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Engineering education on sustainability and the reuse of electronic components: a novel, hands-on educational method that emphasizes student creativity

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Introduction: Engineering students are experientially introduced to the concepts of sustainability, recycling and the cyclic economy through a novel educational method proposed, implemented and evaluated within an Electrical and Electronics Engineering undergraduate curriculum.
Methods: Students work in groups in a hands-on laboratory to disassemble damaged electrical/electronic devices, reclaim electronic components, recycle the damaged ones and reuse the functional ones, either to repair similar devices or to design and construct new devices. Students get a lived experience of a collaborative sustainability project that aims at developing their cognitive, social/emotional and metacognitive skills, creativity being a central one among them. An educational intervention of two phases is implemented and evaluated via multiple tools.
Results: Results document student gains of varying degrees across all three domains of learning; an increase in creativity, in particular, is measured between the two phases.
Discussion: The formation of a community of learning is another important outcome that opens directions for future research.

KEYWORDS
sustainability, recycling, cyclic economy, engineering education, e-waste, hands-on lab, creativity measurement, community of learning

1 Introduction

1.1 Motivation

Education in general and engineering education in particular face many challenges in the era of the Knowledge Society, the double aim of developing both the "vertical" (within subject or discipline) skills and the "horizontal" (across subjects or disciplines) skills of the students being a considerable one among them (Lloyd and Payne, 2002). Young engineers are expected to combine mastery of their subject with the horizontal or "soft" skills necessary in order to succeed in the current Knowledge-based Economy (Organisation for Economic Co-operation and Development, 1996). The so-called "21st century skills" rank high among them: communication, collaboration, critical thinking and creativity, along with the various literacies (ICT, media, etc.) are sought and valued equally to good knowledge of the respective field and further specialization in it (Ananiadou and Claro, 2009; Binkley et al., 2012; Geisinger, 2016).

From another aspect, Quality Education is the 4th of the 17 Sustainable Development Goals (SDG) put forth in 2015 by the United Nations in the 2030 Agenda for Sustainable Development.[1] Quality Education includes Target 4.7 Education for Sustainable Development and Global Citizenship, which requires that education for global citizenship and sustainable development be mainstreamed in national education policies, curricula, teacher education, and student assessment. Alongside society, the environment is central to both paradigms of sustainable development and global citizenship.

Researchers on Education for Sustainable Development (ESD) agree that the term has had multiple "readings" up to now, ascribed to its inherent trans-disciplinarity (Seatter and Ceulemans, 2017). As a result, various paths or approaches have been shaped within ESD, each of them employing different pedagogies and methods for teaching and learning (Kioupi and Voulvoulis, 2019). When pedagogies employed in ESD are carefully examined, however, the mismatch between the means (pedagogies and teaching/learning methods) and the message (sustainable development) becomes conspicuous. In their study on ESD in Higher Education, Seatter and Ceulemans (2017) find a "vast dissimilarity between the potential challenge to students" critical and creative thinking processes, open-mindedness, and resultant transformative learning, within the inherently provocative and complex nature of sustainability work and the disengagement of the learner within much of Higher ESD today and conclude that it is urgent to "overcome the paradox of a powerful sustainability message framed within a powerless pedagogy". This view agrees with the results of Leifler and Dahlin (2020), who study how engineering curricula across their country (Sweden) integrate sustainability, and find a misalignment between learning objectives/learning content and the type of learning activities organized to teach/learn this content and achieve these objectives. At the same time, they find that inter-disciplinary or even trans-disciplinary thinking and activities constitute the essential – albeit, lacking – element for a successful engineering curriculum, i.e., one that builds critical competences and skills in young engineers ("strategic sustainability competences"). Given the high expectations modern societies place on engineering students as agents of future technological, environmental and societal change, the latter point becomes crucial—even more so, when the same authors find that less than half of the expected learning outcomes are actually sought in current engineering curricula, while pedagogies of active learning are not preferred over traditional ones. Indeed, the least frequently employed activities are laboratory experiments and educational games.

The findings and considerations outlined above have motivated the present research that is aimed at proposing, implementing and evaluating an educational method within an Electrical and Electronics Engineering (EEE) undergraduate curriculum. The concepts of sustainability, recycling and the cyclic economy are central to this method; these are introduced through hands-on laboratory activities rather than lecturing. In the lab, students work in groups to disassemble electrical/electronic devices that are damaged or at End-Of-Life (EOL) condition and to reclaim, identify and classify electronic components out of them. Damaged components are recycled while functional ones are used either for the repair of similar devices or for the innovative design and prototype construction of new devices. Through such pairs of Analysis (Disassembly) and Synthesis (Design and Construction) phases, possibly repeated over time, students get a lived experience of a collaborative sustainability project that aims at developing their cognitive, social/emotional and metacognitive skills. The Synthesis (Design and Construction) phase, in particular, aims at developing creativity, a much-valued skill in engineering that is not straightforward to measure. In the present research, consequently, considerable effort is dedicated to the measurement of student creativity, on the basis of artefacts (new devices) designed and constructed by the student groups according to specifications and using as many of the reclaimed components as possible.

The proposed method is put to test with a group of volunteering undergraduate EEE students. Electric/electronic circuit design, analysis and measurements are in the core of the EEE discipline, rendering the EEE curriculum advantageous as a testbed for the proposed method. The latter is generic enough, however, to be applicable to other engineering disciplines with a few modifications. An initial, more elementary form of this method has been conceived and implemented by the same authors in a Vocational Education and Training (VET) curriculum on Electronics and Automation (Nikoloudakis and Rangoussi, 2024b). Results from this pilot implementation and evaluation have inspired the modification of the method into a form suitable for engineering students.

1.2 Literature review

The three essential elements of the present research are (i) the subject of sustainability, recycling and cyclic economy, approached through reclaiming and reusing electronic components from devices at EOL, (ii) the applied educational character, based on educational interventions that are planned, implemented and evaluated in a hands-on laboratory setting, and (iii) the education grade and discipline (engineering, undergraduate, EEE). A bibliographic search for publications of relevant research studies yields rather poor results, when all 3 elements identified above are considered. This observation agrees to a similar one, recently reported in Nikoloudakis and Rangoussi (2024a), which led those authors to extend the scope of their review and cover formal and informal settings across K-12, tertiary and adult/community education. The findings of this systematic review, that covered 27 publications in the decade of 2013–2022, are summarized here, since they are pertinent to the present study as well:

- Although publications on sustainability and e-waste keep increasing, those on actual educational interventions with students have a rather limited presence; they appear mostly in conference proceedings rather than in journals.
- The experimental type of research on ESD is performed primarily (i) in tertiary (academic) education, (ii) in engineering or science faculties and (iii) in face-to-face delivery mode.
- Interventions are embedded in (engineering) curricula and often in existing courses therein and are implemented as practical activities in the lab.
- The majority of the 27 educational interventions reviewed involve e-waste (75%) and proceed to extract and reuse components to construct artefacts from them.

1 https://sdgs.un.org/goals/goal4

- Innovative content is aligned with innovative pedagogies: all reviewed interventions adopt modern, learner-centered, constructionistic and collaborative pedagogies.

A comparably low number of publications is reported the review by Gutierrez-Bucheli et al. (2022), this one restricted to engineering curricula: 48 relevant publications are retrieved since 1990, only 16 out of them include laboratory/experimental activities.

More recent studies (2023–2025), such as Benyeogor et al. (2023), Boya-Lara et al. (2023), Pantos et al. (2023), Lin et al. (2024), and Zwane and Schoeman (2025), contain hands-on, construction educational activities or Science, Technology, Engineering, Arts and Mathematics (STEAM)-type instruction aimed at developing knowledge and skills on the proper handling of e-waste. These studies bear similarities with the present research aimed at educational interventions of the hands-on lab type. When applied in Higher Education, STEAM strengthens problem-solving, collaboration and creative thinking skills through design and construction/implementation activities that combine theory to practical experience. Thanks to its strong inter-disciplinary and sustainable character, STEAM has a transformative impact on modern education (Carter et al., 2021). Within an engineering curriculum, STEAM components can be structured into a learning path of progressively more demanding steps, each cultivating a specific, desired skill – creativity none the least among them (Burns et al., 2021; Montes et al., 2022).

In terms of sustainability, sustainable development and raising social awareness on these issues, recent publications by Corral et al. (2023), Urbaniak et al. (2024), Angelaki et al. (2024), Michael et al. (2024), Bernardes et al. (2024), and Hashim et al. (2024) are aimed at monitoring and evaluating the adoption by academia and/or workplaces of "green" and sustainable procedures regarding e-waste. The studies by Neves et al. (2024), Owen et al. (2024), Yang et al. (2025), and El-Sherif et al. (2024) employ socio-economic analysis to identify established procedures as well as difficulties faced in the proper handling of e-waste and in recycling and to correlate them to the design, production and consumption of electronic devices. Games are employed to promote more sustainable practices while bibliometric analysis is exploited to estimate the life cycle of electronic devices, the current status with e-waste and a techno-economic projection to the near future. Machine learning and deep learning algorithms and tools are used in the studies of Puttero et al. (2024), Baker et al. (2023), and Lu et al. (2023), in order to automate the disassembly of EOL devices and the classification of components extracted from them. Policies to be adopted, deployed or even enforced by governments or other decision-making bodies towards embedding recycling procedures in the production system as well as in the education system, are proposed in the studies by Wang et al. (2024) and Purkiss et al. (2024). The same double target is present in the studies by Correia et al. (2024), Padovano et al. (2024), and Lord and Finelli (2023), who focus on environmental management and advocate the application of sustainable practices both in the production and in the education programs. The studies by Reyna et al. (2024) and Kiran et al. (2023) investigate sustainable attitudes and behaviors in academic institutions and, in particular, in engineering faculties.

On the other hand, it is worth noting that across all studies mentioned above, both earlier and more recent ones, evaluation of the effectiveness of the educational interventions in terms of the gains of the learners across major domains of learning has not received the deserved attention. In fact, evaluation is rarely included in these studies, and, whenever included, (i) it is not rigorously performed: it employs the standard tools such as pre-and post-tests, questionnaires, interviews and field observations, yet, under mostly ad-hoc protocols, or (ii) it is of a limited scope, in the sense that it assesses student gains in the cognitive domain (content knowledge); skills developed in the social/emotional and metacognitive domains or "21st century skills" are scarcely ever evaluated. Furthermore, as pointed out by the findings in Gutierrez-Bucheli et al. (2022) regarding engineering study programs, the difference between expected and actual learning outcomes of these programs is evident.

In contrast to the studies mentioned above, the present research is based on an educational intervention that is carefully planned and evaluated. It is carried out with EEE students, who take part in a hands-on laboratory project aimed at developing their cognitive, social/emotional and metacognitive skills, with emphasis placed on the cultivation and assessment of creativity. Accordingly, the following Research Questions (RQs) are defined:

- RQ1: What is the effectiveness of the proposed educational method in developing student cognitive skills (a) at the basic level and (b) at higher levels?
- RQ2: What is the effectiveness of the proposed educational method in developing student social/emotional skills?
- RQ3: What is the effectiveness of the proposed educational method in developing student metacognitive skills (motivation, confidence, self-regulated learning and development of personal learning strategies)?
- RQ4: What is the effectiveness of the proposed educational method in developing student creativity?
- RQ5: Can this type of educational intervention create a Community of Learning and, further on, instigate a Community of Practice of students on the subject?

2 Materials and methods

2.1 The proposed educational method

The proposed educational method is aimed at enhancing the cognitive, social/emotional and metacognitive skills of students as well as at cultivating their creativity. In the cognitive domain, students are expected to learn (i) how to analyze electric circuits and understand their operation, (ii) how to read and decipher schematic diagrams, and (iii) good practices on sustainability and circular economy, through recycling/reclaiming and reusing electronic devices and components. In the social/emotional domain, students are expected to enhance their communication and collaboration skills and have a pleasant learning experience that will motivate them for learning further on. In the metacognitive domain, students are expected to increase their confidence, self-esteem and self-regulated learning. These objectives are pursued through.

(a) A pedagogical approach that combines elements from active learning, experiential learning, learning by doing, discovery learning and collaborative learning, and

(b) An education scenario that combines theoretic knowledge to hands-on laboratory experience and employs open-type and closed-type evaluation activities.

More specifically, the proposed educational method is aimed at experientially teaching students

(i) How to disassemble electronic devices at EOL stage.
(ii) How to reclaim, identify and classify functional components from these devices.
(iii) How to reuse these components either to repair other damaged devices or to design and construct new devices.

The method consists of a pair of *Analysis—Synthesis* phases, repeated more than once, if necessary. The whole sequence is headed by an *Introductory session* (Figure 1).

Each of the Analysis and Synthesis phases starts with an *Introduction and Brainstorming session*, where students propose and discuss alternative paths and jointly shape an action plan, followed by the main *Implementation session* and concluded by an *Evaluation session*. A typical, single-pair-of-phases project would roll out as follows:

- *Introductory session*: students are briefed on the aim of the project, on laboratory safety regulations and on laboratory conduct rules, are familiarized with the equipment and tools they will use and are also given access to the devices at EOL to be disassembled.
- *Analysis phase*:
  (i) Introduction and Brainstorming session.
  (ii) Implementation session (Figure 1): students work in small groups with supervision; they disassemble the devices at EOL down to the component level; identify and classify the extracted components; test their functionality by measurements; retain the functional ones and recycle the rest.
  (iii) *Evaluation session*: Student gains in the cognitive domain are evaluated through a closed-form written knowledge test coupled with an open-form activity.
- *Synthesis phase*:
  (i) Introduction and Brainstorming session.
  (ii) Implementation session (Figure 1): students work in small groups with supervision, in either of the following two streams:
    (a) *Maintenance and Repair stream*: students use components reclaimed during the Analysis phase to repair other damaged devices of the same type.
    (b) *Innovative design and construction of prototype stream*: students create (design and construct) new artefacts based (chiefly) on the components reclaimed during the Analysis phase.
  (iii) Evaluation session:
    (a) *Maintenance and Repair stream*: students are evaluated through a closed-form knowledge test and an open-form, collaborative activity.
    (b) *Innovative design and construction of prototype stream*: social/emotional skills are evaluated through field observation and creativity is formally measured on the basis of the artefact created by each group.

For the needs of the Classification task included in the *Analysis* phase, students are led to construct a hierarchy of classes. The 3 classes identified at the top level are (i) mechanical components, (ii) electrical/electronic components, and (iii) enclosures and other hardware components (Figure 2). Further classification into sub-classes is

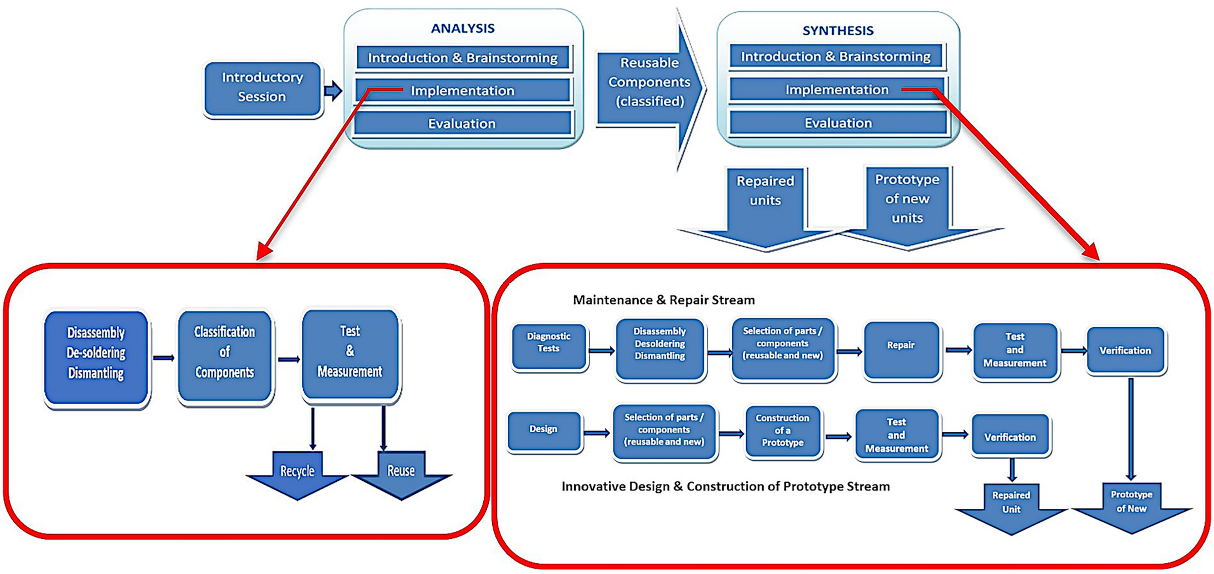

FIGURE 1
The proposed method outlined for a single pair of analysis – synthesis phases project. The analysis phase results in components classified as "recycle" or "reuse". The synthesis phase runs along two streams: (1) Maintenance and Repair stream; (2) Innovative Design and Construction of Prototype stream. Adapted from Nikoloudakis and Rangoussi (2024b).

FIGURE 2
The hierarchical classification scheme of reusable components extracted from WEEE (the 3 top-level classes). Adapted from Nikoloudakis and Rangoussi (2024b).

organized down to the component level. During this task, students are required to closely observe, identify, name, compare, contrast, differentiate and eventually classify items into the correct class (decision making), i.e., they practice mental activities of the 1st up to the 5th level of the (modified) Bloom taxonomy of learning (cognitive domain) (Bloom et al., 1956; Anderson et al., 2001) and they develop higher order and transversal intellectual abilities and skills. The interested reader is referred to Nikoloudakis and Rangoussi (2024b) for more details.

2.2 Educational intervention data and sample

The educational intervention was planned and implemented in two (2) successive terms, referred to as "Lab-I" and "Lab-II". Undergraduate students of the 3rd and of the 4th semester, respectively, of a 5-year EEE curriculum were invited to participate on a voluntary basis. Lab-I and Lab-II were embedded in the practicum component (hands-on lab) of the (mandatory) Analog Electronics I or Analog Electronics II module, respectively. For students that completed Lab-I and/or Lab-II, a 30% of the final grade given in the respective module came from their participation in Lab-I and/or Lab-II.

A call for volunteers was issued and announced through the departmental web site and the official E-learning platform (Open E-Class) twice, in the beginning of Fall [Spring] semester 2024–25 for Lab-I [Lab-II]. Calls were addressed to all students enrolled in the Analog Electronics I and II courses in academic year 2024–25.

Among the 60 students who volunteered for Lab-I, 16 (13 men and 3 women) were admitted on merit basis (grade in a preceding relevant course). The percentage of women is compatible with their presence in the total EEE student population (around 20%). All 16 students signed an informed consent form that had been approved by the University Research Ethics Committee. The 16 volunteers formed 8 groups of 2, as dictated by the workstations available in the laboratory. Students were allowed to form the groups (pairs) by themselves. Lab-I spanned 2 months in the fall semester of 2024–25 and consisted of 6 weekly meetings of 3 h each. It ran as a single-pair-of-Analysis-Synthesis-phases project, including both streams in the Synthesis phase.

The same procedure was repeated for Lab-II. The second call did not exclude Lab-I participants. Among 100 volunteers, 16 students plus 3 runners-up were selected; 11 of them were Lab-I participants. The runners-up were eventually admitted, thus raising the total number to 19 students (15 men and 4 women). They all signed the same informed consent form as in Lab-I. The 19 volunteers formed 5 groups (4 groups of 4 students each and 1 group of 3 students); the number of groups is intentionally lower than that of Lab-I in order to increase the group size – a modification expected to increase the novelty and variety of ideas and solutions proposed. Furthermore, students were again allowed to form the groups by themselves, on the condition that every group should include at least one Lab-I participant and at least one new participant. Lab-II spanned 2 months in the spring semester of 2024–25 and consisted of 6 weekly meetings of 3 h each. It ran as a single-pair-of-Analysis-Synthesis-phases project, the Synthesis phase including only stream 2 (Innovative design and construction of prototype).

2.3 Preparatory actions

For the purposes of this project, electronic devices at EOL stage were collected from schools, companies and shops that maintain "green"/recycling bins where such devices may be dropped. A departmental laboratory room, already arranged and equipped for practicum classes of curriculum courses related to electronics, was reserved for both Lab-I and Lab-II; these were scheduled for dates/times when this room was free.

All necessary learning content was uploaded in the Open E-Class University Learning Management System (LMS) platform, in an electronic course prepared especially for this project. The same platform was used for assignments and online student evaluation tests. Other tools such as Google docs and draw.io were used for open-form student evaluation activities. The pre-test and the feedback questionnaire were handed out in paper form. Some of the Open E-Class material was also made available in paper form, as a handy reference during lab sessions.

3 The implementation of Lab-I and Lab-II educational interventions

Lab-I and Lab-II educational interventions were scheduled and implemented on the basis of weekly meetings with physical presence in the designated laboratory room, as outlined below.

3.1 Lab-I implementation plan

3.1.1 Day 1 plan: (a) introductory session and (b) analysis phase (introduction and brainstorming; implementation)

Major Activities: (a) Informed Consent forms; Laboratory Conduct Rules and Safety Regulations; Student groups. (b) Access to EOL devices (printers-scanners-faxes); Disassembly of EOL devices; Brainstorming on action plan and on a component classification system; Actual classification of components into bins.

Skills sought: Cognitive domain (knowledge).

Evaluation: Pre-test (quiz).

3.1.2 Day 2 plan: analysis phase (implementation; evaluation)

Major Activities: Students studied essential material on Power Supply Units (PSUs) (Linear and Pulse Width Modulation (PWM) type); Internet search to answer questions; Students checked the function of the PSUs available to them; Damaged PSUs retained for component extraction; Electronic components extracted; Electronic components classified into bins.

Skills sought: Social–emotional domain; Student experience.

Evaluation: Focus group (student groups and class instructor).

3.1.3 Day 3 plan analysis phase (implementation; evaluation)

Major Activities: Students studied essential material handed out on electronic component measurements; Internet search to answer questions; Students brainstormed to jointly compile a measurement guide with steps; Students directly applied their guide to measure each component and to retain only the functional ones; Evaluation of knowledge by online test 1 and an open-form assignment.

Skills sought: Cognitive domain (knowledge).

Evaluation: 1st online test; Composition of a "Semiconductor Measurement Guide" (collaborative, asynchronous).

3.1.4 Day 4 plan: synthesis phase-stream 1 (introduction and brainstorming; implementation; evaluation)

Major Activities: Introduction to essential material on PSUs, Metal Oxide Field Effect Transistors (MOSFETs) and voltage regulators; Brainstorming on possible repair action plans; Internet search on MOSFETs; Actual repair of damaged PSUs using components extracted in the Analysis phase; Evaluation of knowledge by online test 2 and an open-form assignment.

Skills sought: Cognitive domain (knowledge).

Evaluation: 2nd online test; Composition of a "PSU Repair Flow Chart" (collaborative, asynchronous).

3.1.5 Day 5: synthesis phase-stream 2 (introduction and brainstorming; implementation)

Major Activities: Brainstorming on possible new devices; Regulated Power Supply Units (R-PSUs) of various technologies; Internet search for alternatives; Circuit design, circuit connection on prototyping PCBs.

Skills sought: Cognitive domain; Social–emotional domain; Metacognitive skills; Creativity.

Evaluation: (–).

3.1.6 Day 6: synthesis phase-stream 2 (implementation; evaluation)

Major Activities: Student groups resumed working on their artefacts (R-PSUs) and completed them; Test and verification; Feedback Questionnaire; Creativity evaluation on the basis of artefacts; Photo documentation of artefacts.

Skills sought: Cognitive domain; Social–emotional domain; Metacognitive skills; Creativity.

Evaluation: Feedback Questionnaire; Creativity measurement.

3.2 Lab-II implementation plan

3.2.1 Day 1 plan: introductory session

Major Activities: Informed Consent forms; Laboratory Conduct Rules and Safety Regulations; Student groups; Access to EOL devices; Access to Artificial Intelligence aiding tools; Comparative evaluation of Artificial Intelligence (A.I.) tools on task-specific questions; Selection of Google Gemini.

Skills sought: Cognitive domain (knowledge).

Evaluation: (–).

3.2.2 Day 2 plan: analysis phase (introduction and brainstorming; implementation)

Major Activities: Roles assigned and duties explained ("veterans" and "novices"); Semiconductor Measurement Guide prepared in Lab-I handed out to all groups for reference; Access to EOL devices (PSUs, printers-scanners-faxes); Disassembly of EOL devices; Students study the Semiconductor Measurement Guide; Internet search to answer questions; Students checked functionality of the PSUs; Damaged PSUs retained for component extraction; Electronic components extracted and checked; Functional components classified into bins.

Skills sought: Cognitive domain; Social–emotional domain; Metacognitive skills.

Evaluation: (–).

3.2.3 Day 3 plan: synthesis phase-stream 2 (introduction and brainstorming; implementation)

Major Activities: Brainstorming on action plan; Decision to design a "fan/ventilation" device; Students were discouraged to share and discuss ideas among groups; Students groups finalized "fan/ventilation" artefact; Internet search for designs; Search in EOL devices store for chassis and casings.

Skills sought: Cognitive domain; Social–emotional domain; Metacognitive skills; Creativity.

Evaluation: (–).

3.2.4 Day 4 plan: synthesis phase-stream 2 (implementation)

Major Activities: Student groups resumed work on their artefacts; Various problems and decisions; Certain groups seek help from A.I. tool; Breadboard circuits copied to Printed Circuit Board (PCB).

Skills sought: Cognitive domain; Social–emotional domain; Metacognitive skills; Creativity.

Evaluation: (—).

3.2.5 Day 5 plan: synthesis phase-stream 2 (implementation)

Major Activities: Student groups resumed work on their artefacts; Testing and verification of artefacts; Final touches; Unused components returned to recycle bins; Lab clean-up.

Skills sought: Cognitive domain; Social–emotional domain; Metacognitive skills; Creativity.

Evaluation: (—).

3.2.6 Day 6 plan: synthesis phase-stream 2 (evaluation)

Major Activities: Student groups presented their artefact to the plenary; Pros and cons of each artefact and difficulties faced are discussed; Creativity measurement on the basis of the artefacts created; Student peer-evaluation of artefacts by voting; Prize conferred; Pizza party for closure.

Skills sought: Cognitive domain; Social–emotional domain; Metacognitive skills; Creativity.

Evaluation: Creativity measurement; Student group reports prepared and uploaded.

It is worth mentioning here that in fact Lab-II was scheduled and implemented as a follow-up activity of Lab-I, in order to further investigate and measure student creativity. Creativity measurement results obtained during Day 6 of Lab-I showed low levels of variety in the artefacts produced by the student groups. A review of daily logs revealed that this outcome was a result of student groups sharing and discussing ideas among them. They thus gradually converged to a sole solution considered as the best one among alternatives. All groups practically "copied" that solution, with minor modifications. This is an understandable behavior of novices that opt for the safe side. It was considered worth trying to "lure" students out of this safe practice; it would take a second Lab, namely, Lab-II, where this type of sharing and "copying" ideas on solutions would be discouraged.

4 Results (Lab-I evaluation)

Evaluation of the learning outcomes of the first educational intervention, Lab-I, across various domains, is based on the following evaluation activities:

1. Close-ended knowledge evaluation tests: pre-test, 1st online test, 2nd online test.
2. Open-ended knowledge evaluation activities: assignments asking students to collaborate and compose (i) a Semiconductor Measurement Guide and (ii) a power supply repair flowchart, in the form of a mind map.
3. Feedback questionnaire with close-ended and open-ended questions on the social, emotional and metacognitive skills developed (collaboration, affect and attitudes).
4. Creativity measurement on the basis of the artefacts created by each student group.
5. Field observations by the class instructor, in the form of notes.
6. Focus group held as an intermediate evaluation – feedback to the class instructor.

Results are presented in the following sections, organized per evaluation activity.

4.1 Close-ended knowledge evaluation tests

The pre-test, 1st online test and 2nd online test evaluate knowledge on the subject of electrical and electronics circuits and measurements (cognitive domain) through close-ended questions. Each test consists of 10 questions of the multiple-choice type, for quantitative assessment (student grading). After having completed each test, students would receive immediate feedback on their score, while the correct answers would be projected on the class board in the plenary and students would discuss correct and wrong answers with the teacher.

Results are shown in Figure 3 for all 3 tests. Pre-test was delivered on Day 1, 1st online test on Day 3 and 2nd online test on Day 4. Along these 3 tests, class average (± standard deviation) grade over 10.00 increased from 5.125 ± 1.147 in the pre-test to 7.531 ± 1.118 in the 1st online test and to 8.625 ± 1.360 in the 2nd online test, while the standard deviation remained low. Besides average grades, all individual student grades also increased along the 3 tests, showing knowledge gains at the individual scale, achieved over a period of 1 month (4 weeks).

4.2 Open-ended knowledge evaluation activities

Two open-ended evaluation activities were assigned to the students, namely, to compose (i) a "Semiconductor Measurement Guide" (Day 3), and (ii) a "PSU Repair Flow Chart" (Day 4). Student collaboration on both tasks started in class and continued asynchronously from home. They worked together in Google Forms and used draw.io to design the flow chart. Sample pages of the Semiconductor Measurement Guide are shown in Figure 4A, and a section of the PSU Repair Flow Chart is shown in Figure 4B, in original (Greek) language.

The overall outcome of these two open-ended evaluation activities was qualitatively evaluated as "excellent" and given the top grade (5 on a 1-to-5 grading scale) by the class instructor. Furthermore, individual participation and contribution was measured through indices of access to the online collaboration tools and quality of the individual contribution therein. The class average (± standard deviation) was 7.23 over 10.00 (± 2.78), which is a high-level result, yet, with large variation across students.

4.3 Feedback questionnaire on social, emotional and metacognitive skills

The feedback questionnaire on social, emotional and metacognitive skills, delivered at the end of Lab-I (Day 6), consists of 10 questions of the open-ended type. Out of these 10 questions,

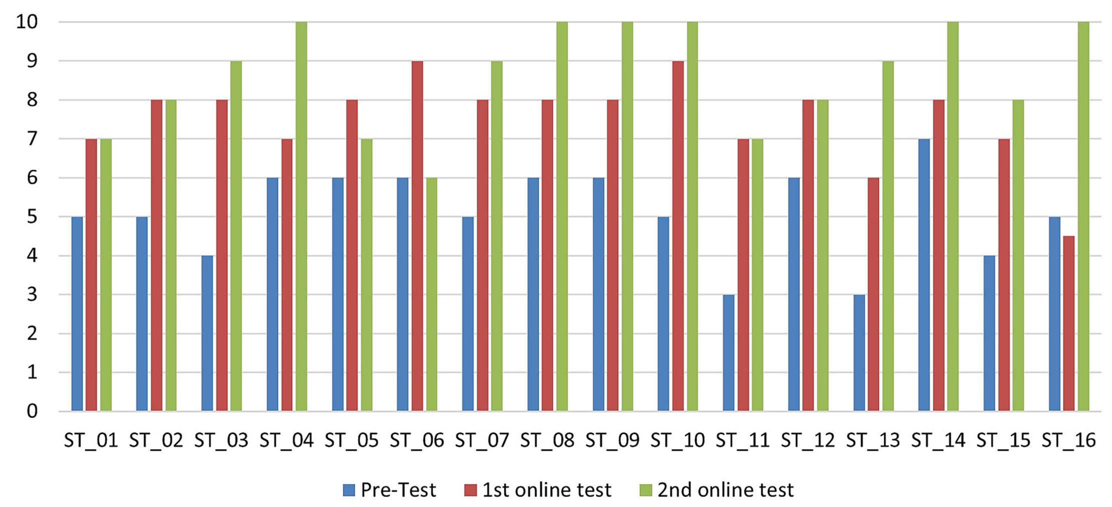

FIGURE 3
Student grade (0 to 10) versus student ID (ST_01 to ST_16). Pre-test, 1st online test and 2nd online test grades, comparatively shown for each student ID.

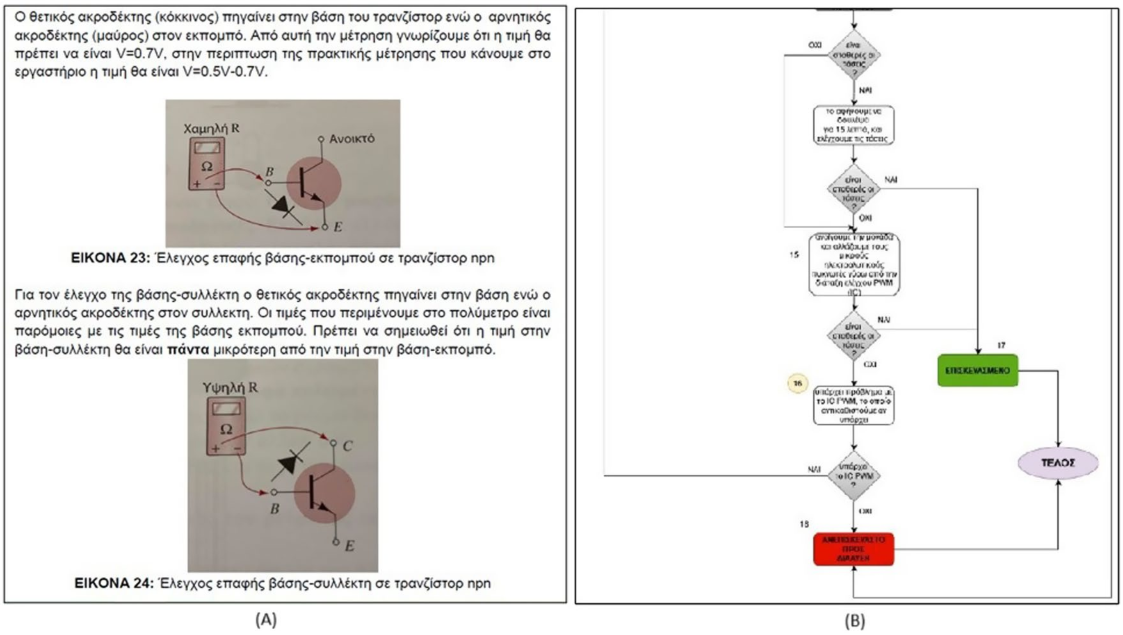

FIGURE 4
Sample page of the semiconductor measurement guide **(A)** and sample section of the PSU repair flow chart **(B)**, collaboratively composed by students (in Greek).

questions 1 and 3 belong to the social domain, questions 2 and 4 to the emotional domain, while questions 5–10 inquire on metacognitive skills, attitudes and motivation. The questions along with (grouped) student answers are shown in Table 1.

4.4 Creativity measurement

Creativity is measured by the class instructor, on the basis of the new devices designed and constructed in the form of prototypes by the student groups during Lab-I Days 5 and 6. For comparability purposes, students were asked to jointly decide on a sole type of electronic device; each group would design and construct variations of this device. They were also required to use as many of the reclaimed functional electronic components from the Analysis phase, as possible. Following a discussion of various alternatives held in the plenary, and taking in account the reclaimed components, students decided to design and construct Regulated Power Supply Units (R-PSUs) of various technologies. The prototypes eventually constructed are depicted in Figure 5 per group; they are 7 instead of 8, because groups 3 and 4 worked jointly to produce a single device, due to a technical problem in a workstation.

TABLE 1 Feedback questionnaire and student answers (Lab-I, Day 6).

Nr.	Question	Student answers (grouped)
1	How many others did you collaborate with during this project?	Extended collaborations with 1 to 3, 4 to 6, 7 to 10, or more than 10 other students are reported.
2	Did you find any difficulties in the hands-on part? If yes, at what point?	Half of the students did not face any difficulty (8 out of 16); 6 students had difficulty only in the beginning; 2 students reported difficulty in soldering.
3	Do you consider that you have learned things through your collaboration with peers in this project?	All 16 students reported having learned useful things; they have also developed social skills – smooth collaboration with others (8 students); have developed solidarity, mutual understanding, team spirit and collegiality (6 students); have developed practical skills (3 students); have developed problem-solving skills (2 students); have developed creativity (1 student).
4	How would you characterize your feelings at the end of this experiential lab project?	"Very pleasant" feelings (9 out of 16 students); "pleasant" feelings (6 students); neutral feelings (1 student); no negative feelings reported.
5	Has this project inspired you to get involved in other similar activities? If yes, what are they?	9 out of 16 students replied "yes"; 5 students had already engaged in similar activities; 4 students are eager to do that in the near future; students referred to repair of EOL devices at home, computers, LED lamps, or construct a PSU.
6	Having completed this project, has your attitude towards WEEE changed or not?	7 out of 16 students would check operation of the device first and then decide on the triplet {repair; reclaim and reuse components; properly recycle as WEEE}; 3 students referred solely to recycling as WEEE; 1 student referred solely to reclaiming and reusing; 1 student referred solely to repairing. Finally, 3 students gave general-type answers revealing raised awareness.
7	Which piece of knowledge gained during this project do you consider as most valuable?	Students valued most having learned how to: read, analyze and understand schematic diagrams of electric circuits (11 out of 16 students); use tools (9 students); identify components and their functionalities (6 students); repair damaged devices (4 students); do reverse engineering (3 students); apply theoretic knowledge on electric/electronic circuits (3 students); measure electric quantities (3 students); construct new devices (2 students); reuse the reclaimed electronic components (1 student).
8	Which is the skill developed during this project that you consider as most valuable?	Students valued most having develop the following skills: Collaboration (3 students); Autonomous and focused information retrieval (3 students); Critical thinking (2 students); Help and support among peers (2 students); Analytic thinking (1 student); Communication (1 students); Diligence (1 student). Three (3) students misunderstood skills for knowledge; their answers are counted in the previous question.
9	Do you think it is likely that knowledge, skills and experience you have gained in this project will be needed in the future?	All students (16 out of 16) answered to the positive; 10 out of 16 students "strongly agreed" that such knowledge, skills and experience will be required of them at some point.
10	How do you think you are going to exploit the knowledge, skills and experience gained in this project?	All students answered that in the near future they intend to: continue along this path to gain more knowledge and experience (16 students); reclaim and reuse electronic components for repair (13 students); reclaim and reuse components either for repair or for construction of new devices (10 students); reclaim components for sale (6 students); design new, environmentally friendlier devices (2 students); engage in a new project (1 student); engage in repairs (1 student); continue in order to fully understand the underlying electric/electronic circuit theory (1 student).

Creativity was measured following the SVS method proposed by Shah et al. (2003). Creativity is considered as domain-specific (Belski, 2017). Among the various methods proposed for measuring it, certain are more suitable for Social Sciences (Miller et al., 2020), such as the Consensual Assessment Technique (CAT) (Amabile, 1996), while others are more suitable for engineering, such as PSA (Owens et al., 1957), PCT (Harris, 1960) and more recently SVS (Shah et al., 2003) and CEDA (Charyton and Merrill, 2009).

SVS is selected because (i) it has been extensively applied, ever since its appearance, either in the original form or in modified editions (Fiorineschi and Rotini, 2023), while (ii) it measures creativity on the basis of novel design of artefacts ("ideation") without the limitations of other methods as to the time allowed or the maximum number of solutions accepted. Internally, the SVS method uses 4 different metrics or components to quantify creativity, namely, (i) Novelty (M1), (ii) Variety (M2), (iii) Quality (M3), and (iv) Quantity (M4) of the different ideas conceived, designed and materialized into devices. Out of the two approaches proposed in Shah et al. (2003), the a-priori approach is adopted here, as more suitable for the current setup.

As the evaluation and grading of student artefacts bear a degree of subjectivity, it was deemed necessary to use more than one human evaluator, in order to get more objective results. Two electronic engineers of the same University Department as the class instructor, both experts in electronic design and construction, were employed as lab assistants for the evaluation task. They performed evaluation independently of each other and of the class instructor, after being briefed on the purpose of the intervention as well as on the method, tools and scales set for evaluation. Differences in the grades given by the 3 evaluators (class instructor and 2 lab assistants) were resolved by discussion among them, in order to reach a unanimous decision. Eventually, in case of grade differences remaining after discussion, the proposed method adopts the average of evaluator grades.

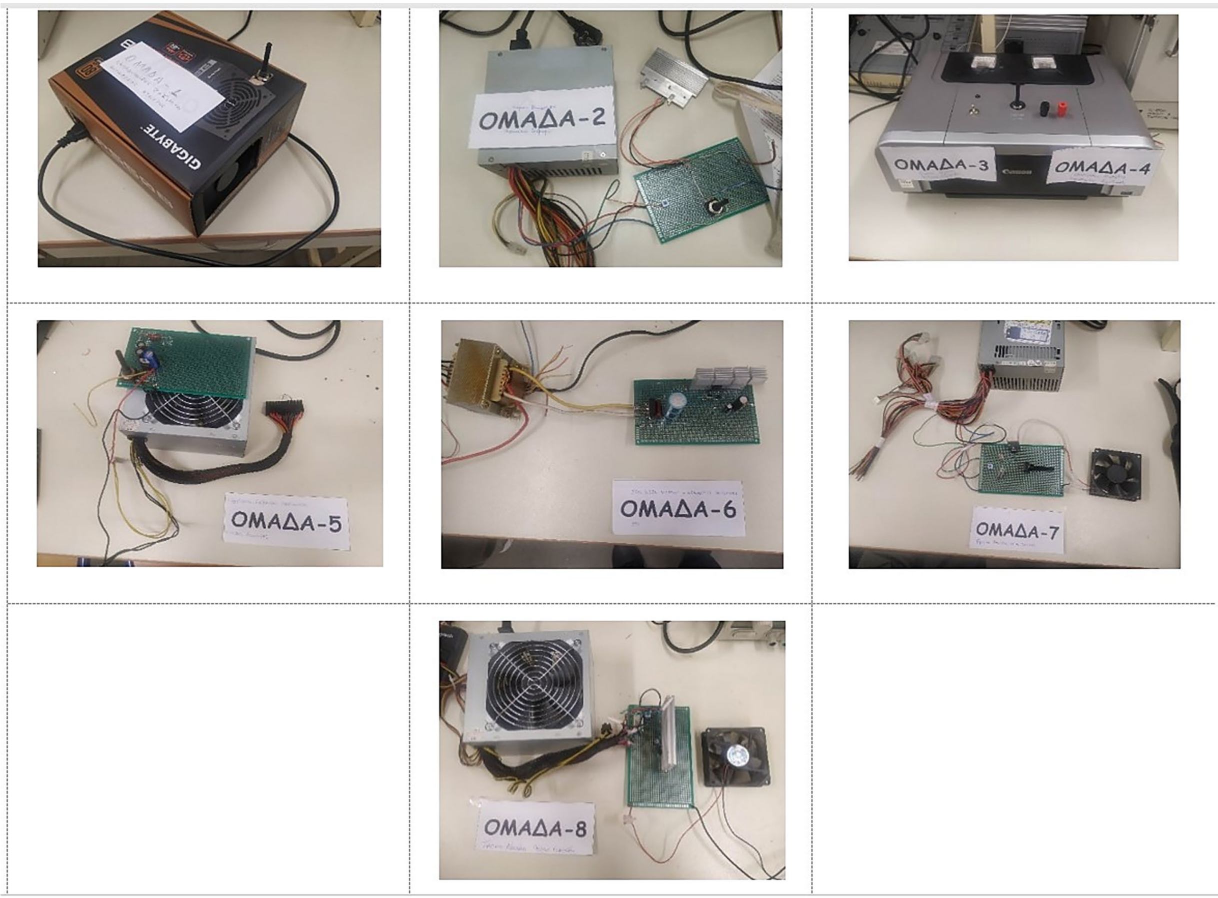

FIGURE 5
Lab-I device prototypes (R-PSUs) designed and constructed by each student group: 8 groups, 7 devices.

4.4.1 Novelty (M_1 score)

Novelty is calculated as the weighted average of the scores achieved in the following 3 components or stages, identified by the authors acting as field experts on the taught subject: (a) rectification (DC input), (b) regulation and (c) voltage setting method, as detailed below. Each device is graded over 10 across these 3 components. Individual device scores and class averages can thus be calculated. The weights applied to each component are decided empirically, taking in account the functionalities and the relative importance of the corresponding properties of an actual R-PSU device:

a) Rectification (DC input) (20%): this stage could come out of (i) a Personal Computer (PC) – ATX cage type PSU rectifier (10 over 10); (ii) a printer PSU rectifier (7 over 10), and (iii) any linear rectifier using transformers or bridges or capacitors (3 over 10). Grades are assigned according to the efficiency of each technology (that is directly connected to sustainability) and the flexibility it offers, starting from the linear solution and advancing to the switching mode – single voltage output solution and to the switching mode – multiple voltage outputs solution: 12 V, 15.3 V (−12 V to +3.3 V), 17 V (−12 V to +5 V), 24 V (−12 V to +12 V).
b) Regulation type (40%): this stage can be implemented through one of six available technologies, namely, (i) resistance plus Zener diode (2 over 10), (ii) power transistor led by a Zener diode (3 over 10), (iii) Integrated Circuit (IC) comparator with a transistor and a Zener diode (4 over 10), (iv) LM317 IC regulator (5 over 10), and (v) PWM switching mode regulator (10 over 10). Grades are assigned according to the efficiency of each technology and the flexibility it offers.
c) Voltage setting method (40%): this stage can be implemented as one of five available technologies, namely, (i) voltage divider with a potentiometer (3 over 10), (ii) potentiometer, transistor comparator and a Zener diode (5 over 10), (iii) potentiometer, Operational Amplifier (Op-Amp), transistor and a Zener diode (10 over 10), Grades are assigned according to the efficiency of each technology and the flexibility it offers.

Artefacts are evaluated on this grid, along each of the 3 components, independently by the class instructor and by 2 lab assistants who are electronics engineering experts. Grades given to each artefact are unanimous, thanks to the detailed scale set. These are shown in Table 2, both per student group (artefact) and as class averages (Table 2, bottom row).

The class average Novelty is $M_1 = 4.51$ over 10, a low score that is essentially due to the poor choice of regulation type and of voltage setting method, as Table 2 reveals. Indeed, all groups have uniformly opted for the less efficient and less flexible solutions of a linear

TABLE 2 Lab-I creativity measurement – novelty (M_1 score).

Student group nr.	Rectification (DC input)	Regulation type	Voltage setting method	M_1 score (a-priori)
	20%	40%	40%	
1	10	5	2	4.80
2	10	5	2	4.80
3–4	7	5	2	4.20
5	10	5	2	4.80
6	3	5	2	3.40
7	10	5	2	4.80
8	10	5	2	4.80
Class average over 10	8.57	5.00	2.00	4.51

TABLE 3 Lab-I creativity measurement – quality (M_2 score).

Student group nr.	Specifications	Usability	Reliability	Robustness	M_2 score (a-priori)
	10%	20%	30%	40%	
1	10	10	10	7	8.80
2	10	3	10	10	8.60
3–4	7	10	10	7	8.50
5	7	3	10	3	5.50
6	7	3	10	3	5.50
7	3	3	10	3	5.10
8	3	3	10	7	6.70
Class average over 10	6.75	5.63	10.00	5.88	7.15

regulator (IC LM317) and a voltage divider-plus-potentiometer as voltage setting method. These choices earned them 5 over 10 and 2 over 10 in the respective components, thus resulting in a low average M_1 score.

4.4.2 Quality (M_2 score)

Quality is the weighted average of the scores achieved in the following 4 components or stages: (a) specifications, (b) usability, (c) reliability, and (d) robustness, as detailed below. Each device is graded over 10 across these 4 components. Individual device scores and class averages can thus be calculated. The weights applied to each component are decided empirically, taking in account the functionalities and the relative importance of the corresponding properties of an actual R-PSU device:

- (i) Specifications (10%): grading of this component is quantized at 3 levels, 10 for perfectly detailed specs, 7 for satisfactory specs and 3 for acceptable specs.
- (ii) Usability (20%): grading of this component is quantized at 3 levels, 10 for high usability, 7 for average usability and 3 for low usability.
- (iii) Reliability (30%): grading of this component is quantized at 3 levels, 10 for high reliability, 7 for average reliability and 3 for low reliability.
- (iv) Robustness (40%): grading of this component is quantized at 3 levels, 10 for high robustness, 7 for average robustness and 3 for low robustness.

Artefacts are evaluated on this grid, along each of the 4 components, independently by the class instructor and by 2 lab assistants who are electronics engineering experts. Grades given to each artefact are not all unanimous, because of the subjective nature of these 4 components. In case of disagreement, the final grade is decided after discussion among the 3 evaluators. These are shown in Table 3, both per student group (artefact) and as class averages (Table 3, bottom row).

Quality score $M_2 = 7.15$ over 10 is satisfactorily high, indicating that all artefacts are of adequate quality regarding the chosen properties of specifications, usability, reliability and robustness. It is noted that this high score is mainly due to the Reliability property, that is given a 10 over 10 across all artefacts.

4.4.3 Variety (M_3 score)

Variety is the weighted average of the same 3 components or stages as Novelty, and with the same corresponding weights (20–40 – 40%). Each of these 3 components is internally analyzed into a hierarchy of levels along which the variety is evaluated, namely, (i) the set of ideas, (ii) principle of operation, (iii) implementation, and (iv) construction details. For each level following the top one, scores are set to $S_1 = 10$, $S_2 = 7$ and $S_3 = 3$, so as to reflect the impact on Variety that differentiated choices at the corresponding level of the hierarchy may have.

a) Rectification (DC input) (20%): a decision tree is constructed with branches wherever different options are adopted by

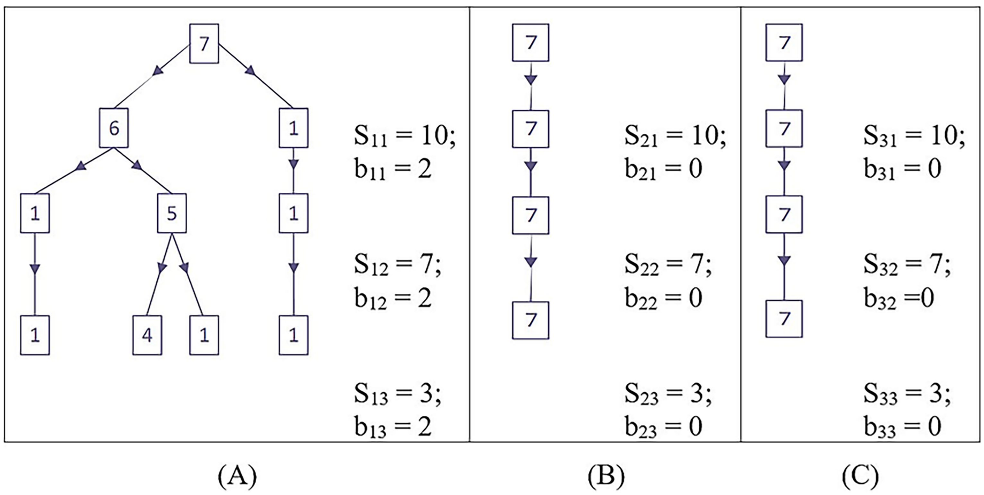

FIGURE 6
The hierarchical trees of choices that decide variety by the degree of branching $\{b_{ij}\}$ at each level j = 1, 2, 3 of the corresponding component i = 1, 2, 3. **(A)** Rectification (DC input) component (i = 1, weight 20%), **(B)** regulation type component (i = 2, weight 40%), and **(C)** voltage setting method component (i = 3, weight 40%).

different student groups (Figure 6A). The total set of 7 ideas (as many as student groups are) at the top level 0 branches into 2 different principles of operation at level 1 ($S_{11} = 10$, $b_{11} = 2$), further down the tree, these branch into 3 different implementations at level 2 ($S_{12} = 7$, $b_{12} = 2$), and, finally, branch into 4 different construction detail types at level 3 ($S_{13} = 3$, $b_{13} = 2$).

b) Regulation type (40%): the decision tree is reduced to a linear structure (Figure 6B), because when deciding the regulation stage technology to be adopted, all 7 student groups select the same principle of operation ($S_{21} = 10$, $b_{21} = 0$, no branching), the same implementation ($S_{22} = 7$, $b_{22} = 0$, no branching) and the same construction details ($S_{23} = 3$, $b_{23} = 0$, no branching).

c) Voltage setting method (40%): the decision tree is reduced to a linear form (Figure 6C), because when deciding the voltage setting method to be adopted, all 7 student groups select the same principle of operation ($S_{31} = 10$, $b_{31} = 0$, no branching), the same implementation ($S_{32} = 7$, $b_{32} = 0$, no branching) and the same construction details ($S_{33} = 3$, $b_{33} = 0$, no branching).

According to the values in Figures 6A–C, the Variety score M_3 is calculated as:

$$M_3 = 10 * \sum_{j=1}^{3} f_j * \sum_{k=1}^{3} \frac{S_k b_k}{M_{3\max}} =$$

$$10 * \left(f_1 * \sum_{k=1}^{3} \frac{S_k b_k}{M_{3\max}} + f_2 * \sum_{k=1}^{3} \frac{S_k b_k}{M_{3\max}} + f_3 * \sum_{k=1}^{3} \frac{S_k b_k}{M_{3\max}} \right) =$$

$$= 10 * f_1 * \left(\frac{S_{11} b_{11}}{M_{3\max}} + \frac{S_{12} b_{12}}{M_{3\max}} + \frac{S_{13} b_{13}}{M_{3\max}} \right) +$$

$$10 * f_2 * \left(\frac{S_{21} b_{21}}{M_{3\max}} + \frac{S_{22} b_{22}}{M_{3\max}} + \frac{S_{23} b_{23}}{M_{3\max}} \right) + \ldots$$

$$\ldots + 10 * f_3 * \left(\frac{S_{31} b_{31}}{M_{3\max}} + \frac{S_{32} b_{32}}{M_{3\max}} + \frac{S_{33} b_{33}}{M_{3\max}} \right) =$$

$$= 10 * 0.2 * \left(\frac{2*10}{70} + \frac{2*7}{70} + \frac{2*3}{70} \right) + 10*0.4*0 + 10*0.4*0 = 2*\frac{40}{70}$$

where:

- $f_1 = 20\%$ = weight of component 1, $f_2 = 40\%$ = weight of component 2, $f_3 = 40\%$ = weight of component 3.
- M_{3max} = maximum Variety = 7 ideas X 10 score each = 70.

Multiplicative factor of 10 is used in order to normalize the maximum M_3 score to 10.

The total M_3 score of 1.14 over 10 is very low; Figure 6 reveals that this is due to the uniform choices of all student groups across regulation and voltage setting method components, and along all the levels of the decision tree hierarchy (principle of operation, implementation, construction details).

4.4.4 Quantity (M_4 score)

Quantity is the total number of artefacts; here, this equals the number of devices designed and constructed by the student groups, which gives $M_4 = 7$.

4.4.5 Overall creativity score in Lab-I

The overall creativity score CS is reported as the quadruple of scores $\{M_1, M_2, M_3, M_4\}$ without any type of averaging. This is suggested in Shah et al. (2003) as these 4 metrics are essentially independent and therefore unsuitable for summation or averaging, even after normalization to a common numerical scale.

The Quantity metric, M_4, may be further differentiated from the set of the other 3 metrics, M_1, M_2, M_3, because it constitutes some kind of common ground or prerequisite for them to function properly. On the one hand, high or low values in M_4 do not automatically imply a positive or a negative result on the quality of the intervention or on Creativity, since they may be dictated by external factors such as the number of students that respond to the call for volunteers or the number of workstations available in the lab room. On the other hand, very low values in M_4, such as 2 or 3, would not allow the variety, novelty or quality potential of a set to artefacts to unfold and become measurable by M_1, M_2, and M_3. Higher values in M_4 would provide that ground or possibility, without of course being able to guarantee it.

The scores in the other 3 metrics, M_1, M_2, M_3, are all given on a 0-to-10 numerical scale and may be directly interpreted as congruent with Creativity: an increased/decreased value in either of them has a direct increasing/decreasing impact on Creativity. An intervention that would boost just one of them is still meaningful, if at the same time it does not decrease the others perceptibly. It is therefore meaningful to retain and report all 4 independent scores as final Creativity score.

Along these lines, the overall creativity score in Lab-I is reported as CS-I = {$M_1 = 4.51$ over 10.0; $M_2 = 7.15$ over 10.0; $M_3 = 1.14$ over 10.0; $M_4 = 7$}. These results show that student artefacts have scored low, especially as regards the Novelty ($M_1 = 4.51$) and Variety ($M_3 = 1.14$) components. More effort should therefore be put into these two components, in order to increase the overall creativity.

4.5 Lab-I field observations by the class instructor

Field observations by the class instructor, in the form of personal notes kept during each day of Lab-I, are summarized below.

4.5.1 Practical skills (use of tools)

Students had no difficulty in getting to know how to use and in using:

- Mechanic tools, such as screwdrivers of various types (Philips/Torx/Allen/flat, etc.), pliers, jigsaws, hammers, air-compressors, etc.
- Soldering tools, such as soldering guns, soldering fume extractors, solder wicks, etc. measurement tools for electric quantities, such as digital voltmeters, multimeters, oscilloscopes, etc.

4.5.2 "Vertical" skills in the EEE discipline

Students learned and practiced:

- Reading and understanding electric circuit diagrams of various types.
- Applying reverse engineering to deduce the circuit and functionality of devices not accompanied by documentation.
- Checking the functionality of (i) devices, and (ii) of electronic components, through the appropriate measurements.
- Carrying out basic repair tasks for specific electric devices (PSUs).

4.5.3 Sustainability, recycling and the cyclic economy

Students progressively moved from their initial, naive concepts (recycling is good; recycling is always the way to go) towards the formation and articulation of more elaborate mind constructs of the "if-then-else" type:

- Check damaged device first; if it cannot be repaired, then recycle it (properly) else repair it.
- If the device is to be recycled, extract the components first; check their functionality; retain the functional ones for use; recycle the rest.

4.5.4 Social skills

Student communication was free, fluent and continuous, both within each group and across groups. That was particularly evident during brainstorming sessions. The language used was polite and the dialogues and debates that took place never did raise the temperature. The absence of strict time limitations on the various tasks has probably helped that way.

Competitiveness was not introduced at any point of Lab-I; therefore, students felt free to exchange ideas, thoughts and suggestions, and help each other in practical difficulties. They jointly used the lab computers to seek help of resources over the Internet, and then discussed findings and singled out the ones promising for implementation.

4.5.5 Metacognitive skills

Students practiced on focused and independent search for information across multiple sources (manuals, Internet sources, textbooks, etc.). They practiced in keeping personal record of their work, for documentation (notes, etc.).

As the project proceeded, their self-confidence increased and they were willing to take initiatives and try things out by themselves. They progressively became less dependent on the class instructor for help and guidance. As they had to work their way through a series of decisions on design and implementation issues, they cultivated critical thinking and problem-solving skills.

The culmination of the project into successful constructions of prototype devices for each group boosted student self-confidence and self-esteem, and inspired them to engage in similar activities. However, students did not really cultivate their imagination and creativity, since all groups adopted an essentially identical design of new device Regulated PSU, with minor differences across groups.

4.6 Focus group intermediate evaluation

At the closure of Day 2, students were invited to hold a focus group (Manzano, 2022; Ansay et al., 2024) with the class instructor, in groups of 5 or 6. This was meant as a feedback to the instructor on student experience up to that point, in order to estimate whether any modifications to the original plan were needed. The topics proposed by the instructor for discussion, along with summarized student answers, are as follows:

1. *Topic-1 Strong points of the intervention (up to now):* Collaboration in a friendly/ polite/pleasant/supportive environment; Students help each other, learn from each other, exchange ideas and complement each other's skills; Positive emotions; Collegiality, non-competitive atmosphere.
2. *Topic-2 Weak points of the intervention (up to now):* Reading and understanding schematic diagrams of electric/electronic

circuits should be given more attention and time; Student should be introduced to the various types of electronic components before actually desoldering and extracting them from devices.
3. *Topic-3 Difficulties faced in practical tasks:* None reported; None reported regarding collaboration, either.
4. *Topic-4 Intention to engage in similar projects out of class:* Yes, if other assignments and study obligations allow for some free time.
5. *Topic-5 Make a pertinent comment:* "Lab sessions of other courses should be organized like that"; "1st year lab sessions, in particular, should be organized like that".

Student responses value the fact that the intervention runs smoothly in a collaborative, collegial and non-competitive atmosphere. The two points students raise under Topic-2 on "weak points", are valid and at the same time indicative of the interest and motivation of students to go deeper into the subject, that the intervention has inspired in them.

5 Results (Lab-II evaluation)

Lab-II is focused on student creativity which is measured following the same procedure as in Lab-I, on the basis of new devices designed and constructed by the 5 student groups of Lab-II. Evaluation of the learning outcomes of Lab-II across various domains is based on the following evaluation activities:

1. Creativity measurement on the basis of the artefacts created by each group.
2. Field observations by the class instructor.
3. Student group reports accompanying the constructed prototypes.

Results are presented in the following sections, organized per activity.

5.1 Creativity measurement

For comparability purposes, students were asked to jointly decide on a sole type of electronic device; each group would design and construct variations of this device. They were also required to use as many of the reclaimed functional electronic components available from the Analysis phase, as possible. Following a discussion of various alternatives held in the plenary, and taking in account reclaimed components, students decided to design and construct "a device with ventilation/fan plus light." At that point, students were discouraged to communicate among groups their ideas on the specific device to design and construct, in order to retain high levels of variety and novelty. Collaboration and exchange of ideas and help would restart after all groups had decided on their designs and submitted them to the class instructor.

The new devices conceived, designed and eventually constructed in the form of prototypes by each group are depicted in Figures 7. These are (A) room ventilator with soldering fume extractor, air freshener and light, (B) laptop cooling pad with Light-Emitting Diode (LED) light for the keyboard, (C) ventilator, digitally controlled by an Arduino and LM35, (D) personal head cooler with LED light, and (E) portable fan/cooler for camping tent, with LED light and a photovoltaic (PV)-rechargeable power bank for mobile phones.

5.1.1 Novelty (M_1 score)

Novelty is calculated as the weighted average of the scores achieved in the following 4 components or stages, identified by the authors acting as field experts on the taught subject: (a) casing, (b) fan rotation control, (c) light control and (d) power source. Each device is graded over 10 across these 4 components. Individual device scores and class averages can thus be calculated. The weights applied to each component are decided empirically, taking in account the functionalities of all 5 devices and the relative importance of the corresponding properties of an actual device:

a) Casing (40%): metal, wood, plastic and paper are the materials students used for the outer shell (casing) of their devices. Grades (3, 7 or 10 over 10) are assigned according to the complexity of the construct, the fitting between different materials and the quality of the result.
b) Fan rotation control (30%): this stage can be implemented through one of three alternative technologies, namely, (i) binary (on/off) control by switch or push button (3 over 10), (ii) fan control by a potentiometer and an LM317 IC regulator (7 over 10), (iii) PWM digital fan control by Arduino (10 over 10). Grades are assigned according to controllability and power efficiency of each solution.
c) Light control (20%): this stage can be implemented through one of three alternative technologies, namely, (i) binary (on/off) control by switch or push button (3 over 10), (ii) light control by a potentiometer and an LM317 IC regulator (7 over 10), (iii) PWM digital light control by Arduino (10 over 10). Grades are assigned according to controllability and power efficiency of each solution.
d) Power source (10%): this stage can be implemented through one of three alternative technologies, namely, (i) 12 V PSU extracted from a WLAN router (3 over 10), (ii) batteries (7 over 10), (iii) PV panel extracted from an outdoor lamp (10 over 10). Grades are assigned according to flexibility and power efficiency of each solution.

Artefacts are evaluated on this grid, along each of the 4 components, independently by the class instructor and by 2 lab assistants who are electronics engineering experts. Grades given to each artefact are not all unanimous, because of the subjective nature of the first component, in particular. In case of disagreement, the final grade is decided through discussion among the 3 evaluators. Grades are shown in Table 4, both per student group (artefact) and as class averages (Table 4, bottom row).

The class average Novelty is $M_1 = 5.92$ over 10, which constitutes a 45% increase over $M_1 = 4.51$ obtained in Lab-I.

5.1.2 Quality (M2 score)

Quality is calculated as the weighted average of the scores achieved in the following 4 components or stages, as identified by the authors: (a) portability, (b) usability, (c) reliability, and (d) robustness. Each device is graded over 10 across these 4 components. Individual device

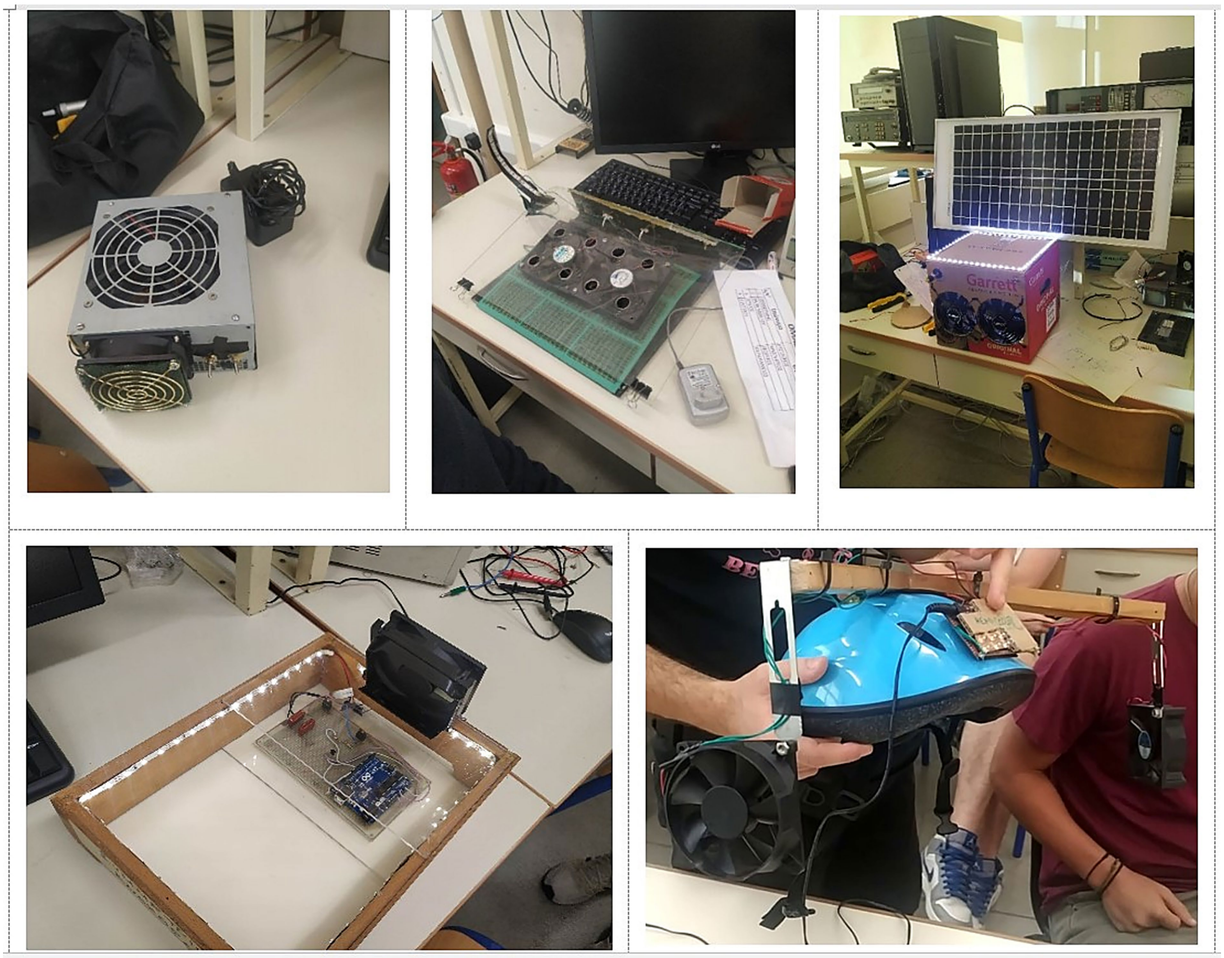

FIGURE 7
Lab-II device prototypes ("devices with ventilation/fan and light") designed and constructed by each student group (5 groups).

scores and class averages can thus be calculated. The weights applied to each component are decided empirically, taking in account the functionalities of all 5 devices and the relative importance of the corresponding properties of an actual device:

a) Portability (10%): grading of this component is quantized at 3 levels, 10 for high, 7 for medium and 3 for acceptable portability.
b) Usability (20%): grading of this component is quantized at 3 levels, 10 for high usability, 7 for medium usability and 3 for low usability.
c) Reliability (30%): grading of this component is quantized at 3 levels, 10 for high reliability, 7 for medium reliability and 3 for low reliability.
d) Robustness (40%): grading of this component is quantized at 3 levels, 10 for high robustness, 7 for medium robustness and 3 for low robustness.

Artefacts are evaluated on this grid, along each of the 4 components, independently by the class instructor and by 2 lab assistants who are electronics engineering experts. Grades given to each artefact are not all unanimous, because of the subjective nature of these 4 components. In case of disagreement, the final grade is decided after discussion among the 3 evaluators. These are shown in Table 5, both per student group (artefact) and as class averages (Table 5, bottom row).

Quality score $M_2 = 7.90$ over 10 is satisfactorily high, indicating that all artefacts are of adequate quality regarding portability, usability, reliability and robustness. Furthermore, it is slightly increased as compared to the $M_2 = 7.15$ over 10 score obtained in Lab-I.

5.1.3 Variety (M_3 score)

Variety is calculated as the weighted average of the same 4 components or stages as Novelty, and with the same corresponding weights: (a) casing (40%), (b) fan rotation control (30%), (c) light control (20%), and (d) power source (10%). Each of these 4 components is internally analyzed into a hierarchy of levels along which Variety is evaluated, namely, (i) the set of ideas, (ii) operation or construction principle, (iii) implementation, and (iv) construction details. For each level following the top one, scores are set with decreasing importance, to $S_1 = 10$, $S_2 = 7$ and $S_3 = 3$, so as to reflect the impact on Variety that differentiated choices at the corresponding level of the hierarchy may have.

TABLE 4 Lab-II creativity measurement – novelty (M_1 score).

Student group nr.	Casing	Fan rotation control	Light control	Power source	M_1 score (a-priori)
	40%	30%	20%	10%	
1	3	7	7	3	5.00
2	10	3	3	3	5.80
3	3	10	10	3	6.50
4	10	3	3	7	6.20
5	7	3	7	10	6.10
Class average over 10	6.60	5.20	6.00	5.20	5.92

a) Casing (40%): a decision tree is constructed with branches wherever different options are adopted by different student groups (Figure 8A). The total set of 5 ideas (as many as student groups in Lab-II) at top level 0 branches into 2 different operation/construction principles at level 1, namely, single-material casing (2 groups) or combined-materials casing (3 groups) ($S_{11} = 10$, $b_{11} = 2$); further down the tree, at level 2, the "single-material casing" node branches into 2 different implementations, namely, metal (1 group) or paper (1 group) while the "combined-materials casing" node branches into another 2 different combinations, namely, wood and plastic (2 groups) or paper and plastic (1 group) ($S_{12} = 7$, $b_{12} = 4$). Finally, at level 3, the "wood and plastic" node branches into 2 different construction details of 1 group each, with regard to a lightweight/portable construct ($S_{13} = 3$, $b_{13} = 2$).

b) Fan rotation control (30%): the decision tree is given in Figure 8B. The total set of 5 ideas at top level 0 branches into 2 different operation/construction principles at level 1, namely, analog control (1 group) or digital control (4 groups) ($S_{21} = 10$, $b_{21} = 2$); further down the tree, at level 2, the "digital control" node branches into 2 different implementations, namely, binary (on/off) control (3 groups) or Arduino-based control (1 group) ($S_{22} = 7$, $b_{22} = 2$). Finally, at level 3, the "on/off control" node branches into 2 different construction details, namely, push button (2 groups) or switch (1 group) ($S_{23} = 3$, $b_{23} = 2$).

c) Light control (20%): the decision tree is given in Figure 8C. The total set of 5 ideas at top level 0 branches into 2 different operation/construction principles at level 1, namely, analog light control by the LM317 IC (2 groups) or digital light control (3 groups) ($S_{31} = 10$, $b_{31} = 2$); further down the tree, at level 2, the "digital control" node branches into 2 different implementations, namely, binary (on/off) control (2 groups) or Arduino-based control (1 group) ($S_{32} = 7$, $b_{32} = 2$). Finally, at level 3, the "on/off control" node branches into 2 different construction details, namely, push button (1 group) or switch (1 group) ($S_{33} = 3$, $b_{33} = 2$).

d) Power source (10%): the decision tree is given in Figure 8D. The total set of 5 ideas at top level 0 branches into 2 different operation/construction principles at level 1, namely, conventional energy source (4 groups) or renewable energy source (a PV panel) (1 group) ($S_{41} = 10$, $b_{41} = 2$); further down the tree, at level 2, the "conventional energy source" node branches into 2 different implementations, namely, 12 V PSU extracted from a WLAN router (3 groups) or batteries (1 group) ($S_{42} = 7$, $b_{42} = 2$). Neither of these nodes did branch any further at level 3 ($S_{43} = 3$, $b_{43} = 0$).

According to the values in Figures 8A–D, the Variety score M_3 is calculated as:

$$M_3 = 10 * \sum_{j=1}^{4} f_j * \sum_{k=1}^{3} \frac{S_k b_k}{M_{3\max}} = 10 * \ldots * \left(\begin{array}{l} f_1 * \sum_{k=1}^{3} \frac{S_k b_k}{M_{3\max}} + f_2 * \sum_{k=1}^{3} \frac{S_k b_k}{M_{3\max}} + \\ f_3 * \sum_{k=1}^{3} \frac{S_k b_k}{M_{3\max}} + f_4 * \sum_{k=1}^{2} \frac{S_k b_k}{M_{3\max}} \end{array} \right)$$

$$= 10 * \left[\begin{array}{l} f_1 * \left(\frac{S_{11}b_{11}}{M_{3\max}} + \frac{S_{12}b_{12}}{M_{3\max}} + \frac{S_{13}b_{13}}{M_{3\max}} \right) + \\ f_2 * \left(\frac{S_{21}b_{21}}{M_{3\max}} + \frac{S_{22}b_{22}}{M_{3\max}} + \frac{S_{23}b_{23}}{M_{3\max}} \right) + \ldots \\ \ldots + f_3 * \left(\frac{S_{31}b_{31}}{M_{3\max}} + \frac{S_{32}b_{32}}{M_{3\max}} + \frac{S_{33}b_{33}}{M_{3\max}} \right) + \\ f_4 * \left(\frac{S_{41}b_{41}}{M_{3\max}} + \frac{S_{42}b_{42}}{M_{3\max}} \right) \end{array} \right]$$

$$= 10 * \frac{1}{50} * \left[\begin{array}{l} 0.40 * (10*2 + 7*4 + 3*2) + \\ 0.30 * (10*2 + 7*2 + 3*2) + \ldots \\ \ldots + 0.20 * (10*2 + 7*2 + 3*2) + \\ 0.10 * (10*2 + 7*2) \end{array} \right]$$

$$= 0.2 * \left[\begin{array}{l} 0.4 * (20 + 28 + 6) + 0.3 * (20 + 14 + 6) + \\ 0.2 * (20 + 14 + 6) + 0.1 * (20 + 14) \end{array} \right] = 9.00,$$

where:

- f_1 = 40% = weight of casing component, f_2 = 30% = weight of fan rotation control component, f_3 = 20% = weight of light control component, f_4 = 10% = weight of power source component.
- M_{3max} = maximum Variety = 5 ideas X 10 top score each = 50.

TABLE 5 Lab-II creativity measurement – quality (M_2 score).

Student group nr.	Portability	Usability	Reliability	Robustness	M_2 score (a-priori)
	10%	20%	30%	40%	
1	3	7	10	10	8.70
2	7	7	10	3	6.30
3	3	7	10	10	8.70
4	10	10	10	7	8.80
5	10	10	10	3	7.20
Class average over 10	6.60	8.20	10.00	6.60	7.90

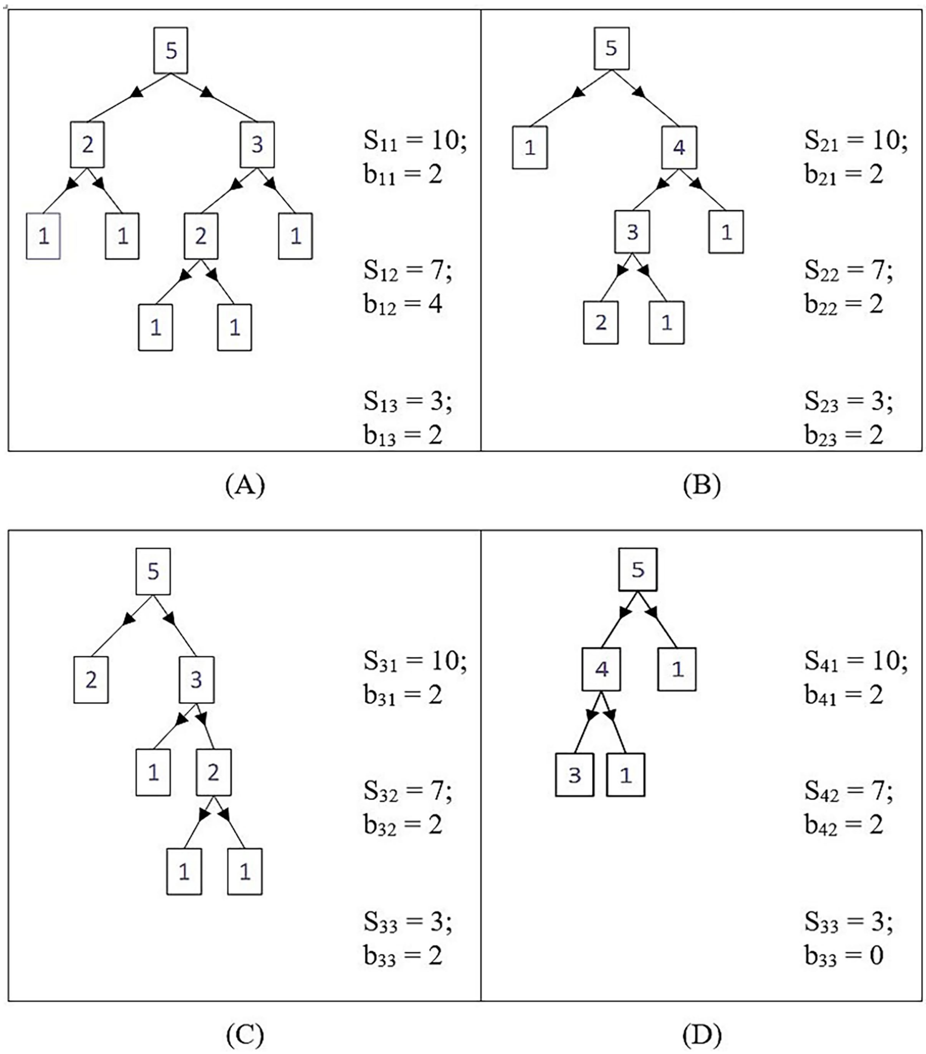

FIGURE 8
The hierarchical trees of choices that decide variety by the degree of branching $\{b_{ij}\}$ at each level j = 1, 2, 3 of the corresponding component i = 1, 2, 3, 4. **(A)** Casing component (i = 1, weight 40%), **(B)** fan rotation control component (i = 2, weight 30%), and **(C)** light control component (i = 3, weight 20%), and **(D)** power source component (i = 4, weight 10%).

Multiplicative factor of 10 is used in order to normalize the maximum M_3 score to 10.

The M_3 score of 9 over 10 constitutes a spectacular increase over $M_3 = 1.14$ calculated in Lab-I (almost 8 times higher or 800%). Figure 8 reveals that this is due to the distinct choices of all student groups across practically all 4 components, and along all the levels of the decision tree hierarchy in Figure 8 (set of ideas, operation/construction principle, implementation, construction details).

5.1.4 Quantity (M_4 score)

Quantity score is the total number of artefacts; here, this equals the number of devices designed and constructed by the student groups, which gives $M_4 = 5$.

5.1.5 Overall creativity score in Lab-II

Following the same rationale as in Lab-I (Section A.5), the overall creativity score in Lab-II is reported as CS-II = {M_1 = 5.92 over 10.0; M_2 = 7.90 over 10.0; M_3 = 9.00 over 10.0; M_4 = 5}.

For comparison purposes, Table 6 gives the differences per metric, in absolute numbers and percentages.

The 3 first metrics are increased in Lab-II as compared to Lab-I. Variety is increased by +7.68 over 10.0 (+690%), Novelty by +1.41 over 10.0 (+31%) and Quality by +0.75 over 10.0 (+10%). These encouraging results are the outcome of modifications decided and put in effect by the class instructor in Lab-II, based on the experience gained in Lab-I. In particular, in the beginning of Lab-II, a discussion was held in the plenary, where students were discouraged to circulate ideas among them during the incubation phase, in order to avoid all groups unintentionally converging to similar designs. In view of that policy, groups of 3–4 people each were formed in Lab-II, whereas groups in Lab-I consisted of 2 people each. The value of creative thinking was stressed and students were encouraged to discuss ideas in their respective groups but not among groups at that point. The outcomes have "rewarded" this modification, as shown by the increased 3 metrics in Table 6. On the other hand, the same policy had the side effect of decreasing the Quantity metric (M_4 score) from 7 in Lab-I to 5 in Lab-II (−2 or −28%): in order to increase the group size and guarantee a spectrum of ideas within each group, the 19 volunteers of Lab-II were grouped into 5 groups of 3–4 people each.

5.2 Lab-II field observations by the class instructor

Field observations by the class instructor, in the form of personal notes kept during each day of Lab-II intervention, are summarized as follows:

5.2.1 Practical skills (use of tools) and critical thinking – problem solving

Students used A.I. tools (Google Gemini) to get help and advice on various design and implementation issues. Prompts included:

1. How to control fan rotation speed by temperature (Arduino coding).
2. How to improve a circuit design.
3. How to select materials for a PV-powered portable fan.
4. How to calculate power efficiency of a PV-powered portable fan.

It is quite interesting that students critically considered the answers provided by the A.I. tool, and rejected some of them after discussion and justification. For example, in case 2 above, they examined the alternative (supposedly, improved) circuit design proposed by the A.I. tool and altogether rejected it, because of the obviously wrong placement of components it proposed. In case 3 above, they cross-validated the list of materials proposed by A.I. with the class instructor and resorted to Internet sources and their own ideas, thus producing a modified final list.

It may be claimed that the role of the A.I. tool was auxiliary; student knowledge and experience gained during Lab-I, independent Internet search, student imagination and the advice of the class instructor had more impact on their decisions than the A.I. tool advice.

While A.I. tools are already revolutionizing modern education, involved parties continuously discover new opportunities and challenges these tools bring about (Han et al., 2023). The discussion on how A.I. should be incorporated in Higher Education is loaded with concerns on ethical and pedagogical issues raised by such a development, e.g., Nguyen (2025). Positive aspects of the pedagogical role of A.I. reported by relevant research, such as personalized learning, student engagement and motivation, immediate feedback, aid in creating and updating learning content, more inclusive and accessible education, and – most importantly – fostering critical thinking and creativity, are coupled with calls for careful and balanced steps towards A.I. tools that will aid teachers and learners, enhance equitable access to knowledge and extend human competencies rather than replacing them (Toksha et al., 2022; Oneţ, 2025). The need for a pedagogy ensuring that AI complements traditional learning, the need to safeguard academic integrity, and the need for users with critical thinking skills are stressed by researchers and education practitioners alike, e.g., Nguyen (2025). Although a detailed discussion of this topic is beyond the scope of the present study, it is certain that all stakeholders in education follow relevant developments with great interest and concern.

5.2.2 Social skills

Quality of student communication and collaboration in Lab-II was as high as in Lab-I.

"Veterans" were very serious and responsible in their role of introducing "novices" to the concept, aims, tools and procedures of the project. They took time to explain, let novices fail and retry, and correct them tactfully. This behavior was exhibited during the first part of Lab-II; when novices gained a certain confidence and felt as central group members, the veterans shifted to the role of active and equitable members, collaborated equitably with the novices.

Novices felt safe to work under the "shield" of the more experienced veterans and were very positive in receiving advice, help, corrections and feedback from them.

The setup was very productive, in the sense that a certain flow of knowledge and experience from veterans to novices did take place, as

TABLE 6 Comparison of Lab-I and Lab-II results across the 4 metrics of creativity.

Creativity metric (class average)	Lab-I score	Lab-II score	Lab-II – Lab-I difference (%)
Novelty (M_1 score)	4.51 over 10.0	5.92 over 10.0	+1.41 (+31%)
Quality (M_2 score)	7.15 over 10.0	7.90 over 10.0	+0.75 (+10%)
Variety (M_3 score)	1.14 over 10.0	9.00 over 10.0	+7.86 (+690%)
Quantity (M_4 score)	7 devices	5 devices	−2.00 (−28%)

manifested by the fluent communication, discussions, exchange and debate of ideas, comments, thoughts and feedback between the two groups.

5.2.3 Metacognitive skills

Student creativity was the major result that was evident during Lab-II. The absence of competitiveness was certainly helpful in that aspect. Student groups formed their proposals for new devices through brainstorming, Internet search and consideration of A.I. proposals. Pluralism was greatly increased as compared to Lab-I.

The high quality of the results gave a great boost to self-confidence, self-esteem and the sense of self-efficacy of all students, men and women. Discussions among them revealed their motivation to engage further into such projects, either as intra-or extra-curricular activities, in order to learn more and get more experience in the subject. A few students placed the skill obtained under a professional perspective.

5.3 Student reports

As a result of a proposal by the class instructor rather than a strict requirement, students of 3 out of the 5 groups in Lab-II included a paragraph in their final reports, where they summarized their perceived experience, knowledge and skills obtained, and lessons learned out of their participation in this project. A qualitative analysis of their texts identifies the following major topics, organized across domains in the list below (the numbers in brackets indicate the number of appearances of this answer):

1. Cognitive Domain:
   - Acquired knowledge on hands-on tools, on Internet search tools, on getting help from A.I. tools; Gained a lot of knowledge on the subject; Learned how to reclaim and reuse components; Try to repair first and then recycle; Proper recycling of e-waste beyond repair, as an engineering "duty" to protect the environment and promote cyclic economy [4].
   - Knowledge discovery by the student; Learned how to perform independent and focused search across different information sources [2].

2. Social/emotional domain:
   - Collaboration, allocation of tasks, team spirit; The choice of new device to be constructed was the result of group discussion and agreement [5].
   - Old members (veterans) offered new members (novices) practical help and guidance regarding tools and procedures; New members (novices) were given the time to get familiar with tools and procedures; Students learned things from other students [2].

3. Metacognitive domain:
   - Creativity; Novel/unique idea on a new device; Be creative and inventive [3].
   - Problem-solving skills—tackle unexpected problems; Work out solutions for unexpected problems [2].
   - Time organization; (Better) time management [2].
   - Mutual respect [1].
   - Self-imposed discipline [1].
   - Critical thinking development [1].

6 Discussion

6.1 Research question 1

> "What is the effectiveness of the proposed educational method in developing student cognitive skills (a) at the basic level and (b) at higher levels?"

Quantitative results presented in Figure 3 show measurable student gains in the cognitive domain. Student answers given in Table 1 (Question 7) along with field observation by the class instructor convey the same positive view from a qualitative aspect. Student responses given in Table 1 (Question 6) reveal raised environmental awareness in all students as they all mention one or more of the 3 actions {check device functionality and try to repair; extract components; properly recycle} while, most importantly, half of them clearly referred to these 3 actions not as independent ones but as one composite "if-then-else" mind construct.

Student gains as to higher-level knowledge and skills are documented by the successful collaborative authoring of the Semiconductor Measurement Guide and the PSU Repair Flow Chart (Figures 4A,B, respectively). These quality outcomes along with field observation by the class instructor and student responses given in Table 1 (Questions 3 and 8) reveal the development of skills such as independent and focused information retrieval, critical and analytic thinking, problem-solving, creativity, synthesis and presentation.

6.2 Research question 2

> "What is the effectiveness of the proposed educational method in developing student social/emotional skills?"

Student gains on the social domain are documented through the open-ended evaluation outcomes (Figure 4), field observation by the class instructor, as well as student responses given in the Feedback questionnaire of Table 1 (Questions 1, 3 and 8) and in the focus group discussion (Section 4.6, Topic-1). The social skills developed are primarily collaboration, communication/presentation, helping each other and learning from each other, collegiality and team spirit. Collaboration ("smooth collaboration"), in particular, is the top student answer both in Questions 3 (8 out of 16 students) and 8 (3 out of 16 students) of Table 1 as well as in Topic-1 of Section 4.6.

Furthermore, students report positive emotions at the end of Lab-I, an outcome that is verified by the observations of the class instructor during both Lab-I and Lab-II. Student answers in Table 1 (Question 4) and in Section 4.6 (Topic-1) reveal a pleasant, non-competitive climate in class that elicits positive emotions in all but 1 student, who reports neutral emotions. It is important that no negative emotions are reported or observed.

6.3 Research question 3

> "What is the effectiveness of the proposed educational method in developing student metacognitive skills (motivation, confidence,

> self-regulated learning and adoption of personal learning strategies)?"

Student gains in the metacognitive domain can be deduced by their answers in Table 1, Question 5, where the majority refers to inspiration to engage in similar activities out of class – and, in fact 4 out of 16 students had already done so; in Table 1, Question 10, that reveals strong (100%) student motivation for study and learning, for going deeper into the subject, and for engaging in additional activities of the same type; in Table 1, Question 2, where students state having face difficulties "only in the beginning" thus revealing increased self-confidence as the intervention proceeded; in Table 1, Questions 3 and 7, where students mention creativity and the design of new devices as major gains; in Table 1, Question 8, where autonomous and focused search and retrieval of information, critical and analytic thinking and personal effort/ diligence are considered by the students as their major gains. This last point indicates that students are led through the interventions to recognize their own personal learning style and preferences and to shape their own approach to learning (self-regulated learning). Student initiatives and student control over learning pace and learning path are integral parts of the proposed educational method. Indeed, students are encouraged by the class instructor to function autonomously and undertake initiatives, to brainstorm, to discuss and compare alternatives, to search and retrieve information, to collaborate and learn through trial-and-error cycles. As the intervention proceeds, student dependency on the class instructor gradually decreases while their autonomy, self-confidence and eventually their self-esteem gradually increase.

The class instructor's field observations indicate that the interventions did raise student awareness on sustainability and green practices, such as extracting and reusing components instead of recycling complete devices. This is an experiential approach that teaches notions of sustainability and cyclic economy through practice instead of theoretic study, definitions and examples.

6.4 Research question 4

> "What is the effectiveness of the proposed educational method in developing student creativity?"

Results of creativity measurements both in Lab-I (Section 4.4) and Lab-II (Section 5.1) indicate that the proposed method has a strong potential in developing engineering students' creativity. Furthermore, the specific measurement method adopted here is capable of quantifying creativity along 4 independent metrics, namely, Novelty, Quality, Variety and Quantity. This is valuable in order to steer and focus educational interventions towards specific goals, e.g., towards increasing Variety or Novelty.

Quantitative measurements given comparatively in Table 6, on the other hand, constitute a warning for the sensitivity of the results to the methodology adopted and the rules set during action. For example, if the modifications mentioned in Section 5.5 were not decided and put in effect in Lab-II, a creativity score in Lab-II as low as that in Lab-I would be highly probable. After all, "copying" or "mimicking" successful examples of others, such as ideas, designs or implementations, is a valid method for learning – especially for novices, who try to get started in a new area or field or task. The "copying" phase may possibly offer them that minimum level of confidence needed before engaging in more demanding and risky tasks of novel designs of their own.

A closer look into the proposed method would ascribe the positive results obtained along the creativity axis to the following essential features of the method, as implemented in Lab-II:

- Students were given a problem and a goal but not the solution, either complete or as a rough sketch. They were encouraged to search across available sources, discover necessary pieces of knowledge and construct the solution on their own.
- Students started their journey by a brainstorming session held in the plenary, and continued with subsequent brainstorming sessions held within each group. These sessions allowed for ideas to be generated, shared, shaped, debated, rejected or modified.
- The schedule of the intervention (one lab session per week) allowed students the critical amount of time between session for:
    - o The *incubation* of their ideas.
    - o The *illumination or "a-ha! moment"*, where each group conceived the idea for an artefact to design and construct.

  Students had time to collaborate remotely between sessions, to search and discover missing pieces of information and knowledge, either over the Internet or via prompting an A.I. tool, hold online discussions and jointly "coin" a solution.

- From the *illumination* phase onwards, students were discouraged to exchange ideas between groups, in order to preserve the original variety in the group solutions and designs.
- The rich variety of components and raw materials made available to the students, thanks to their extraction from EOL devices at no cost, triggered their imagination and inspired them to propose and test a multiplicity of combinations, leading to novel designs.
- The participation of a "veteran" member in each group created an atmosphere of safety for the novices; this motivated them to experiment and allowed their imagination to flourish.

6.5 Research question 5

> "Can this type of educational intervention create a Community of Learning and, further on, instigate a Community of Practice of students on the subject?"

Collaborative learning is the broader term used today to collectively refer to learning in groups as opposed to individual learning, as formalized by the socio-cultural theories of learning (Lave and Wenger, 1991). Examples include peer learning, peer tutoring, peer-assisted learning, cooperative learning, and communities of learning (CoL) (Yang, 2023). CoL, in particular, are formed within educational environments, formal or informal; they may be interest-or action-or location-or profession-based and may focus on conceptual, factual or procedural knowledge. CoL may involve teachers and/or students and/or administration staff. Student Learning Communities (SLC) in particular, refer to groups of students who share learning goals and collaborate to achieve them.

On the basis of Lab-I and Lab-II results and field observations by class instructor, as presented in Sections 4 and 5, it may be claimed that indeed both Lab-I and Lab-II have succeeded in creating a CoL, since they meet all 6 major characteristics of a CoL (NIU Center for Innovative Teaching and Learning, 2012), as itemized in Table 7. Table 7 implies a positive answer to the first part of RQ5 as it offers an indication rather than a "proof" that interventions of this type have the potential to create a CoL.

On the other hand, Communities of Practice (CoP), a term defined by Lave and Wenger (1991), refer to "groups of people who share a concern or a passion for something they do and learn how to do it better as they interact regularly" (Wenger, 1998). The 3 crucial elements that identify a group of people as a CoP are the domain, the community and the practice. CoP are primarily conceived as groups of professionals who voluntarily meet and participate in activities and exchange knowledge and experience related to their profession. Furthermore, they invite and welcome novices and help them develop into skilled, "central" members. In Education, e.g., a CoP would be formed by teachers seeking to improve their teaching efficiency. Other types of CoP are nevertheless possible. Learning by doing is essential in CoL; it is a necessary but not sufficient condition in CoP, however (Rettler-Pagel, 2023). The additional ingredient needed to transform a CoL into a CoP is situated learning (Lave and Wenger, 1991).

Of interest here is the fact that a CoP does not emerge only as an initiative of professionals. It may also "evolve from a learning community regarding a group of newly trained people who continue the collaborative experience even after the end of the training course" (EPALE, 2023). Along this line, it may be argued that interventions of the Lab-I/Lab-II type may inspire a long-term interest in students, as implied by their answers in Questions 5 and 10 of the Feedback Questionnaire (Table 1), and further on may instigate a CoP of students on the subject, the latter expected to evolve out of the CoL and extend beyond the study period. In fact, of the 3 essential elements of a CoP, the *domain* is clearly present here (that of electronics and the reclaiming/reusing of electronic components from e-waste) as well as the *community* (as supported by student answers in the Feedback Questionnaire in Table 1). Practice however is an element that would need more time to mature, for the CoP to fully emerge. Consequently, a longitudinal study would be needed to back up a positive answer to the second part of RQ5 with evidence.

A final point worth discussing in the context of RQ5 has to do with student roles. Each group in Lab-II included at least one Lab-I participant, called a "veteran", as well as at least one "novice". All Lab-I and Lab-II students belong to the same cohort (year of study); experience gained during Lab-I, however, gave the "veterans" a clear advantage. It was interesting to see how they would use it. A careful examination of relevant literature shows that what actually happened

TABLE 7 Lab-I and Lab-II evaluation results along the 6 major characteristics of a CoL.

Nr.	Major characteristic of a CoL	Lab-I and Lab-II evaluation results
1	Voluntary membership	Both Lab-I and Lab-II participants responded to an open call for volunteers
2	Shared goals, objectives, values and vision	Although educational goals and objectives were set by the instructor and included in the call, students' answers verified that they adopted these goals and furthermore, they developed a common vision: In Feedback Questionnaire (Table 1) – Question 10, for example, all 16 students state that they intend to continue along this path to gain more knowledge and experience and enhance their skills, as they expect such skills to be demanded of them in the future (Question 9). During focus group discussion (Section 4.6), the fact that they all express similar views on the knowledge and experience gained (Topic-1 on "strong points") and on the requests for more (Topic-2 on "weak points") is another indication of the development of shared goals, objectives and vision. Common values, on the other hand, is an aspect that would need more time in order to grow in the group and become observable/assessable. Certain points made in student reports (Section 5.3) are an indication of such common values starting to form.
3	Connectedness, trust and mutual respect (a safe and secure learning environment where members feel free to discuss issues)	Students have unanimously referred to having experienced such an atmosphere, in Feedback Questionnaire (Table 1) – Question 1 (collaboration), Question 3 (smooth collaboration, solidarity, mutual understanding, team spirit and collegiality), Question 4 (very pleasant feelings) and Question 8 (collaboration), in focus group discussion (Section 4.6) – Topic-1 (collaboration in a friendly/polite/pleasant/non-competitive atmosphere), and in student reports (Section 5.3), where decisions reached after discussion, learning from each other, and mutual respect are mentioned.
4	Supportive environment	Students have expressly referred to the supportive environment created in the lab, in Feedback Questionnaire (Table 1) – Question 8 (help and support among peers, collegiality), in focus group discussion (Section 4.6) – Topic-1 (collaboration in a supportive environment; students help each other; collegiality; non-competitive atmosphere), and in student reports (Section 5.3) where students describe how the "veterans" have scaffolded the "novices"
5	Open communication (certainly, no anonymity) including problems, ideas, solutions, feelings and thoughts	The free and continuous communication among students is a major field observation by the instructor. Furthermore, students refer explicitly to communication in Feedback Questionnaire (Table 1) – Question 8 (communication) and in focus group discussion (Section 4.6) – Topic-1 (exchange of ideas).
6	Instructor, when there is one, acting as a facilitator	The class instructor set the educational goal and objectives and introduced students to them in the Introductory session. He set the stage (lab space, equipment, tools, EOL devices for disassembly, etc.) to facilitate student interaction and collaboration. He was present in all Lab-I and Lab-II sessions and made field observations during them. He coordinated evaluation tests and activities. He did not teach students, however; rather, he directed them to search for the necessary pieces of knowledge to complete their tasks. Student reports (Section 5.3) verify that behavior by omission: all references are to student, rather than teacher, actions and initiatives.

does not exactly fall under any of the major existing categories of peer tutoring (Griffiths et al., 1995; Topping, 1996), peer coaching (Joyce and Calhoun, 2018; Le et al., 2024), peer mentoring (Boillat and Elizov, 2014), peer learning (Topping, 2005), or peer-assisted learning (PAL).

- In PAL, learning is facilitated and supported by other, more advanced or skilled students, the peer leaders or peer coaches, e.g., Bugaj et al. (2019) and Siddiqi et al. (2020). In the present case, the "veterans" acted as peer coaches and scaffolded the "novices" with practical and technical help and advice, yet only in the beginning of Lab-II. The "veterans" soon shifted to the position of active groups members, and collaborated with all other members at equal terms to complete the project and be evaluated for it.
- If "veteran" behavior is compared to peer tutoring – "same level peer tutoring with unequal status", in particular (Falchikov, 2001) – is does not strike a match, either. Tutors are not directly involved themselves in the same learning process or activity as their tutees, who are younger and less competent.

Consequently, despite the different student roles within Lab-II groups, the overall functionality remains compatible with a CoL rather than PAL or peer tutoring.

6.6 Discussion on the limitations and the replication of this study

The present study suffers certain limitations resulting mainly from practical constraints. The two major limitations in the educational intervention are (i) the small sample size, and (ii) the absence of a control group. The latter limitation, in particular, renders this study a *quasi*-experiment rather than a *pure* experiment and characterizes the results obtained as indications rather than proofs (Cohen et al., 2018). The practical constraints that dictated the particular organization of the study are (i) the number of students who volunteered, and (ii) the need for a minimum number of groups and students per group for the creativity measurement to be meaningful. The subset of volunteering students that qualified for participation was not enough to form two equivalent sets and use one as the control group and the other as the experimental group. Future research with a large student group is therefore necessary in order to verify that results obtained are ascribed solely to the proposed method and not to other intervening factors. A point worth discussing is what the conventional education method to be used in the case of a control group should amount to. Volunteering students of the present study come from an EEE curriculum that does not include collaborative learning and where hands-on laboratory student practice is directed and supervised; in most of the cases, students are expected to put together electrical/electronic circuits and take measurements to verify theoretically expected outputs. They are not given the space, tools and initiative to design and construct new devices. It would take a reform of the current curriculum and the inclusion of more student-centered, open-ended activities before creativity of the control group could be measured.

In case this study is to be replicated in its current form, for verification purposes, or applied with modifications or extensions made to address any of the limitations mentioned above, the following steps are outlined as a guide for the class instructor:

1. Define the curriculum and the subject that will host the intervention; define student participation/selection criteria (e.g., background knowledge on the subject, grades in prerequisite courses, etc.) and the way student groups are to be formed (not homogeneous, use "veterans" and "novices", if applicable).
2. Select students; brief them on the purposes of the study; obtain their written informed consent.
3. Secure suitable lab space with a big collaboration table in the middle and a whiteboard with a projector, for use in brainstorming sessions; secure enough work stations, one for each group, each station equipped with a computer, tools and measurement equipment.
4. Collect and store as many and as various devices at EOL as possible.
5. Schedule the intervention in periodic lab sessions; allow some time between sessions (e.g., one or two sessions per week).
6. Prepare learning content, manuals, etc., as well as evaluation material (tests, open-ended activities, rubrics or other evaluation scales) in electronic form; upload it in an asynchronous e-learning platform; enroll students in the electronic class.
7. Regarding creativity measurement, study the SVS methodology and then define in detail all components to be evaluated in order to measure Novelty, Quality and Variety, along with the weight of each component, as in sections 4.4 (Lab-I) or 5.1 (Lab-II).
8. Secure the help of 1 or 2 lab assistants for objective evaluation; brief them and get them acquainted with the method and tools.
9. Implement the educational intervention including evaluation; advice students to keep personal notes during sessions for reflection and reporting.
10. Analyze collected data and obtain results.

Although the replication of any educational intervention is inevitably prone to variations, due to fact that education is a social science rather a pure science, the above guidelines are expected to minimize the effect of variations on the results and achieve a fairly accurate replication.

7 Conclusion – further research

A novel educational method to experientially introduce engineering students to notions of sustainability, recycling and the cyclic economy is proposed and evaluated in this paper. The proposed method is tested with EEE undergraduate students who work in groups in a hands-on lab to disassemble devices at EOL stage, reclaim electronic components and reuse functional ones either to repair damaged devices or to design and construct new devices. Student gains in the cognitive domain as well as the social/emotional and metacognitive domains are assessed, with a special interest in creativity. Positive results of varying degrees are obtained across all 3 domains, as documented by the outcomes measured in both lab parts of the intervention. Although gains in the cognitive domain are more straightforward to measure and document, e.g., Figures 3, 4, gains in the social/emotional and metacognitive domains, including creativity, are considered as the most valuable result of this study.

Despite the limitations discussed in the previous section, outcomes of this study are strongly encouraging as they indicate the potential of the proposed method in changing student attitudes as to the handling of damaged devices, devices at EOL stage and e-waste. Student creativity, in particular, is seen to flourish within the right environment and procedures. A more extensive deployment and evaluation of the proposed method, with larger student samples and possibly a control group, is certainly needed before its strong and weak points be fully understood and its possible shortcomings be addressed.

A weak point in the way the proposed method was applied here is uni-disciplinarity. Indeed, both Lab-I and Lab-II interventions were organized within the EEE faculty, discipline and curriculum; therefore, it cannot be claimed that they promoted inter-or trans-disciplinarity principles in the students. As mentioned in the Introduction section, these properties are considered as essential ingredients for successful educational interventions of the present type. Future research should address that point, given that the proposed method is not uni-disciplinary in its essence. At a first level, an inter-disciplinary extension of this method would draw students from more than one curriculum and form joint groups. Examples of suitable inter-disciplinary engineering projects are robotics (electrical/electronics and mechanical engineering), sensor networks for precision agriculture (electrical/electronics, environmental and chemical engineering), wearable devices (biomedical, electrical/electronics, materials and textiles engineering), drones (electrical/electronics, mechanical and surveillance engineering), etc. The Analysis-Synthesis basic structure of the proposed method can be embedded in any one of these example projects to enrich them with the concepts of sustainability through reclaiming and reusing functional components. Creativity can also be embedded in these projects, through the innovative design and construction stream of the proposed method. At a second level, trans-disciplinarity could possibly arise out of such inter-disciplinary projects, if students are motivated and inspired to produce something essentially new and innovative.

Finally, of great interest is the potential of the method to inspire the students and instigate a community of practice among them, that could last beyond the extent of their current study program. While this article is being written, a group of students (all Lab-II participants) are already meeting and discussing how to launch their next similar project, this time out of their own free will and intrinsic motivation rather than a call by their teachers.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Research Ethics Committee (R.E.C.) of the University of West Attica, Greece, Act 27th/04-10-2024, Decision number 88436-11/10/2024. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

NN: Formal analysis, Conceptualization, Data curation, Writing – original draft, Investigation. MR: Conceptualization, Methodology, Supervision, Writing – review & editing. GL: Validation, Supervision, Methodology, Writing – review & editing, Conceptualization. PS: Writing – review & editing, Validation, Methodology.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

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