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Plug-and-Play Adaptive Approach to Integrating Model-Based Systems Engineering Concepts into Academic Curriculum

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Abstract. Model-based Systems Engineering (MBSE) is coveted for improving productivity and product quality. However, adoption is slow because the workforce lacks training. Therefore, a group of MBSE experts at an R-1 university developed a series of MBSE online learning modules that can be integrated into existing courses. Rather than adding courses to engineering programs, this project presents a "plug-and-play" adaptive approach to implementing new topics into existing courses. Faculty can select elements from the modules that best fit their courses and their students' learning needs. To evaluate the effectiveness of the approach and content, parts of the first MBSE module were incorporated in a graduate level engineering course. Surveys and descriptive analysis revealed students' learning experiences and feedback (n = 81). The research findings suggest students had positive experiences with the content and their interest in MBSE increased. Further module design improvement is included and discussed in the paper.

Introduction and Literature Review

New knowledge and technologies are constantly finding their way into industry, with potential to change and evolve engineering practice. Given that industry is one of the major stakeholders of engineering education, many engineering programs try to cater to the evolving needs of industry. However, balancing those evolving needs with the realities and other priorities of the programs can be a challenge. For example, educators must strike a balance between the amount of theory and practice covered in the program (Wang et al. 2015). They also struggle with the alignment between management, faculty development, and pedagogies (Hasna 2010). In many cases, there is a lack of understanding of teaching formats that work well with the new content (Yao et al. 2005). Changing engineering curricula also poses difficulties to educators since a majority of the current engineering curricula are inflexible and contain an overwhelming amount of coursework (Tseng, Chen & Sheppard 2011). Additionally, teaching emergent topics requires people knowledgeable in those new technologies who are available to assist in the design of new learning experiences. Model-based systems engineering (MBSE) is increasingly seen as an advantageous approach for different kinds of industries (Akundi & Lopez 2021) leading to an emerging need for a workforce more knowledgeable in MBSE. The manufacturing industry is demonstrating an increasing demand for model-based systems engineers to use various kinds of models to study, design, and integrate complex systems into the manufacturing industry (Fernández & Moreno 2016).

Currently, approaches to integrate the model-based approach to systems engineering (SE) into post-secondary programs include two formats: graduate certificates, and singular MBSE courses for students to add onto their current graduate-level degree. The content for most existing certificate programs is divided between SE and MBSE, usually with a small proportion of the courses inside the curriculum focusing on MBSE while the rest focuses on laying the background knowledge in systems and systems thinking (e.g., Air Force Institute of Technology 2019; Missouri University of Science and Technology 2021; Purdue University 2021). In terms of creating MBSE courses, some higher education institutions also partner with online education platforms to offer online graduate-level courses in MBSE (e.g., University at Buffalo & The State University of New York 2021). Some institutions have developed introductory level MBSE courses for students to select (e.g., Georgia Tech 2021; Johns Hopkins University 2021).

One strategy to support engineering instructors who teach concepts connected with MBSE is to design adaptive ready-to-go units of curriculum (modules, for short) that can be administered within existing courses where teaching MBSE is not a primary course objective in a way that is similar to embedding a toy building block during plug-and-play activities. These units should require minimal effort from the instructor, ensuring that even instructors without much knowledge of the topic could incorporate the units into their teaching practice. Our team designed a suite of modules to teach a variety of learners how to apply MBSE tools and methods in their engineering discipline. We chose this design approach to ensure that current and future engineering practitioners can have a positive experience with our learning units.

When creating units of curriculum, literature points to the importance of considering the learning experiences of the target students—leading to a student-centered approach in the design of our modules. Case-based instruction is reported as a form of instruction that can get students to exercise their knowledge in authentic problem-solving situations, helping students develop a greater understanding of the course content when the concepts are structured around the cases (Yadav et al. 2014). A sociocultural approach to learning also emphasizes the usage of authentic discussions and scenario-based assessments within a supportive community environment (Hall 2007). Therefore, we designed our units considering experiential learning theory and social learning theory in order to support the previously mentioned learning experiences (Gadola & Chindamo 2019; Hassan 2011). This study examines students' experiences with one of these modules when it was incorporated into a pre-existing course.

Objectives

To provide learning opportunities related to applying MBSE tools and methods, our team of faculty members, students, and industry experts investigated an approach for implementing MBSE as a set of vertically integrated units of curriculum for current and future engineering practitioners. We developed a total of seven online modules that cover topics that range from the fundamentals of systems engineering all the way to a capstone project. However, we needed to investigate how people in different settings engaged with these units to understand if our team was successful in creating learning experiences that were accessible and engaging learners of diverse backgrounds.

The objective of this paper is to examine learners' feedback on the implementation of a MBSE module into their graduate level course. We believe that the learners' perspectives for this unit—about the curriculum design, its usefulness, and their perceived learning of MBSE—can help us understand if our unit design is appropriate for this set of learners, and if we managed to instill them with a sense of further curiosity about the topic. Therefore, the research question addressed in this study is: How do students react to the design of a pre-existing MBSE unit of curriculum when it is implemented into a graduate-level system-of-systems modeling course? Specifically, we ask for student feedback on the module's design in terms of their learning experiences, their perceived learning outcomes, and how the module could be improved.

Background

The activities reported in this piece are part of a larger research project with the goal of developing, deploying, and evaluating a set of adaptive online learning units that teach MBSE. In the following subsections, we will explain the larger context of this research project, and how it led to the specific use of the first module that is our focus in this paper.

The Complete Curriculum

We are executing our research project through six steps: the identification and grouping of topics into different learning units, the identification of pedagogies that would best fit each of the topics in the units, the development and deployment of the units, an evaluation of their effectiveness, dissemination of the results, and the continued offering of courses designed for this project for at least five years. The first one of those steps led to the planning of the MBSE curriculum in the form of seven learning modules, described in detail in Table 1.

Table 1: Modules Developed for the Program in Model-Based Systems Engineering Foundations and Applications to the Production Enterprise (Purdue University 2022).

Module	Description
Introduction to Systems Engineering (SE) and Model-Based SE for Production Systems	Introduces learners to fundamental concepts in SE and MBSE. Concepts include the importance of SE and MBSE, natural and engineered systems, simple and complex systems, models of systems, the foundations of systems engineering, and the ongoing transition to model-based systems in production and manufacturing engineering.
Engineering a System with Systems Modeling Language (SysML)	Designed for learners who want to prepare to work in an environment where MBSE is used. Topics include an overview of systems modeling with SysML, foundations of modeling preparation and organization, systems engineering using SysML, options for presenting results, and an introduction to MBSE tools that can be used for managing the life cycle of a system.
SysML Implementation and Applications	This module is for learners who will be directly involved in developing models used in MBSE. Learners will get hands-on experience building SysML models according to the principles learned in the previous module. Topics include learning to use an MBSE tool demonstrating the ability to form and use models for system requirements analysis, physical, functional, and allocated architecture, system integration and verification, model validation, and documentation.
Quantitative Methods Supporting MBSE	Designed for learners who want to develop or refresh analytical skills for data analysis, this module provides instruction on interpreting simulation results and making effective design and business decisions. The module presents statistical foundations such as distributions and probability, hypothesis testing, and confidence intervals. It also covers applications and decision-making, including value/objective functions and optimization, simulation (including Monte Carlo), and decision trees.
Production Engineering and MBSE	This module provides an overview of production engineering processes, systems, and key performance indicators. Modeling and simulation in production engineering are discussed along with their benefits. Examples of the use of simulations in both a manufacturing process and a production system are explored. At the end of this module, learners will be able to identify manufacturing characteristics that should be considered in creating SysML diagrams and understand how SysML diagrams provide information on manufacturing domain models and vice versa.
Digital Engineering and the Model-Based Enterprise	Learners completing this module will be able to explain the importance of integrating and connecting MBSE to the Digital Enterprise to enable collaboration and how MBSE data and models flow and are shared throughout the different stages of the product lifecycle. Topics explored in the module include the state of MBSE tools and technology with respect to the digital enterprise infrastructure, the digital thread, MBSE and PLM integration, traceability and change management.
MBSE Capstone Project	Learners apply the ideas and concepts learned in prior modules to a real-world problem and demonstrate the business value of the project using quantitative methods. In the capstone project, learners will be able to identify stakeholders, write a set of requirements, and develop a top-level architecture for a particular system. Individuals taking the module will be able to select from a set of pre-defined projects or propose projects of their interest.

Design and Description of the Unit of Curriculum

Our team started the design and development of the module with an extensive period of needs assessment. We first contacted several representatives from industrial partners and conducted interviews to inquire about the most needed skills and knowledge for SE and MBSE in the current workforce. Then, we gathered the topics included in similar programs from other higher education institutions and online education platforms such as EdX and Coursera to obtain the general scoping of topics to include in programs and certificates of various lengths. Our team also discussed the acceptable format and time requirement for the modules with our industry partners, accounting for the time to access the learning materials and finish the required learning activities. The unit would also adopt a format that allows learners to complete all the learning activities remotely and asynchronously. Considering the length and format of our module, our team of content experts selected suitable topics based on the anticipated prior knowledge of our targeted learners and the emerging need for the workforce. As a result, the module consists of 10 hours of content and is made up of several components including a series of short lecture videos (approximately 20 minutes each), three case study videos (approximately 10 minutes each), online group discussions questions, a group assignment in the form of a case study, and topic quizzes based on the lecture videos. All learning assessments (discussion questions, group assignment and quiz) can be used as stand-alone assignments when accompanied by the lecture videos, offering instructors more freedom to select which components to embed in their existing curriculum to better suit the learner's need and facilitate achieving their course's learning goals.

Development of the Unit

After identifying the topics to include in the unit, the content expert worked with our education team to develop the learning objectives, refine the scoping for each topic and worked together to generate content and assessments that align with the learning objectives. Among the learning activities included in the unit, discussion questions and the group assignment are team-based to create authentic learning experiences for learners, as industry often requires collaborations. Both activities are designed to be completable via remote and asynchronous collaborations among learners, offering more flexibility to instructors and learners. Depending on the constraints, instructors can choose to select the learning activities that are the most suitable to their course design.

Purpose and Content Covered in the Module

We designed the first module shown in Table 1 to introduce students to the basics of SE and MBSE, preparing them for the future units in our suite. We divided the content of this unit into six different topics to facilitate the flow of content and align it with the learning objectives. The first topic sets up the motivation for learning about systems engineering and contrasting traditional systems engineering with model-based systems engineering. The second topic introduces students to systems: their definition, characteristics, properties, and attributes. This leads to the topic that explores what is systems thinking and why it is important in the realm of engineering. The fourth topic introduces students to what models are, what are the types of models and their purposes. The end of the unit covers systems engineering and how to practice it.

Method

Participants and Setting

The context of this research was a graduate level Aeronautics and Astronautics course offered at large Research I institution in Midwestern US. The purpose of the course was to familiarize students with the concept and applications of a system-of-systems, enabling them to model, simulate, and analyze this type of system in real-life applications. The course is lecture-based with individual and team projects. The research occurred in the Spring semester of 2021, with 81 students participating in our study, coming from more than six undergraduate, master's and Ph.D. programs. The instructor implemented the first module of the MBSE curriculum, including the lecture videos and topic quizzes as required course activities. The instructor administered the survey of learner experiences via Qualtrics after students had completed the module, with students receiving course credit for participating in the survey. We recorded a total of 92 answers to the survey, but filtering for submissions that had completed at least 50% of the survey items resulted in 81 answers.

Table 2: Distribution of Study Participants by Program and Level of Study.

Program	Undergraduates	Masters	Ph.D.	Combined BS/MS	Total
Aeronautics and Astronautics	21	20	4	2	47
Civil Engineering	0	1	1	0	2
Electrical and Computer Engineering	0	5	0	0	5
Industrial Engineering	0	1	0	0	1
Engineering Management	0	3	0	0	3
Mechanical Engineering	2	6	1	0	9
Interdisciplinary engineering	0	8	0	0	8
Systems engineering	0	2	0	0	2
Other	0	4	0	0	4
Total	23	50	6	2	81

Survey of Learner Experiences with Module

We designed the survey to elicit students' impressions about the design of the unit, perceived learning outcomes, satisfaction with the unit, and suggestions for improving the unit. This included 19 Likert-type items—15 of those on a scale of 1 to 6, and 4 on a scale of 1 to 5—and nine open-ended questions. The Likert-type questions were designed to have students select how much they agreed or disagreed with the statements we were presenting, or to have students select how satisfied or dissatisfied they were with different aspects of the unit design. Only four of the open-ended questions were mandatory: "What, if any, additional topics or aspects should be covered in this module?", "What do you think was the most challenging concept(s) in the module?", "What about this module did you like?", and "What about this module do you think could be improved, and how?" The other five open-ended questions appeared only when students selected some level of disagreement with statements about content delivery, asking for specific improvement suggestions.

Data Analysis

For the Likert-type items in the survey, we present a set of descriptive statistics about each question, including the averages, medians, and standard deviations. As for the open-ended questions, we performed a thematic analysis of the responses to the four mandatory questions, coding them into recurring themes. Two of our researchers followed the general procedure for thematic analysis proposed by Braun and Clarke (2006), going through steps including data familiarization, initial coding, generating themes, reviewing themes, defining and naming themes. The researchers used inductive coding and independently examined all of the answers to the open-ended questions without any pre-determined coding schema and detected recurring themes that could be used to code the answers (Braun & Clarke 2006). During the coding process, the researchers used latent coding approach to move the data analysis beyond the scope of the surface meaning of the language and discover the underlying meaning of students' responses (Braun & Clarke 2006). After an initial round of independent review, our researchers shared their proposed codes and negotiated their differences with the help of other researchers in the team to generate a common code that they agreed could satisfactorily represent the recurring themes in the answers. Then, our researchers independently recoded the questions using the new coding scheme, and once again negotiated the differences and came to consensus.

Results

Our research question frames our interest in understanding how students reacted to a pre-existing MBSE unit of curriculum being implemented in a systems modeling course. Therefore, the results we present below are organized according to the students' responses about their learning experience, their perceived learning outcomes, and their general feedback from the open-ended questions.

Learning Experience

The questions related to the learning experience asked students about the design of the unit they experienced, the design of the assessments they had to complete, and their satisfaction with the unit. The items related to the design of the unit are presented in Table 3. Overall, at least 65% of students agreed or strongly agreed to all items related to the design of the unit, with highlights including the clarity of the instructions given in the unit and the order in which the topics were covered. We emphasize that most students were satisfied with the depth and breadth of the topics covered, as well as with the clarity of the video lessons.

Table 3: Descriptive Statistics of Responses for Items About Unit Design.

Item	***M***	***Mdn***	***SD***	***N***
I understood the instructions for all assignments and activities.	5.09	5	0.87	81
The topics were covered at a depth that met my expectations.	4.72	5	0.95	81
The breadth of information provided on the topics met my expectations.	4.73	5	0.97	81
The topics of the module were presented in an effective order.	4.99	5	1.09	81
The videos provided clear information for learning the topic.	4.74	5	0.97	81

Note: scale of 1 (strongly disagree) to 6 (strongly agree).

The quiz was the only form of assessment used in the unit, and students' opinions of its value varied widely. The responses to the questions about the quiz were mixed, and students were not in a general agreement about its structure and its usefulness in their learning process. Table 4 shows that students were almost evenly split between positive and negative perspectives on most aspects of the quiz except for its length, which seemed to please most of them.

Table 4: Descriptive Statistics of Responses to Items Related to the Assessment Used in the Unit.

Item	*M*	*Mdn*	*SD*	*N*
This module provided the knowledge for me to be successful in the quiz.	3.58	4	1.44	77
The quiz was beneficial for learning the topic.	3.64	4	1.44	81
The quiz questions effectively assessed the content in the module.	3.52	3	1.44	81
The quiz was within reasonable length.	5.23	5	0.81	81
There was busywork in this module.	2.95	3	1.34	81

Note: scale of 1 (strongly disagree) to 6 (strongly agree).

Even though students' attitudes towards the unit quiz showed a decline of satisfaction when compared to the lecture videos, our results still show that the learners were overall satisfied with the unit and that they are likely to recommend the unit to colleagues and friends interested in MBSE. We asked students about their agreement with the sentences "Taking this module was a good use of my time" (N=80) and "This module was engaging to me" (N=77), respectively reporting averages of 4.26 and 4.29, medians of 4 and 5, and standard deviations of 1.21 and 1.19. Table 5 reports students' satisfaction with the overall module, videos, and the quiz in the unit, highlighting once again their negative perception of the quiz but an overall positive view of the unit in its entirety. Finally, when asked about their likelihood of recommending the unit to a friend interested in MBSE on a scale of 1 (highly unlikely) to 6 (highly likely), students reported an average of 4.40, a median of 5, and a standard deviation of 1.34 (N=77).

Table 5: Distribution of Responses for Learner Satisfaction Items.

Item	*M*	*Mdn*	*SD*	*N*
Overall module	3.75	4	0.71	*77*
Videos	4.23	4	0.71	*77*
Quiz	2.70	2	1.15	*77*

Note: scale of 1 (highly unsatisfied) to 5 (extremely satisfied).

Perceived Learning Outcomes (Understanding of MBSE)

The items in this category give us insights into how well students were able to learn and understand the topics of MBSE that were the focus of the unit. Students had to report in a scale of 1 (strongly disagree) to 6 (strongly agree) their feelings toward the affirmation "I acquired knowledge of the fundamentals of SE taking this module." For this question, we had an average of 4.57, a median of 5, and a standard deviation of 1.04. When asked about how effective students thought the unit was in helping them learn MBSE fundamentals on a scale of 1 (highly ineffective) to 5 (highly effective), 70% of them selected either "effective" or "highly effective". This question had an average of 3.84, a standard deviation of 0.87, and a median of 4. The results suggest that most of the students perceived a satisfactory level of learning and understanding of the MBSE topics introduced in the unit.

Feedback on Unit

Our thematic analysis coded the answers that students provided for the four mandatory open-ended questions in our course experience survey. The first question investigated what additional aspects students would have liked to see covered in the unit, and we identified three recurring themes in this question. First, students expressed a desire for more examples of the topics being applied in real-life situations. An example of this is in the student response "loved the real-world examples - more of these would be great!". Second, students frequently mentioned a curiosity for additional methodologies and tools that are used in industry when working with MBSE, evidenced by quotes such as "typical modeling methods for SE [should be covered]" or "it could be useful to include a bit more about the various tools used for SE such as Modeling tools (e.g., Enterprise Architect, Requirements management tools, etc.)." We also identified a set of sub-themes that include specific methodologies and tools that students demonstrated interest in, such as computer software, risk analysis, digital engineering, and economic management. And third, students expressed a desire for stronger connections between knowledge and applications. For example, one student expressed willingness to know about "best practices when applying SE fundamentals" with other students making similar statements.

The next question asked students to identify what they thought were the most challenging concepts in the unit, with three emerging themes within the answers. The first theme expresses difficulties that students had with how the quiz questions were written—they often mentioned that the questions and the content that was taught in the unit felt disconnected and that questions were ambiguous. One student highlighted that they "found that the quizzes were a bit too vague/subjective, [especially] those with multiple choices, and was hard to answer some questions properly even though I felt I understood the material." The second theme was students' difficulty in understanding some of the concepts that were taught in the unit, as they felt that they were overly abstract, unclear, or vague. As examples of such concepts, students often mentioned the taxonomy used and the differences between structure, purpose, function, and behavior. There are no prerequisite courses in systems for the system-of-systems course, which may be the source of these concerns. Finally, students also expressed difficulties in relating the concepts in the unit to real world scenarios, as is exemplified by the quote: "Applying the module to real systems and making sense how the system could be [classified]."

We also asked students what they appreciated in the learning unit. Students praised the usage of real-life examples to demonstrate the application of knowledge and facilitate learning in an engaging way: "The examples [provided] in the module videos are interesting and helpful to understand the concepts." Another recurring theme we identified was the structure of the topics in the unit: Many students were pleased with the way that the content was divided, and with how the topics were organized. They stated this helped them pace the content according to their availability: "I like how the module was broken down into parts to help with viewing." The third theme related to engagement, with students often mentioning that the instructor in the videos to be very enthusiastic and that the unit managed to engage them in the learning process. A student wrote that "The presentation format was engaging and the information was well structured."

The last question asked students how the unit of curriculum could be improved. Students indicated that there was a disconnection between the quizzes and the content that was being taught—the scope of the content in the quizzes did not match what they were being exposed to with the instructional materials, leading to a mismatch between what was being assessed and the expected learning outcomes. In the words of one student: “The quizzes seemed to have about 2 or 3 relevant questions to the material and the other 2 or 3 were completely left field or much more specific than the information provided.” The second aspect is still in reference to the quizzes: students felt like the wording and the format of the questions were confusing, leading them to misinterpret questions, even bordering on subjectivity for some of them. One student stated that “Some of the quizzes were confusing, particularly the way the multi-part questions were set up.” For some of the topics in the unit, students expressed that they had an insufficient number of examples to properly understand how those topics work in real life, even though they praised the examples that were in the unit. In this case, students wanted examples for specific topics, such as the student that wanted examples “using specific diagrams (real case using Vee diagram).” The last recurring theme is related to the instructional materials—students reported some issues with the editing of the videos (audio imbalances and visual distractions) and with the structure of some of the presentations used by the instructors, with a student highlighting that “The modules used slides with lots of information. More images on the slides could help keep the attention of the user.”

Discussion

In this section, we will make sense of students’ survey responses regarding their learning experience and perceived learning outcomes using the quantitative results and the emerging themes that we identified through thematic analysis.

Learning Experience

Overall, students had a positive impression of the module’s structure, including the scope of the content, the order of the content, and the videos that were used as the main instructional material. However, even considering this overall positive reception, students still had a few suggestions for improving this unit. For many of them, making the connection between theory and practice was a priority, and including even more examples would be a way of accomplishing this. In the words of a student, “[There was a] good use of case studies but I think adding extra for people to look at on their own time would be helpful.” Some of them also showed a strong desire to learn about additional methodologies and tools that are used in MBSE, which is a valid concern; but ultimately, we believe it would not be a good idea to add these topics to a unit that is focused on introducing students to the basic concepts of MBSE, instead reserving these ideas for later units.

Students’ preference toward real-life examples is aligned with how experiential learning theory defines significant learning. In experiential learning theory, providing students with opportunities to engage with authentic problems while promoting active reflection about their experiences with such problems is what leads to significant learning (Gadola & Chindamo 2019). The original unit design included case studies that were designed to satisfy these conditions, but in this case, the instructor chose to not adopt the case studies as a mandatory part of the unit and some students expressed desires to work through these authentic problems. However, we should look into other ways of incorporating learning experiences into the unit to ensure that instructors can provide authentic experiences without limiting their choices whenever they are adapting the unit. An option would be to strengthen the student-to-student community building efforts in our unit, favoring the type of learning endorsed by sociocultural theory (Hassan 2011).

Students' difficulties with the quizzes suggest that assessing the abstract concepts of SE and MBSE exclusively through multiple-choice questions is not enough: they often mentioned a desire for more real-life examples and authentic experiences. Other formats of formative and summative assessments may be necessary to ensure better alignment between the content and assessment of the unit. However, considering the format of our plug-and-play unit, these assessments need to be easy to grade—ensuring that the unit could work in varying contexts. Shani et al. (2020) describe an approach to assess students' modeling skills within the context of MBSE with real-time feedback in a massive open online course while also noting that students reported a high level of perceived contribution to their learning from the activities. This type of assessment provides an interesting alternative to be further explored by instructional designers in the MBSE space.

To ensure that we addressed the negative feedback, we traced the answers to the open-ended questions from students that showed some level of dissatisfaction with the unit. This individualized analysis allowed us to understand that most of these students were frustrated with the quiz, giving it a low satisfaction score while being critical of its writing and of the lack of feedback. One of the students was specifically critical about the level of the content being taught in the unit, stating that it was too basic for them. Perhaps this comment comes from a misalignment of expectations and reality, but we reaffirm that this unit was designed as an introduction to MBSE. Another student was critical of the teaching format, highlighting that, in its current form, the unit does not add anything that the student would not be able to understand if they were studying by themselves. For this student, the module should focus on showing the applications of MBSE, leaving the studying of theory to the learners. A third student complained about how basic the unit was for them, citing previous Aeronautics and Astronautics courses that had already taught them those same concepts, even though this class had no SE prerequisites. This same student also complained that the instructional materials were often convoluted. Essentially, it seems like the module was too basic for this particular student, and our team is currently preparing a tool that prospective learners can use to understand which of the seven modules will be appropriate for them considering their previous experiences, education, and job responsibilities. The last student we would like to discuss was critical of the case studies, particularly in how they did not effectively connect to the lectures in the student's view. This final student also discussed how they would have appreciated having more opportunities to get feedback from the instructor.

Perceived Learning Outcomes

Over 70% of students reported a 4 or a 5 on the scale of effectiveness of the unit in helping them learn about MBSE fundamentals (1 being "highly ineffective" and 5 being "highly effective"). When asked about their acquisition of knowledge of the fundamentals of SE, approximately 90% of the students reported a positive perceived outcome. These results suggest that the instructional unit attained the intended outcomes at least in some level in the students' perspectives. However, there was still a percentage of learners that reported lower values in the learning outcomes scale from taking this unit. When examining the results from open-ended questions in our thematic analysis, we found a recurring theme about students not fully understanding definitions in the unit. Common complaints were that the definitions occasionally felt too vague, overly abstract, or unclear, with connections to real applications being difficult to make. Some key quotes that demonstrate this point include “concepts in this section [introduction to systems engineering] tended to be more abstract than others”, “the most challenging concepts were when things were addressed at a high level but with multiple layers. Such as the system architecture diagrams”, and “[systems thinking] is a more abstract concept with no clear definition.”

Students’ difficulties to learn abstract SE concepts coincided with the challenges to teach and learn SE summarized by previous studies. In their work, Muller & Bonnema (2013) stated that the broad scope, multidisciplinary nature, and the generally ambiguous, ill-defined problems full of uncertainties and multiple correct solutions in SE all pose challenges for inexperienced learners. As a result, innovative approaches and scaffolding to teach SE- related concepts should be explored in the future. An immersive experiential roleplay project that is highly similar to real-life problems system engineers will encounter in their job, separating students into management teams and subject matter teams, to allow students to examine the problem from different perspectives (Muller & Bonnema 2013). Another pedagogy to teach systems thinking skills in undergraduate curriculum is to use a diagnostic activity, asking students to analyze the various systems using a disassembly of an electronic toaster and offering them real-life examples with hands-on opportunities to learn the concepts (Huang et al. 2015). The Systems Engineering Experience Accelerator uses an in immersive simulation to engage leaners in problem-solving that is intended to create an experiential, emotional state in the learner to accelerate their learning as compared to the pace of on-the-job training that is typical for systems engineering (Turner et al. 2017). Others have explored the use of virtual worlds for interactive learning of aerospace systems design (Okutsu et al. 2013). These comments validate previous scholarly research that indicates that systems thinking is primarily developed using experiential learning (Bawden et al. 1984; Davidz & Nightingale 2008; Ginzburg et al. 2019).

Conclusions

The results from our course experience survey suggest that the plug-and-play approach to implementing MBSE content into engineering curricula is a viable one. Students that took this initial offering of the module reported overall high levels of satisfaction with the unit and a high degree of perceived understanding of MBSE fundamentals. This suggests that our team was successful in designing a course that can be adapted into different settings, something that we accounted for when we decided to design the units with a variety of learners in mind.

However, these students were also critical of a few aspects of the unit that our team is now looking to change as a way to improve its quality. First, we concluded that the quizzes used in the unit need to go through revisions because students consistently reported issues in understanding the questions due to how they were worded, and issues with the content of the questions. Second, we identified that students had issues in understanding a few of the concepts in the unit—namely system architecture and system attributes such as structure, function, purpose, and behavior. Therefore, our instructional team is going to review the quiz questions for their writing and their compatibility with the core content in the unit, as well as review how those aforementioned systems engineering concepts are explained.

Our findings suggest a bright future for updating engineering courses and curricula with the plug-and-play instruction unit, but future studies still need to investigate the implementation of this unit in other engineering contexts to understand how broad the appeal of our unit is—including undergraduate programs. We also wish to investigate the other units by themselves, and in the larger context of this MBSE program. Finally, future studies will investigate students understanding of MBSE topics in our modules, and we can look into the correlation of students' main area of study and their understanding.

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