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Introducing Green, Eco-Friendly Practices and Circular Economy Principles in Vocational Education Through a Novel Analysis-Synthesis Method: Design, Implementation and Evaluation

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Abstract

Purpose: A novel, Project- and Collaborative Learning-based educational method is proposed, implemented and evaluated in this paper. The aim is to exploit hands-on laboratory modules in Vocational Education in order to experientially introduce students to green, eco-friendly practices and the principles of sustainability and circular economy. Besides their apparent individual and social benefits, such knowledge and skills are also expected to raise qualifications and employability of Vocational Education graduates.

Methods: The proposed method is tested through a quasi-experimental methodology, via an educational intervention with a class of Vocational Lyceum students, in the field of Electrical and Electronics Engineering. The learning content focuses on the reclaiming and reuse of operational components from damaged electrical/electronic equipment at end-of-life stage. Through repeated Analysis and Synthesis phases, students learn to extract, measure, classify and reuse operational components either to repair similar equipment or to design and construct novel devices.

Results: Evaluation is carried out via closed and open type activities as well as by observation sheets of the teacher. Learning outcomes are evaluated through knowledge post-tests of the

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closed type while social/emotional outcomes are evaluated through questionnaires. Evaluation results indicate that the proposed method does produce cognitive and social/emotional skills gains for the students. The development of metacognitive skills and the stimulation of imagination and innovative thinking in the students is also observed by the teacher, but not formally evaluated due to practical constraints.

Conclusions: The proposed method is implemented and pilot-tested with positive results both as to the cognitive and as to the social/emotional domain – yet, these results are of an indicative value, due to the limited scale of the educational intervention. Future research is necessary in order to evaluate the proposed method in extent and possibly compare results across education grades or engineering fields, as the method is generic enough to be easily adaptable for different ages/grades and engineering/technical fields of study.

Keywords: Outcomes of Vocational Education and Training, VET, Technical Education, Educational Innovation, Learning Method, Experiential Learning, Green skills

1 Introduction

Educational systems have always been in dialog and interaction with their contemporary societies and the prevailing economy and production/industry systems in them. The chief motivation for the current research stems from the following major developments observed in society, economy and (vocational) education during the last 20 years:

The Industrial Society era has left us with a grave degradation of the quality of the natural environment and an exhaustion of natural sources to an extent that threatens life on planet Earth, at least as we know it. The Knowledge Society era that followed, is critically dependent on Information and Communication Technology (ICT) and the multitude of devices that support it; as a result, an unthinkable volume of e-waste is being produced at an increasing rate. Environmentally friendly science, technology and production/industry have urgently been sought by the end of the 20th century, in an attempt to stop and reverse this path (Kang et al., 2013). The 'green' / 'think globally – act locally' movements have extended these demands to the social and eventually the political level. R*ecycling, end-of-life equipment, waste management, environmental footprint, green practices, sustainable development* and recently *circular economy* are terms that have dominated the social discourse, e.g., (European Parliament, 2015) and have made their way into educational programs (e.g., 'Environmental education', 'Environmental Engineering', 'Sustainability and Circular Economy' study programs, etc.) (Laurent, 2015). The exhaustion of conventional, non-renewable energy sources has early become a top priority of these efforts.

Globalization along with local warfare and other disasters has resulted in a series of crises at the planet level, the refugee waves being a conspicuous example. Moreover, because of globalization the economic crisis of 2008 rapidly swept economies world-wide throwing the global economy in an instability and recession phase it has taken long to overcome. The Covid-19 pandemic that followed in 2020, along with the Russian invasion in Ukraine in 2022 and the great energy and food crises it has brought about (Association of the Mediterranean Chambers of Commerce and Industry, 2022; Meredith, 2022), have also had severe economic and financial consequences world-wide as recognized in (United Nations, 2010, 2013, 2020; World Economic Forum, 2022). On top of being exhaustible, energy from conventional, non-renewable sources is now getting 'rationed' and very expensive, making energy savings an imperative. The concepts of recycling, sustainable development and circular economy obtain an increased importance because of these events (Kiddee et al., 2013). Attention is now shifted to repairs than replacement, to sharing than owning, to reusing than building from scratch (i.e., from raw materials), as reflected in recent EU legislation (European Parliament, 2021). As the production model is changing, education, especially technical education and VET, is (and can be used as) a critical asset in the process (European Commission, 2020). Indeed, the 17 Sustainable Development Goals (SDGs) declared by the United Nations are accompanied by a compilation of suitable educational resources for all education grades, (United Nations Educational, Scientific and Cultural Organization [UNESCO], n.d.).

Among the various issues brought up by the international community of researchers on Education, an important one has to do with the discrepancy detected between the output of Vocational Education and Training (VET) and the requirements or expectations of the job market: Indeed, job market complains that the available human resources, even the highly qualified layers, lack indispensable knowledge, skills and competences (Joynes et al., 2019; Roll & Ifenthaler, 2021; Tran, 2021). Researchers find out that modern undergraduate curricula fail to align with the job market needs, as they should according to the Bologna process – a finding which predicts that the aforementioned discrepancy will remain or even deepen (Baethge & Wolter, 2015). A possible explanation is that typical education is not flexible enough to catch up with an ever-accelerating technological progress. The need to reform VET curricula and strengthen apprenticeship-like forms of learning is stressed by Baumann and Vossiek (2022), among others, in the aftermath of Covid-19 crisis. On the other hand, students or learners of any age in their everyday life become apt users of modern technologies as soon as the latter reach the commodity level. A window of opportunity opens up at this point: Could Education build on these skills and motivate students to further cultivate them to the expertise/professional level – and how? Quite relevantly, in 2018 OECD (Organization for Economic Cooperation and Development) has launched 'The Future of Education and Skills 2030 project' to answer (1) *'what knowledge, skills, attitudes and values will today's students need to thrive and shape their world? '* and (2) *'how can instructional systems develop these effectively?'* (OECD, 2018).

A closer look into the knowledge, skills and competences deemed necessary reveals the three-fold aim for cognitive as well as social/emotional and metacognitive skills. In fact, it is in the last two categories, often collectively described as '21st century', 'higher order' or 'horizontal' skills, where the higher deficiencies are detected: Both academic education and VET fail to provide the job market with graduates that can communicate effectively their ideas, collaborate smoothly in teams, solve problems through analysis and synthesis, think critically and innovatively, be creative, take initiatives and lead groups (Schwendimann et al., 2018). Empathy, self-efficacy and the ability to self-regulate one's own learning are also highly desirable emotional/metacognitive skills in the era of lifelong learning (Ahmid et al., 2023; Karably & Zabrucky, 2009). All these are the essential components of the '21st century learning compass' compiled by OECD (OECD, 2018). In the Society of Knowledge, these skills should ideally be developed during K-12 education and then be strengthened and exploited in academic and VET curricula (Papert, 1980; Dreyfus & Dreyfus, 1980). Despite the wide consensus on these principles, however, few are as yet the countries that have materialized them into specific curricula or other organized education actions (Care et al., 2016). From another aspect, it is quite interesting that such educational goals are best served by methods and scenarios under progressive learning theories that promote open-type educational activities (Dib, 1988).

The current research focuses on VET in the field of Electrical and Electronics Engineering and aims to propose, apply and evaluate a novel educational method that attempts to address the major issues outlined above. In particular, a successful novel educational method (1) should educate and train students in modern fields of study that are aligned with the current needs of the job market; (2) should aid students to develop 21st century skills by drawing on progressive learning theories such as constructivism/constructionism and collaborative learning and on open-type learning activities; (3) should place environmental issues in the center of its design, introduce students to the concepts of sustainability and circular economy and aid students to develop and adopt green, eco-friendly practices for life (UNESCO, 2018).

Along these lines, the present work proposes a novel educational method and pilot-evaluates it in order to answer the following two research questions: (a) What are the *cognitive domain gains* of the students, and (b) What are the *social/emotional domain gains* of the students, as these are measured during the application of the proposed method. Both questions are meaningful because, besides the cognitive gains, the proposed method is expected to increase the students' social skills (communication, collaboration). Other skills that the proposed method is expected to develop include the students' problem-solving skills, the organization of their thinking (ability to summarize and extract meaning or outline a procedure in terms of steps) and their motivation, initiative and self-esteem. Due to practical constraints, however, only the first two of these axes (cognitive gains and social/emotional gains) have been evaluated, with positive results. A preliminary form of the proposed method is presented in Nikoloudakis and Rangoussi (2019).

Existing research has addressed these issues by proposing and implementing a variety of methods that jointly develop 'vertical' and 'horizontal' skills in various fields of electrical and electronics engineering or STEM (science, technology, engineering and math), focusing on recycling and green practices. Certain of these research projects involve an educational intervention. In Boya-Lara et al. (2022), students work at home due to Covid-19 conditions and construct robotic devices from recycled electronic and other components (WEEE; Waste from Electrical and Electronic Equipment). In Djulia and Simatupang (2021) students engage in a long-term collaborative project to design and construct prototypes of new devices using STEM and recycled components. Low-cost, microprocessor-based designs that make use of recycled components are investigated in Loukatos et al. (2021) where an air flow control system with a fan is designed for internal spaces. A scrap-processing model for engineering education is proposed in Bula et al. (2019) where a robotic device is constructed from WEEE components. A low-cost solution for an optics course support material is put together in Andre and Jones (2019) where WEEE components are disassembled and re-purposed. Environmental awareness and green practices through the reuse of WEEE components in a Robotics course are developed in Teixeira et al. (2018). In Przestrzelski et al. (2018), through the construction of artifacts from materials/parts-trash collected over a week, students are led to the experiential conclusion that creativity can come from practically anywhere. A laboratory exercise that employs recycling when consumer electronics reach their End-Of-Life (EOL) stage is described in Kangas & Seibel (2018); the devices disassembled are desktop computers. A social institution where very low-income people can live and work is the setting of the educational intervention carried out in Taylor et al. (2017). Institution members are active in recycling and the recovery of materials from which they construct new artifacts. Control of an autonomous moving robot through Dual Tone Multi-Frequency (DTMF) signaling produced by the mobile phone keypad is the project presented in Artal et al. (2014). A recycled old cell phone is used as the remote control for the robot. In Kopacek and Kopacek (2007) a model is developed that evaluates alternatives and finds optimal strategies for the recycling of specific devices near their EOL stage. Automated extraction of rare materials from scrap and their subsequent use for automation training is implemented to evaluate this model. The economic aspects of dismantling and disassembly in developing countries are also considered.

Although all these works bear similarities with the method and approach proposed in the present research, there are also significant differences. The method followed in Loukatos et al. (2021), for example, does not include the recovery of parts or components from the EOL devices – in contrast, this is an educationally critical phase in the method proposed here. The same holds true for the research by Djulia and Simatupang (2021), which in addition does not propose or even outline a specific method or approach. On the other hand, a phase of construction of new artifacts/prototypes is not included by Przestrzelski et al. (2018) – another educationally critical phase of the method proposed here. Evaluation phases or tasks are often not reported (Andre & Jones, 2019; Kangas & Seibel, 2018; Kopacek & Kopacek, 2007; Taylor et al., 2017; Teixeira et al., 2018). In Artal et al. (2014), the educational benefits from the in-class project are not presented or discussed, while in Boya-Lara et al. (2022) students work individually at home – a different setting that cannot support the development of collaboration and other social/emotional skills and that also raises security issues due to the lack of proper teacher surveillance. In light of the above comparisons, the method proposed here addresses the same issues yet in a more comprehensive and systematic way, through a clear methodology that includes evaluation at each step.

2 Research Objectives

Regarding the learning content, the current research focuses on the field of Electrical and Electronics Engineering and more specifically on the area of green, eco-friendly technologies and practices. Specifically, the proposed educational method starts with an Introductory Session to introduce students to the notions of ecosystems, sustainability, recycling/reclaiming/reusing and the circular economy. The pairs of Analysis-Synthesis phases that follow, as described in the Methodology section below, focus on a specific device type that constitutes potential Waste Electrical Electronic Equipment (WEEE) at its EOL stage. Examples of suitable device types are personal computers/laptops/tablets, gaming consoles, printers, fax machines, copiers, mobile phones, routers and other active network devices, UPS units, radio communication units (CB, VHF, UHF), television sets and audio-video home or car systems, microwave ovens, air-condition units, LED bulbs and strips, battery drills and domestic electric appliances in general (coffee makers, vacuum cleaners, etc.). Students are led to discover knowledge on the specific device (a) by disassembling a (possibly damaged) unit, extracting, identifying and classifying its components, measuring them to select the operational ones and (b) by reusing the functional components either to repair similar damaged units or to design and construct new items or devices or products. This 'reverse engineering' approach, that leads students first to analyze and then to (re-)construct, jointly addresses (1) the introduction and study of the learning content, (2) the development of green, environmentally friendly practices and (3) the cultivation of technical as well as social and metacognitive skills. These aims are sought through the design, implementation and evaluation of a structured educational intervention.

3 Method

The research methodology adopted, the proposed educational method and its grounding on specific theories of learning, as well as its embedding in VET curricula are outlined in this section.

3.1 The Proposed Educational Method

The 'building block' of the proposed educational method is an Analysis-Synthesis pair of phases; such a pair may be repeated more than once if needed. A block diagram for a single pair of Analysis-Synthesis phases is depicted in Figure 1. Each Analysis or Synthesis phase includes an Introduction and Brainstorming session, an Implementation session and an Evaluation session. The contents of each session are outlined along with their pilot application in the next section '4. Implementation of the proposed method in a VET class'. The series of Analysis-Synthesis pairs is headed by an Introductory Session that orients students as to the purposes, the steps and the expected outcomes of the process.

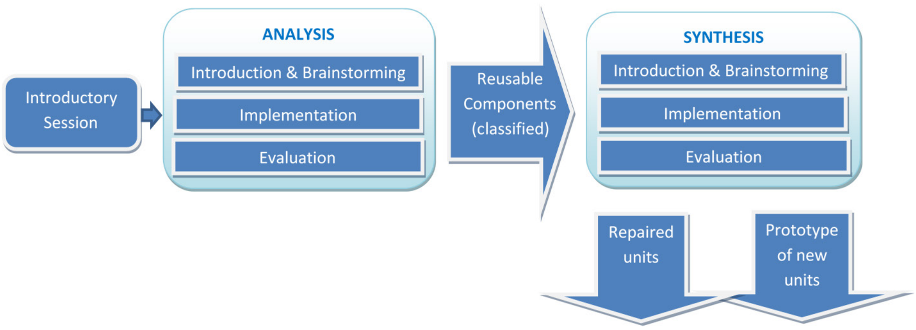


Figure 1: The Structure of the Proposed Method in Block Form: A Pair of Analysis and Synthesis Phases With Outcomes

3.2 Theoretical Basis

Regarding the educational/pedagogical model employed, the proposed method constitutes primarily *Project-Based Learning* (PBL) (Korenic, 2014; Mills & Treagust, 2003), each project built around a device type that is a potential source of WEEE and a target for disassembly, component reclaiming and reuse. Lab work accounts for the major part of the whole process and consists of hands-on activities that characterize the proposed method as *Active Learning* (Prince, 2004), *Experiential Learning* (Kolb, 1984) and *Learning-by-doing* (Dewey, 1966).

It may be argued that the proposed method draws from more than one theory of learning: Primarily, (social) constructivism, (Palincsar, 1998; Piaget, 1963; Vygotsky, 1978), constructionism (Papert, 1980) and collaborative learning (Dillenbourg, 1999; Holmes et al., 2001). Indeed, the structure of Analysis and Synthesis phases shows that

1. in the Analysis phase (disassembly and dismantling), students acquire new knowledge on the internal structure, mechanisms and functionalities of the target devices. This knowledge is to be added on already existing knowledge on the macroscopic uses and functionalities of the devices – a *constructivistic* learning paradigm;

2. in the Synthesis phase, students are going to build new devices from one or more of the reclaimed components, after having tested and possibly repaired them, if necessary. Through this construction phase they learn to use their imagination and inventiveness and acquire new knowledge through the repeated trial and error phases up to the successful assembly of the new device – a *constructionistic* learning paradigm;

3. Analysis and Synthesis phases are both organized as *Collaborative Learning* activities: Students work in the lab in small groups of two to three members each and develop their social skills of communication and collaboration.

Accordingly, the term *'Recyclo-constructivism'* is proposed to name the specific pair of educational method and learning content.

3.3 Research Methodology – Advantages and Limitations

The current research project refers to the pilot implementation and evaluation of the proposed method. To this end, an educational intervention is designed and carried out with a class of students, to collect data and answer the research questions defined in the outset of the study.

By virtue of its designed nature, this research constitutes an *experimental study* rather than a case study. Moreover, in the educational intervention designed and implemented, practical constraints dictated the use of convenience sampling and the involvement of a single group of students ('experimental group') without a control group for comparison; these features render it a *quasi-experiment* rather than a pure experiment.

The major advantages of the proposed methodology are (1) the modular structure in clearly defined steps, (2) the applied, hands-on character that offers students lived experience and thus fosters deeper learning, (3) the phases of the method constitute a comprehensive sequence of activities leading gradually from tightly guided, closed-type activities to constructive, open-type activities that require creativity. Limitations of the proposed method are detailed and discussed in Section '6.1 Limitations of this intervention'.

3.4 Embedding the Proposed Method in VET Curricula

Any realistic proposition as to the embedding of the proposed method in VET curricula should consider that national VET curricula vary significantly in their internal structures and layers. Based on the experience with the structure of the national VET curriculum in the authors' country, the proposed method may be implemented alternatively either

– *as an interdisciplinary lab-only module in the curriculum, placed in the last year(s) of it*: Given the complex nature of all devices that rely on the coordinated operation of different parts (mechanical, electrical/electronic, structural, etc.), an educational scenario that is built around such a device rather than around a field of study, inherits this interdisciplinary character, which, in turn, aids students to connect the isolated 'islands' of knowledge acquired through specific modules and to mentally build integral, multi-faceted knowledge constructs; or

– *as the lab component of an existing, inherently interdisciplinary module*: Robotics is an example of such a module present across many curricula. The subject of Robotics does lend itself nicely to the targeted type of instruction thanks to a curriculum that typically includes a hands-on lab module, e.g., for the assembly and operation of model vehicles and drones. This is an ideal setting for the exploitation of components (mechanical, electrical/electronic or structural) extracted in the Analysis phase and targeted for reuse in the Synthesis phase.

4 Implementation of the Proposed Method in a VET Class

The implementation of the proposed method through an educational intervention is described in this section, following a sequence of phases and steps. Evaluation activities are interleaved with teaching and learning activities in order to collect data for analysis.

4.1 The Setting and Sample of the Educational Intervention

The setting of the educational intervention is the Electrical and Electronics Engineering class of a public VET Lyceum in Athens, Greece. VET in the subject of Electrical and Electronics Engineering is ideally suited for the introduction of students to the notions of environmental awareness and sustainability (Ledley et al., 2017; Murphy et al., 2009; UNESCO, 2020), to the recycling / reclaiming / remanufacturing concepts (Gray & Charter, 2007; Ijomah, 2008; Soh et al., 2014) and to the important subject of 'green' electronics and WEEE treatment (European Commission, 2019).

The intervention took place in the class of Robotics, classroom and lab, where the first author of this paper is the class instructor. The class consists of 14 students (13 male, one female), all adults that hold morning jobs in parallel. The intervention cov-ered approximately two months of the previous academic year (December 2022 to January 2023). Students were asked to sign an informed consent form before enrolling in the project.

It should be clarified that the proposed method is inspired by the practical experience of both authors as educators in VET curricula (first author) and in academic, electrical and electronics engineering curricula (second author), respectively. The common background is their laboratory teaching experience during which the educa-tional value of hands-on and reverse engineering approaches was greatly appreciated. Officially the VET school administration granted permission and hosted the interven-tion but was not otherwise involved in the experimental setup or planned for the adop-tion of the method as a standard school practice. The interest from the academic side is strong, however, and the results are currently being evaluated as to their transferability to the academic level and the adoption by the second author's hosting institution as a lab teaching method. Furthermore, this pilot intervention has served as the basis for a PhD proposal of the first author.

4.2 Contents and Materials of the Intervention

The intervention implements a single pair of Analysis-Synthesis phases; the Synthesis phase includes both a 'Maintenance and Repair' stream and an 'Innovative Design and Construction of Prototype' stream.

The learning content selected is the test and repair of power supply units (PSUs) coming from desktop personal computers (ATX towers). A set of 18 damaged PSUs had been collected from the VET school's computer rooms; 10 units out of them were judged beyond repair and marked for disassembly (Analysis phase) while the other eight units were marked for repair (Synthesis phase – Maintenance and Repair stream). In the Synthesis phase – Innovative Design and Construction of Prototype stream, the learning content is the conversion of a damaged LED TV set into an X-Ray film viewer, eventually donated to the Department of Nursing in the same school.

4.3 The Analysis Phase, in Concept and in Practice

The concept of each internal session of the Analysis phase is outlined below:

In the *Introduction & Brainstorming session*, the class instructor explains the purpose of the Analysis phase and the learning outcomes expected from it. The students are given brief instructions as to the procedure of dismantling and disassembly of the devices and the measurement procedures in order to test the extracted components. Students take part in a brainstorming and active collaboration on the lab whiteboard, regarding the classification and measurement tasks for the extracted components. They are then directed to Internet sources to retrieve manuals, data sheets and relevant material. Finally, the class instructor refers in detail to the safety measures in the lab regulation they have to observe at all times.

In the *Implementation session*, students work in teams of two to three members each. Their first task is to disassemble, desolder and dismantle the target device down to the component level (Figure 2). While doing so, they classify all reclaimed components into separate bins to be checked for operation status. In this process, students may consult manuals or data sheets regarding the internal structure of the device, either in paper or online, and find out the names, characteristics and functionalities of each and every component in the device. They gradually construct a complete and detailed mind model of the device; being able to verify each detail by hand and tool, they learn by doing – a type of knowledge considered much more enduring than that obtained through reading sketches and manuals or watching demos.

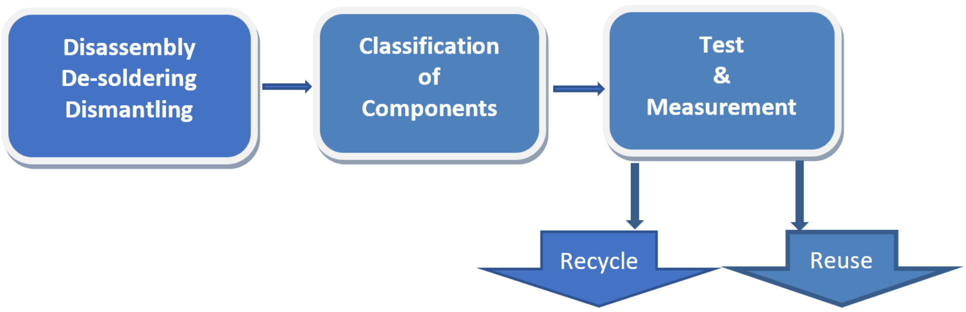


Figure 2: The Sequence of Tasks in the Analysis Phase / Implementation Session

In the *Classification* task that follows (Figure 2), students are guided by the instructor to organize a hierarchy of classes that reflects the complex, interdisciplinary nature of any complete device. For WEEE, three obvious candidate top-level classes are (1) mechanical components, (2) electrical/electronic components, and (3) enclosures and other structural components. Further classification into sub-classes is shown in Figure 3 (a), (b) and (c), for each one of the three top-level classes, respectively. The classification task develops higher order and transversal intellectual abilities and skills as it urges students to closely observe, identify, name, compare, contrast, differentiate and eventually classify items into the correct class (decision making) – all these mental activities fall into the first up to the fifth level of the (modified) Bloom taxonomy of learning (cognitive domain) (Anderson & Krathwohl, 2001; Bloom et al., 1956).

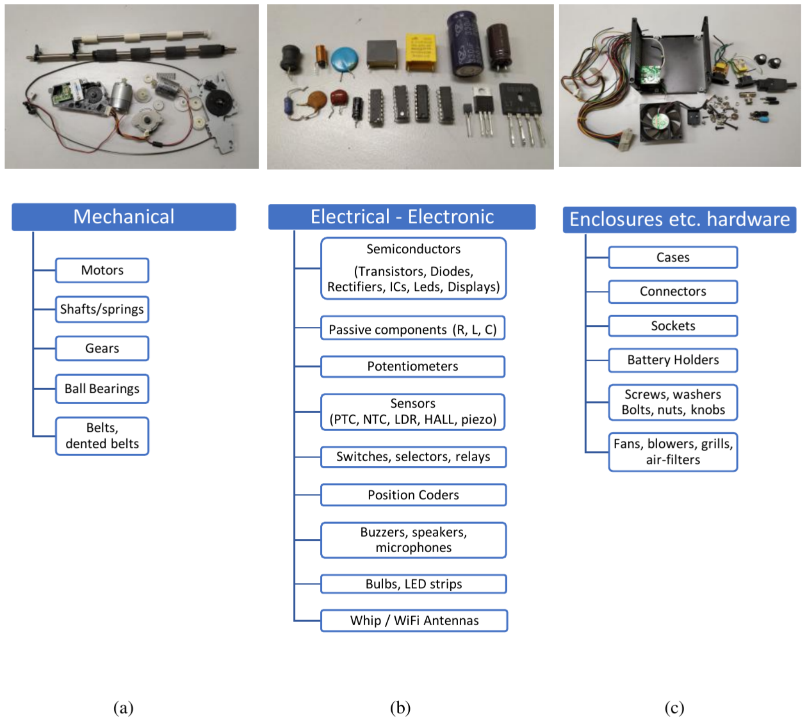


Figure 3: The Hierarchical Classification Scheme of Reusable Components From WEEE: The Three Top-Level Classes and Their Subclasses (Nikoloudakis & Rangoussi, 2019)

In the final *Test and Measurement task* (Figure 2), students focus successively on each one of the classification bins obtained in the previous stage. Through the appropriate set of tests and measurements, students check the operation status of each component, and further separate them into 'good' ones (those targeted for *reuse*) and 'off' ones (those targeted for *recycling*). Test and measurement constitute a demanding and skill developing process, as it requires mental activities at the fourth and fifth level of the Bloom taxonomy.

In the *Evaluation session*, students take part in a closed-type evaluation through (online) questionnaires and an open-type evaluation, where they are asked to compile a guide for the test and measurement of electronic components.

The Analysis phase was put to practice following the three sessions detailed above. Specifically, the Introduction and Brainstorming session (Figure 4) as well as the Implementation session took place in the lab, under the supervision and guidance of the class instructor.

In the Dissassembly-Desoldering-Dismantling task, students worked in pairs to disassemble the 10 PSUs (Figure 5). The extracted parts (diodes, transistors, MOSFETs, etc.) were roughly classified in bins, according to their external similarity. This was soon considered unsatisfactory, so the students proceeded to put together a hierarchical classification scheme (Figure 3), on the basis of their previous knowledge and experience, and re-classified the extracted components according to the new scheme. To do that, they all worked together as one team around a big lab table (Figure 6).

Figure 4: Brainstorming on Class Whiteboard

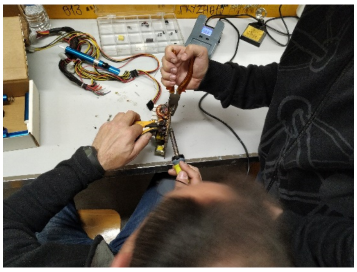


Figure 5: Disassembly – Desoldering

Figure 6: Component Classification – Collaboration Around the Lab Table

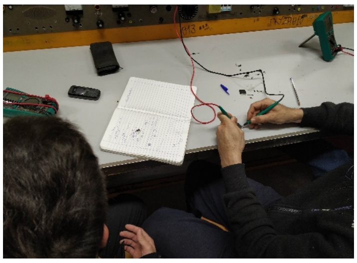


Figure 7: Test and Measurement of Components While Taking Notes

In the Test and Measurement task, students worked in pairs and used multimeters to measure all components and select the operational ones. They often consulted each other and resorted to the Internet on their mobile devices, to clarify difficult points. They also took notes for subsequent use (Figure 7). The net outcome was a set of recycle bins with the damaged components, classified according to their level of hazard.

To conclude the Implementation session, a debriefing was held in class, where students recapitulated and summarized the acquired knowledge and freely discussed and exchanged their experiences, views and conclusions. Moreover, they were prompted by the instructor to judge the type, level and usefulness of such knowledge and experience and to think about ways to exploit it and build on it in their next projects.

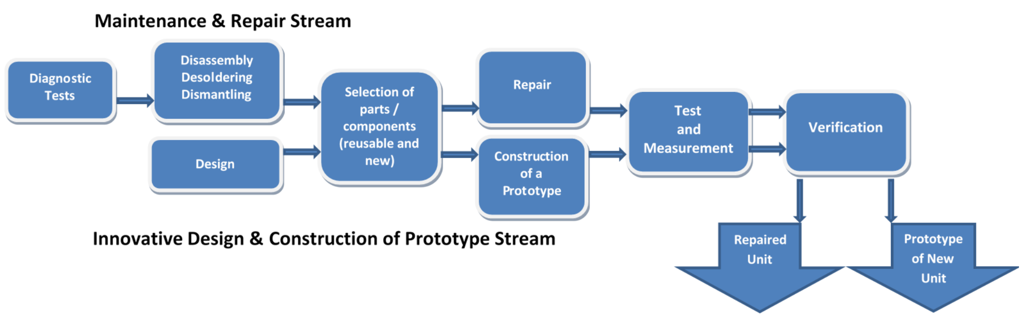
In the Evaluation session, students completed an online questionnaire (closed-type evaluation). They also took part in an open-type evaluation activity, where they were asked to compile a guide for the test and measurement of electronic components. Details on the evaluation tasks along with the obtained results are presented in Section 5.

4.4 The Synthesis Phase, in Concept and in Practice

The concept of each internal session of the Synthesis phase is outlined below:

In the *Introduction & Brainstorming session*, the class instructor explains the purpose of the Synthesis phase and the learning outcomes expected from it. The students are prompted to recall existing knowledge they will need in this phase (basic knowledge, block diagrams, schematics, etc.). The class instructor hands out the necessary support material, refers in detail to the safety measures in the lab regulation students have to observe at all times and personally checks safety conditions on the lab benches (1:1 auto-transformers, discharging of capacitors etc.).

In the *Implementation session*, students work in teams of two to three members each. Implementation may proceed along two different streams that share certain common tasks (Figure 8). Specifically, the reuse of parts/components reclaimed during Analysis may be directed either (1) to the Maintenance and Repair of damaged equipment (Figure 8 – upper stream), or (2) to the Innovative Design and Construction of Prototype of new objects (Figure 8 – lower stream).



Note. Upper path: Maintenance and repair stream; lower path: Innovative design and construction of prototype stream.

Figure 8: The Sequence of Tasks in Synthesis / Implementation Session

The Maintenance and Repair stream constitutes an activity both instructive and constructive; it does not set the bar high, however, as far as inventiveness, imagination and innovation are involved. The Innovative Design and Construction of Prototype stream, on the other hand, places the emphasis primarily on the development of these qualities while at the same time it yields new products of a reduced environmental footprint, thanks to the reused components integrated in it. The prototypes of the new objects may or may not fall in the same categories with the devices the components are coming from. For example, motors may come from printers and end up in model vehicles or drones. The mental activities of designing, creating, constructing, modeling and modifying the new objects, required in this stream, fall into the sixth level of the Bloom taxonomy for the cognitive domain, which means that they aid students develop the highest level of intellectual abilities.

Common to both streams are the two final tasks, namely, Test and Measurement and Verification (Figure 8); these are necessary in order to ensure that the repaired units or the constructed prototypes function properly. At a more practical level, the Synthesis phase overall constitutes a valuable training experience for VET students as future professionals.

In the *Evaluation session*, students take part in a closed-type evaluation through (online) questionnaires and an open-type evaluation, where they are asked to collaborate and compile a Troubleshooting Flowchart (mind map) for the repair process.

The Synthesis phase was put to practice following the 3 sessions detailed above and tasks therein. Students first took part in a Maintenance and Repair stream, where they repaired damaged ATX PC PSUs and then in an Innovative Design and Construction of Prototype stream, where they transformed a damaged TV screen into a backlit panel for X-Ray film viewing.

In the *Introduction and Brainstorming session*, students were prompted to recall existing knowledge (the basics of voltage rectification, block diagram and schematic of a generic PSU, Pulse Width Modulation for motor control). The class instructor handed out sets of necessary support material including the block diagram of a switching PSU, the circuit of a switching PSU for an ATX computer along with its pin connection diagram and a PSU repair guide in steps. Finally, he referred in detail to the safety measures in the lab regulation they have to observe at all times and he personally checked safety conditions on the lab benches (1:1 autotransformers, discharging of PSU capacitors).

In the *Implementation session* - Maintenance and Repair stream that took place first, students worked in teams of two to three members each. Each team took one of the damaged units, air-sprayed it clean from dust and completed the repair using the components reclaimed in the Analysis phase and classified in repositories. Intra- and inter-team collaboration was strong and all students discussed issues and consulted one another throughout the session. Each repaired unit was marked as 'OK'; eventually, seven out of the eight units were repaired in a single three-hour session. This session clearly boosted students' self-confidence and self-esteem. Moreover, they all enjoyed the experience and left the lab in a state of enthusiasm.

In the *Evaluation session* for the Maintenance and Repair stream, students took part in (a) a closed-type knowledge test they took online by completing a questionnaire in Google Forms, and (b) an open-type evaluation activity, where they were asked to use the Draw.io web tool and create a Troubleshooting Flowchart (mind map) for the repair of PSUs. Evaluation results are presented in Section 5.

The Implementation session - Innovative Design and Construction of Prototype stream followed, after a brief introduction that took place directly in the lab. The first task set by the instructor was to check the operation status of the TV screen and try to repair it, if damaged (Figure 8, upper stream).

The device was found damaged, indeed: When connected to power supply and antenna, it produced audio but not video. The students were directed to the Internet to search for its type and features. They found out that this was a LED-backlight LCD screen (liquid crystal display). They proceeded to disassemble it and recognize its structural parts and supply cable. They measured the supply power at 140 V.

To repair the panel, the students searched for instructional videos; following these instructions, they executed the disassembly with extreme care, they removed all layers from the LCD down to the last reflective surface and revealed the LED strips. They were directed to search the local market online for a provider of individual LED units, each on a separate PCB complete with its own diffusion lens and with technical specifications identical to the original ones. They ordered 10 pieces and, when delivered, they replaced the destroyed LEDs with the new ones, connected them in series and re-assembled the screen. All LEDs gave light. When the screen was reconnected, it lit up but could not form a correct image; it produced vertical stripes of different intensities instead (Figure 9).

Figure 9: Disassembly of the TV Screen and Check for Operation

Figure 10: The New Device (X-Ray Film Viewer) Constructed From Components Reclaimed From the Damaged TV Screen is Being Donated to the Department of Nursing

The repair aim having thus failed, students were redirected to the second stream, that of Innovative Design and Construction of Prototype (Figure 8, lower stream). They were prompted by the instructor to search and find other uses for the components of this device. After discussions in class and repeated online searches, they concluded that it is possible to use the screen without the LCD part as a backlit panel for the viewing of X-Ray films. They would have to achieve a more uniform light intensity level, however, for a usable result.

To this end, they removed the LCD layer and searched online for the role of the intermediate layers on the intensity level. They experimented aiming for uniform intensity, which they tested with available X-Ray films. When a satisfactory uniform intensity was achieved, they donated the new device to the Department of Nursing of the same school, to be used in the training of these students (Figure 10).

The Evaluation session of this second stream took place after a brief discussion in class on the outcomes and the experience of this activity. It consisted of a closed-type test in the form of a questionnaire in Google Forms. The test included questions on the learning content as well as on the social skills and the type of experience students had had. Evaluation results are given in Section 5.

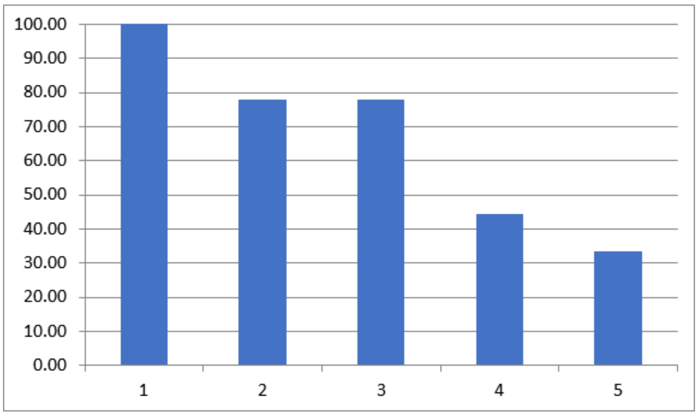
5 Evaluation Results

Quantitative and qualitative evaluation results are presented in this section, as obtained during the analysis phase and the synthesis phase.

5.1 Evaluation Results of the Analysis Phase

For a quantitative evaluation of learning gains, students were asked to complete asynchronously (at home) a knowledge post-test in the form of an online, anonymous questionnaire in Google Forms. As none of the students had been exposed to this material before, a pre-test was not considered necessary. The test consists of nine questions, seven of the multiple-choice type and two of the free-text answer type. A sample multiple-choice question is *"What is the reading on DMM when a short-circuited diode is measured?"* [(a) 0.7V; (b) 0.2V; (c) 0V; (d) 1.5V], while a sample question of the free-text type is "*What is the first thing you need to do before you use a DMM to measure a MOSFET?"*.

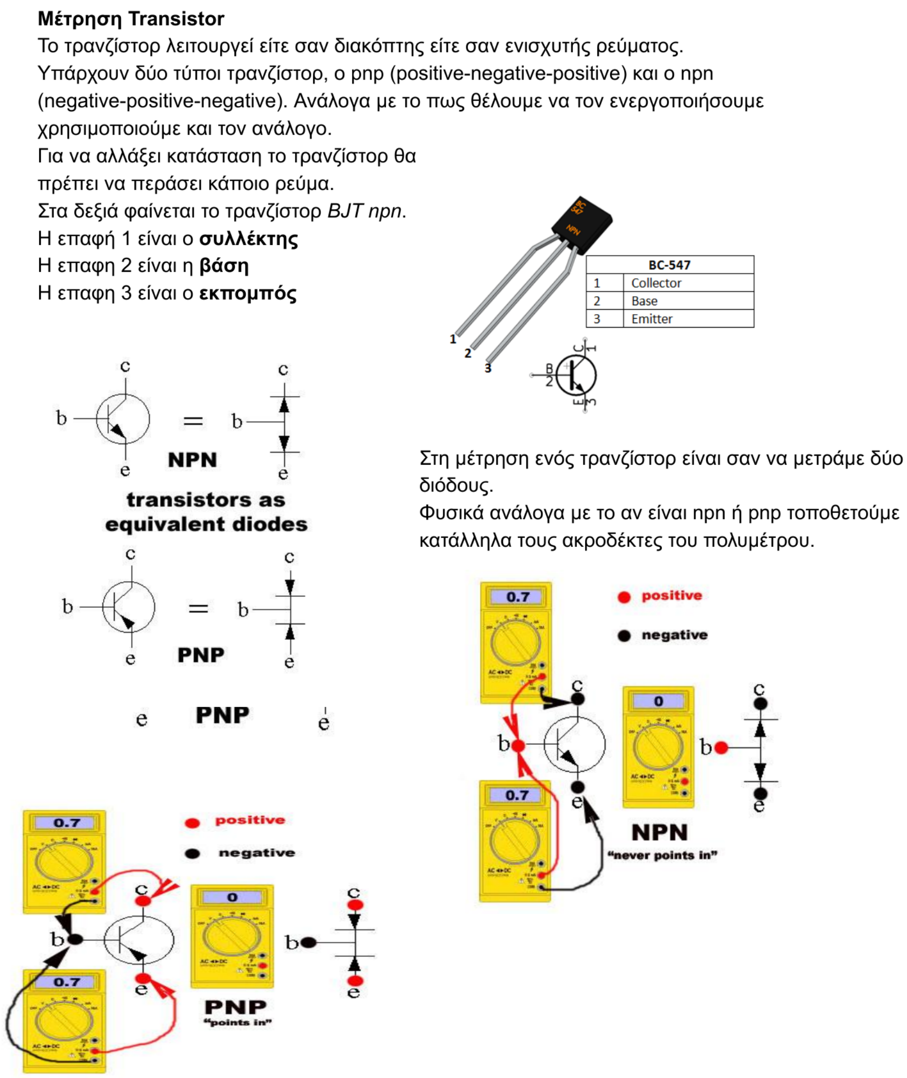
Results are given in Figure 11, in the form of student grades over 100, obtained by the students who did take the test. Even though students knew that the platform guaranteed anonymity, their participation was rather low: Only five out of the 14 students (35%) did complete the questionnaire. This is probably due to a general fear of failure they feel in front of any test and a prejudice against evaluations – stronger in VET students, due to their lack of a robust background in their field of study.



Note. Student grades in the first knowledge test across student nr., for the five students who took the test (maximum score = 100, class average score = 66.67).

Figure 11: Student Grades in the First Knowledge Test

In the open-type evaluation activity that followed, in order to assess learning outcomes, the instructor asked students to collaborate on the Google Docs platform in order to use the experience gained from the lab and put together a Semiconductor Measurement Guide to be used by the students of the next year. This proved a quite strong motive, especially as the digital material would bear the authors' names. A brief outline was first sketched collaboratively in class with the aid of the instructor. Students who already had an account with Google were registered in the project file on the platform at the invitation of the instructor; the rest of the class went on to create accounts with Google on the lab computer, with the help of their classmates – an opportunity to develop their digital skills and strengthened their collaboration. The platform supports communication and the co-editing of texts either real-time or asynchronously. Students started working on it in class and completed it at home, via online collaboration (a sample page in Figure 12, in Greek).



Μέτρηση Transistor
Το τρανζίστορ λειτουργεί είτε σαν διακόπτης είτε σαν ενισχυτής ρεύματος.
Υπάρχουν δύο τύποι τρανζίστορ, ο pnp (positive-negative-positive) και ο npn (negative-positive-negative). Ανάλογα με το πως θέλουμε να τον ενεργοποιήσουμε χρησιμοποιούμε και τον ανάλογο.
Για να αλλάξει κατάσταση το τρανζίστορ θα πρέπει να περάσει κάποιο ρεύμα.
Στα δεξιά φαίνεται το τρανζίστορ *BJT npn*.
Η επαφή 1 είναι ο **συλλέκτης**
Η επαφη 2 είναι η **βάση**
Η επαφη 3 είναι ο **εκπομπός**

BC-547	
1	Collector
2	Base
3	Emitter

Στη μέτρηση ενός τρανζίστορ είναι σαν να μετράμε δύο διόδους.
Φυσικά ανάλογα με το αν είναι npn ή pnp τοποθετούμε κατάλληλα τους ακροδέκτες του πολυμέτρου.

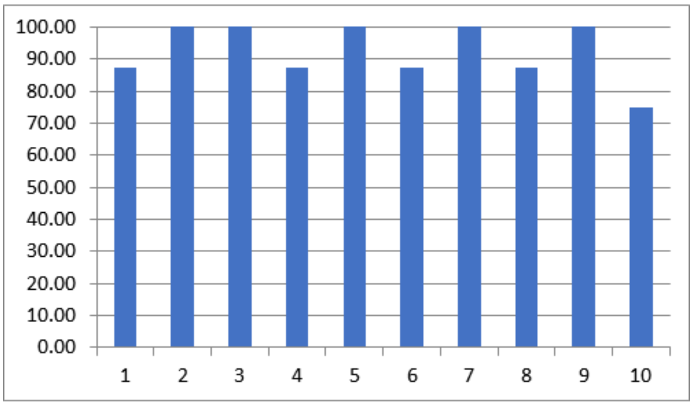
Figure 12: The Semiconductor Measurement Guide Created During the Analysis Phase Evaluation Session (Sample Page, in Greek)

The result was well beyond the instructor's expectations: In addition to the personal notes kept during Analysis, students spent time and further searched for material in books and on the Internet. They also enriched their Guide with informative figures and images.

5.2 Evaluation Results of the Synthesis Phase

In order to evaluate the Maintenance and Repair stream of Synthesis, a knowledge post-test was delivered in the form of an anonymous questionnaire in Google Forms. This test contains 8 questions of the multiple-choice type. A sample question is *"As soon as we remove the supporting bolts of the PCB so that it can be lifted from the device:"* [(a) we measure the rectifier bridge; (b) we discharge the electrolytic capacitors via a 1-5KΩ / 5W resistor; (c) we measure the safety fuse].

Results are given in Figure 13. This time participation has doubled to 70%, as 10 out of the 14 students responded. This is an indication that students have gradually become familiar to the digital tools used for evaluation and have trusted them. Furthermore, the tasks assigned and carried out, both hands-on and digitally/online, have boosted students' confidence as to the learning content (PSU repair) and as to the use of digital tools. On top of increased participation, their scores are also increased: The class average score has risen from 66.67/100 in the first post-test to 87.50/100 in the second post-test. This is an indication that the digital tools used throughout the intervention are capable of increasing the learning outcomes – their specific contribution, however, remains to be quantified in more detail.



Note. Student grades in the second knowledge post-test across student nr. (maximum score = 100, class average score = 87.50).

Figure 13: Student Grades in the Second Knowledge Post-Test

In the open-type evaluation activity that followed, students were asked to use the Draw.io web tool and create a Troubleshooting Flowchart (mind map) for the repair of PSUs. The instructor explained that this task would help them to organize their thinking and to start learning by themselves. They would also take up the role of instructors and thus learn by teaching. As an aid, the instructor handed out a sample troubleshooting chart from a video training manual. Students started working collaboratively in class and continued on-line from home. They sent the first draft to the instructor for corrections and circulated the final form among them. Figure 14 shows the Troubleshooting Flowchart created (in Greek), as an indication of the complex cognitive structure they have constructed.

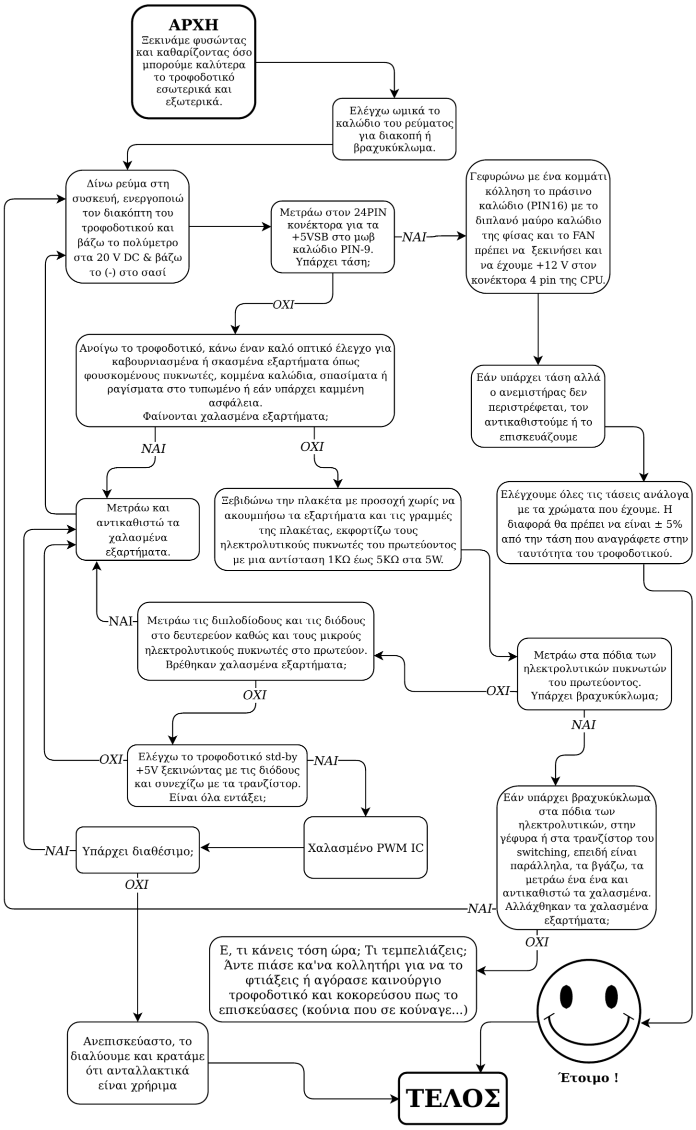
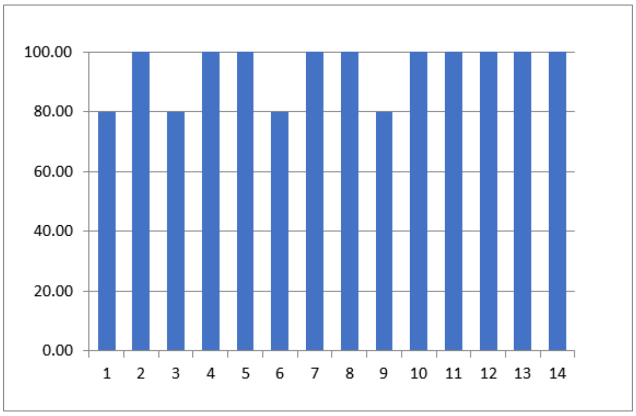


Figure 14: The Troubleshooting Flowchart Created by the Students in the Evaluation of Synthesis / Maintenance and Repair Stream (in Greek)

For the evaluation of the second stream of Synthesis phase, a post-test was delivered in the form of an anonymous questionnaire in Google Forms. This test contains 10 questions, five that assess cognitive gains (results in Figure 15) and five that assess the experience of the students and the level of collaboration among them (results in Table 1). A sample question of the first group is *"Which of the following screen technologies has the lowest power consumption?"* [(a) CRT; (b) LED; (c) Plasma].



Note. Student grades in the third knowledge post-test across student nr. (maximum score = 100, class average score = 94.28).

Figure 15: Student Grades in the Third Knowledge Post-Test

Table 1: Results on the Five Questions on Student Experience and Collaboration Level

Q6. Did you face difficulties in this activity? If yes, at what stage?			*Q7. Did you learn anything through the collaboration with your classmates during this activity?*			*Q8. Has the experience of this activity inspired ideas on new similar ones?*		
Answer	Student count	Student count %	Answer	Student count	Student count %	Answer	Student count	Student count %
YES (*)	2	14.29%	YES	13	92.86%	YES	14	100.00%
NO – ATTENTION REQUIRED (*)	2	14.29%	NO	1	7.14%	NO	0	0.00%
NO	10	71.43%	TOTAL	14	100.00%	TOTAL	14	100.00%
TOTAL	14	100.00%						

Q9. How many classmates have you collaborated with in this activity?			*Q10. Characterize your feelings after this experience:*		
Answer	*Student count*	*Student %*	*Answer*	*Student count*	*Student %*
10	1	7.14%	NEGATIVE	0	0.00%
7	1	7.14%	NEUTRAL	0	0.00%
6	1	7.14%	POSITIVE	8	57.14%
5	1	7.14%	ENTHUSIASTIC	6	42.86%

4	3	21.43%	TOTAL	14	100.00%
1	4	28.57%			
0	3	21.43%			
TOTAL	14	100.00%			
AVERAGE nr. of classmates	3.14				

(*) «YES»: a) In assembly. b) In the tests to identify the damaged SMD – LED.

(*) «NO – ATTENTION REQUIRED»: In assembly.

This time all students took the test as they had become familiar with the procedure and had trusted the instructor on it; moreover, the average score obtained in the first five questions on knowledge in the subject were increased to 94.28 / 100.

As it is indicated by the answers in Table 1, questions seven and nine, students did collaborate during this project. Indeed, only three out of the 14 students worked individually; each student collaborated with approximately three other students during this activity. This is verified by the class instructor's observation sheets completed after every session with this class. Moreover, they found the experience tractable (question six, 12 out of the 14 students) and they all left it with positive/enthusiastic feelings (question 10, 14 out of the 14 students). The total agreement (question eight, 14 out of the 14 students) that this activity inspired in them ideas on similar projects is an indication that this method stimulates the imagination and innovative thinking of the students. The strongest evidence to that is the very outcome of this activity, i.e., the conceived and materialized idea of converting the damaged TV screen into an X-Ray film viewer.

6 Discussion

Regarding the two research questions defined in the outset of this study, the results presented in the previous Section show that the proposed method does produce cognitive and social skills gains for the students. The class participation in the three post-tests/questionnaires has progressively increased from five to 10 to all 14 students and the class average grade in the knowledge-related questions has increased as well from 66.67 to 87.50 to 94.28 over 100 points.

The social skills of the students were also enhanced, as revealed by the last questionnaire (Table 1, Questions 7 and 9). In particular, most students collaborated with classmates during the project and stated that they learned something out of this collaboration. Another interesting social aspect is the practical aid the students offered to their school community, by repairing damaged equipment or donating a useful new device – an opportunity to learn how to make good use of resources, especially the public ones.

Besides the above results obtained through the three questionnaires, the class instructor used his observation sheets to put down a series of observations on the behavior and attitude of the students towards the subject, the learning content, the procedure (new method) and furthermore towards the profession they are being prepared for in this VET class:

- During this educational intervention, students obtained a lived experience on the advantages of repairing instead of replacing, of reclaiming components instead of recycling down to the level of chemical substances and of reusing components in new functionalities/devices. They approached the notions of green, eco-friendly practices, circular economy and sustainability through activities rather than theoretic definitions and examples. Knowledge thus obtained is expected to have a much more enduring effect, although a longitudinal study would be required in order to verify and quantify this effect.

- As dictated by the proposed method, students were encouraged by the instructor to act autonomously and take initiatives; to the degree that the outcomes of these initiatives were successful, they gained self-confidence and self-esteem: They learned how to resort to external sources for information, data and instructions, and how to collaborate in order to solve problems. As a result, their dependency on the class instructor decreased with time.

- The students learned how to organize their inquiries on specific subjects, the time they put on a project and each specific phase of it, and their thoughts over a hierarchical model of a new area of knowledge. These are all aspects of self-regulated learning – a desirable metacognitive skill.

Of practical interest are two properties of the proposed method: (1) Applicability within the VET framework of other countries and (2) transferability, considered either 'vertically', in other education grades, or 'horizontally', in similar technical faculties. The former property is ensured by the use of (1) lab equipment and tools (e.g., soldering stations, voltmeters / multimeters, etc.), (2) software tools (e.g., Google Forms, draw.io, etc.) and (3) materials and devices (e.g., PSUs extracted from damaged computer units), that are standard, widely available and can be easily found (or replaced by equivalent) in any country. The Robotics class context is also widespread and can be found in almost any VET school offering technical faculties. Transferability, on the other hand, is ensured by the nature of the method, conceived at the abstract level as a sequence of analysis-synthesis phase pairs – an abstraction that can be transferred to practically any technical faculty after slight modifications of the sub-processes internal to each of the two phases.

Limitations of the Intervention

The proposed method has certain limitations worth discussing. The major limitations are methodological.

(1) As already discussed in Section 3.3, the intervention does not constitute a pure experiment; it is a quasi-experiment that uses 'convenience sampling' instead of a randomized sample and no control group. Specifically, the class instructor (first author) has used his already existing class in Robotics. This is a result of a severe under-population problem VET schools across all country have been facing since the Covid-19 period. Many VET programs – especially those in technical faculties – are closing down due to limited enrollment. In fact, the 14 students engaged in this intervention constituted the full cohort enrolled in the class of Robotics in 2022-23. The plan to split students into control and experimental groups was consequently dropped in favor of a single, more substantial experimental group. The fact that the sample is small renders the results of a merely indicative value. An extensive intervention under a design with experimental and control groups would be necessary in order to draw conclusive results on the merits of the method. Furthermore, the single experimental group involved is typically a disadvantage. In the present case, however, it is arguable whether it would be meaningful to plan for an equivalent control group that would learn the same content via 'conventional methods' – exactly what would the latter be? Besides, the learning content is spread across various subjects in the curriculum, rendering a two-groups experimental design rather impractical.

(2) The advantage of well-defined and pre-designed sequence of phases and tasks is a limitation at the same time: It renders the method rigid and does not easily allow for real-time modifications as may be needed.

(3) The need for a repository of devices at EOL stage for disassembly is another practical issue. Devices may vary across different interventions, rendering each project a novel, unique case.

(4) The method depends critically on experienced class instructors and lab aids that can efficiently handle all project phases including evaluation. Pre-training may be necessary to ensure coordination and smooth cooperation of the staff involved in the intervention.

Another limitation has to do with time: the intervention had to run in parallel to the standard weekly schedule of the class and it was thus not given the amount of time necessary for a full deployment of the method. The class instructor was not allowed to have a second observer/helper in class; the evaluation tools employed are therefore limited to questionnaires, photos and observation sheets.

In order to render the process attractive for the students, the class instructor has opted for voluntary participation as well as voluntary and anonymous assessment tests. The latter, especially, was a deliberate decision in order to convince students that assessment and grades obtained within the intervention do not affect their official final grade in Robotics, which is obtained through other activities. While all students partici-pated enthusiastically, reluctance was obvious in test taking – especially at the first test – which subsided only at the third test, when the method and the instructor had gained the students' confidence.

The axes of evaluation are limited to the cognitive and the social/emotional domain. Metacognitive skills are also detected in the instructor's observation sheets, however, which means that this method requires a more comprehensive and rigorous evaluation. Motivation of the students and the stirring of their imagination and inventiveness should clearly be among the extra axes to be evaluated.

A final comment has to do with the very nature of the second stream of the Synthesis phase as it was realized in this intervention: Despite the innovative elements present, the conversion of a device is not exactly the same as the innovative design and construction of prototype of a new device 'from scratch' – another point that has to be addressed in future research.

7 Conclusions

A novel educational method for VET is proposed, implemented and evaluated in the field of Electrical and Electronics Engineering. The aim of this method is to introduce students to green, eco-friendly practices and the principles of sustainability and circular economy through hands-on experience rather than study of definitions and examples. The proposed method uses pairs of Analysis and Synthesis phases to experientially teach students how to disassemble electronic devices at EOL stage and reclaim and classify operational components to be reused either for repair of other devices or for the design and construction of new devices. It is a Project-Based Learning approach that falls under the constructivism/constructionist theory of learning; it also employs Collaborative Learning as students work in small groups. An initial evaluation along the cognitive and the social/emotional domains has yielded very encouraging results – yet, of indicative only value, due to the limited scale of the intervention and the sample. Future research should evaluate the proposed method in more detail and possibly compare results across education grades or engineering fields, given that the method is generic enough to be easily adapted for different ages/grades and engineering/technical fields of study.

Ethics Statement

The current research involves the subjects (adult students) of the first author's Vocational Education class in the previous academic year. It was not possible to obtain an ethics approval or ethics opinion by his school authorities, because such a committee or procedure has not been set up as yet. To ensure that the current research meets ethical and legal requirements, the authors have (1) obtained the informed consent of the subjects before the beginning of the educational intervention, (2) taken special care to protect the subjects' personal data throughout the process, according to the GDRP, (3) taken special care to collect and store only anonymized data in order to ensure the subjects' privacy, anonymity and data protection, (4) documentation of the educational intervention by photo instances in the lab was made on the subjects' informed consent and taking special care to remove or obscure any facial or other person identification data or items.

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