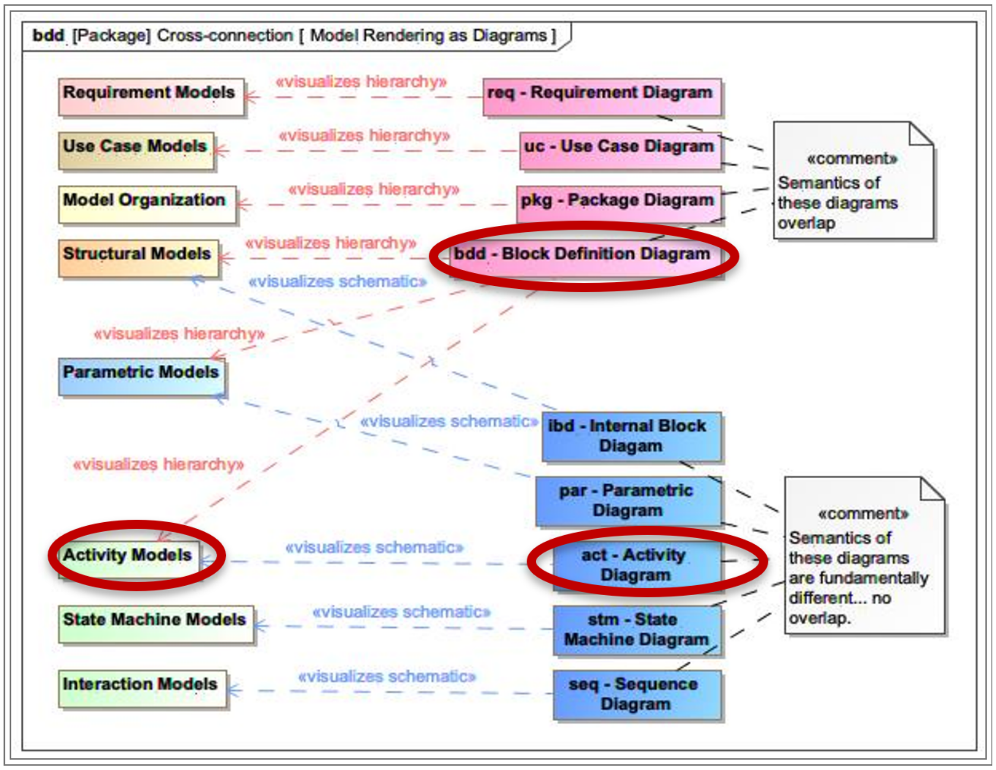

Figure 2: Syllabus diagram relevant to Module 2, Week 7

regards to the learning objectives, the balance of content delivery and interactive demonstration, and the relevance of the knowledge and skills they were practicing.

As part of this anonymous survey, students were also encouraged to state what they liked about the course, and any suggestions they may have to improve the way this course is taught. A selection of positive quotes is provided below:

- “I liked that we had an application final instead of a knowledge based final. I think that helps with learning the tool.”
- “I liked the example models shown and how diverse other models in the class were, I didn’t realize how applicable MBSE could be in so many areas.”
- “There was a lot of constructive feedback.”
- “It is practical with helpful feedback.”
- “Great feedback.”
- “I enjoyed the chance to apply the key concepts of the course to a personalized project I chose. This motivated me to apply what I learned in class and practice my critical thinking skills.”
- “Clearly structured course material.”

A selection of suggestions to improve the course are provided below:

- “Rubrics were not clear, felt like students, Teaching Assistants, and instructor all understood different things.”
- “I did feel like earlier lectures were redundant and more in depth concepts later on weren’t covered as well.”
- “More examples that cover more scenarios.”
- “Maybe do more demos.”
- “Maybe do simpler demos, where students are encouraged to follow along and/or complete.”

Table 6: Summary of student feedback in the form of Likert scores
(1 = strongly disagree, 5 = strongly agree)

Statement	Mean Likert Score
I was encouraged to participate in class activities, projects, and/or assignments.	4.71
This part of the course expanded my knowledge and skills in this subject matter.	4.79
I was encouraged to analyze and/or apply the concepts and skills taught in this part of the course.	4.79
The learning goals for this part of the course were clear to me.	4.57
This part of the course helped me to connect the concepts and skills we learned to the world around me.	4.71
I received feedback on my coursework and/or assignments that helped me learn.	4.79

5 Discussion and Future Work

We are not claiming that the approaches presented in this paper have resulted in the optimal ‘Model-Based Systems Engineering’ course. Rather, we have presented the approaches that we adopted for this course, and our justification for adopting them, in order to provide other instructors with a list of considerations that they may wish to review in the context of their own engineering courses. We have attempted to highlight what did and did not work well in the context of our course. Clearly, therefore, there are opportunities to develop this work further. We discuss some of them in this section.

The feedback from students has highlighted some areas of the course that require further improvement. Demonstrations should range both in difficulty (i.e., simple models to complex models) and in application (e.g., spacecraft, automotive, sociotechnical). The modeling assignment rubrics may be reviewed and revised to ensure that they are unambiguous. However, while the Likert scores summarized in Table 6 suggest a good degree of student satisfaction, there is no control to which we can compare. This means that we are not able to use this information to determine whether these approaches have improved student performance in the class. Furthermore, only highly satisfied students may have been motivated to respond to the survey, while dissatisfied students may not have been willing to provide feedback. Future work may address this by continuing to review the satisfaction of the students as the course is developed.

We have highlighted some of the active learning techniques that require further attention. We have implemented a *semi-flipped* approach to the class. This means that we do not expect students to complete introductory reading prior to class so that we can focus on demonstration in the class. The result is that we structure the first class of the week as a traditional lecture-style class, while the second involves an interactive demonstration. A fully flipped classroom would reserve all class time for the interactive demonstrations. In their feedback, a greater number of interactive demonstrations is something that the students repeatedly said that they would like. Future iterations of this course may reconsider the fully flipped classroom approach.

One of the recurring themes of the feedback was that students would have liked to have seen more demonstrations of this kind. This observation has also been recorded by other investigations of engineering education[40]. The feedback provided to students and the opportunity to make corrections based on it was clearly appreciated. While the goal of the rubric was to provide a clear set of criteria that the students could aim to meet, the feedback suggests that these rubrics themselves could have been made clearer.

There were also practical considerations with regards to the deployment of many of the active learning techniques. The course was split with approximately 50% of students online and 50% of students attending in person. In-person participation sometimes came at the cost of the online students, who found it difficult at times to keep up with the discussion in class – particularly if the discussion was taking place between two students in the classroom. This needs to be considered when developing active learning strategies for a hybrid classroom.

One possible direction for future development of this course is the development of a model-based validation suite to support grading. Students would be encouraged encouraged to employ this suite within their model to flag wellformedness errors before each modeling assignment submission.

As digital engineering technologies continue to be developed, the implementation of this technology into the engineering curriculum needs to be considered in more detail. Research exploring these possibilities is currently underway[41,11]

6 Conclusion

In this paper, we have described how active learning techniques can be leveraged to support teaching in a 'Model-Based Systems Engineering' course. The goals of this paper have been to identify possible techniques that instructors of similar courses may wish to implement, to highlight their justification in the literature, and to note any other considerations that we believe may be useful. We have also documented our experience as we attempted to implement these techniques in our course and have recorded the feedback we received from students. Using class time to focus on interactive modeling demonstrations rather than the delivery of course content was particularly well-received. Similarly, the students appreciated the provision of formative feedback and the opportunity to implement corrections based on that feedback. Future work will consider how to ascertain more robust feedback from students, and will aim to clarify the rubrics and align them more closely with the learning outcomes.

References

[1] Jon Holt, Simon Perry, Richard Payne, Jeremy Bryans, Stefan Hallerstede, and Finn Overgaard Hansen. A model-based approach for requirements engineering for systems of systems. *IEEE Systems Journal*, 9(1): 252–262, 2014.

[2] Joe Gregory, Lucy Berthoud, Theo Tryfonas, Antonio Prezzavento, and Ludovic Faure. Investigating the flexibility of the mbse approach to the biomass mission. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 51(11):6946–6961, 2020.

[3] Kaitlin Henderson and Alejandro Salado. Value and benefits of model-based systems engineering (mbse): Evidence from the literature. *Systems Engineering*, 24(1):51–66, 2021.

[4] Object Management Group. SysML Specifications: Current Version - OMG SysML 1.6, 2023. URL `https://sysml.org/sysml-specs/`.

[5] Object Management Group. GitHub - Systems-Modeling/SysML-v2-Release: The latest incremental release of SysML v2., 2023. URL `https://github.com/Systems-Modeling/SysML-v2-Release`.

[6] Christian Nigischer, Sébastien Bougain, Rainer Riegler, Heinz Peter Stanek, and Manfred Grafinger. Multi-domain simulation utilizing sysml: state of the art and future perspectives. *Procedia CIRP*, 100:319–324, 2021.

[7] Joe R Gregory. *A Model-Based Framework for Early-Stage Analysis of Spacecraft*. PhD thesis, University of Bristol, 2022.

[8] Azad M Madni and Michael Sievers. Model-based systems engineering: Motivation, current status, and research opportunities. *Systems Engineering*, 21(3):172–190, 2018.

[9] Joe Gregory, Lucy Berthoud, Theo Tryfonas, Alain Rossignol, and Ludovic Faure. The long and winding road: Mbse adoption for functional avionics of spacecraft. *Journal of Systems and Software*, 160:110453, 2020.

[10] Didem Gürdür Broo, Okyay Kaynak, and Sadiq M Sait. Rethinking engineering education at the age of industry 5.0. *Journal of Industrial Information Integration*, 25:100311, 2022.

[11] Joe Gregory and Alejandro Salado. Implementing a Student Rover Design Exercise in the Digital Engineering Factory. In *IEEE Aerospace Conference*, Big Sky, MT, USA, 2024.

[12] Manuel Caeiro-Rodríguez, Mario Manso-Vázquez, Fernando A Mikic-Fonte, Martín Llamas-Nistal, Manuel J Fernández-Iglesias, Hariklia Tsalapatas, Olivier Heidmann, Carlos Vaz De Carvalho, Triinu Jesmin, Jaanus Terasmaa, et al. Teaching soft skills in engineering education: An european perspective. *IEEE Access*, 9: 29222–29242, 2021.

[13] Ramesh Kuppuswamy and Duncan Mhakure. Project-based learning in an engineering-design course–developing mechanical-engineering graduates for the world of work. *Procedia CIRP*, 91:565–570, 2020.

[14] Michael Handford, Jan Van Maele, Petr Matous, and Yu Maemura. Which “culture”? a critical analysis of intercultural communication in engineering education. *Journal of Engineering Education*, 108(2):161–177, 2019.

[15] Rui M. Lima, Pernille Hammar Andersson, and Elisabeth Saalman. Active Learning in Engineering Education: a (re)introduction. *European Journal of Engineering Education*, 42(1):1–4, 2017. ISSN 14695898. doi: 10.1080/03043797.2016.1254161. URL `https://doi.org/10.1080/03043797.2016.1254161`.

[16] Marcela Hernandez-de Menendez, Carlos A Escobar Díaz, and Ruben Morales-Menendez. Engineering education for smart 4.0 technology: a review. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 14:789–803, 2020.

[17] Kristin Børte, Katrine Nesje, and Sølvi Lillejord. Barriers to student active learning in higher education. *Teaching in Higher Education*, 28(3):597–615, 2023.

[18] Lenny Delligatti. *SysML distilled: A brief guide to the systems modeling language*. Addison-Wesley, 2013.

[19] Ference Marton and Roger Säljö. On qualitative differences in learning: I—outcome and process. *British journal of educational psychology*, 46(1):4–11, 1976.

[20] Richard M Felder and Rebecca Brent. The abc's of engineering education: Abet, bloom's taxonomy, cooperative learning, and so on. In *Proceedings of the 2004 American society for engineering education annual conference & exposition*, volume 1. American Society for Engineering Education, 2004.

[21] Daniela Pusca and Derek O Northwood. How to engage students in the context of outcome-based teaching and learning. *World Trans. on Engng. and Technol. Educ*, 13(3):268–273, 2015.

[22] Jay McTighe and Grant Wiggins. Understanding by design framework. *Alexandria, VA: Association for Supervision and Curriculum Development*, 2012.

[23] Huda Alenezi. Learning as the prize: Enhancing students' intrinsic motivation through backward design. *International Journal of Pedagogy & Curriculum*, 23(1), 2016.

[24] Gökçe Akçayır and Murat Akçayır. The flipped classroom: A review of its advantages and challenges. *Computers & Education*, 126:334–345, 2018.

[25] Lisa Bomia, Lynne Beluzo, Debra Demeester, Keli Elander, Mary Johnson, and Betty Sheldon. The impact of teaching strategies on intrinsic motivation., 1997.

[26] Shui-fong Lam, Rebecca Wing-yi Cheng, and William YK Ma. Teacher and student intrinsic motivation in project-based learning. *Instructional Science*, 37:565–578, 2009.

[27] Ann Bainbridge Frymier and Gary M Shulman. "what's in it for me?": Increasing content relevance to enhance students' motivation. *Communication Education*, 44(1):40–50, 1995.

[28] Liudmila Mikalayeva. Motivation, ownership, and the role of the instructor in active learning. *International Studies Perspectives*, 17(2):214–229, 2016.

[29] Brian M Selvy, Charles Claver, and George Angeli. Using sysml for verification and validation planning on the large synoptic survey telescope (lsst). In *Modeling, Systems Engineering, and Project Management for Astronomy VI*, volume 9150, pages 236–248. SPIE, 2014.

[30] Sara C Spangelo, James Cutler, Louise Anderson, Elyse Fosse, Leo Cheng, Rose Yntema, Manas Bajaj, Chris Delp, Bjorn Cole, Grant Soremekum, et al. Model based systems engineering (mbse) applied to radio aurora explorer (rax) cubesat mission operational scenarios. In *2013 IEEE Aerospace Conference*, pages 1–18. IEEE, 2013.

[31] Brian J Sauser, Richard R Reilly, and Aaron J Shenhar. Why projects fail? how contingency theory can provide new insights–a comparative analysis of nasa's mars climate orbiter loss. *International Journal of Project Management*, 27(7):665–679, 2009.

[32] Matthias Hinz. *Communicating meaning and purpose of spatio-temporal data analysis*. PhD thesis, Institute for Geoinformatics, 2016.

[33] Moti Frank, Ilana Lavy, and David Elata. Implementing the project-based learning approach in an academic engineering course. *International Journal of Technology and Design Education*, 13:273–288, 2003.

[34] Jacob C Perrenet, Peter AJ Bouhuijs, and Jan GMM Smits. The suitability of problem-based learning for engineering education: theory and practice. *Teaching in higher education*, 5(3):345–358, 2000.

[35] Julie E Mills, David F Treagust, et al. Engineering education—is problem-based or project-based learning the answer. *Australasian journal of engineering education*, 3(2):2–16, 2003.

[36] Valerie J Shute. Focus on formative feedback. *Review of educational research*, 78(1):153–189, 2008.

[37] Subha Ramani. Reflections on feedback: Closing the loop. *Med Teach*, 38(2):206–207, 2016.

[38] Kirsten R Butcher. Learning from text with diagrams: Promoting mental model development and inference generation. *Journal of educational psychology*, 98(1):182, 2006.

[39] Keli Yerian. Using a graphic syllabus with second language learners. *ORTESOL Journal*, 27:9, 2009.

[40] CP Simion, GC Slusariuc, RD Stanciu, and O Bucovetchi. Improving the engineering education system–a students' perception. In *IOP Conference Series: Materials Science and Engineering*, volume 568, page 012096. IOP Publishing, 2019.

[41] Joe Gregory and Alejandro Salado. A Digital Engineering Factory for Students. In *CSER*, Tucson, AZ, USA, 2024.