Fostering Entrepreneurial Competencies through Sustainable Digital Fabrication and Active Methodologies: Independent Educational Interventions in Higher and Secondary Education in Panama

Carmen Castaño[1,5]; Maria De Los Ángeles Ortega Del Rosario[2,5,6*]; Ricardo Caballero[1]; Bolivar Bernal[1]; Juan Carlos Noguera[3]; Miguel Chen Austin[4,5,6]

[1]Research Group in Industrial Engineering (Giii), Faculty of Industrial Engineering, Universidad Tecnológica de Panamá, Panamá, *carmen.castano@utp.ac.pa, ricardo.caballero@utp.ac.pa, bolivar.bernal1@utp.ac.pa*

[2]Research Group in Design, Manufacturing and Materials (DM+M), School of Mechanical Engineering, Universidad Tecnológica de Panamá, Panama, *maria.ortega@utp.ac.pa,*

[3]Rochester Institute of Technology, USA, *jcnfaa@rit.edu*

[4]Centro de Investigación e Innovación Eléctrica, Mecánica y de la Industria (CINEMI), Universidad Tecnológica de Panamá, Panama, *miguel.chen@utp.ac.pa*

[5]Centro de Estudios Multidisciplinarios en Ciencia, Ingeniería,y Tecnologia (CEMCIT-AIP), Panama,

[6]Sistema Nacional de Investigación (SNI), Clayton Panama City, Panama,

Abstract*– This study compares two independent educational interventions in Panama designed to foster entrepreneurial competencies through sustainability challenges, active learning, and digital fabrication. The first, implemented with final-year industrial engineering students, involved designing sustainable products from recycled HDPE while integrating flipped and mirror classroom strategies, circular economy principles, and green entrepreneurship. The second engaged secondary school students from public institutions through Design Thinking, challenge-based learning, and CAD/CAM training to address local sustainability issues aligned with the UN Sustainable Development Goals. Both interventions employed pre- and post-assessment instruments to evaluate learning outcomes. In higher education, knowledge acquisition and key competencies such as collaboration, strategic thinking, and contextualization demonstrated large to medium effect sizes (Cohen's d = 0.90 and 0.74). In secondary education, all competencies, including teamwork, innovation, sustainability awareness, and technical skills, showed large effects (d > 0.8). Together, these findings highlight the effectiveness of integrating active methodologies and digital fabrication in promoting sustainability-oriented entrepreneurship across educational levels.

***Keywords*-- Entrepreneurial competencies, green entrepreneurship, sustainable digital fabrication, Design Thinking, active methodologies**

I. Introduction

Entrepreneurship education, particularly when integrated with sustainable innovation, has gained increasing attention across all educational levels. In both higher education and secondary schooling, equipping students with entrepreneurial competencies is now seen as essential for fostering innovation and addressing global sustainability challenges [1], [2], [3], [4].

Sustainable entrepreneurship is considered a critical competency in higher education, particularly for engineering programs, influencing students' entrepreneurial intentions and enhancing their ability to contribute to the Sustainable Development Goals (SDGs) through innovative practices [5].

The engineering curricula must adapt to the labor market. The Technology Innovation and Engineering Education (TIEE) model, for instance, highlights the need to restructure academic programs to foster entrepreneurship and socio-economic sustainability [6], [7], [8].

In secondary education, entrepreneurship acts as an early driver for developing competencies aligned with sustainability. For example, controlled trials with school-aged students have shown that sustainable entrepreneurship education (SEE) significantly enhances entrepreneurial intention and its key antecedents, attitude, subjective norm, and perceived behavioral control, based on the Theory of Planned Behavior, with consistent effects observed across genders [9]. These findings support the integration of entrepreneurship not as an extracurricular activity but as a transversal competency embedded within the school curriculum. Moreover, entrepreneurship education in this context bridges science, society, and market demands, fostering creative problem-solving and ethical awareness through active methodologies such as Design Thinking (DT) [10]. However, realizing its full potential requires enabling conditions, including infrastructure, teacher training, alignment with public policy, and contextual relevance, as implementation gaps still persist in many educational systems [11], [12], [13].

Thus, the intersection of entrepreneurship education and sustainable innovation is pivotal in shaping the future workforce. By embedding entrepreneurial principles into higher and secondary education, institutions can cultivate a generation of innovators equipped to tackle complex global challenges. Developing curricula that emphasize sustainable entrepreneurship is crucial to achieving these goals.

The integration of digital fabrication and active methodologies in education has gained significant attention in recent years [14], [15], [16], [17], [18]. However, there remains a notable lack of comparative studies that evaluate independent interventions across different educational levels. This gap is particularly concerning given the potential of digital fabrication to enhance learning experiences and outcomes.

Digital fabrication, which encompasses technologies such as 3D printing and CNC machining, offers unique opportunities for hands-on learning and creativity [16], [18], [19]. It enables students to design and produce tangible artifacts, fostering skills relevant to today's technology-driven world. [20]. Despite these advantages, research indicates that the pedagogical approaches to digital fabrication vary widely across educational levels [21].

Affective learning, which emphasizes emotional engagement in the learning process, is another critical aspect that has been explored in the context of digital education. Integrating digital fabrication with active methodologies can enhance both cognitive and affective learning outcomes [22]. However, the lack of comparative studies limits understanding across education levels and contexts.

Moreover, the challenges faced by educators in implementing digital fabrication technologies are often underreported. Research highlights that teachers encounter various impediments, including a lack of familiarity with digital tools and the need for professional development to integrate these technologies into their teaching practices effectively [23]. This suggests that without targeted support and training, the benefits of digital fabrication may not be fully realized in primary and secondary education.

While the promise of digital fabrication and active methodologies in education is evident, the absence of comparative studies across different educational levels limits the understanding of their effectiveness. Future research should address this gap, offering insights to guide best practices and enhance education at all levels.

The main goal of this work is to understand how different educational settings can help students build an entrepreneurial mindset while addressing real sustainability challenges. Specifically, the aim is to see whether combining active learning strategies with digital fabrication and circular economy principles could create meaningful changes in how students think, collaborate, and solve problems.

This research offers a fresh perspective on how entrepreneurship can be nurtured in university and high school environments without requiring a traditional business or startup framework. Instead, it shows that entrepreneurship starts with mindset: the ability to see opportunities, design sustainable solutions, and work creatively with limited resources.

By bringing together the use of virgin and recycled materials, such as recycled high-density polyethylene (HDPE), digital fabrication, and hands-on problem-solving, the study bridges technical education with green innovation principles, such as the circular economy, while addressing problems from a perspective aligned with the SDGs. It contributes to the growing conversation on how circular economy principles can move beyond industry and become a foundation for entrepreneurial learning. It shows that sustainability-driven entrepreneurship can start early, empowering students as changemakers for social and environmental good.

II. Theoretical Background

Entrepreneurial competencies encompass the skills, knowledge, and attitudes that enable effective entrepreneurial action. They are increasingly valued in both higher and secondary education, especially in engineering, for enhancing employability, driving innovation, and supporting economic growth. In the context of engineering higher education, entrepreneurial competencies encompass a range of skills, including problem-solving, creativity, critical thinking, and effective communication. As found by Tsalapatas et al. [24] there is a need for engineering education to modernize and align with labor market demands by integrating active learning approaches that promote these competencies. Students must not only acquire theoretical knowledge but also develop transversal skills that are crucial for navigating the complexities of the modern workforce.

Moreover, the implementation of Education 4.0 in engineering curricula has been shown to impact students' perceptions of their competencies significantly. Beke and Tick [25] surveyed engineering students and found that those in problem-based learning (PbL) showed stronger self-management and teamwork, key skills for entrepreneurial success and for integrating soft skills into technical education.

In secondary education, the development of entrepreneurial competencies is equally critical, marking them as essential competencies. Valero [26], for instance, highlights barriers in engineering education reform and calls for a competency-based approach that develops personal and professional skills early on. Integrating entrepreneurship into secondary curricula helps build an innovation- and problem-solving-oriented mindset essential for future success. They enhance employability, drive innovation, and strengthen economic adaptability. Their integration into curricula is crucial to prepare students for an increasingly complex and dynamic world.

Moreover, active learning methodologies are key to fostering entrepreneurial competencies in higher and secondary education. They promote engagement through experiential learning, collaboration, and problem-solving, skills essential for entrepreneurship. Research indicates that active learning strategies, such as PbL and DT, significantly enhance students' deep learning and retention of knowledge [27], [28]. In engineering education, integrating active learning not only cultivates entrepreneurial skills but also prepares students to tackle real-world challenges, thereby bridging the gap between theoretical knowledge and practical application [29].

Furthermore, the implementation of active learning in secondary education has shown to nurture early entrepreneurial mindsets, aligning with the SDGs [30], [31]. Besides, by engaging students in empathy-driven ideation and low-cost prototyping, these methodologies promote critical thinking and innovation, essential traits for future entrepreneurs [32], [33]. The positive outcomes of such educational interventions underscore the importance of incorporating active learning strategies across diverse educational settings, ultimately contributing to a more entrepreneurial and sustainable future [34], [35]. Recently, the intersection of digital fabrication, circular economy principles, and green entrepreneurship has gained significant attention in educational contexts. This convergence addresses pressing environmental challenges and fosters innovative thinking among students, preparing them for a sustainable future, as can be observed in the following lines.

Digital Fabrication and the Circular Economy

Digital fabrication refers to the use of digital technologies to create physical objects, enabling precise control over the manufacturing process. This approach aligns well with the principles of the circular economy, which emphasizes resource efficiency, waste reduction, and the sustainable use of materials [36]. Their intehration into curricula allows students to design products that are functional, circular, and sustainable.

HDPE Recycling in Educational Settings

HDPE, one of the most recycled plastics, is ideal for sustainability-focused educational projects. Students can collect, process, and repurpose HDPE waste into new products, gaining practical knowledge of material properties and recycling while fostering environmental responsibility [37]. For example, students might design and fabricate furniture or tools from recycled HDPE, thereby applying their engineering skills in a context that promotes sustainability. They learn technical aspects of fabrication and the principles of sustainability [38].

Green Entrepreneurship

Green entrepreneurship is gaining prominence in education, especially in higher education. Programs centered on this concept encourage students to develop business ideas that prioritize environmental sustainability. Studies show that self-efficacy and commitment to green practices strongly influence students' intentions to pursue sustainable ventures [39]. By incorporating green entrepreneurship into the curricula, educational institutions can nurture a new generation of entrepreneurs who are not only innovative but also environmentally conscious.

Examples in Education

Educational institutions increasingly recognize the value of integrating sustainability and entrepreneurship into their curricula. Universities, for example, are offering courses that combine digital fabrication with sustainability principles, enabling students to explore material lifecycles and environmental impact. Likewise, secondary schools can introduce sustainability and entrepreneurship through projects using recycled materials [40]. These initiatives enhance students' technical skills and promote a culture of environmental awareness and responsibility.

This integration of digital fabrication, circular economy principles, and green entrepreneurship in education presents a unique opportunity to prepare students for the challenges of the future. Students can gain valuable skills while contributing to a more sustainable world. As educational institutions evolve, the incorporation of these concepts will be crucial in fostering innovation and environmental stewardship among future generations.

Moreover, assessment of learning and competencies is a critical aspect of educational research. This assessment often employs various methodologies, including pre-/post-testing and self-assessment, to evaluate the effectiveness of educational interventions. A key statistical measure used in this context is Cohen's d, which quantifies the effect size of an intervention, providing insight into its practical significance.

Pre/Post Testing

Pre/post-testing are widely used methods to measure the impact of educational interventions. In this approach, students' knowledge or skills are assessed before (pre-test) and after (post-test) the intervention. For instance, a study at Nanyang Technological University found that virtual reality (VR) learning games improved engineering students' post-test scores by approximately 24.8%, demonstrating the effectiveness of VR in enhancing learning outcomes [41].

In secondary education, a pre-/post-test study on skills-based learning materials for English 9 reported a large effect size (Cohen's d = 1.16), indicating significant performance gains compared to a control group [42]. This highlights the effectiveness of pre-/post-testing in measuring learning outcomes from specific educational strategies.

Self-Assessment

Self-assessment is another valuable tool in evaluating learning and competencies. It encourages students to reflect on their understanding and skills, fostering metacognitive awareness. In a study exploring STEM self-efficacy among South African students, self-assessment data collected before and after a non-formal learning experience indicated significant increases in self-efficacy related to conceptual understanding [43]. This highlights the role of self-assessment in promoting student engagement and ownership of their learning process.

Cohen's d for Effect Size

Cohen's d is a widely recognized measure of effect size that quantifies the difference between two means in standard deviation units. It is particularly advantageous in educational research to assess the magnitude of an intervention's impact. For instance, in a study examining the use of Virtual Reality (VR) training for enhancing spatial visualization skills among engineering students, Cohen's d values ranged from small (0.10) to very large (2.40), indicating significant effects of task load and spatial characteristics on learning outcomes [44]. This suggests that VR training can substantially improve students' spatial skills, which are crucial in engineering disciplines.

However, it is essential to consider the limitations of Cohen's d. While it provides a standardized measure of effect size, it may not capture the full complexity of educational interventions. Researchers are encouraged to complement Cohen's d with other effect size statistics to provide a more comprehensive understanding of their findings [45].

In summary, the assessment of learning and competencies through pre-/post-testing and self-assessment, coupled with the application of Cohen's d for effect size, offers valuable insights into the effectiveness of educational interventions. These methodologies are relevant in engineering higher education and secondary education, where understanding the impact of teaching strategies is crucial for continuous improvement.

III. Methodology

This study follows a comparative case analysis approach, looking at two separate educational interventions designed independently but with a shared goal: to strengthen students' entrepreneurial thinking through sustainability challenges, digital fabrication, and active learning. Each case reflects the unique context and level of education, one in higher education and the other in secondary school, allowing us to observe how similar goals take shape differently across learning environments.

A. Case Study A: Higher Education

Module Overview

The Module for Production and Sustainability Systems (MPPS) was developed for final-year Industrial Engineering students at the Technological University of Panama. The goal was to give students hands-on experience designing sustainable products while applying what they had learned throughout their degree. Over one semester, students explored real-world sustainability challenges, worked in teams, and used recycled HDPE to prototype their own solutions [46].

To create an engaging learning environment, the module used two innovative teaching strategies: the flipped classroom and the mirror classroom. Instead of relying on lectures, students alternated between self-paced online study and collaborative group work. Through the mirror classroom setup, instructors could connect with students across different campuses in real time using video conferencing, helping make the experience more inclusive and flexible.

Participant Selection

Eight students were selected based on an open application and interview process in the first cohort while twelve students were selected in the second cohort. All participants were in their final semester and completed foundational courses like Project Management, Quality Control, and Manufacturing Processes. The group included students from three regional campuses to encourage diversity in perspectives and experiences.

Learning Activities and Project Work

Students started with online sessions and creative teamwork to understand sustainability and user-centered design. Working in small teams, they used Design Thinking to guide their process, from empathizing with users to defining problems, brainstorming ideas, and building early prototypes.

The highlight of the module was a one-week hands-on workshop, where students brought their ideas to life using recycled HDPE. They set up a small-scale production line with five stages: sorting and cleaning plastic waste, extruding filament, 3D printing, and final post-processing. The experience wasn't just technical; it required teamwork, critical thinking, and adapting designs to meet both sustainability goals and user needs.

Throughout the course, students received ongoing feedback from instructors in agile-style check-ins. At the end, they presented their prototypes and reflected on both the process and their personal growth as future engineers and problem-solvers.

Evaluation instruments

To determine the approach for assessing competencies, the systematic review of [47] served as a reference. Consequently, the questionnaires were administered using time triangulation, incorporating both pre- and post-questionnaires. This occurred before the commencement of the module. Two questionnaires were used: one aimed at gauging knowledge across the five courses of the module and another focused-on measuring competencies through self-assessment before the module began. The questionnaire, designed to assess prior knowledge, included three general questions for the students and twenty questions about essential understanding of the five subject areas within the module. The self-assessment questionnaire featured three general questions and thirty questions associated with the following competencies for sustainability: integrated problem-solving, interdisciplinary collaboration, normative expertise, self-awareness, strategic thinking, impact assessment/ forecasting, and critical thinking. A five-point Likert scale was employed.

Additionally, questionnaires were supplemented with interviews to enhance the study's validity. For this purpose, an open feedback session was conducted with the student participants after the module. During this session, five questions were posed to the students to gather their insights on the module. Furthermore, two post-questionnaires were administered following the module's completion.

B. Case Study B (Secondary Education):

Program description in public schools

The secondary education program aimed at fostering innovation and sustainability competencies among students and teachers in two public schools in Panama Oeste, Panama. The program introduced Design Thinking (DT) as a structured problem-solving methodology, aligned with project-based and challenge-based learning approaches, to help students identify local community issues, ideate sustainable solutions, and develop basic prototypes.

To strengthen the connection between creativity and practical skills, the program integrated elements of digital fabrication and Industry 4.0, including exposure to CAD design, CAM preparation, and additive manufacturing. The creation of an Ideas and Innovation Laboratory (L2I) in each school provided the physical and technological infrastructure to support ideation, hands-on experimentation, and prototyping activities.

Participants selection

Participants were recruited directly by teachers at each school, prioritizing students with high motivation and availability to complete the entire program, while trying to maintain gender equality. In the first school, students from 8th and 9th grade participated in a weekly 1.5-hour morning session before their regular classes. A slight majority of participants were girls, though gender balance was encouraged. For the second school, students from 10th and 11th grade attended 3-hour Saturday workshops to accommodate both morning and afternoon shifts. Selection criteria also considered gender balance and continuity throughout the program's duration. All participants signed informed consent forms, and teachers from both schools were trained to replicate and support the activities.

Learning Activities and Project Work

The program followed a progressive learning sequence that introduced sustainability, creativity, and technical skills before engaging students in Design Thinking projects:

- Foundational Modules: Students began with workshops on sustainability, the SDGs, local problem identification, innovation concepts, and basic scientific research. These sessions included brainstorming exercises, problem mapping, and exposure to circular economy concepts, linking school projects to real-world challenges.
- Design Thinking Implementation: Students applied the five DT stages (empathize, define, ideate, prototype, test) to identify community-relevant issues and develop potential solutions. Teachers facilitated empathy-based exercises, idea generation sessions, and group discussions to guide problem definition.
- Prototyping and Digital Skills: Students learned introductory CAD design and 3D printing (FFF and digital light processing technologies) to create low-cost prototypes of their solutions. Activities included collaborative model design, manual post-processing, and iterative improvements based on peer feedback.
- Project Presentation and Reflection: Each student team presented their final prototypes or conceptual solutions, reflecting on teamwork, creativity, sustainability awareness, and technical skills gained. This step also prepared participants to connect their school experience with broader community impact.

Evaluation instruments

A mixed-methods approach was applied, combining a structured pre-/post-student survey with qualitative classroom evidence to assess competency development and triangulate the results.

- Student Pre/Post Survey (Competencies Questionnaire). The survey instrument was designed to capture self-reported changes in transversal and technical competencies across four dimensions:

  A. Teamwork & Problem Solving: Items addressed collaboration comfort, decision-making, and problem identification or solution generation, with paired before/after prompts on 4-point Likert scales (Very comfortable to Uncomfortable; Very easy to Difficult).

  B. Creativity: Items assessed idea generation, iterative improvement based on feedback, and the ability to integrate knowledge from DT, CAD, and additive manufacturing (AM). Iteration frequency used categorical anchors (Always to Never).

  C. Items evaluated the ability to identify local problems linked to the SDGs, propose sustainable solutions, and the motivation to adopt sustainable behaviors.

  D. Technical Competencies (CAD/CAM/FFF). Items captured prior exposure to 3D design and post-intervention self-efficacy in CAD modeling, model preparation/slicing (CAM), and 3D printer operation (FFF).

Each item was presented in a "Before the project" and "After the project" format to enable paired measurement of change. Composite scores were calculated per dimension, and differences between pre- and post-results were summarized using Cohen's d to indicate practical significance. The proportion of students who improved by at least one response category (such as, from Regular to Comfortable/Secure) was also tracked for descriptive interpretation.

Qualitative evidence was collected during workshops and teacher-facilitated sessions, including focus group discussions, guided reflections, classroom artifacts (post-its, DT canvases), photographic records, and attendance logs. These materials provided contextual insight into engagement, teamwork dynamics, and transfer of skills from ideation to CAD/AM prototyping and were used to triangulate the quantitative findings.

Participation was voluntary and based on informed consent signed by parents or legal guardians. Confidentiality was ensured throughout, student identities were anonymized in all outputs, and data were stored securely under the supervision of the principal investigator following institutional ethics requirements.

IV. Results

A. *Case Study A*

Diagnostic Test

Two cohorts of students participated in the training program. For both groups, a diagnostic test was conducted before and after the program to measure changes in their understanding of the subject. Tables I and II show the difference in scores (post-test minus pre-test) for each cohort, allowing us to see whether there was an improvement in their level of knowledge after completing the program.

TABLE I
DIFFERENCE IN SCORES BEFORE AND AFTER

First Cohort	
Student	Difference
S1	3
S2	12
S3	1
S4	1
S5	-1
S6	0
S7	1
S8	7

TABLE II
DIFFERENCE IN SCORES BEFORE AND AFTER

Second Cohort	
Student	Difference
S1	2
S2	2
S3	-1
S4	1
S5	1
S6	3
S7	6
S8	0
S9	3
S10	1
S11	2
S12	1

In both cohorts, we observed an overall increase in participants' scores, indicating that the program had a clear impact on their level of knowledge. In the first cohort, 75% of the students (6 out of 8) achieved higher scores compared to their initial assessment, while in the second cohort, 83.3% (10 out of 12) improved their results from the pre-test. These findings suggest a consistent learning process, as in both groups a large majority of students showed measurable gains in knowledge, exceeding three-quarters of the participants in each case.

To measure the effect of the intervention, we used Cohen's *d* statistics. For the first cohort, the effect size was 0.90, which is considered large, meaning the program significantly enhanced students' knowledge. In the second cohort, the effect size was 0.74, which falls within the medium-to-high range, again indicating a substantial impact of the training on participants' learning outcomes.

Self-Assessment

To evaluate competency development before and after the program, we used an instrument that measured seven key competencies. Table III summarizes the number of students who improved their scores (+), maintained them (0), or showed a decrease (-) across each competency. The competencies assessed were integrated problem-solving (C1), interdisciplinary collaboration (C2), critical thinking (C3), normative expertise (C4), self-awareness (C5), strategic thinking (C6), impact assessment/ forecasting (C7)

TABLE III
EVALUATION OF COMPETENCIES

	First Cohort			Second Cohort		
Competency	-	0	+	-	0	+
C1	1	0	**6**	3	0	**9**
C2	**5**	1	1	3	1	**8**
C3	2	2	**3**	3	0	**9**
C4	**5**	0	2	3	0	**9**
C5	**5**	0	2	3	1	**8**
C6	1	2	**4**	3	0	**9**
C7	1	1	**5**	1	3	**8**

For the second cohort, about two-thirds of the students showed consistent improvement in their competencies after completing the program. This progress can largely be credited to the lessons learned from the first group. We brought the initial cohort together for a feedback session to hear about their experience, which gave us valuable insights to adjust the way the content was delivered and how knowledge was managed. These changes helped create a smoother, more balanced learning experience for the second cohort. The facilitators incorporated this feedback directly into the updated program content.

To measure competency development, Cohen's d statistic was used to determine the effect of the intervention. Fig. 1 summarizes the values obtained for each cohort. Overall, the first cohort showed greater variability in effect sizes, indicating that the intervention's impact on competency development varied significantly across evaluated competencies. In contrast, the second cohort displayed less variation in Cohen's d values across the assessed competencies, suggesting a more consistent effect.

Specifically, in the first cohort, three competencies: interdisciplinary collaboration, strategic thinking, and impact assessment/ forecasting, achieved values above 0.8, which indicates a strong effect of the intervention and significant improvement among participants. The remaining competencies scored below 0.5, suggesting smaller gains with a lower overall impact.

At the end of the first cohort, a feedback session was held, which allowed the team to implement adjustments and improvements to the program. These refinements led to different outcomes in the second cohort. For this new group, the effect was moderately high for competencies such as interdisciplinary collaboration, critical thinking, normative expertise, self-awareness, and strategic thinking. On the other hand, integrated problem-solving and impact assessment/ forecasting, registered lower effect sizes according to Cohen's d.

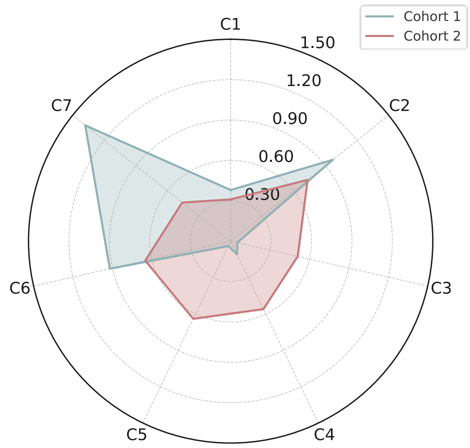

Fig. 1: Cohen's Value by Assessed Competency.

B. Case Study B

To evaluate the effectiveness of the intervention, a pre-experimental pretest-posttest design was applied, targeting secondary school students across various grade levels (7th to 12th). The educational intervention combined Design Thinking, project-based learning, and challenge-based learning methodologies, supported by CAD/CAM/FFF tools. The goal was to strengthen competencies in three core areas: innovation, sustainability, and technical skills. Participation was voluntary and supported by informed consent from parents or guardians.

A structured questionnaire was administered before and after the intervention. It consisted of 12 items distributed across four thematic sections: (1) teamwork and problem solving, (2) innovation and creativity, (3) sustainability and systems thinking, and (4) technical competencies related to CAD/CAM and additive manufacturing, as depicted in Fig. 2. Responses were collected using a 4-point Likert scale, and descriptive and inferential statistics were employed to analyze the data.

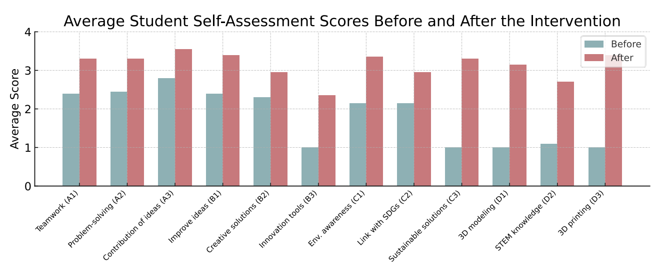

Fig. 2: Average student scores before and after the intervention for Case B.

Fig. 2 depicts the average scores obtained before and after intervention for each question. Questions I1–I6 addressed teamwork and innovation skills, including problem-solving, contribution and improvement of ideas, creative solution proposal, and the use of innovation tools. Items S1–S3 focused on sustainability awareness and systemic thinking, such as recognizing environmental challenges, understanding the SDGs, and proposing sustainable solutions. Finally, questions T4–T6 targeted technical competencies related to CAD, STEM knowledge, and 3D printing. Notable increases in self-assessed scores were observed across most items, indicating a positive shift in students' perceived competencies following the project-based and Design Thinking intervention.

The analysis revealed that the project had a significant impact on students, particularly in competencies related to innovation, problem-solving, and teamwork. The Wilcoxon signed-rank tests showed improvements in several survey items that were statistically significant. However, due to the number of participants, Cohen's d was used for further analysis. Moreover, the effect size analysis (Cohen's d) indicated substantial gains in most areas of interest, demonstrating the effectiveness of the intervention, as shown in Fig. 3.

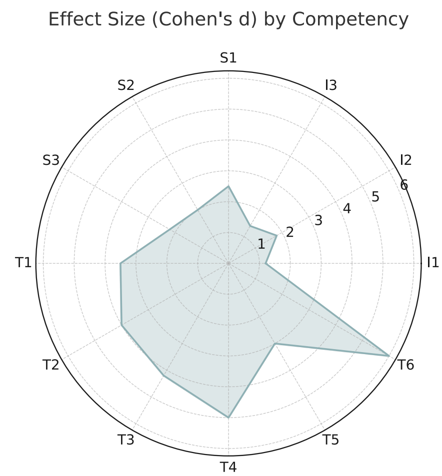

Fig. 3: Cohen's d Value by Assessed Competency for Case B.

The quantitative analysis revealed high effect sizes across all competency areas, with robust gains in technical competencies such as T6 (Cohen's d > 6). Survey items with large or very large effect sizes (Cohen's d ≥ 0.8) were considered strong indicators of success in intervention. The most positively impacted areas were:

- Innovation: Substantial progress was observed in competencies related to creative thinking, ideation, and the application of innovation methodologies.
- Technical Competencies: Significant gains were seen in students' ability to apply technical knowledge in practice, particularly in areas such as CAD/CAM and 3D printing. These results indicate students' growing confidence in translating engineering concepts into tangible outputs.

These findings suggest that the intervention effectively enhanced students' capacity to develop innovative solutions to complex problems using technical tools.

Although all items demonstrated large effect sizes (Cohen's d > 0.8), suggesting that the intervention led to substantial improvements across all competency areas, some survey items exhibited comparatively smaller gains within this high-impact range.

- Sustainability: While effect sizes in this area remained high, certain items showed slightly lower scores relative to others. This could be attributed to the inherent complexity of sustainability-related competencies, which often demand greater theoretical knowledge, systems thinking, and maturity, skills typically developed in later stages of engineering education. These findings suggest that, although progress was substantial, future interventions could include additional scaffolding or context-based applications to enhance learning in this domain further.
- Technical Competencies: Some items, especially those related to original 3D design creation, displayed relatively modest improvements compared to other technical skills. This was likely due to the initial complexity of tools such as Autodesk Fusion. The subsequent transition to Tinkercad facilitated engagement and usability. Nevertheless, given that these skills are usually introduced in later academic years, the observed high effect sizes are especially notable and demonstrate the efficacy of early exposure through simplified tools.

Although some prior interpretations suggested limited impact on sustainability or CAD-related items, the observed effect sizes (all above 0.8) indicate that the intervention produced substantial improvements across the board. These findings suggest that students perceived significant gains even in areas previously considered more challenging, likely due to the scaffolding provided during the intervention.

Both interventions demonstrated similar outcomes in collaboration, creativity, technical proficiency, and systems thinking, making them valuable for drawing comparable results across two different educational levels, as depicted in Fig. 4.

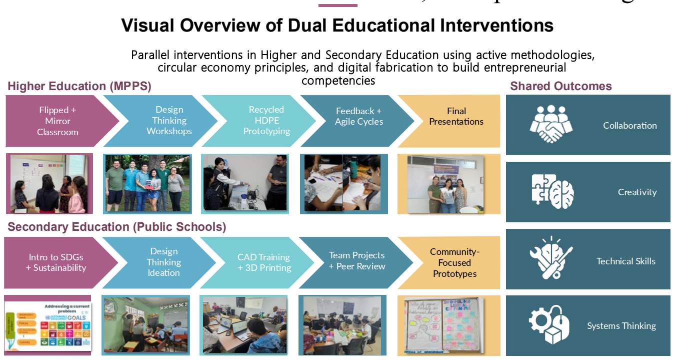

Fig. 4. Visual Overview of Dual Educational Interventions.

IV. Conclusions

This study looked at two distinct educational settings, a university course for engineering students and a program in public secondary schools and explored how both could nurture entrepreneurial thinking through sustainability challenges, hands-on learning, and digital fabrication. Although designed independently and tailored to different age groups, both interventions produced clear and consistent impacts on students' knowledge and competencies.

In the higher education case (MPPS), the final-year industrial engineering students showed remarkable growth. Knowledge gains were substantial, with effect sizes reaching large and medium-to-large levels (Cohen's $d = 0.90$ and 0.74). Competencies like working across disciplines, strategic thinking, and envisioning future solutions improved significantly ($d > 0.8$). The combination of flipped and mirror classroom strategies with practical digital fabrication allowed students to move beyond theory. By designing and prototyping sustainable products with recycled HDPE, they connected engineering skills with circular economy principles and green entrepreneurship in a very tangible way. However, variations in competency gains suggest that while the intervention was effective, certain areas, such as self-awareness and normative competence, may require more explicit integration of ethical and sustainability-focused reflection within the technical workflow.

The secondary school program told a similar story in a different context. The findings indicate that the intervention had a consistently positive effect on students' self-perceived competencies, with all assessed items demonstrating large effect sizes (Cohen's $d > 0.8$). Robust gains were observed in areas related to creativity, innovation, and technical competencies such as CAD/CAM and 3D printing. These results suggest that the project-based and Design Thinking–oriented approach effectively fostered meaningful learning and skill development, even in a pre-university context. The intervention not only enhanced students' confidence in addressing real-world challenges but also encouraged interdisciplinary collaboration and critical reflection. Notably, competencies related to sustainability, although improved, showed comparatively smaller gains, possibly due to the abstract nature of systems thinking and environmental complexity at younger educational levels.

Taken together, these results show that entrepreneurship rooted in sustainability can be developed at multiple levels of education when students are given real challenges, hands-on tools, and space to experiment. Both cases demonstrate how active methodologies and digital fabrication can empower learners to see themselves as changemakers capable of designing solutions that make a difference in their communities and beyond.

Despite these promising outcomes, several opportunities for improvement were identified. Methodological reinforcement is recommended, mainly through hands-on workshops in areas such as sustainability, where students may require additional support to grasp and apply complex systems-thinking concepts fully. To address the specific challenge of teaching systemic and environmental competencies, future interventions could integrate more dedicated scaffolding, such as using concrete, local case studies of environmental impact, incorporating simple system mapping exercises, or facilitating guided discussions that directly connect students' projects to broader ecological and social systems.

For other institutions, the core model shows promise for replication, though its scalability depends on key enabling factors such as access to digital fabrication tools, teacher training in active methodologies, and curricular flexibility. Specifically, a clear roadmap for educator preparation and detailed accounting of the necessary physical and digital resources would be required for effective implementation in new contexts. In resource-limited settings, scalability could be pursued through mobile labs or shared community.

It is also crucial to consider the limitations of this study. For instance, the small sample sizes in higher education (n=8 and n=12) limit the statistical power and generalizability of these findings. The findings rely partly on self-assessed competencies, which could be influenced by self-reporting bias. Future research would benefit from triangulating these self-assessments with direct observation or analysis of project outputs. The specific context and sample size also suggest that broader generalizations should be made cautiously.

Continuous monitoring of student progress is also essential to allow for timely adjustments during the learning process. Embedding formative assessments would further enhance the development of competencies by providing students with regular feedback. Finally, reinforcing the link between theoretical knowledge and practical applications, through authentic, real-world problem-solving, can help ensure that students internalize and apply the competencies gained. These combined strategies support the continued refinement and scalability of this educational model, with potential for broader implementation in early engineering education across diverse educational settings.

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