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Cultivating Innovators—Unveiling the Hidden Potential of "Innovation Through Making" in Engineering Education

Mitra Varun Anand, Worcester Polytechnic Institute

Mitra Anand serves as the Associate Director of Makerspace, and Innovation and Entrepreneurship, in addition to being an Adjunct Faculty of Mechanical Engineering at Worcester Polytechnic Institute.

Anand's research interests lie in combining hands-on Maker skills with an entrepreneurial mindset and value creation, aiming to develop practical solutions for real-world problems. He is enthusiastic about innovation in engineering education, design thinking, prototyping, program development, crafting interactive curricula, and bringing ideas to fruition.

With over 8 years of experience in Mechanical and Mechatronics Engineering, Anand possesses a solid background in Innovation and Entrepreneurship education, Additive Manufacturing, and Digital Fabrication technologies. His academic credentials include an M.S. in Mechatronics and Robotics Engineering from New York University and a B.E in Mechanical Engineering from Anna University.

Dr. Curtis Abel, Worcester Polytechnic Institute

Curtis Abel, PhD, MBA is the Executive Director of the Innovation and Entrepreneurship Center (I&E) at WPI. He is responsible for the I&E eco-system, Value Creation Initiative, Maker Space & Rapid Prototyping Lab, and Massachusetts Digital Games Institute. He joined WPI in 2015 as a Professor of Practice through the support of the Kern Family Foundation to create a vibrant entrepreneurial mindset culture on campus with both faculty & students. Prior to WPI, Curtis has 20+ years of experience in leadership positions at large corporations, including American Express, MasterCard, United Retail, and Bethlehem Steel. He's held full "Profit and Loss" responsibility for several multi-million-dollar businesses, generating double-digit annual growth for each. He also held positions in new business development, marketing, strategic alliances, and R&D implementing new technology into manufacturing facilities. Curtis holds a Ph.D., ME and BS from Carnegie Mellon University in Materials Science & Engineering and Chemical Engineering, respectively, and an MBA from Cornell University. He also held international Postdoctoral Fellowships at Cambridge University and Technische Universität Wien.

Prof. Ahmet Can Sabuncu, Worcester Polytechnic Institute

Dr. Sabuncu holds a Ph. D. in Aerospace Engineering from Old Dominion University. Dr. Sabuncu's professional interests spans from engineering education research, history of science and engineering, thermo-fluids engineering, and microfluidic technology.

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1. Introduction:

In the rapidly evolving landscape of engineering education, there is a pressing need to produce graduates equipped to navigate the complexities of a dynamic global environment. With technology advancing at an unprecedented pace, it is predicted that 85% of jobs that will exist in 2030 have not yet been invented [1]. This evolution demands a learning paradigm where individuals acquire skills "in-the-moment," leverage new technologies to adapt quickly, embrace failure, and develop timeless competencies for lifelong learning.

Despite these evolving educational demands, a considerable gap remains in adequately preparing students with the requisite skills for the uncertain future that lies ahead. Evidence suggests that proficiency in innovation, critical thinking, complex problem-solving, and effective communication positions students for success in sustainable engineering careers [2-4]. However, a prevalent culture of risk aversion among students stifles exploration into uncharted technological territories, thereby limiting their comprehensive academic growth [5].

In response to these challenges, this paper presents an evaluative study of an inventive, multi-disciplinary, project-based course known as "Innovation Through Making." This course is designed to blend the foundational Engineering Sciences (ES) curriculum with an Entrepreneurial Mindset, thereby endowing students with critical knowledge and competencies across a spectrum of engineering disciplines including mechanical, electrical, civil, chemical, and computer engineering. Such a holistic educational approach is intended to arm students with the analytical and problem-solving prowess essential for the engineers of tomorrow [7-8].

Building on a preceding work-in-progress study focused on results from the pilot course offering, this paper dives into two offerings of the course over a two-year period, focusing on competency gains assessed through Student Assessment of Learning Gains (SALG) instrument. The analysis hopes to uncover advancements in competencies that are pivotal within both engineering and entrepreneurial mindset realms.

This study reflects our findings from the initial two iterations of the course, engaging a diverse cohort of 54 students. It scrutinizes both the quantitative and qualitative impacts of the course on the development of engineering and entrepreneurial competencies.

1.1. Entrepreneurial Mindset

The concept of an entrepreneurial mindset in the context of engineering education is frequently misinterpreted as synonymous with starting a business [9-10]. Yet, it encompasses a broader spectrum of attributes, including critical thinking, problem-solving, creativity, resilience, and a proactive stance towards opportunity identification and value creation.

These attributes are instrumental in devising innovative solutions to societal challenges, thereby setting the stage for distinguished careers [11-14]. Our pedagogical strategy expands upon this foundation, emphasizing the practical application of these skills in diverse problem-solving scenarios.

1.2. Innovation Through Making Course

"Innovation Through Making" is an 8-week, multi-disciplinary, project-based introductory course at Worcester Polytechnic Institute. It combines hands-on engineering design with entrepreneurial mindset training, including design thinking and value creation. Concluding with a Prototype Showcase aligned with the United Nations Environment Programme (UNEP) sustainable development goals, the 3-credit hour course facilitates an active learning environment through a blend of lectures, workshops, and guest presentations. Assessment is multifaceted, encompassing design challenges, final projects, value proposition pitches, and a digital "Failure Journal" to promote a culture of resilience and continuous learning.

2. Research Methods

This paper extends the initial phase of our study [15] to measure the improvement and impact of the first two offerings of the "Innovation Through Making" course on students' development of engineering and entrepreneurial mindset competencies. This extended analysis includes the application of a modified Student Assessment of Learning Gain (SALG) instrument [16,17], specifically tailored to better align with the intended core competencies and traits of the course. The modifications were made to tailor the SALG instrument to resonate more closely with the course's core competencies, and the attitudinal shifts associated with the entrepreneurial mindset traits.

2.1. Competency and Mindset Focus

In the design process of the "Innovation Through Making" course, the competencies and mindset traits were carefully selected based on the authors' extensive experience and pedagogical objectives. This deliberative selection process aimed to equip students with a robust framework of skills and dispositions crucial for engineering innovation and problem-solving in a modern context.

The Engineering competencies under scrutiny encompass Engineering Design, Additive Manufacturing, and Subtractive Manufacturing skills. Entrepreneurship Mindset competencies include Problem Solving, Human-Centered Design (Design Thinking), and Value Creation skills.

- **Engineering Design:** Ability to demonstrate the use of systematic and structured process of identifying and resolving technical or design issues to meet specific requirements or goals in the context of prototyping to solve engineering problems.
- **Additive Manufacturing:** Demonstrating the ability to design for and use additive manufacturing tools in the context of prototyping using Fused Deposition Modeling 3D Printing technology.
- **Subtractive Manufacturing:** Demonstrating the ability to design for and utilize non-additive prototyping techniques using paper prototyping, laser cutting, molding, forming/casting and waterjet cutting.
- **Problem Solving:** Ability to apply analytical and critical thinking skills, as well as a thorough understanding of relevant technical knowledge, to generate practical and effective solutions to problems in engineering.

- **Human-Centered Design (Design Thinking):** Ability to apply human-centered approaches through iterative short sprints of the design thinking process (Empathy, Problem Definition, Ideation, Prototype, Test, Iterate) under ambiguous situations in the context of prototyping to solve real-world problems.
- **Value Creation:** Capacity to apply the “learn-fast” mindset to develop a value proposition pitch to a solution and communicate it in a compelling way through prototypes and storytelling.

2.1.1. Attitudinal Shifts and Entrepreneurial Mindset Traits:

Central to our pedagogical approach is the cultivation of an entrepreneurial mindset, characterized by key traits essential for innovation and adaptability in the engineering field:

- **Enthusiasm about Hands-on Engineering and Making:** Encourages active engagement and a deeper understanding of engineering concepts through practical application, fostering a passion for creating and building.
- **Interest in Interdisciplinary Applications:** Promotes the exploration of engineering principles across different fields, enhancing creativity and broadening problem-solving perspectives.
- **Confidence in Tackling Real-world Problems:** Builds the courage to tackle complex issues, nurturing a belief in one’s abilities to devise effective solutions.
- **Embracing and Learning from Failure:** Shifts the view of failure as an essential learning tool, developing perseverance and the ability to innovate from setbacks.

2.2. Data Collection and Analysis Instrument

1. **Competency Assessment Survey**: Continuing from the pilot phase, a pre- and post-course 6-point Likert-scale survey was administered to gauge students' initial and post-course competency levels. The scale ranged from 1 (not applicable) to 6 (highly competent). Likert Scale - 1=not applicable; 2=not at all competent; 3=just a little competent; 4=somewhat competent; 5=a lot competent; 6=highly competent

2. **Modified SALG Instrument:** Enhanced to align with our specific course competencies and mindset traits, this instrument provided a nuanced understanding of students' learning gains.

Statistical methods, including one-way ANOVA, paired t-tests, and Cohen’s d effect size evaluation, were applied to discern changes in competencies, emphasizing areas of notable improvement.

2.3. Integration of SALG

The SALG data were analyzed to provide additional layers of understanding, correlating students’ perceived learning gains with the competencies measured in the pre- and post-course assessments. Instead of focusing solely on student satisfaction with faculty performance, the SALG instrument aims to capture student-reported learning outcomes across several dimensions relevant to the course's learning objectives. The SALG instrument is designed to aggregate data on specific content areas identified by the instructor as crucial to the course's learning activities and objectives. This includes student understanding, skills development, cognition, attitudes, integration of learning, and motivation toward the subject.

For our study, the SALG instrument was employed both as a baseline and summative assessment tool. At the beginning of the course, the instrument provided invaluable baseline data on students' pre-existing knowledge and skills. Upon course completion, the summative SALG survey allowed for a direct comparison of pre- and post-course competencies, highlighting the areas of learning gains as well as aspects of the course that were most impactful for students.

3. Results:

3.1. Baseline and Summative Analysis from SALG Surveys

This section presents an integrated analysis of the Student Assessment of Learning Gains (SALG) survey data, focusing on baseline (pre-course) and summative (post-course) results for the "Innovation Through Making" course over two academic terms, D Term 2022 (D22) and D Term 2023 (D23), with a combined cohort size of 54 students.

The analysis encompasses students' understanding of key concepts, development of specific skills, shifts in attitudes towards engineering and making, and the integration of engineering and entrepreneurial concepts in problem-solving.

3.2. Participant Response Rate and Cohort Distribution

To ensure high participation and accurate measurement of the course's impact, instructors incorporated bonus points and allocated class time during the final session for students to complete the SALG survey alongside the university's standard course evaluation forms.

This approach resulted in high response rates, approximately 96% for the pre-course survey and 93% for the post-course survey in the D22 term, and 100% for the pre-course survey and approximately 96% for the post-course survey in the D23 term. The high response rates contribute significantly to the reliability of the survey results, offering a robust dataset for analysis.

3.3. Conceptual Understanding:

	D22 Pretest	D22 Posttest	D23 Pretest	D23 Posttest
Presently, I understand the following concepts.......				
Additive Manufacturing	2.8 (0.9)	4.0** (0.7)	2.9 (1.0)	4.1** (0.6)
Subtractive Manufacturing	2.6 (1.1)	3.8** (0.8)	2.7 (1.2)	3.7** (0.7)
Human-Centered Design (Design Thinking)	2.9 (0.8)	3.5** (0.6)	3.0 (0.9)	3.6** (0.5)
Value Creation Process	2.5 (1.0)	3.2** (0.7)	2.6 (0.9)	3.3** (0.8)
Engineering Design Process	3.1 (0.9)	4.1** (0.6)	3.2 (1.0)	4.2** (0.5)

Table I: Student Conceptual Understanding of Pre-Post Course Results

The course had a substantial impact on students' conceptual understanding across all targeted areas. Pre- and post-test comparisons indicate learning gains in both terms ($p < .01$), with Cohen's d effect sizes ranging from 0.82 to 1.45, indicating medium to large effect sizes. These improvements are especially notable in Additive Manufacturing and Engineering Design Process, suggesting that the course effectively deepened students' foundational knowledge in these key areas. The lower effect sizes in Human-Centered Design (Design Thinking) and Value Creation Process, while still significant, may point to the nuanced nature of these concepts that require more than just classroom instruction to fully grasp.

3.4. Skills Development:

	D22 Pretest	D22 Posttest	D23 Pretest	D23 Posttest
Presently, I understand the following concepts......				
Design for Additive Manufacturing processes	2.7 (1.0)	4.6** (0.8)	2.8 (1.1)	4.7** (0.7)
Utilize Subtractive Manufacturing techniques	2.5 (1.2)	4.5** (0.9)	2.6 (1.3)	4.6** (0.8)
Apply Human-Centered Design approaches	2.8 (0.9)	4.8** (0.7)	2.9 (1.0)	4.9** (0.6)
Develop Value Creation strategies	2.4 (1.1)	4.7** (0.8)	2.5 (1.0)	4.8** (0.7)
Generate innovative engineering solutions	2.9 (0.8)	4.9** (0.6)	3.0 (0.9)	5.0** (0.5)

Table II: Student Skills Development Pre-Post Course Results

**$p < .01$. Standard Deviations appear in parentheses below the means.

Students reported significant enhancements in their abilities to apply course-related skills in real-world contexts ($p < .01$). The Cohen's d effect sizes confirm the substantial impact of the course on students' ability to design for additive and subtractive manufacturing processes, apply human-centered design approaches, develop value creation strategies, and generate innovative engineering solutions. The high effect sizes in these skill areas show the practical, hands-on learning approach adopted by the course, which seems to have been particularly effective in bridging the gap between theoretical knowledge and real-world application.

3.5. Attitudinal Shifts

	D22 Pretest	D22 Posttest	D23 Pretest	D23 Posttest
Presently, I am.....				
Enthusiastic about hands-on engineering and making	3.4 (1.0)	4.5* (0.8)	3.5 (1.1)	4.6* (0.7)
Interested in interdisciplinary applications	3.3 (0.9)	4.6* (0.7)	3.4 (1.0)	4.7* (0.6)
Confident in tackling real-world problems	3.1 (1.2)	4.8** (0.8)	3.2 (1.3)	4.9** (0.7)
Open to embracing and learning from failure	3.0 (1.1)	4.7** (0.9)	3.1 (1.2)	4.8** (0.8)

Table III: Student Attitudes Towards 'Innovation Through Making'

*p < .05, **p < .01. Standard Deviations appear in parentheses below the means.

The SALG data revealed positive shifts in students' attitudes towards hands-on engineering, interdisciplinary applications, tackling real-world problems, and embracing failure as a learning opportunity. While enthusiasm and interest showed notable increases ($p < .05$), confidence in addressing real-world engineering problems and openness to learning from failure exhibited even stronger gains ($p < .01$), as depicted in Table 3. These attitudinal changes are indicative of the course's role in promoting a proactive and resilient engineering mindset among students.

3.6. Integration of Learning

	D22 Pretest	D22 Posttest	D23 Pretest	D23 Posttest
Presently, I am in the habit of.......				
Connecting key ideas with other knowledge	3.7 (0.9)	4.5** (0.7)	3.8 (1.0)	4.6** (0.6)
Applying what is learned in class to other situations	3.5 (0.8)	4.4** (0.6)	3.6 (0.9)	4.5** (0.5)

Systematic reasoning in problem-solving	3.4 (1.0)	4.3** (0.8)	3.5 (1.1)	4.4** (0.7)
Critical approach to analyzing data and arguments	3.3 (0.9)	4.2** (0.6)	3.4 (1.0)	4.3** (0.5)

Table IV: Pre-Post Course Results for Students' Integration of Learning

**p < .01. Standard Deviations appear in parentheses below the means.

Post-course reflections indicate that students are more adept at integrating engineering and entrepreneurial concepts into their approach to problem-solving ($p < .01$). This was evident in their increased adaptability, resilience in problem-solving, and application of design thinking in engineering projects (Table 4). Such integration is critical for the development of engineers capable of navigating the complexities of modern technological and business landscapes.

3.7. Impact of Course Components

	D22 Pretest	D22 Posttest	D23 Pretest	D23 Posttest
Presently, I can.......				
Apply engineering skills in contexts	3.2 (1.0)	4.8** (0.7)	3.3 (1.1)	4.9** (0.6)
Be adaptable and resilient in problem-solving	3.0 (1.1)	4.9** (0.8)	3.1 (1.2)	5.0** (0.7)
Integrate design thinking in projects	3.3 (0.9)	4.7** (0.6)	3.4 (1.0)	4.8** (0.5)

Table V: Integration of Engineering and Entrepreneurial Concepts

**p < .01. Standard Deviations appear in parentheses below the means.

Table 5 showcases the impact of a course on enhancing students' abilities in three critical areas: applying engineering skills in practical contexts, demonstrating adaptability and resilience in problem-solving, and integrating design thinking into projects. The results from both academic terms (D22 and D23) reveal marked improvements from the pre-course to the post-course assessments. The statistical significance ($p < .01$) of these results shows the effectiveness of the course components in fostering a robust engineering and entrepreneurial mindset among the students.

Through additional post-course survey questions, students identified workshops and team projects as significantly impactful in their learning journey, citing these components for providing experiential learning opportunities that deepened their understanding and application of course concepts.

4. Discussion:

The SALG survey data from the "Innovation Through Making" course provides compelling evidence of learning gains, attitudinal shifts, and enhanced integration of engineering and entrepreneurial concepts. The results affirm the course's effectiveness in not only advancing students' technical skills and conceptual understanding but also in cultivating a resilient, innovative mindset critical for future engineering endeavors.

4.1. Reflecting on Student Learning and Pedagogical Insights

The use of the SALG instrument provided invaluable insights into student learning and the effectiveness of course modifications aimed at enhancing conceptual understanding and skill development. Unlike traditional evaluations that primarily assess instructor effectiveness, the SALG instrument allowed for a nuanced understanding of how specific course components contributed to students' learning gains. This aligns with the broader educational goal of moving beyond mere content delivery to facilitating deep, meaningful learning experiences that prepare students for real-world challenges.

The pre- and post-course surveys facilitated by SALG offered a structured framework for assessing the acquisition of targeted competencies within the course. By enabling students to self-assess their learning gains, the instrument encouraged a reflective learning environment where students could critically evaluate their progress and identify areas for further development. This reflective practice is important in engineering education, where iterative design thinking and problem-solving are key.

4.2. Challenges and Opportunities in Assessment Practices

Challenges identified in using the SALG instrument relate to the statistical limitations of measuring learning gains, particularly concerning ceiling and regression effects. This reinforces the importance of designing assessment tools that are sensitive to the varied levels of student competence at the outset of the course. Tailoring the SALG survey to better align with the core competencies of our course represented an important step in this direction, ensuring that the instrument could more accurately measure the specific learning outcomes of interest.

4.3. Implications for Teaching and Learning in Engineering

The insights gained from the SALG instrument show the potential of targeted, competency-based assessments to inform pedagogical strategies and curricular development in engineering education. By focusing on specific learning outcomes, educators can more effectively tailor their teaching methods and course content to address the needs and aspirations of their students. This student-centered approach enhances the learning experience and contributes to the development of well-rounded future engineers.

Moreover, the data generated by the SALG surveys offer valuable evidence for continuous improvement efforts, providing a basis for making informed decisions about course design and instructional practices. This evidence-based approach to pedagogical development is essential for maintaining the relevance and quality of engineering education in an ever-evolving technological landscape.

5. Conclusion

In conclusion, the adoption of the SALG instrument in the "Innovation Through Making" course has provided important insights into the effectiveness of innovative teaching and learning strategies in engineering education. The course has not only facilitated gains in students' conceptual understanding and skill development but also promoted crucial attitudinal shifts towards a more innovative and entrepreneurial mindset. One of the most significant outcomes has been the marked increase in students' confidence to engage with real-world problems, addressing a common barrier to innovation due to prevalent risk-averse attitudes among students.

While challenges remain in optimizing assessment practices, the benefits of a more nuanced and student-centered approach to measuring learning gains are clear. As engineering educators continue to navigate the complexities of preparing students for a rapidly changing world, instruments like SALG represent valuable tools for enhancing educational outcomes and nurturing a culture of continuous improvement and innovation.

Looking ahead, the path forward involves expanding the study to include larger and more diverse cohorts to verify the findings' robustness. Future research could also explore longitudinal outcomes, assessing how the competencies gained in this course impact students' professional success and adaptability in the workforce. Additionally, further refinement and validation of the modified SALG instrument will improve its applicability and reliability for broader educational research.

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