Development of STEM Curriculum for Digital Electronics Education in Secondary School

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***Abstract*—STEM (Science, Technology, Engineering and Mathematics) education is crucial, rising the demand for technological skills driven by the Industry 4.0 digital transformation, and fostering problem-solving, autonomy, computational thinking, creativity, innovation, and effective teamwork skills. To properly address the lack of structured materials in secondary schools, an Educational Design Research (EDR) project was developed to introduce young students to STEM, and particularly to electronics field. For this purpose, the developed approach combines instructionism and constructionism methods, through three educational projects and "Drops of knowledge" modules. The developed material was applied to 9th and 12th grades of a secondary school, with the achieved results showing that this immersive approach effectively provides students with the necessary competencies to tackle the initial technological challenges of electronics. The project was recognized by the Directorate General of Education of Portugal as a recommended practice of a digital initiative within secondary schools.**

***Index Terms*—STEM education, Educational Design Research.**

I. Introduction

Technological advancements have continuously provided humanity with tools to interact with and shape the commonplace world according to their interests. The pervasive growth of technology has particularly influenced the field of education, where the goal is to develop knowledge and skills that are aligned with this continuously evolution [1].

Emerging professions are requiring a workforce exhibiting an extensive range of specific technical competencies, as well as soft skills like creativity, innovation, critical thinking, logical problem-solving, and team work [2]. These aspects, complemented with the easier access to digital technologies, have stimulated the increasing demand for STEM (Science, Technology, Engineering, and Mathematics) education.

Consequently, curriculum planners and educators have shown a growing interest in incorporating STEM approaches into formal education [3]. However, there is confusion regarding the exact definition of an integrated STEM approach. For many, it implies the inclusion of only science and mathematics subjects, but a comprehensive STEM education should not only enhance knowledge of technology-related topics but also incorporate more engineering principles into the education process [4]. Furthermore, instructional guidelines often lack the necessary clarity to effectively support teachers [5], hindering the successful implementation of the STEM education due to the numerous challenges it poses, e.g., struggling to incorporate it into the regular classroom setting, and creating a strong connection between the STEM knowledge and real-life problems. Those are non-trivial tasks that requires teachers to design lessons that enable students to perceive the integration between academic concepts and practical applications [6]. Many educators find the design of STEM-focused lessons to be time-consuming and demanding [5], leading to a reduced number of secondary schools successfully implementing STEM education approaches [7]. One potential solution to address these challenges is to develop a well-structured STEM education curriculum, providing materials that directly and clearly address the demands of the STEM education, where educators are more likely to effectively integrate these concepts into their teaching practices [8]. As example, designing project-based activities that require students to solve real-world problems using their soft-skills can foster a deeper understanding of the subject matter and its practical implications.

Having this in mind, this paper describes the development of an innovative project addressing the lack of existing materials and the need for comprehensive STEM resources. Guided by an EDR (Educational Design Research) approach, it was developed curriculum materials that targeted math, science, and engineering standards. For this purpose a project called "Arduino for students" was designed and implemented considering the developed materials and successfully applied in regular classes of Information and Communication Technologies (ICT) of 9th and 12th grades. The learning outcomes of students were measured using standardized tests, and the effectiveness of the developed resources was assessed through qualitative and quantitative criteria, by students and teachers, allowing to feed the EDR cycle with valuable feedback.

The rest of the paper is organized as follows: Section II presents the related work and Section III introduces the proposed approach and describes the first phase of the developed EDR based educational materials, focused on the analysis and exploration of the STEM education. Section IV presents the phase 2, centred in the development and prototyping of the educational materials and Section V is devoted to the phase 3, where the results are analysed and discussed. Finally, Section VI rounds up the paper with the conclusions and points out the future work.

II. Related Work

Constructionism and instructionism are two learning and teaching methods that emerge in the field of education, which differences are summarized in Table I.

TABLE I: Comparison of constructionism and instructionism teaching methods.

Method	Advantage	Disadvantage
Instructionism	Traditional and widely used method, promoting the passive learning, characterized to be teacher centered and using a structured environment for learning.	Does not encourage creativity or critical thinking.
Constructionism	Promotes the active learning, enabling students to learn at their own rhythm and develop critical thinking.	Challenge for students who cannot work independently.

Instructionism is a more traditional teaching method that emphasizes the transmission of knowledge from the teacher to the students [9], providing a clear structure and direction for learning, ensuring that essential concepts are effectively provided. Instructionism can be particularly beneficial in introducing new topics, ensuring a foundation of knowledge, and delivering important information efficiently [10]. However, this approach may reduce the student's autonomy and creativity, as it primarily relies on the teacher-centred instruction [11].

On the other hand, constructionism is a teaching method that empowers students to take on a central role in their own learning process, encouraging them to actively participate, explore concepts, and develop solutions through hands-on experiences [12]. This approach fosters creativity, problem-solving and critical thinking skills, as students engage in building projects, conducting experiments, and reflecting on their learning. However, one potential weakness of constructionism is the need for a proper guidance and structure to ensure that students stay focused and achieve the desired learning outcomes [13]. Project-Based Learning (PBL) is an example of the constructionist approach, which has the student as the main player to solve real problems, being structured for students to design and create projects aimed at addressing the resolution of these problems that are presented by the teacher or by themselves [14].

Upon careful examination of these factors, it becomes evident that a combination of these two methodologies would facilitate the active student engagement in the construction of knowledge, while simultaneously harnessing the instructive support and direction provided by both instructional materials and the teacher. By incorporating elements of both approaches, students can acquire a deeper understanding of concepts and develop practical skills that are applicable in real-world contexts. This approach will promote the pro-active student engagement, critical thinking, and problem-solving skills, while also benefiting from the structure and guidance provided by the teacher and available materials, creating a learning experience that is comprehensive, effective, and tailored to meet the different needs of the students.

EDR is a methodology that combines the educational theory and practice to design and refine innovative educational interventions, aiming to improve the teaching and learning outcomes [15]. This research framework encompasses a comprehensive investigation into the design, development, and evaluation of educational activities, encompassing programs, learning processes, learning environments, teaching-learning materials, products, and systems [16]. Regardless the purpose of the educational design research, an effective research process should include three phases, as illustrated in Figure 1: analysis, development, and evaluation. The analysis phase is related to analyse the educational problem and review the existing knowledge, and the development phase involves creating and implementing the innovative activities, including the educational materials. Finally, the evaluation phase is related to the assessment of the effectiveness of the education activities, allowing the refinement of the design and implementation of the education process [16].

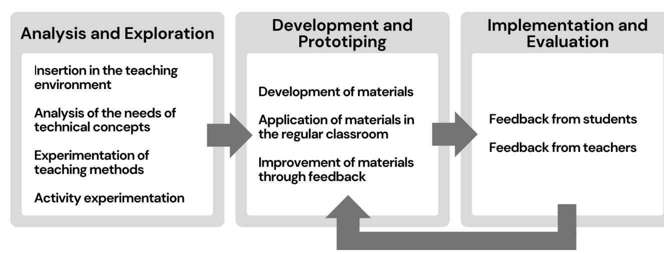

Fig. 1: General structure of the implemented EDR approach.

In the presented work, constructionism and instructionism methods are combined, using the EDR approach to design and implement the educational material for learning digital electronics in secondary schools. Next sections will detail each one of the three implemented EDR phases.

III. Phase 1: Analysis and Exploration

The objective of this phase was to understand the needs and expectations of secondary students regarding the STEM education. For this purpose, it was chosen to voluntarily participate in a robotics club at a secondary school, where meetings were held for students from 9° to 12° grades, aiming to gather information on which electronics and programming concepts are interesting and effective for the construction of the educational material. After the analysis and exploration, the structure and content of the curriculum to be developed in Phase 2 were designed. The resulting curriculum framework, presented in Fig. 2, comprises three projects of increasing difficulty, where the first project addresses actuators, the second combines digital sensors and actuators, and finally the third project considers an analog sensor.

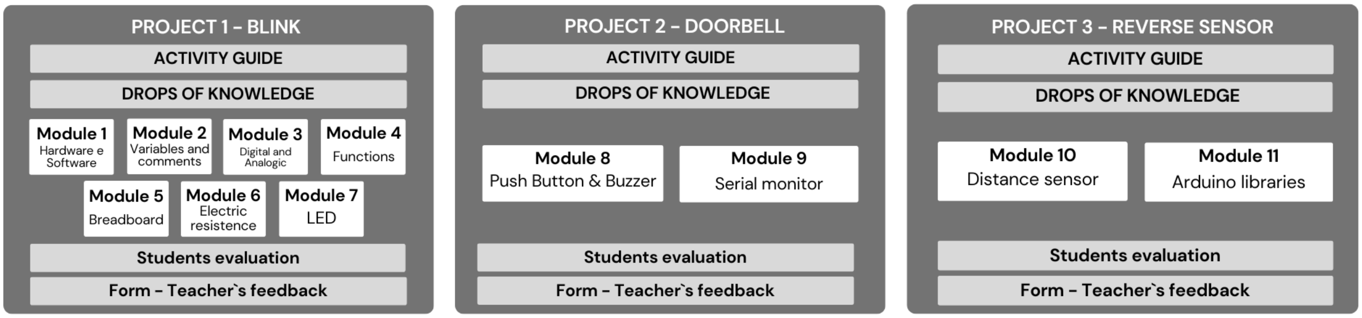

Fig. 2: Structure and contents of designed educational projects.

Basically, each project comprises four main components:

- **Activity guide:** document that provides instructions and challenges that guide the students in learning activities related to electronics topics, created to help them to perform the activities.
- **Drops of knowledge:** documents that enhance the understanding of the basic concepts, thereby ensuring that students who have prior familiarity with the subject remain engaged and motivated. Additionally, they serve to enliven more technical aspects of the projects, serving to go deeper into the learning subject.
- **Students evaluation:** application of assessment methods, at the end of each learning project, to measure and verify the progress of students' learning, thinking and reasoning.
- **Feedback from teachers:** collection of the teachers' feedback related to the learning process.

The selection of the projects contents considered several criteria, e.g., the component availability, affordability, simplicity (ensuring that complex circuitry was not required), and flexibility (to accommodate both simple and intricate circuit arrangements). Since projects were based on the Arduino platform, compatibility was a major issue, selecting components that operate efficiently on the Arduino voltage source and consuming low energy.

The learning curve of the target age group was also taken into account, aiming to provide achievable steps and support students facing difficulties with advanced concepts. A gradual increase in difficulty level was incorporated across the three projects, allowing for a progressive learning experience. This incremental approach aimed to prevent the demotivation and frustration of students, offering accessible challenges to enhance their learning journey.

IV. Phase 2: Development and Prototyping

In this phase, the focus shifts to the development and prototyping of the educational materials designed in the previous phase. The developed materials offers interactive activities, encompassing the physical model construction and virtual simulations, enabling students to actively construct their understanding of the presented concepts and ideas. These activities foster the engagement and participation, allowing students to be active participants in their learning process.

The developed materials will be briefly described by using the project "Blink".

A. Activity Guide

This document serves as a valuable resource, providing detailed instructions and challenges to support the students' learning. The digital format allows the easy access, enabling students to navigate through the guide and access supplementary materials. The guide comprises the following six main components:

1) Introduction: this material highlights the expected learning objectives to be developed through each stage, and provides a comprehensive list of materials to execute the experiment, ensuring that students have all the necessary resources to successfully complete the activities and achieve the desired learning outcomes. Fig. 3 shows an example of a piece of educational material focusing the introduction component.

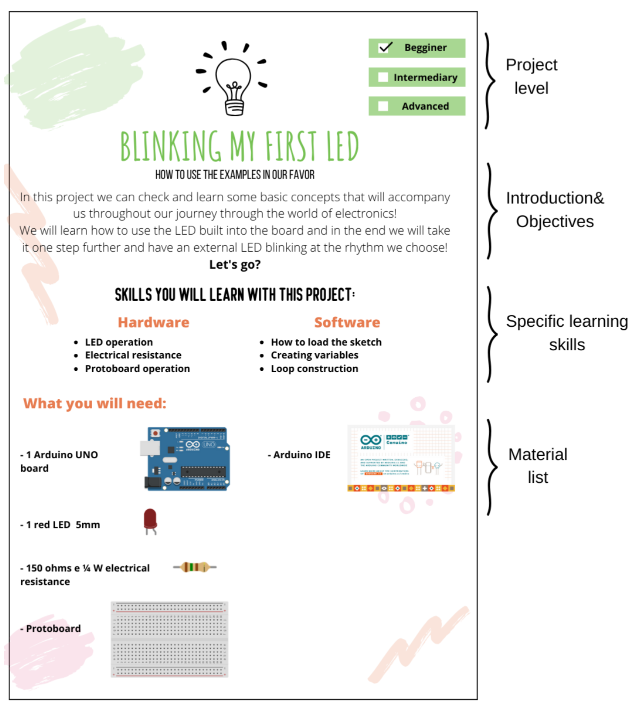

Fig. 3: Example of an activity guide educational material focusing the introduction component.

2) Simulation: this material provides a set of instructions enabling students to conduct simulations using the Tinkercad software package, as shown in Fig. 4. This tool provides a block-based programming interface, facilitating the project implementation process for students with limited programming experience and testing their electronic circuits without the associated risks and complexities involved in the physical implementation.

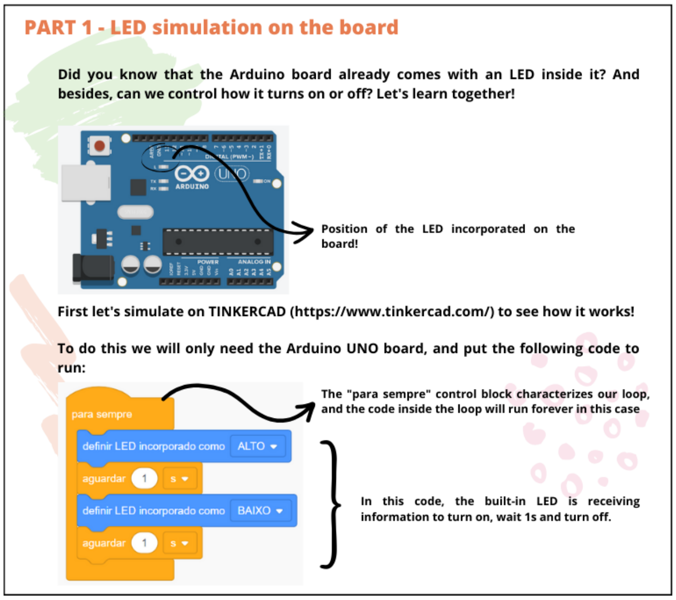

Fig. 4: Example of an activity guide educational material focusing the simulation component.

3) Physical system assembly: this material outlines the step-by-step process of connecting the electronic components, configuring the necessary wiring, and ensuring the correct functioning of the system, allowing students to bridge the gap between theoretical knowledge and practical application, as shown in Fig. 5.

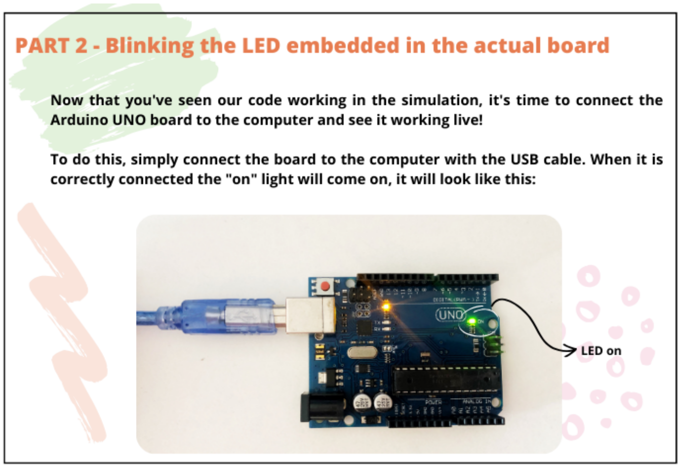

Fig. 5: Example of an activity guide educational material focusing the physical system assembly component.

4) Collaborative activities: To facilitate the student's understanding, the activity guide includes collaborative activities titled ”Let's understand together”, which provides detailed explanations and discussions about the structure of the code used in the project, as illustrated in Fig. 6. This process aims to consolidate their programming knowledge and enhance their comprehension of how the code contributes to the overall functionality of the project, developing critical thinking skills, and reinforcing their ability to apply programming principles in practical scenarios.

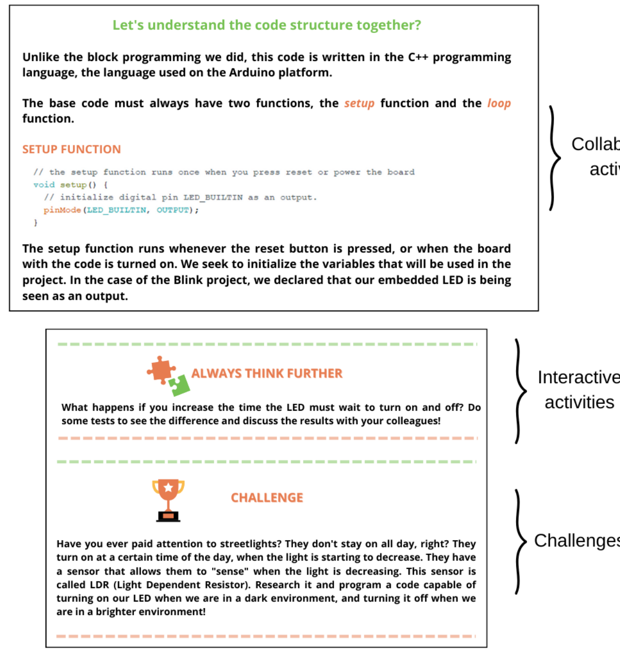

Fig. 6: Example of an activity guide educational material focusing the collaborative activities, interactive activities and challenges components.

5) Interactive activities: called ”Always think further”, these activities invite the student to go further in the knowledge that is being built, being exposed to questions and challenges to be solved during the project, normally requiring a greater level of understanding on the addressed subjects.

6) Challenges: these activities allow students to explore and apply their knowledge to solve problems independently, encouraging the critical thinking and creativity, enabling the use of acquired skills in a real-world scenario. As shown on Fig. 6, they are designed to test the student's understanding, problem-solving abilities, and creativity in the context of electronics.

B. Drops of knowledge

At the end of each project, the student is provided with a collection of learning modules referred as ”Drops of knowledge”, which aim to consolidate the concepts covered in the project (see Fig. 7). They are presented separately, allowing the student to dive deeper into their understanding of each used component and gain a better grasp of the overall system.

Each module offers detailed explanations, further insights, and additional information regarding the specific components, fostering a more thorough comprehension of the subject matter.

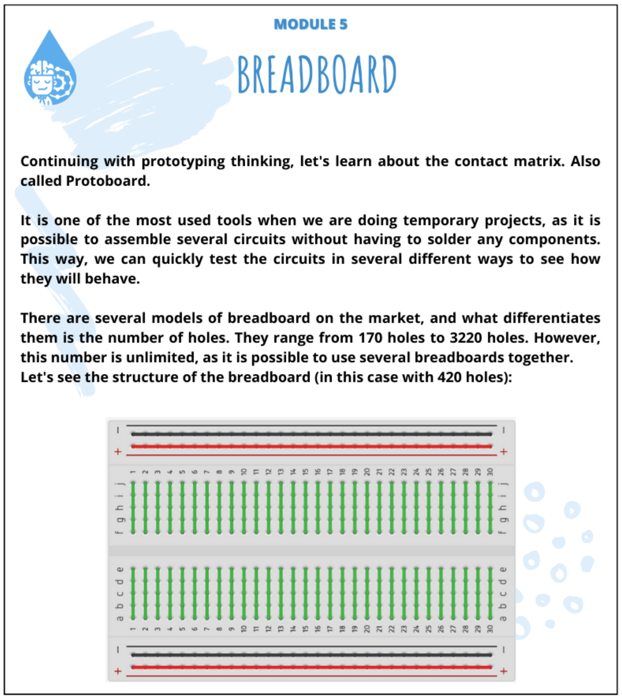

Fig. 7: Example of a Drop of knowledge module aiming to explain the usage of the breadboard.

C. Students Evaluation

The students' assessment was performed through Kahoot!, a game-based learning platform that allows to create and manage questionnaires, surveys and discussions [17], based on an interactive and engaging learning environment, which can help to improve the student's motivation and understanding. Students can participate in these activities by accessing on their own devices, e.g., smartphones or laptops. During the evaluation process, quiz questions were asked related to theoretical concepts and practical developments using multi-choice and true/false questions (see Fig. 8).

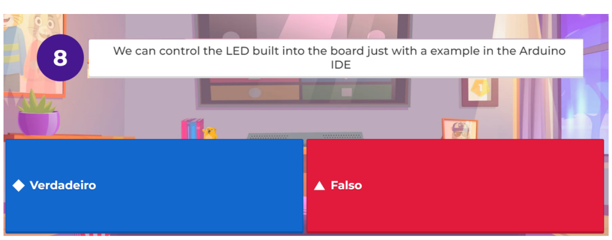

Fig. 8: Example of a question in Kahoot!.

In order to be aligned with the EDR methodology, students were also asked to provide feedback related to the way the project was implemented, through an online form that used a Likert scale. These questions were designed to guide the student to reflect on the implementation of the project, addressing diverse aspects, e.g., the content, design and technical quality of the materials, the learning experience, the level of difficulty of the materials, as well as the motivation to continue learning electronics topics.

D. Feedback from Teachers

To align with the principles of the EDR methodology, the teacher's expertise was considered crucial in providing valuable feedback on the content, design, and technical quality of the developed materials. As part of this process, an online Google form was provided to the responsible teacher at the end of each project, including qualitative and quantitative questions, guiding the teacher's reflection on the implementation process. The questionnaire encompassed various aspects, e.g., the students' learning experience, the teacher's experience in instructing the students, the integration of the educational materials into the curriculum, and suggestions for potential improvements. The insights and inputs provided by the teachers played a vital role in evaluating and enhancing the effectiveness of the projects from an educational point of view, and supporting the continuous improvement of the learning process.

V. Phase 3: Implementation and Evaluation

The school project called "Arduino Project for Students" was implemented in the Emídio Garcia Secondary School, involving two classes from the 9th and 12th grades, comprising students aged from 12 to 15. The primary objective of this testing phase was to assess the effectiveness of the educational materials in fostering successful learning outcomes.

Each developed project was programmed to be applied in the planned weekly ICT class, which lasts two class hours (90 minutes), to provide students with a focused and structured schedule to complete their work. The testing phase took place for a total of 12 class hours, where the target classes used the developed educational material.

During the implementation of the project, the teacher assumed the role of facilitator rather than a primary source of information. This approach empowered students to become active participants in their own learning process. By creating an environment that fostered exploration and discovery, students took ownership of their knowledge and developed a deeper understanding of STEM concepts through hands-on activities.

Throughout the activities, students were observed and evaluated to assess their comprehension and application of the taught concepts. As previously discussed, the assessment of educational material and methodology was conducted by students and teachers, which results offer valuable insights into the effectiveness of the constructionist approach to learning in the ICT classroom. Furthermore, it allows a reflection on the students' understanding and provides an opportunity to make the necessary adjustments for future lessons.

A. Results of the Students Assessment

For the implementation, it was decided to divide both classes into trios, to facilitate the collaboration and teamwork, totaling 6 trios in the 9th class, and 7 trios in the 12th class. To start applying the material in the classroom, the objective of the project was first presented to the class and at the end of each class they were invited to answer the questionnaires via Kahoot!, where the data collected would be important for analyzing the effectiveness of the developed materials.

Taking as example the project 1 entitled ”Blink”, this was applied in both grades on distinct days, being the 9th grade the first one to use the developed materials. The application lasted the entire 90 minutes of the class, including 15 minutes for the student evaluation. The evaluation consisted of 22 questions related to the project content, where the answers were provided by the group, and not individually. Fig. 9 summarizes the achieved results for the assessment of the project.

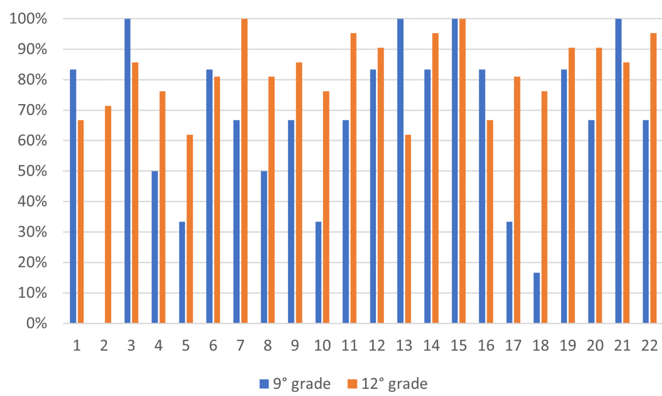

Fig. 9: Results of the students assessment.

Briefly, the ninth-grade class achieved an average of 65.9% correct answers, while the twelfth-grade class achieved 82.5% correct responses. Besides the maturity of 12th grade students, this disparity may arises due to the implementation of the project in the ninth-grade class first, where they only had access to the material in the moment of the class, which resulted in a reduced period of time for the complete reading and understanding of all content. The teachers feedback related to the 9th grade also confirms the importance of providing the material to students in advance. Because of this, the flipped classroom approach was adopted when applying the project on the 12th grade, whereby students study the content before attending the class.

The use of feedback and iterative enhancements in the learning process, reinforces the success of the developed material and the EDR methodology in promoting the continuous improvement of the material for students.

B. Feedback from Students

Fig. 10 presents the results of the students' feedback, providing a visual representation of the responses in each evaluated aspect. This allows a more objective and comparative analysis of the results, identifying areas of focus and possible improvements.

Based on the evaluation results, it is evident that the students express satisfaction with the level of knowledge gained

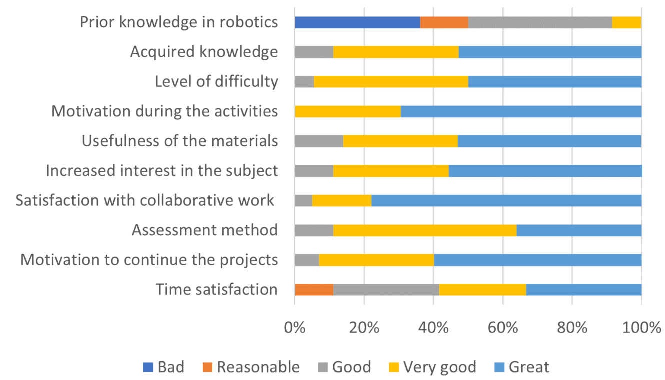

Fig. 10: Students' quantitative feedback.

through the projects. Despite 55% of participants already having prior knowledge in electronics, all students expressed satisfaction with the acquired knowledge and learning outcomes. Collaborative work among students was highly appreciated, with the majority (95%) endorsing teamwork skills. Students emphasized the collective development of skills and the value of diverse perspectives in resolving doubts and challenges.

The teaching material employed in the projects received positive evaluation from the majority of participants (86%) and students perceived the material as an effective tool for instruction, and they found the difficulty level of the activities suitable for their age group and existing knowledge. An additional observed positive outcome was the increased interest in digital electronics and programming fields by all the students, who acknowledged that the projects made programming a more comprehensible subject.

These findings show the positive impact of the curriculum and projects on the student motivation and the creation of a sustained interest in electronics and programming topics. These conclusions underscore the success of the developed learning materials in fostering an enriching learning experience and student engagement in the domains of electronics and programming.

C. Feedback from Teachers

According to the feedback from the teachers, they observed a significant transformation in the students' attitude and engagement with the presented activities. Notably, there was a noticeable improvement in the students' critical thinking and problem-solving skills. Moreover, an important achievement was the development of ”soft skills” through the implemented activities. Teachers emphasized that students exhibited higher motivation and enthusiasm for the proposed tasks, surpassing their engagement in other classroom topics. The provided challenges were deemed appropriate, effectively sustaining the student involvement and motivation.

Teachers praised the projects for stimulating innovation, creativity, and critical thinking among students. They also recognized the practical application of programming and computational thinking as valuable components. The issue of limited availability of equipment within the school was raised, with teachers and students suggesting that certain projects may require more dedicated time beyond a single class period.

VI. Conclusions

This paper describes the development and implementation of educational projects that were designed to introduce beginners to the world of digital electronics, addressing the need for the STEM education. The developed materials provided clear instructions and step-by-step guidance, ensuring that students without prior knowledge or experience could easily follow the learning process. The projects adopted a hybrid approach, incorporating both traditional and constructionist methods through interactive activities and a final challenge. To cater to students who desired a deeper understanding, separate modules called "Drops of Knowledge" were created, offering technical and comprehensive information on various concepts.

The evaluation results were highly positive, demonstrating significant improvement in the students' comprehension and application of the developed material. Students displayed an increased engagement and motivation, actively participating in discussions and activities. Teachers expressed satisfaction, noticing the effectiveness of the materials in meeting the students' needs.

The developed "Arduino Project for Students" was nationally recognized as an exemplary project by the Portuguese Directorate General of Education, showcasing innovative digital practices in schools. This recognition reinforces the success of the developed materials and implemented approach, and encourages the further improvement and sharing of experiences with other educators and schools.

Despite the positive outcomes observed in this study, it is important to acknowledge its limitations, particularly the small sample size. Further research with larger and more diverse samples is needed to strengthen the validity of the results. Additionally, the assessment of the proposed challenges should be incorporated, involving classroom demonstrations where students showcase their individual solutions, fostering discussion and knowledge exchange among peers.

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