2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #51907

Work in Progress: Incorporating Systems Engineering Topics and Practices into Mechanical Engineering Capstone Design

Prof. Mark E Walter, University of California, Irvine

Dr. Walter received his PhD in Applied Mechanics from Caltech. He spent a year as a Fulbright Postdoctoral Fellow doing materials science research at the Universitaet Karlsruhe. He joined the Ohio State University in January of 1997 and spent 18 years there. Since 2015, Dr. Walter has been a Professor of Teaching in Mechanical and Aerospace Engineering at UC Irvine. He has taught a wide variety of mechanical engineering courses at UCI Irvine and is actively involved in student projects and capstone design. In 2024 he became the inaugural director of the School of Engineering's Office for Experiential Learning.

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Abstract

As products become more complex and more connected, following principles and practices of systems engineering is becoming a necessity. Issues related to designing the right product, managing the product lifecycle, meeting safety requirements, and saving money are just a few of the outcomes of good systems engineering. Curricular changes are needed to properly prepare our students for the workforce, to enable them to become innovators, and to give them tools to help transform the way that companies work. These changes include not just what and how we teach but also include hands-on, experiential aspects of learning.

This paper presents a practical approach to integrating systems engineering (SE) concepts into the existing UC Irvine mechanical engineering capstone design course without requiring additional credit hours or standalone courses. Nine key SE topics were incorporated into lectures and project deliverables for a two-quarter capstone sequence with unique open-ended projects that are prototyped and tested. Topics include things such as stakeholder needs and expectations, measures of effectiveness, requirements elicitation and analysis, functional analysis, and integration with continuous verification and validation. Also described is a SE technical elective which initially motivated the capstone course but is now being informed by the capstone student outcomes and other student projects.

Nearly 150 students responded to a 15-item survey that assessed conceptual understanding, perceived career value, and self-efficacy in applying SE practices. Results demonstrate strong student outcomes: 94% recognized connections between SE and traditional design processes, 84% rated SE as extremely or very valuable to their careers, and 92% understood the critical distinction between verification and validation. Notably, 74% of students indicated that more SE content is needed throughout the mechanical engineering curriculum, with many requesting earlier exposure to these concepts. This work in progress reports findings from a single cohort but demonstrates that SE concepts can be effectively embedded within existing capstone experiences, providing students with professional frameworks and systematic approaches to managing complexity.

Introduction and Motivation

The Growing Importance of Systems Engineering in Undergraduate Education

As modern engineering products become increasingly complex and interconnected, the ability to think systemically and manage the entire product lifecycle has become essential for engineering graduates. Today's engineers must not only possess deep technical knowledge in their discipline but also understand how to define stakeholder requirements, manage system architectures, verify and validate designs, and ensure seamless integration across subsystems. Collectively known as systems engineering (SE), these capabilities are no longer specialized skills reserved for senior practitioners but are foundational competencies expected of entry-level engineers across multiple industries.

SE, as defined by the International Council on Systems Engineering (INCOSE), "… is a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods." [1] It is therefore not difficult to recognize how adding SE to open-ended, highly complex "wicked problem" [2] capstone design courses satisfies all the required ABET Criteria 3: Student Outcomes [3], while also addressing industry desires. A comprehensive study examining industry supervisors' perceptions of recent mechanical engineering graduates revealed significant weaknesses in practical experience (59%), communication (52%), engineering codes and standards (47%), and project management (30%) [4], all elements of capstone design classes.

Tech-Clarity surveyed 201 companies globally and found that 69% say that their engineering departments will need to grow over the next five to ten years, and 80% indicate that hiring the right engineers will be either highly or very critical to their future success [5]. The top challenge in managing the engineering workforce is finding staff with the right skills, as there are gaps between what new engineering graduates know and what industry needs. The emphasis is on graduates who can work collaboratively in design teams and possess innovation skills that encompass practical understanding of how devices are designed, produced, and integrated into larger systems. It is also clear that companies strongly favor students with in-depth project experience emphasizing the need for practical, team-based engineering skills over purely theoretical knowledge [6]. These experiences should involve multiple engineering disciplines in simulated corporate environments with complete lifecycle stages, cross-functional collaboration skills, and familiarity with digitalization technologies including systems integration, digital twins, and PLM software. It is essential to have hands-on (*i.e.,* capstone) experiences that emphasize teaching and practicing critical thinking and problem-solving activities involving complex and connected systems [7, 8].

While certainly philosophically related, we make a distinction here between Systems Thinking (ST) [9] and SE. There are calls to engage in more ST in a college education and particularly in engineering design, but ST is generally just a mindset of more holistic critical thinking. On the other hand, SE is process oriented and even has ISO/IEC/IEEE 15288 - System Life Cycle Processes [10] to reinforce specific steps and tools. With that said, SE varies from one company/industry to another. Furthermore, the value of what SE concepts to include in an undergraduate engineering education needs to be considered in the context of all the other fundamental topics that must be covered.

The Current State of Systems Engineering Education

A search of the Worldwide Directory of Systems Engineering and Industrial Engineering Programs [11] reveals about 60 US institutions with undergraduate degree programs that specifically call out SE. This puts the number of schools with a separate undergraduate SE degree at about 15%. It is not possible to determine how many domain-specific degree programs have separate required/elective SE courses and minors, but one can assume that many do. Education in SE is often viewed as an extension of regular engineering courses, reflecting an industry perspective that engineers need foundational background in traditional disciplines plus real-world experience to be effective as systems engineers. One vexing problem with this situation is that the SE courses are likely to be restricted to a particular discipline, which is counter-productive when it comes to real-world SE. On the other hand, there are upwards of 100 institutions that offer MS, PhD, or Professional Masters degrees in SE, with many of those programs being interdisciplinary.

INCOSE is an extremely active society that emphasizes training and certification. The 1600+ page Systems Engineering Body of Knowledge (SEBoK) [12] is actively maintained and promoted, and in addition to multiple national and international conferences, committees on research, and workshops on various topics, INCOSE also has an SE Education division. In part due to INCOSE initiatives, over the years there have been numerous papers that discuss SE education at the university level [13, 14], though there is little distinction between undergraduate and graduate. This work tended to focus on presenting which SE topics should be taught (e.g., [15]).

On to more specific past work related to incorporating SE topics into design courses and capstone design in particular, there appears to have been a big push starting in roughly 2011 and continuing through approximately 2019 (*e.g.*, [16, 17, 18, 19, 20, 21]). More specifically, Looft and colleagues at Worcester Polytechnic Institute described an engineering science course developed specifically to teach essential SE topics to third-year and fourth-year students preparing for capstone projects, using an inverted classroom format where students applied SE principles directly to their own project development [18]. Norwich University reported on introducing SE concepts into a two-semester electrical and computer engineering capstone design course, balancing basic SE principles with hands-on engineering requirements to produce working prototypes [16]. At UT Austin, Chaput and another colleague, also formerly from the aerospace industry, developed a two semester design challenge that had a series of reviews and team adjustments that mimic what typically happens in industry [19]. Carnegie Mellon instructors demonstrated that systems thinking skills can be introduced as early as sophomore year in product design courses, with students showing measurable improvement in systems thinking abilities [21, 20, 22, 23]. A significant challenge in all this work is the variety of capstone formats and the different disciplines (*e.g.*, Mechanical, Electrical, Aerospace, *etc*.), let alone which of the many different SE fundamentals to emphasize. The variety of approaches is seen in the literature and, unlike for the traditional engineering design process, there are also no textbooks that can guide students (and faculty!) through SE concepts in a capstone design project. The current work differs from these in that it focuses more on providing readers with relevant SE topics that augment the traditional mechanical engineering design process. In addition, students' learning of and satisfaction with SE topics within their capstone course are quantified.

The Opportunity: Enhancing Existing Capstone Experiences

Review of typical engineering design curricula reveals that, at least at a basic level, generic design process instruction covers nine or more of the 14 technical processes defined in ISO/IEC/IEEE 15288, the international standard for system life cycle processes [10]. Most design courses address implementation (building/fabricating), verification (testing against specifications), and validation (ensuring the design meets user needs). However, crucial upstream processes, particularly Stakeholder Needs and Requirements Definition, Architecture Definition with RFLP (Requirements, Functional, Logical, Physical) decomposition, and rigorous requirements allocation, often receive insufficient emphasis. Similarly, integration as a distinct process separate from implementation, and formal verification and validation protocols, are typically underemphasized in traditional mechanical engineering design education.

Capstone design courses present an ideal vehicle for introducing and reinforcing SE concepts because they inherently involve open-ended, multidisciplinary projects with real stakeholders and complex requirements. Capstone projects benefit significantly from SE approaches when students must address implementation challenges, unintended consequences, and the interconnectedness of system components [24, 20]. Furthermore, because capstone courses already require substantial deliverables (*e.g.*, design reports, presentations, prototypes, and demonstrations) integrating SE topics does not necessarily add to student workload but rather provides better structure and more professionally relevant frameworks for organizing the work students are already doing.

Research Questions and Paper Organization

This paper examines how relevant SE concepts can be effectively integrated into undergraduate mechanical engineering education, specifically within the capstone design experience and without requiring new standalone courses. At the same time, this work informs what is relevant for a technical elective. We address the following research questions:

1. Can systems engineering concepts be effectively integrated into an existing undergraduate mechanical engineering capstone course without requiring additional credit hours or a standalone course?
2. What are students' self-reported conceptual understanding, perceived career value, self-efficacy, and curriculum attitudes following integration of SE topics into a capstone design experience?

The next section of the paper will present the topics currently covered in UC Irvine's mechanical engineering capstone design class and based on a survey tool, show student learning outcomes from this approach. A subsequent section will discuss the topics presented in a separate Model-Based Systems Engineering course that is offered as a technical elective to interested students. Discussion of the results of this effort and the research questions will then precede a brief conclusions and recommendations section.

Capstone SE Topics, Student Outcomes, an SE Tech Elective

UC Irvine's mechanical engineering capstone design requirement (EngrMAE151AB) is a 2-quarter course. The first two weeks of the first 10-week quarter have three 50-minute lectures per week and subsequent weeks have two 50-minute lectures per week. The lectures present the design process infused with SE language, topics, and examples. There are individual reading assignments in traditional engineering design. In the first two weeks three-person, randomly assigned teams are required to design, build, and test an 18" or taller 10-lb load-bearing-tower from only a single 12"x12" sheet of 1/8" thick plywood. This mini-project gets students thinking about the challenges of manufacturing and gives the instructors time to assign students to their top preferences for the open-ended 3–6-person team projects. These open-ended projects are curated from mentors from industry, faculty, staff, student project teams (with advisor input), and internal design challenges. All projects have complexity with interacting elements (usually moving parts and electronics) and require a prototype by the end of the 2nd quarter. From an MAE151A class materials fee, each team has \$100 per member to complete the prototype. Some project mentors may provide additional materials or funds.

Once on their open-ended project teams, students attend two 80-minute lab sections per week where instructors or a TA check-in with teams regarding various design deliverables and view/grade team PDP (Problem Definition Presentation), PDR (Preliminary Design Review), PoCP (Proof-of-Concept Presentation), RDP (Re-Definition Presentation), and CDR (Critical Design Review). In addition to presentations, teams submit design process documents (*e.g.*, milestones, requirements, standards, verification, testing, and risk analysis). Each project has a mentor who meets weekly with the team for 1 hour. The PoCP requires physical prototyping and is part of a design review at the end of the 1st quarter. There is also a design review with the final prototype at the end of the 2nd quarter. Design reports are submitted at the end of each quarter. There are two main individual assignments, one being requirements identification and functional decomposition for an improved commercially available product (*e.g.*, an improved vacuum cleaner) and the other being an individual component analysis for their team project.

The current 8-unit MAE151AB has been required since the Fall of 2023 and has Fall/Winter and Winter/Spring cohorts. Approximately 270 students take the course each year. Prior to the introduction of MAE151AB, the required capstone courses were as follows:

- a 4-unit one-quarter lecture course with the class also divided into 6-person teams that all undertook the same design challenge (*e.g.*, a golf-ball launcher, a bottle lift and transfer, a self-hitching trailer for an RC car race, *etc.*)
- 3-units of participation on a largely unsupervised competition team project (*e.g.*, FSAE racecars, AIAA Design Build Fly, *etc.*) or student-initiated group project with minimal faculty involvement

The lecture portion of the previous capstone requirement followed traditional engineering design texts like Saterbak and Wettergreen's "Introduction to Engineering Design" [25], Pitaparti's "Design Engineering Journey" [26], McCahan et al.'s "Designing Engineers: An Introductory Text" [27], and Ulrich and Eppinger's "Product Design and Development" [28]. In the spring of 2022 and 2023 a product lifecycle management (PLM) / model-based systems engineering (MBSE) / digital transformation (DX) technical elective course was piloted. The following SE topics from this developmental course were added to the new MAE151AB offering:

1. Stakeholder identification and business mission analysis
2. ConOps and use-case scenarios
3. Stakeholder needs and expectations
4. Measures of effectiveness
5. Requirements elicitation, analysis, and management
6. Functional analysis and architecture
7. Logical and physical architecture
8. Risk Analysis
9. Integration with continuous verification and validation

The lectures have a variety of SE examples for the aforementioned topics, largely in list and diagram form. The traditional SE V-Diagram [29] is a fundamental model of the overall SE process that presents the relationship between design decomposition and integration/verification, and the V-Diagram is shown throughout the course together with parallels to the traditional engineering design process. The project teams must submit documents and give presentations that apply the SE topics to their open-ended projects throughout both quarters of MAE151AB.

MAE151A has a greater emphasis on application of SE methodologies. MAE151B emphasizes integration with verification and validation of 2-3 prototypes and is therefore more hands-on and iterative. This is consistent with the notion that the majority of SE is carried out up front to "build the right system" [30] in less time and for less money. With this in mind, students in the Fall 2025 offering of MAE151A were surveyed to gauge their satisfaction with the SE topics and learning outcomes.

Assessment Methodology and Results

A 15-item survey to assess students' self-reported understanding of SE concepts, their perception of the value of these concepts, and their confidence in applying SE practices was distributed electronically at the end of finals week, with 143 students completing it (response rate >95% of enrolled students).

The survey instrument consisted of 14 Likert-scale items and one open-ended question. Likert items used a 5-point scale for agreement statements (Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree) and a 5-point scale for value/confidence statements (Not at all valuable/confident through Extremely valuable/confident). Questions were designed to assess:

1. **Conceptual Understanding**: Students' grasp of fundamental SE concepts (requirements vs. needs, verification vs. validation, decomposition, etc.)
2. **Perceived Value**: Students' assessment of how valuable SE concepts will be for their careers
3. **Self-Efficacy**: Students' confidence in their ability to perform SE tasks
4. **Curriculum Adequacy**: Students' opinions on the amount and quality of SE content in the mechanical engineering curriculum

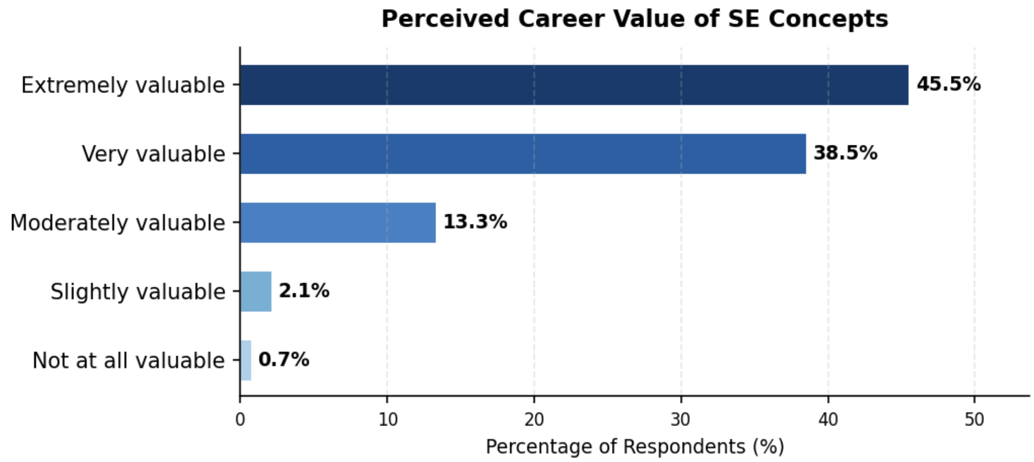
At the same time, the questions span a progression of learning depth consistent with Bloom's Taxonomy: *knowledge and recall* (can students reproduce the V-diagram and define key terms?), to *comprehension* (do students understand the distinction between verification and validation?), to *application* (are students confident performing requirements management tasks?), to *evaluation* (do students recognize the career value and broader relevance of SE practice?). It is also acknowledged that a single-quarter exposure to SE is more likely to produce awareness and comprehension than mastery-level application. With many questions focusing on individual knowledge checks to provide curriculum feedback, formal survey reliability (*e.g.*, Cronbach's alpha) was not assessed.

Recognition of SE in the Design Process

Students strongly recognized the connection between SE and the engineering design process. When asked "Do you recognize similarities between the engineering design process and systems engineering topics?" 94.4% of respondents selected "Yes" (135 students), with only 5.6% selecting "No" (8 students). This high affirmative response indicates that students successfully made the connection between generic design methodology and formal SE practices, suggesting that the integration approach was effective in making SE concepts feel appropriate for a capstone class.

Perceived Career Value of SE

Students demonstrated strong recognition of the career value of SE concepts. When asked "How valuable do you think the systems engineering concepts introduced in MAE151A are to your future career?" responses showed overwhelmingly positive sentiment:



Combining the top two categories, 84.0% of students viewed SE as extremely or very valuable to their careers. The mean response on the 5-point scale was 4.26 (SD = 0.79), significantly above the neutral midpoint of 3.0. This strong perceived value suggests that students understand the professional relevance of these concepts and should be motivated to develop these competencies.

Systems Thinking Benefit

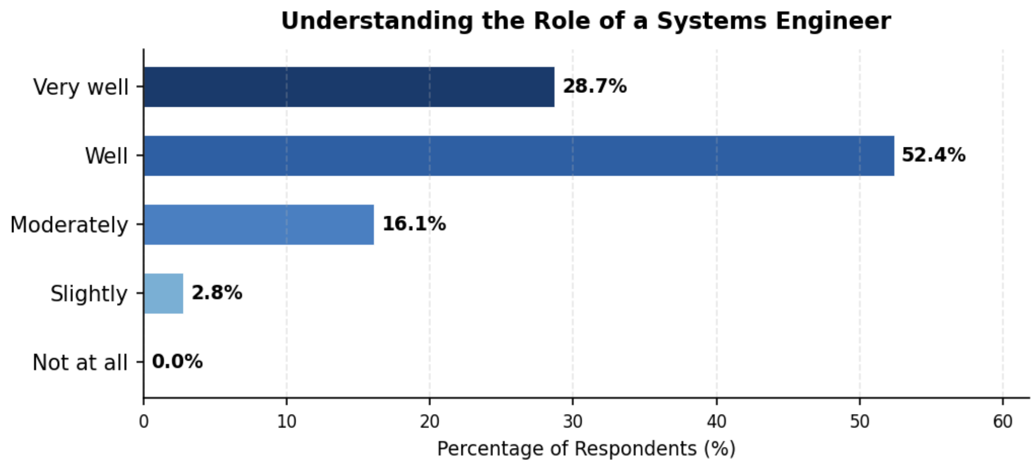
When asked "What is the benefit of taking a 'systems thinking' approach to mechanical design?" students provided thoughtful qualitative responses demonstrating understanding. Representative themes included:

- "Helps you understand how different components interact and affect each other"
- "Allows you to see the big picture while managing details"
- "Prevents problems by considering the whole system, not just individual parts"
- "Makes it easier to trace requirements and verify that everything works together"
- "Helps teams coordinate when different people are working on different subsystems"

These responses indicate that students grasp the core value proposition of systems thinking: holistic understanding, interface management, and integration of complex designs.

Role of Systems Engineers

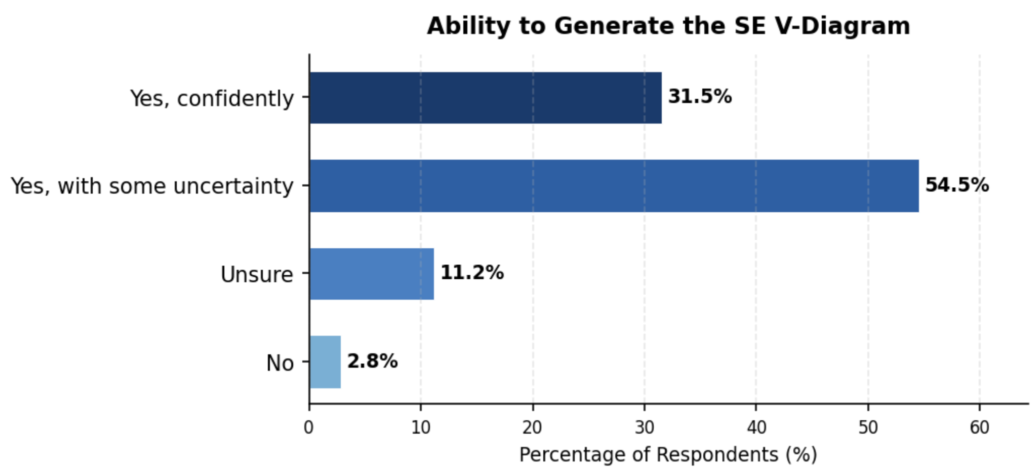
Students reported good understanding of systems engineers' roles in industry. When asked "Reflecting on what was taught in MAE151A, indicate how well you understand the role of a systems engineer in industry" responses showed:



The mean response was 4.07 (SD = 0.75), with 81.1% reporting they understand the role well or very well. This is particularly noteworthy given that most mechanical engineering students have limited prior exposure to SE as a distinct discipline.

Technical Knowledge: V-Diagram

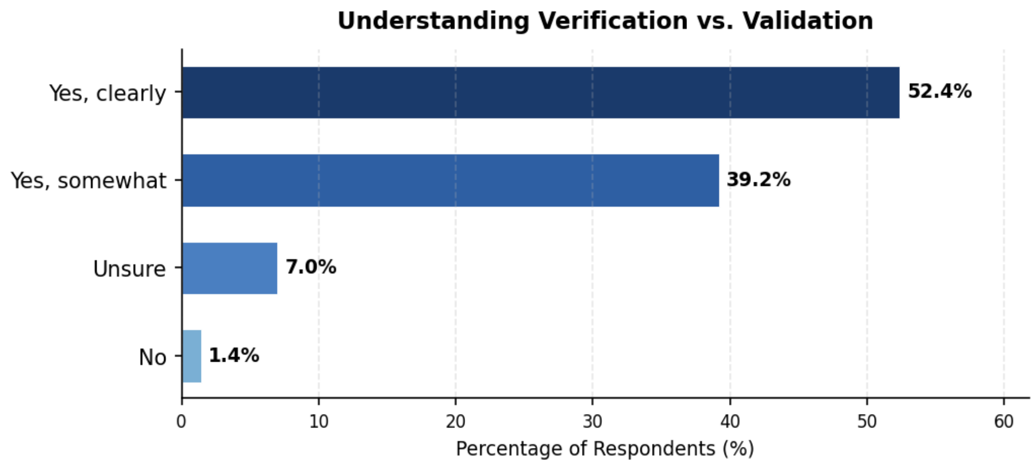
Students demonstrated solid understanding of the SE V-Diagram. When asked "Can you generate the systems engineering V-Diagram by labeling items on both sides of the V?" results showed:



With 86.0% reporting they can generate the V-Diagram at least with some uncertainty, this indicates successful knowledge transfer of this key SE model. The high percentage in "with some uncertainty" (rather than "confidently") suggests students would benefit from additional consideration of where they are, where they have been, and where they need to go in their open-ended design project iterations.

Verification vs. Validation

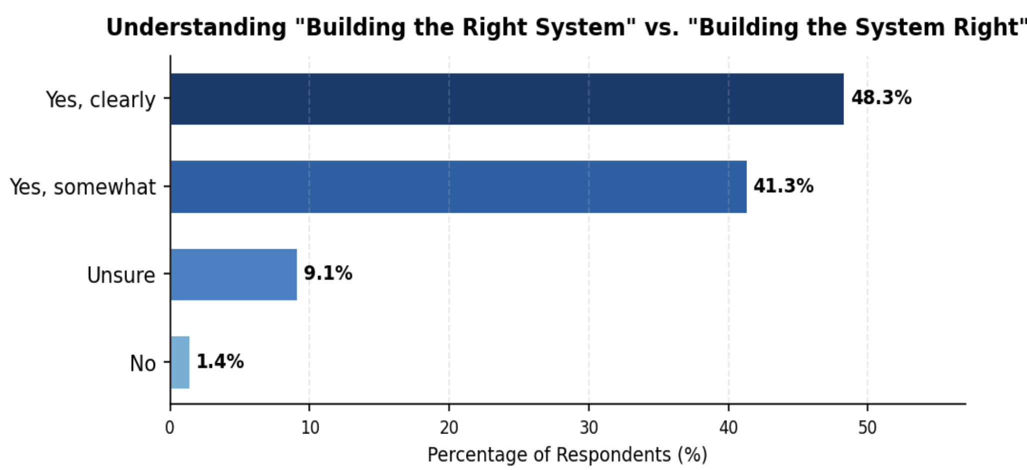
Understanding the distinction between verification and validation is fundamental to SE practice. When asked "Do you know the difference between Verification and Validation?" student responses demonstrated strong comprehension:



With 91.6% reporting at least some understanding of this critical distinction, students appear to have successfully internalized one of the most important conceptual differentiations in SE. The substantial percentage reporting "clear" understanding (52.4%) is particularly encouraging, but given the emphasis on this topic in class, could also be better.

Building the Right System vs. Building the System Right

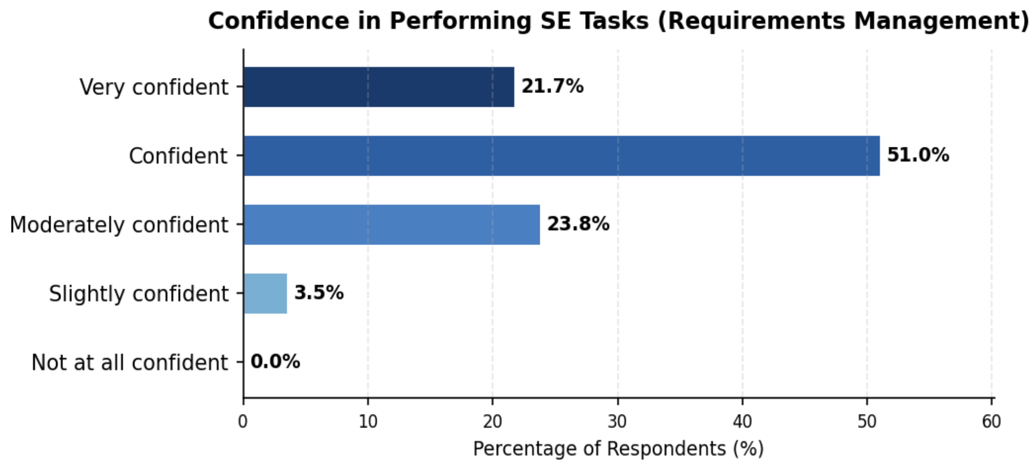
Closely related to verification and validation is the distinction between "building the right system" (validation) and "building the system right" (verification). When asked if they understood this difference:



With 89.6% reporting understanding, students demonstrated good grasp of this concept, which reinforces the verification/validation distinction from a slightly different perspective.

Confidence in Performing SE Tasks

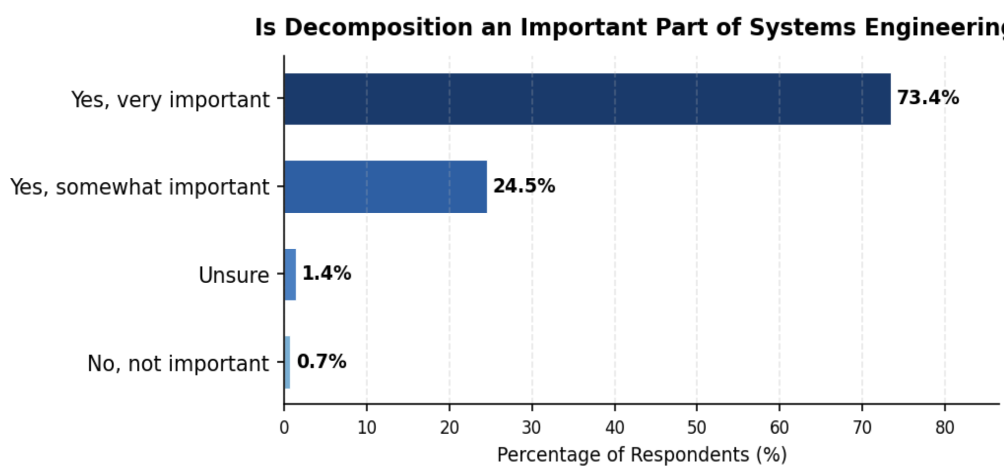
Students were asked to rate their confidence in performing three specific SE tasks related to requirements management. The three tasks were "Identify and document stakeholder requirements, translate stakeholder needs into technical requirements, manage requirement changes throughout a project" and the resulting confidence levels are:



The mean confidence was 3.91 (SD = 0.77), with 72.7% reporting they are confident or very confident. While this is positive, the lower percentage of "very confident" students (compared to agreement on career value) suggests that while students understand the importance of these tasks, they recognize they still need more practice to achieve mastery. This is perhaps appropriate for an introductory exposure to SE within a capstone course.

Importance of Decomposition

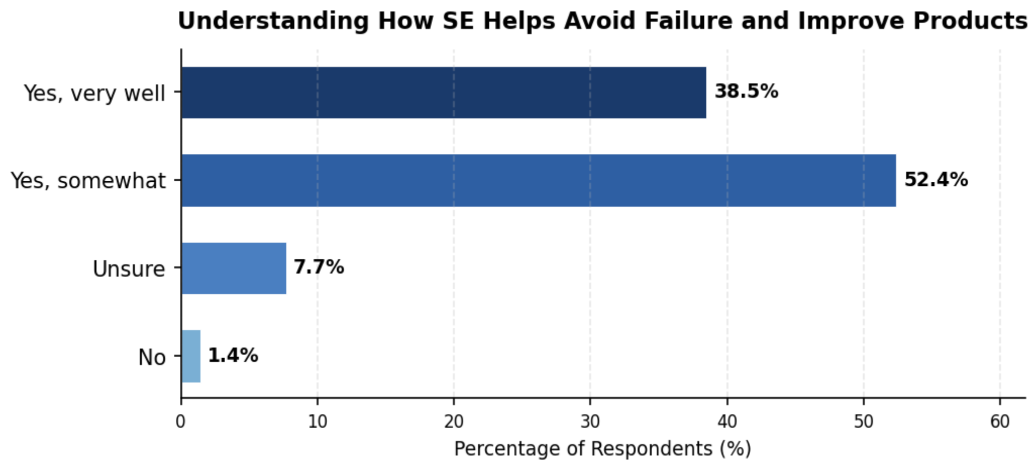
When asked "Is decomposition an important part of systems engineering?" student responses showed near-unanimous recognition:



With 97.9% recognizing decomposition as important, and 73.4% recognizing it as very important, students clearly understand this fundamental SE principle. Decomposition was heavily emphasized in the functional analysis portion of the course, and this result confirms successful learning of this concept.

SE for Product Success

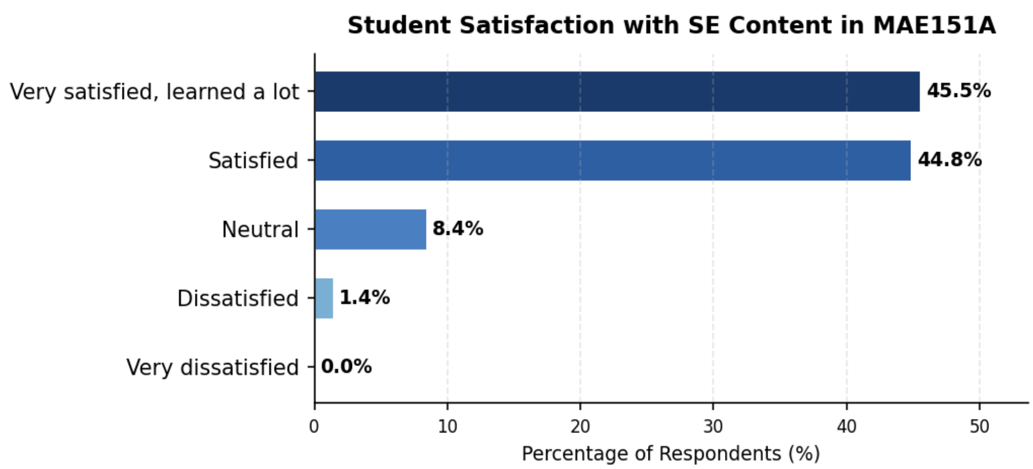
Students were asked whether they understand "how systems engineering can help avoid product failure and/or bring better products to life in a shorter period of time." Responses indicated strong understanding:



With 90.9% reporting understanding, students appear to look beyond the technical practices and grasp the business case and why organizations invest in these approaches. This understanding of the "why" behind SE may contribute to the strong perceived career value reported earlier.

Student Satisfaction with SE Content

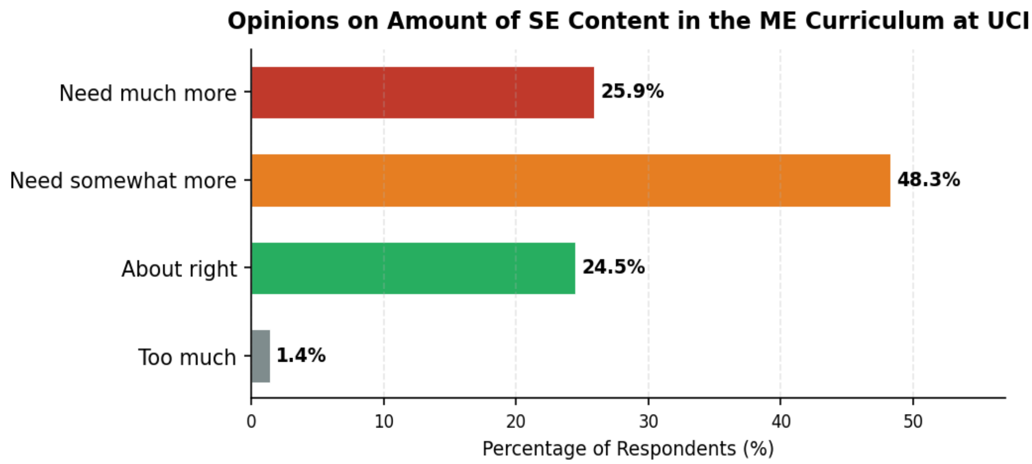
When asked "How do you feel about the systems engineering content in MAE151A?" student responses showed high satisfaction:



With 90.3% satisfied or very satisfied, and nearly half very satisfied, students responded positively to the integration of SE into their capstone experience. The low dissatisfaction rate (1.4%) suggests the material was well-received and appropriately integrated without overwhelming students.

Curriculum Adequacy Assessment

Students provided valuable feedback on the amount of SE content in the overall mechanical engineering curriculum at UC Irvine. When asked "How do you feel about the amount of SE content in the ME curriculum at UC Irvine?" responses revealed:



Notably, 74.2% of students indicated that more SE content is needed in the curriculum (combining "need much more" and "need somewhat more"), while only 24.5% felt the current amount is appropriate. This feedback provides strong student validation for expanding SE content beyond just MAE151A.

Recommended Additional Topics

Students were asked the open-ended question: "What systems engineering topics should be added to the ME degree at UC Irvine?" Responses varied, with several recurring themes:

Most frequently mentioned topics are summarized as follows:

- Model-Based Systems Engineering (MBSE) and digital tools (SysML, Cameo, etc.)
- More depth on requirements management and requirements engineering
- Project management and scheduling techniques (Gantt charts, critical path)
- Risk management and reliability engineering
- Systems integration and interface management
- Cost estimation and trade studies
- Standards and regulatory requirements

Other representative comments were:

- "More hands-on practice with requirements tools used in industry"
- "MBSE software: this seems to be what companies actually use"
- "I wish we had learned this earlier, maybe sophomore or junior year"
- "More examples from real industry projects would be helpful"
- "Integration across disciplines: how ME works with EE and software"
- "Cost and business considerations should be included"

Only about 15% of the 143 respondents indicated "N/A" or stated they felt the current coverage was sufficient. The predominant sentiment was that the SE content in MAE151A was valuable and should be expanded or introduced earlier in the curriculum.

The optional free-response question "If you have any other comments or insights related to systems engineering, please provide them here" yielded valuable qualitative insights. Approximately 40% of students (57 responses) provided substantive comments. Key themes included:

- Many students noted that SE concepts directly improved their capstone projects:
    - "The requirements process helped us avoid wasting time building the wrong thing"
    - "Breaking down functions made it much easier to divide work among team members"
    - "We caught several interface problems early because we documented them"
    - "Verification planning forced us to think ahead instead of just building and hoping"
- A recurring theme was that students wished they had learned SE earlier in their academic career:
    - "This should be taught in sophomore or junior year, not just senior year"
    - "Would have helped in other design courses and research projects"
    - "By senior year we already have bad habits from earlier projects"
- Students frequently mentioned professional relevance and connections to internships and career goals:
    - "My internship used a lot of these same concepts; I wish I had known them before"
    - "Job descriptions for systems engineering positions make much more sense now"
    - "Companies I interviewed with specifically asked about requirements and V&V"
- Some students noted challenges:
    - "It felt like a lot of new terminology at first"
    - "Hard to balance SE documentation with actually building things"
    - "More examples of how industry actually does this would help"
    - "Some of the concepts felt abstract until we applied them to our project"
- A few students who transferred from other universities or had friends at other schools noted:
    - "My friend at [another university] had a whole course on this as a junior"
    - "Other schools seem to have more SE content throughout their curriculum"

A Systems Engineering Technical Elective

As alluded to earlier, the teaching of a technical elective that taught topics in MBSE, PLM, and DX helped to motivate the blending of SE topics into capstone design. In the meantime, the reverse is now happening. The MAE151AB topics, student outcomes, application to open-ended, complex capstone projects, and student feedback is fueling new versions of the SE technical elective. There are also external drivers, which include direct conversations with software companies like Siemens, Dassault, and Ansys, and information on the Internet and in archival literature (*e.g.*, [31]) that promote MBSE and Digital Transformation. Developing entry-level SE practitioner expertise and using enterprise tools for creating and using digital twins is another driver for new course content at the undergraduate level.

The original version of the SE technical elective at UC Irvine came from Siemens curriculum content [32] that had hands-on tutorials and exercises that used their Xcelerator Software portfolio. The course is now migrating to PLM software for supporting a digital thread that connects requirements management with architecture models (SysML), CAD, and simulation. There are lectures that emphasize systems of systems with case studies for different aspects of the ISO/IEC/IEEE 15288 14 fundamental technical processes [10]: Business or Mission Analysis, Stakeholder Needs and Requirements Definition, System Requirements Definition, Architecture Definition, Design Definition, System Analysis, Implementation, Integration, Verification, Transition, Validation, Operation, Maintenance, and Disposal. Architecture modeling has been implemented in ARCADIA with the Capella tool [33]. Modeling with SysML V2 is a new topic that will be in upcoming offerings. There are then hands-on exercises with various software. Students are exposed to different software packages so that they do not get tunneled into learning software interfaces but rather are thinking about why and what. The capstone with SE content and SE technical elective have some overlaps. The technical elective is still evolving with the digital transformation of engineering. The capstone content is relatively fixed as increasing the content would adversely affect timelines, leaving project teams unable to build, test, *and* re-build.

Discussion

Effectiveness of the Integration Approach

The integration approach described in this paper aligns with Kolb's Experiential Learning Theory [34] which proposes that lasting learning occurs through a cycle of concrete experience, reflective observation, abstract conceptualization, and active experimentation. In MAE151A, SE concepts are introduced through lecture and examples (abstract conceptualization), are immediately applied to students' own open-ended team projects (active experimentation), and are revisited iteratively across design reviews and deliverables (concrete experience and reflection). This experiential structure likely contributes to the strong perceived value and conceptual understanding reported in the survey results. Repeated application and ensuring that all team members are involved in active application would help close the gap between stated comprehension and lack of confidence.

The survey results provide strong evidence that integrating SE concepts into an existing capstone design course can be effective without adding credit hours or separate required courses. The high perceived value (84% rating SE as extremely or very valuable to careers), strong conceptual understanding (92% understanding verification vs. validation), and high satisfaction (90% satisfied or very satisfied with SE content) all indicate successful curriculum integration. This approach addresses a key challenge facing engineering programs, namely how can we modernize our programs without adding new required courses to already-dense curricula [35, 36]. By embedding SE within existing design education, we demonstrate a scalable model that other institutions could adapt without major curriculum restructuring.

The natural alignment between design processes and the chosen SE topics proved crucial to successful integration. Students recognized similarities between SE and the engineering design process (94.4%), suggesting that framing SE concepts as structured approaches to familiar design activities helped with acceptance and understanding. This finding supports earlier work by Muci-Küchler et al. [21] showing that systems thinking can be effectively introduced in design courses when properly scaffolded.

Student Self-Efficacy and Confidence

While students demonstrated strong conceptual understanding and highly valued SE, their confidence in performing SE tasks (73% confident or very confident) was notably lower than their perceived value of SE (84% rating it extremely or very valuable). This gap between understanding importance and confidence in execution is common in engineering students who tend to rely on practice and application to be confident (self-aware) of their mastery.

This finding has important implications for curriculum design. Two quarters of exposure to SE within a capstone course successfully builds awareness and foundational knowledge, but additional reinforcement throughout the curriculum would likely improve student confidence and competence. The student feedback requesting more SE content (74% wanting more in the curriculum) earlier in their academic career aligns with this interpretation.

Verification, Validation, and Systems Thinking

Students showed particularly strong understanding of the verification vs. validation distinction (52% “clearly” + 39% “somewhat clear”) and the importance of decomposition (98% combined very and somewhat important). These concepts are fundamental to SE practice. The high comprehension rates suggest that explicit instruction on these topics, combined with application in real projects, creates lasting understanding.

The emphasis on "building the right system vs. building the system right" (90% understanding) appears to have successfully conveyed the dual nature of design integration, or in other words, confirming both that the system meets its requirements (verification) and that it addresses stakeholder needs (validation). This distinction is particularly valuable in capstone projects where students often focus exclusively on technical performance without documenting (validating) that they are solving the right problem.

Timing and Curriculum Placement

Student feedback revealed interesting insights about curriculum timing. While our integration into senior capstone was successful, many students (particularly in open-ended comments) wished they had been exposed to SE concepts earlier in their undergraduate education. This sentiment aligns with research by Bedillion *et al.* [22] showing that systems thinking can be effectively introduced as early as freshman or sophomore year.

The request for earlier introduction suggests a potential "design spine" approach where SE concepts are introduced progressively:

- **Freshman/Sophomore**: Basic systems thinking, stakeholder analysis, simple requirements
- **Junior Year**: Functional decomposition, architecture concepts, verification planning
- **Senior Capstone**: Full integration of SE processes with emphasis on professional practice

Once again, adding to an already packed curriculum and curriculum inertia are issues. For UC Irvine, the additional problem is that a) the freshman engineering sequence is not required and b) with nearly 40% transfer students in the mechanical engineering program, a large percentage of our students do not even join until junior year. Our results demonstrate that even late-stage integration (senior capstone only) provides significant value, offering a pragmatic approach for institutions unable to restructure their entire curriculum. One hope for more organic, earlier learning and practice of SE principles is that the capstone students who lead extra-curricular projects will transfer the knowledge to underclassmen on extra-curricular project teams.

Requirements Management as Foundation

The importance of requirements management emerged as a key theme in both quantitative results and qualitative feedback. Students recognized the value of clearly defined requirements (implied by high ratings for systems thinking benefits), and many open-ended comments specifically mentioned how requirements helped their projects stay focused and avoid rework. This finding supports industry perspectives that requirements engineering is one of the most critical SE competencies [4]. However, student confidence in requirements tasks (73% confident) suggests room for improvement. Additional practice with requirements elicitation, analysis, and management tools might strengthen this crucial capability.

Industry Relevance and Employability

The strong perceived career value of SE (84% rating it extremely or very valuable, mean 4.26/5.0) likely reflects students' increasing awareness of industry expectations. Many students noted in comments that internships, job interviews, or discussions with industry professionals highlighted the importance of SE competencies. This finding validates the motivation for integrating SE into undergraduate education, namely that industry increasingly expects entry-level engineers to understand SE principles [4]. Students appear to recognize this expectation and value educational experiences that prepare them for these professional demands.

The high ratings for understanding "how systems engineering can help avoid product failure and/or bring better products to life in a shorter period of time" (91% understanding) suggests students grasp not just the technical concepts but the business rationale for SE. This understanding of the "why" behind SE practices should help enhance retention and application of these concepts in their careers.

Limitations of the Study

Several limitations should be acknowledged when interpreting these results. The study relies on students' self-reported data, the instructor's knowledge of SE literature and on-line resources, and conversations with various industry practitioners. External validation is lacking. There are three additional limitations to consider: results are from a single institution, there is no control group to compare to, and, with results from only one cohort, the study lacks longitudinal data. Despite the limitations of this work in progress, the results are encouraging and point to this being an appropriate path for modernizing students' capstone experience and helping to better prepare them for engineering careers.

Conclusions and Recommendations

The integration of SE into capstone experiences offers multiple benefits beyond simply exposing students to important concepts. First, it provides students with professional vocabulary and frameworks that enable them to communicate effectively with industry practitioners who increasingly expect familiarity with SE terminology and processes. Second, it helps students develop systematic approaches to managing complexity in their projects, from initial stakeholder engagement through requirements definition, architecture development, and formal verification and validation. Third, it creates natural opportunities for students to use modern digital tools for product lifecycle management, requirements management, and system architecture development, activities they are likely to encounter in industry. Finally, and perhaps most importantly, it shifts students' mindset from component-level thinking to system-level thinking, better preparing them for the integrated and multidisciplinary nature of modern engineering practice.

While there are some limitations to the assessment of what UC Irvine has done with integrating SE topics into the mechanical engineering capstone courses, results are encouraging. Students themselves recognize the value of what they're learning. When nearly three-quarters of students say they want more SE content in their curriculum, and when nine out of ten students say SE concepts will be valuable in their careers, we have strong validation that we are addressing real student needs and preparing graduates for professional success. This student enthusiasm, combined with demonstrated learning outcomes, provides a solid foundation for continuing on this path.

The way forward for course content involves continued refinement of lecture materials, continuing to emphasize SE topics within the open-ended team projects (and associated documentation), and developing more authentic individual assignments for multiple stages of the V-Diagram. Assessment will continue with quarterly surveying of students and linking survey self-assessment to assignment grades. At the moment, there are no non-templated assignments that could be used for this linking. The current class assignments tell students to implement various SE activities into project presentations and reports. A future assignment would ask students to outline the process of developing a new product and these outlines will be graded relative to how much SE terminology and activity is present. Another approach would be to administer a survey about SE knowledge essentially prior to the start of the lecture content. This would constitute a pre- and post-conceptual assessment approach. Since this is a 2-quarter capstone design class, there are also opportunities at the end of the 2nd quarter to check for retained SE knowledge. Unfortunately analyzing design reports would not work, as there are SE deliverables in the report templates. The ultimate external validation of the effectiveness and importance of this SE curriculum would be to query employers of our students who enter SE-related jobs and fields. This is a significant undertaking that should be coupled with new efforts to survey both employers and alumni.

Finally, the lessons from this experience will continue to be integrated into the ongoing evolution of the SE technical elective course that is currently offered each year. This technical elective will continue to use enterprise-level software tools and emphasize system modeling (MBSE) that integrates the digital thread for modern product lifecycle management. The instructors of the SE integrated capstone and technical elective would be pleased to discuss this work with other institutions that have similar courses and/or have desires to include more SE content in their curriculum.

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