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Research article

The use of Tinkercad and 3D printing in interdisciplinary STEAM education: A focus on engineering design

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Abstract: STE(A)M education (combining science, technology, engineering, art, and mathematics) has globally become a growing concern, being recognized as having the potential to prepare students for the challenges of the 21st century. However, the levels of integration of the involved disciplines, as well as their relevance, tend to vary. Engineering design (ED) is being used in educational contexts as an ideal STEAM content integrator to solve ill-structured real-world problems, using the practices of engineering as a problem-solving model. The present study aimed to understand how future elementary school teachers can solve an authentic problem that demands the construction of an artifact, using the ED process in the context of 3D printing, focusing on their performance, the perception of the role of the STEAM disciplines, and the potentials and challenges of computer-assisted design (CAD) and 3D printing. We conducted a qualitative exploratory study with 72 pre-service teachers of elementary education. The implementation was based on a didactical experience focused on solving an authentic problem through the ED process using Tinkercad and 3D printing. The research findings revealed that some of the participants did not follow the ED model exactly as it was presented, skipping or merging steps, but all were able to find a solution and reflect about how to improve it. The majority identified concepts associated with all of the STEAM subjects, although they found it easier to refer to mathematics and science topics. They valued the use of Tinkercad and 3D printing, which allowed them to easily build a virtual model and make it tangible, while also recognizing some challenges in the use of these technological resources. This study can contribute to the scarce literature about the interdisciplinary integration of 3D printing technology in STEAM education, promoting awareness of the overlaps in these disciplines and a more equitable disciplinary attention.

Keywords: STEAM education, engineering design, problem-solving, interdisciplinarity, CAD, 3D printing, teacher education

1. Introduction

We are not able to accurately predict the problems and opportunities that the next generations will be engaged in, mainly due to the constant technological advancements and societal challenges [1]. In order to prepare students for this complex reality, it is important to equip them with problem-solving skills in interaction with other essential skills, like creativity, collaboration, and communication [1,2]. STE(A)M education can play a fundamental role in the development of these skills, by promoting the students' engagement with authentic problems and experiences, which can be more effective if deeper levels of integration between the disciplines are achieved [2]. The engineering design (ED) process can contribute to the achievement of an effective integration of science, technology, engineering, art, and mathematics, bringing added value to the curriculum and to the teachers' practices involving hands-on, project-based, multiple-solution, cross-disciplinary problems with an open nature [3]. However, without proper professional development, it can be hard for teachers to see how engineering can be related to the core subjects and how to implement engineering practices [4]. Considering the steps underlying ED, 3D printing may be an effective resource in supporting hands-on learning and design iteration in an interdisciplinary problem-based environment. There is a lack of research studies in the field of education with respect to the interdisciplinary integration of 3D printing technology [5], which can hinder the understanding of how to best integrate 3D printing in the curriculum.

In this study, we focus on the introduction of ED to elementary education pre-service teachers (future teachers of children aged 3–12 years old) associated with 3D printing. Particularly, we aim to understand how the participants can solve an authentic problem that demands the construction of a model using the ED process in the context of 3D printing. To this end, we state the following research questions: 1) How can we characterize the future teachers' performance along the ED process?; 2) What is the future teachers' perception of the role of each of the STEAM disciplines?; 3) Which potentials and challenges can be identified in using computer-assisted design and 3D printing?

2. Theoretical framework

2.1. Current educational trends: the potential of STEAM education

Educational trends have to follow the economic, social, and technological transformations happening in the complex world we live in. The main goal is to equip students with the necessary competencies to address the problems that they will be facing, preparing them for emerging jobs, and contributing to their development as persons, citizens, and professionals [6]. These competencies include not only the acquisition of knowledge, contemplating the changing nature of literacy in the 21st century, but also the reinforcement of skills, values, and attitudes needed to make it meaningful in a diversity of contexts [6,7]. The relationships between knowledge (disciplinary and interdisciplinary), skills (cognitive and metacognitive), attitudes, and values are seen as interconnected and interacting to produce competencies through action [8]. Focusing particularly on the skills, as the ability and capacity to carry out processes and be able to use one's knowledge to achieve a goal [8], the World Economic Forum [1,9] points out critical thinking/problem solving, creativity, communication, and collaboration, the 4Cs, as key skills to approach complex challenges. So, employers are signaling the demand for cognitive skills, but also interpersonal and socio-emotional skills.

In the current context, the role of students in the education system is changing from mere participants in the classroom, learning only by listening to the teachers' directions, to being active participants with both student agency and co-agency, in particular with teacher agency, who also shape the classroom environment [8]. Teachers play a key role in fostering the development of much-needed competencies, aligning their practices more closely to what is expected of their students in the future, by creating adequate learning opportunities in an active learning environment [9–11].

The quality of the students' learning is strongly dependent on the teachers' choices, particularly the nature of the tasks proposed and the strategies used to challenge and engage the students [12,13]. Solving authentic, real-world problems can help boost the development of specific subject knowledge, as well as the 4Cs skills, promoting positive attitudes [6,14,15]. Authentic, real-world problems are interdisciplinary in nature and require the establishment of connections across different subjects and disciplines [16,17], since they provide a context that reflects the way knowledge and skills are used in real life, resembling real-world complexity and limitations [18]. This type of learning environment is nurtured through the use of tasks that motivate and challenge students to become engaged in solving them, which are particularly related to everyday life but above all have an open-ended nature, allowing different approaches and/or different solutions.

Drawing on the previous ideas, there has been a growing emphasis on STE(A)M education, recognizing that working with authentic, real-world problems implies the use of multidisciplinary knowledge and skills as well as interdisciplinary thinking, integrating concepts related to science, technology, engineering, arts, and mathematics [19]. Johnson defines STEM as "an instructional approach, which integrates the teaching of science and mathematics disciplines through the infusion of the practices of scientific inquiry, technological and engineering design, mathematical analysis, and 21st century interdisciplinary themes and skills" [20, p. 367]. STEM education was created to educate and equip students with the high-order and high-tech skills necessary for the expanding STEM job market [21]. The idea of interdisciplinarity and integration underlying STEM education was extended to the arts, generating the acronym STEAM, which adds an emphasis on the arts (fine arts, language arts, liberal arts, and physical arts) as an important component of integration [21,22]. Considering other disciplines besides science, technology, engineering and mathematics, such as art, may help teachers reinforce students' creativity and innovation [21,22], expanding the toolbox of science and engineering through creative thinking and artistic design, and fostering the meaning-making process which will have an impact on students' engagement in STEAM education [21,23].

The consideration of STE(A)M education as an interdisciplinary construct has been the object of interest, however many researchers have expressed concerns over the inequitable disciplinary attention, not guaranteeing an equal statute to the disciplines, and the different interpretations of integration [2,22,24,25]. The perspectives about STEAM integration tend to vary, but due to the inexistence of a STE(A)M discipline in the curriculum of most countries, the tendency is to have one of the subjects having a dominant role or placing the emphasis on two or more disciplines, particularly science and mathematics, since they are officially in the curricular matrix of compulsory education [15]. Given the diversity of STEAM integration models, it is necessary to reflect about these choices, starting by analyzing the contribution of each discipline and how it affects the interdependence among them. Table 1 summarizes the main role of each disciplinary area in terms of the application of specific knowledge and practices [2,22,26].

Table 1. Contribution of science, technology, engineering, arts, and mathematics.

Science	Technology	Engineering	Arts	Mathematics
The body of knowledge about the physical and natural worlds. Used to describe, explain, and predict the natural world and its physical properties.	The form of human knowledge, artifacts, processes, and systems that results from engineering. Technologies are produced by humans to solve problems or meet needs and are the products of the process of engineering.	The application of knowledge to creatively design, build, and maintain technologies. It is used to optimize solutions for problems, needs, and desires while considering resources and constraints.	The construction and demonstration of understanding through an art form. The engagement in a creative process. It provides additional means of expression.	The use of numbers, quantities, shapes, symbols, and other forms of representation to describe relationships between concepts. Many other disciplines, including science and engineering, often use the language of math.

The previous table sheds light on the individual contributions of each discipline, but more importantly, we should reflect on the levels of integration in terms of disciplinary crossing. In this scope, Vasquez et al. [27] present an integration model that displays different levels of interconnectedness among the disciplines: disciplinary, when concepts and skills are learned separately in each discipline; multidisciplinary, when concepts and skills are learned separately in each discipline but within a common theme; interdisciplinary, when closely linked concepts and skills are learned from two or more disciplines with the aim of deepening knowledge and skills; and transdisciplinary, when knowledge and skills learned from two or more disciplines are applied to real-world problems and projects, thus helping to shape the learning experience.

The relation between the disciplines in STE(A)M education should be of an interactive nature in order to highlight structural links and avoid a siloed approach [22]. Usually, these disciplines are taught independently, since each one has a specific curricula and separate goals, but in the real world it is expected that they are closely connected and even overlapped [26]. This justifies that the interdisciplinary and transdisciplinary approaches are gaining endorsement [2] making connections more transparent through an effective integration of procedural, conceptual, and attitudinal contents within STEAM subjects [15]. These ideas are in line with the need to promote the development of students' abilities to solve real-world problems that require the use of knowledge and skills that cut across different disciplines.

2.2. Engineering design as a vehicle for integration in STEAM education

The accomplishment of deeper levels of integration in STEAM education (interdisciplinary, transdisciplinary) is being heavily supported [2,28], advocating that many real-world contexts and problems require the establishment of explicit connections within and across disciplines. For example, scientists use mathematical and technical knowledge to collect, organize, represent, and analyze data from experiments, while engineers use science and mathematical knowledge to solve specific problems and communicate their ideas using technological tools [28]. A possible and common approach that fits these demands is the use of engineering design (ED), known for providing the ideal STEAM content integrator with a more balanced role of the involved disciplines [14,15,29]. Engineering design, through its underlying process associated with engineering practices, hinders the development of 21st century skills, like the 4Cs, applied to authentic problems that require the integration of cross-curricular concepts.

ED is considered a basic competence in engineering, defined as a "systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints" [16, p. 17]. The implementation of the ED process can be described as the ability to tackle a problem, which is ill-structured in nature, identify its constraints, establish the corresponding criteria, and adhere to the criteria and constraints to enact a design process and create a practical solution, usually a model [30]. Based on these ideas, the ED process can encourage an inquisitive mindset, being related to research on general problem-solving theories and considered a problem-solving approach, with similarities to other known approaches, like Polya's model [15]. According to Flavell et al. [31], elementary students' problem-solving strategies are not fundamentally different from those of professional engineers, with the exception that students have less experience and lower levels of sophistication. That is why it is important to begin engineering instruction during the early years by building on children's natural tendency to design, build, and dismantle things to see how they work [3].

According to the literature, in general, design processes are considered to have an iterative nature, following a series of steps, like: (a) defining a problem by identifying criteria and constraints to find acceptable solutions; (b) generating possible solutions and assessing them to determine the one(s) that best meet the problem requirements; and (c) optimizing the solution by systematically testing and refining it [14,32–34]. The ED process focuses on decomposing an ill-structured, frequently complex problem, solving it by generating multiple ideas and accomplishing a goal through an open-ended path, resulting in multiple solutions that must be evaluated [16,35]. Several studies have presented different ED models, which vary according to their goals, context, and emphasis, being divided in prescriptive and descriptive models, represented by charts, recursive diagrams, and decision-making trees [34]. The prescriptive models draw on the conceptualization of the major tasks for each design step, rather than showing a sequential design process; on the other hand, descriptive models have a solution-focused nature, emphasizing successful engineering design processes [34].

We adapted the model of Hester and Cunningham [3], a descriptive model contemplating a five-step ED process (Figure 1).

Figure 1. Hester and Cunningham's model of the ED process.

We can find several frameworks for the ED process inspired by the model proposed by Hester and Cunningham [14,33], an iterative model composed of five-steps (ask, imagine, plan, create, and improve), created in the scope of the *Engineering is Elementary* (EiE) program to make the design processes more accessible during the lower grades. Grounded on these ideas, we changed the designation of some steps to make the process clearer for the students, and introduced the possibility of more iterations, accompanied by guiding inquiring questions and suggestions involving decision-making (see Figure 2).

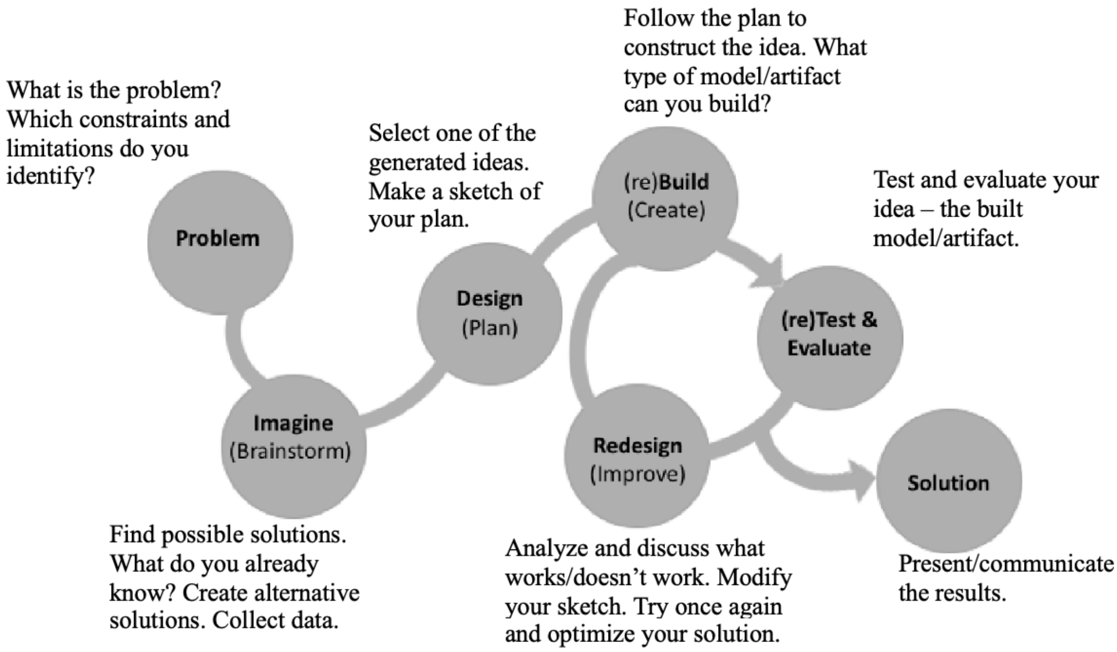

Figure 2. Adapted model of the ED process [15].

The adapted ED process is thus composed of seven steps: problem (define the problem/identify the constraints); imagine (brainstorm ideas/look for possible solutions/choose the best one); design (plan the solution/draw a sketch); (re)build (follow the plan, create and construct the idea); (re)test and evaluate (test and evaluate the idea/the prototype); redesign (discuss what works/what does not work/improve/modify the design to make it better/test it once more); and solution (share and communicate the solution/results/obtained product). As we can see in Figure 2, after the testing and evaluation step, we included the possibility of redesigning, rebuilding, and retesting in case students need to improve the artifact/prototype to meet the required needs.

In conclusion, Yakman's [22] review of education models leads her to conclude that students need to develop knowledge in a range of disciplines in order to be functionally literate, including the arts, since creativity and innovation cannot be treated separately from STEM, but should be seen as a unified whole (STEAM). Although there are several models for the implementation of a STEAM program, the most commonly applied to promote disciplinary integration is the ED process [3,14]. Despite its deep connections to engineering practices, the use of ED generally fosters an inquiry-based learning environment that leads students to learn through questioning and doing. ED can be considered a deep-level integrative approach, aiming to teach and apply scientific concepts but also provide experiential, real-world learning opportunities. In this sense, it can be used to cultivate the scientific, technological, artistic, mathematical, and engineering knowledge of students, expanding their perspectives through a hands-on/minds-on methodology.

2.3. Engineering design powered by CAD and 3D printing

The hands-on experience of making, advocated by the Maker Movement, is considered effective for learning purposes due to its roots in the principles of active learning, which imply the interconnection between cognitive, social, and physical engagement [10,36]. Making is a powerful, personal expression of human thinking and promotes a sense of ownership, creativity, and aesthetics [37] that has a positive impact in students' engagement at all levels [15]. The notion of "making" can be more direct and hands-on, transforming ideas into 3D models using only physical manipulatives, yet it can be a flexible learning process including the production of technology-enhanced artifacts [37]. Technology can have a particular role in this context, supporting the development of ideas and problem-solving, through the use of different resources. The integrative approach to STEAM education through ED can benefit from the use of emergent technologies like 3D printing and computer-assisted design (CAD) software, posing problems that lead to the manipulation and creation of artifacts mediated by technology.

CAD can be seen as a technological extension to traditional hands-on planning, processing, and producing, which allows the creation of virtual representations of physical objects. Engineers and designers frequently use this type of software to engage in the design process and to develop solutions to ED problems [35]. This type of digital resource is usually used to predict the outcome of a certain design or evaluate its performance, supporting the creative engagement with problem solving and the communication of ideas through graphical representations [35]. We can find a diversity of CAD software in the market but not all are adequate for K–12 levels, particularly elementary levels, due to the complex usability requirements. In this study, we chose Tinkercad (Figure 3), a free, easy-to-use CAD software, a web-based platform, with a drag-and-drop feature. The user creates the designs by dragging the shapes from the menu, dropping them in the building plate, and modifying the 3D models which can be manipulated using a simple and intuitive interface [4]. The 3D objects can be designed with block coding, and all subparts (solids) must be created with separate encodings and then grouped [38]. Since it is a web-based software, it does not require installation or special hardware, which reinforces the idea of easier accessibility for both teachers and students.

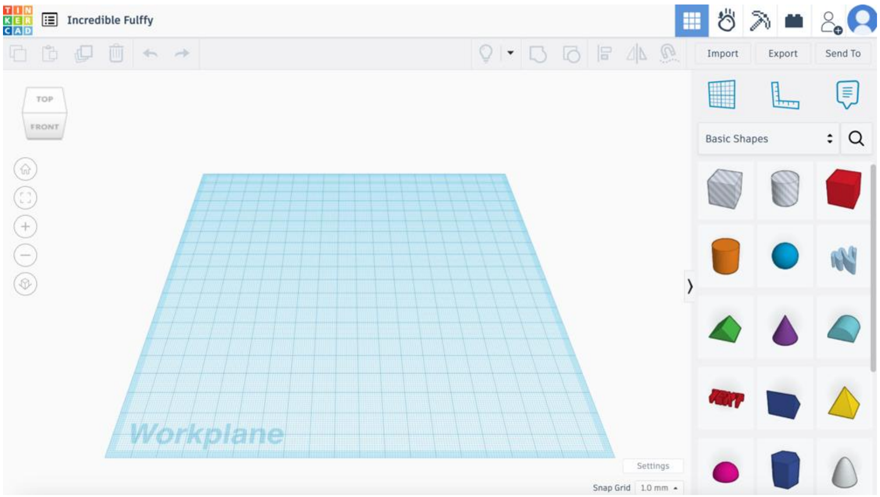

Figure 3. The Tinkercad work environment.

Students may use this type of software to simulate and experiment with different scenarios, learn by trial and error from the process of making mistakes and correcting them, perform problem solving, and establish decision making with little risk and without wasting resources [39], which is in line with the ED process. The CAD environment also facilitates the teaching and learning of elementary and advanced mathematical and scientific concepts [39], supporting the development of a strong foundation on computer-aided design, which is an asset for future careers [37]. The creation of 3D models in this type of virtual environment and the possibility to manipulate them is important for the development of spatial thinking and visualization skills in general, fundamental not only for mathematics proficiency but also in many other fields of knowledge [38,40]. Spatial thinking and the use of spatial representations are applied in design practices, especially when the aim is to obtain a tangible object from a virtual prototype, attending to a series of features, like shapes, sizes, spatial relations, spatial arrangements, perception of space, and proportion [40].

Recently, 3D printers, as emergent computer hardware, are assuming an important role in assisting students in real-world problem-solving, providing a meaningful experience in terms of design practices, particularly creation and manipulation. A 3D printer is a device that converts 3D computer data into tangible objects [41], giving students the opportunity to plan and create 3D models through design thinking skills, bringing virtual objects to life [5]. The possibility of seeing the printing procedure and touching the designed object can constitute a unique experience for students and spark a sense of satisfaction [41]. This process helps promote a more effective learning experience by contrasting theoretical knowledge with practice and recognizing/eliminating possible misconceptions. The type of procedures required by 3D printing demand understanding of science, engineering, technology, arts, and mathematics to design and produce 3D objects, so it can be a powerful resource for integrated STE(A)M education [42]. This approach engages students in authentic problem-solving, particularly in the ED process. Creating a physical object using a 3D printer usually requires several design iterations, in order to adjust the object design, materials, or print density, and allows the user to identify design flaws prior to attempting further modifications [5,43]. The printed physical objects allow students to make concrete the solution to a given problem, examine the success level of their designs, and improve their existing designs with various arrangements [44], as expected in ED. In this sense, 3D printing can also lay the foundation for reflective validation, leading the students to naturally engage in the evaluation of their own work [45].

CAD software and 3D-printing technology are powerful learning tools that can engage students in active learning and particularly meet the requirements of ED. Students have the opportunity to work with authentic problems, designing, building, and evaluating their prototypes in terms of efficiency [15,41,45]. The CAD software is the first step to convert a design into a concrete structure, which can be improved, leading to a more effective or creative proposal. The printed 3D model turns tangible the ideas expressed on paper or on the virtual environment, which allows students to compare former ideas and sketches with the final product, promoting students' awareness about certain details that may be improved [42,45]. Unlike most contemporary technology, 3D printing requires kinesthetic interactions between the users and the printed physical objects, thus, it offers greater potential for engaging students in hands-on and experiential learning, bringing something previously unreachable to life [42].

Despite the potential of 3D printing in STEAM education and, in particular, in the implementation of ED practices, it is important to highlight some challenges in terms of the educational context. One of the first steps when engaging in 3D printing is designing a model within a CAD software which, in some cases, can trigger difficulties with the software's orientation, perspectives, floating shapes, and camera control [46]. There may be other barriers related to the lack of experience with 3D modelling, which may imply the need for educator support, or technical problems such as 3D-printed materials not performing as expected, the time it takes for 3D models to print, or the costs of 3D printing [47]. This implies the need to create previous opportunities to develop students' competences at this level through their engagement with these technologies, increasing their proficiency in the scope of spatial thinking [46]. Other challenges are related to the limited budget of schools to acquire these resources and engage with 3D printing technology, or the teachers' limited skills or lack of knowledge about the use of this hardware as well as its integration into STEAM education [48,49]. Given the utility and potential of 3D printers in different fields and the advances in technology nowadays, it is possible to find this resource at more accessible prices, but (pre-service and in-service) teacher training in this scope is still a pressing need. Teachers' beliefs about technology integration influence teachers' technology integration in the classrooms, and teachers' beliefs can also influence students' cognitive and affective learning outcomes [42]. This supports the general need in teaching education programs for information about 3D printing, which will support their professional development and enabling their ability to teach others about 3D printing and design processes [43,47].

3. Research design and methods

3.1. Methodological options

The study was planned according to an interpretive paradigm, taking the form of a qualitative exploratory design [50]. These methodological options are sustained by the nature of the problem, which focuses on understanding how future elementary school teachers solve an authentic problem that demands the construction of an artifact using the ED process in the context of 3D printing. This implies the development of an in-depth comprehension of a lived experience and construction of new understandings that may have the potential to inform future research [51]. Considering the abovementioned problem, we decided to focus on specific ideas that were translated into the following research questions: 1) How can we characterize the future teachers' performance along the ED process?; 2) What is the future teachers' perception of the role of each of the STEAM disciplines?; 3) Which potentials and challenges can be identified in using CAD and 3D printing?

3.2. Context and participants

This research was conducted with 72 pre-service teachers attending the first semester of the third year of a BSc in Basic Education with the duration of six semesters (future teachers of children aged 3–12 years old). This BSc program was composed of subjects related to the areas of didactics, general education, content knowledge, and practice in formal and non-formal educational contexts. The participants were enrolled in a Didactics of Mathematics unit course, entitled Integrated Mathematics, managed by the researchers, which served as the context for the experience and global data collection. The group of 72 students, divided into three classes, was composed of 70 women and 2 men, with an average age of 24 years old, and willingly and informedly accepted to take part in the study.

The study was immersed in the unit course in a very organic way, given the goals and structure of the program. The work developed during the semester was based on the current curricular guidelines for the teaching and learning of mathematics, focusing on fundamental skills, such as the 4Cs, and the analysis and discussion of rich and challenging tasks, taking into consideration the principles of active learning. It included teaching modules on problem solving, creativity, mathematical connections (internal and external), reasoning, and communication. Considering these topics, we thought it would be pertinent to include the reference to STEAM education as a pathway to globally address previously mentioned ideas, specifically drawing on the importance of problem solving and the potential of the establishment of connections to highlight the discussion of deeper levels of disciplinary integration.

3.3. The didactical experience

The didactical experience underlying the study had four key stages developed during the lessons of the unit course (see Figure 4).

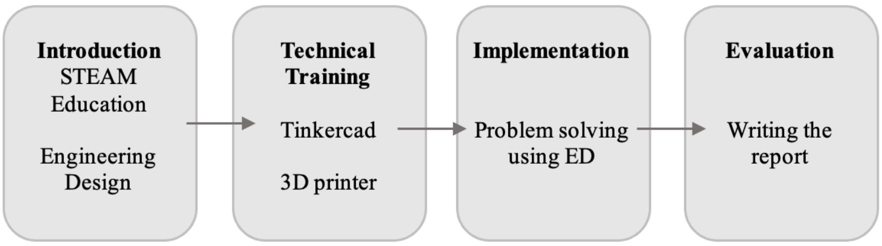

Figure 4. Stages of the didactical experience.

The first stage (one lesson, 3 hours) served to present STEAM education as a current trend with the potential to promote the solving of authentic problems, from an interdisciplinary perspective, where connections can be emphasized. Then, in a more specific outlook, we introduced and analyzed ED as a process that promotes deeper levels of integration between STEAM disciplines, identifying it as a problem-solving model suited for engineering problems, using the Vale et al. [15] model presented in Figure 2.

Before engaging in the implementation stage, the participants needed training regarding the technical component of the tools used. None of the students had previous experiences with CAD software, particularly Tinkercad, and 3D printing, so it was important to give them some time to explore the software and the printer until they felt confident using it (two lessons, 6 hours). This opportunity was also a fundamental training stage, since (pre-service) teachers should know and experience the options they have using a certain technological resource and how to use it in its full potential with their students. During this stage, the participants were challenged to design a keychain with their name in Tinkercad, and then got to see the 3D printer in action to know how it worked.

The third and main stage of the didactical experience (two lessons, 6 hours) was the implementation, corresponding to the presentation of the problem and finding a solution. The proposed problem is presented in Figure 5.

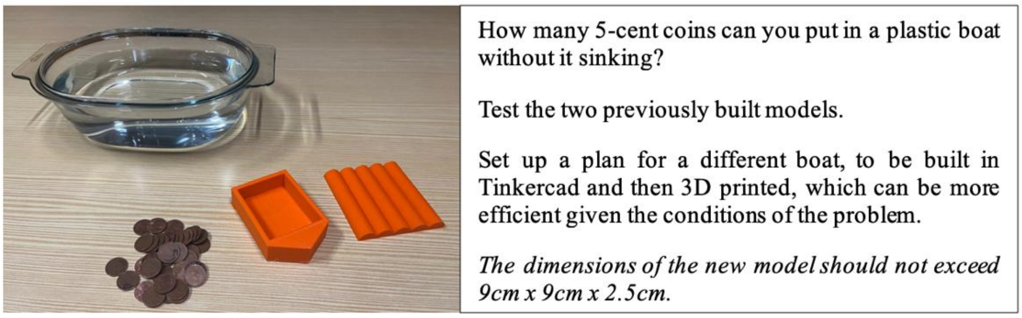

Figure 5. The boat problem.

While selecting and designing the task, we considered some conditions: the possibility of applying the ED process, promoting STEAM integration, and the use of 3D printing and Tinkercad. We had some expectations about the STEAM content and skills students would apply to build the boat, namely: understand principles of fluctuation and distinguish types of forces (science); contact with technological tools that facilitate the design and building process, making it possible to conduct experiments and reach the artifact (technology); engage in the ED process, following the different steps (engineering); show creativity and aesthetic sense in design (art); and make decisions about the most effective three-dimensional shapes (math).

In each class, the participants worked in groups of three or four elements, corresponding to a total of eighteen groups. The hands-on materials needed for the experience were provided by the researchers as well as the 3D printer and the PLA filament. The participants used their own laptops or tablets to work with Tinkercad. Before the implementation, the researchers reminded them of the ED process cycle (see Figure 2) as a reference to facilitate a step-by-step activity.

In the last stage, after solving the problem and reaching conclusions, the participants were asked to produce a group-written report reflecting about the didactical experience. This report should include aspects like: conclusions of the tests carried out with the two initial models, focusing on variables that could influence the results; a description of the work developed to achieve the final 3D model (following the ED process); a comparison of the behavior of the constructed model to the initial ones, analyzing the differences; learning opportunities and difficulties; and the STEAM concepts involved.

3.4. Data collection and data analysis

Data were collected in a holistic, descriptive, and interpretive way [52] consisting of participant observation, documents, artifacts, and photos. The fact that the researchers were also the teachers responsible for the unit course facilitated naturalistic participant observation and the recording of free-flowing notes, focusing on the pre-service teachers' reactions, interactions, conversations, discussions, and interpretations, including a record of facts but also the researchers' commentaries about those facts. The groups' reports complemented the observations, allowing more in-depth access to the participants' ideas and perceptions. Artifacts, namely the 3D models built, evoked the application of the ED process by each group, reinforcing some of the decisions and actions implemented while solving the problem. The photographs, collected both by the researchers and the participants, illustrated specific actions and representations in different moments of the implementation. This research took into consideration ethical concerns, ensuring the confidentiality and anonymity of the participants, obtaining written informed consent for collecting the abovementioned data, and handling the data respecting privacy.

To analyze the data, we used a qualitative, inductive approach, recurring to content analysis [53] to interpret data systematically, drawing upon the multiple sources of evidence collected, seeking complementary data and the reinforcement of credibility, and corroborating data from different sources. After repeatedly consulting and reading the information, as well as cross-referencing the evidence, it was possible to generate categories of analysis, influenced mainly by the research questions, complemented by the theoretical framework and the data collected. These included the performance in ED (Problem, Imagine, Design, (Re)Build, (Re)Test and evaluate, Redesign and Solution); the role of each STEAM discipline; and the potentials and challenges of Tinkercad and 3D printing.

4. Results and discussion

The results will be presented and discussed in three sections, starting with the performance along the ED process (the implementation stage of the didactical experience) and then advancing to the pre-service teachers' perceptions of the role of the STEAM disciplines and the identification of potentials and challenges in the use of Tinkercad and 3D printing. To report the main findings, we used the information from the observational notes, the written reports, the produced artifacts, and the illustrative photos.

4.1. Performance along the ED process

4.1.1. Problem

The presented problem (see Figure 5) was chosen because it had the potential to engage the future teachers in the ED process, making use of all of the STEAM disciplines in an integrative manner.

The participants started by addressing the problem, using the available materials (a bowl of water, 5-cent coins, and two 3D-printed models of boats), identifying the conditions and constraints, and engaging with the situation (see Figure 6). Each group tested the behavior and efficiency of the two initial models, discussing the influence of the shapes, the disposition of the coins, and the positioning of each model in the bowl of water. Different experiments were conducted that led to the exchange of ideas and the formulation of conjectures and assumptions. As shown in Figure 6, they tested the models in different positions (with the flat part facing up and facing down), and also by arranging the coins in different ways (by trying to distribute them in such a way as to maintain the stability/balance of the model).

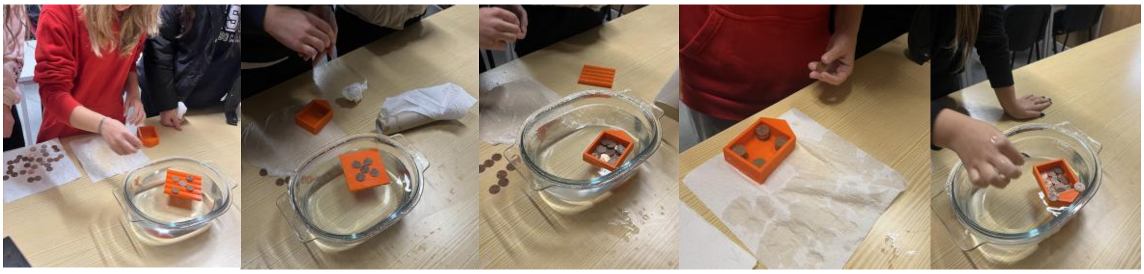

Figure 6. Testing the initial models.

Analyzing the results of the tests, the groups concluded that the "raft" supported an average of twelve coins and the "boat" an average of thirty-two coins. This initial step allowed them to engage with the problem, in a hands-on perspective, making them more aware of the conditions, certain limitations or advantages of the models: "the part corresponding to the triangular prism has implications regarding the center of mass and consequently on the arrangement of the coins", "the raft positioned with the semi-cylinders facing up caused some instability in the moment of disposing the coins", "the recesses between the set of semi-cylinders in the raft made the water enter the space more quickly and the raft to sink with fewer coins than the boat", and "the height of the boat was greater than that of the raft, a variable that influenced a faster submergence of the later". These ideas allowed the participants to make more-informed decisions in the following steps.

4.1.2. Imagine and design

The pre-service teachers were required to create sketches representing their ideas for a new boat, trying to make their plans more concrete and visually communicating their decisions for the intended model. Prior to that step, during brainstorming, they started by sharing and discussing possible solutions to the presented problem. Some of them thought of known references from daily life, such as a container carrier, known for supporting a lot of weight, others resorted to research on the internet, trying to find models of boats that could fit the conditions. Still others based their discussion on the behavior of the models tested in the first step, thinking of ways to adapt them and create a more efficient boat (e.g., joining the two models, adapting the one that sustained more coins, and creating models with compartments/cavities using the maximum height).

Only eight groups made sketches of the model in the planning step of the ED process (design). Others immediately started experimenting possibilities in Tinkercad, transitioning directly from the brainstorming to the building step, without representing their ideas on paper. Some of the groups presented clear sketches of a possible solution, and in certain cases they were thorough enough to represent the evolution of their ideas until they reached the model they chose to build (see Figure 7).

But, not all of the eight groups presented intentional sketches, making drawings that were barely perceptible or not feasible in Tinkercad (see Figure 8).

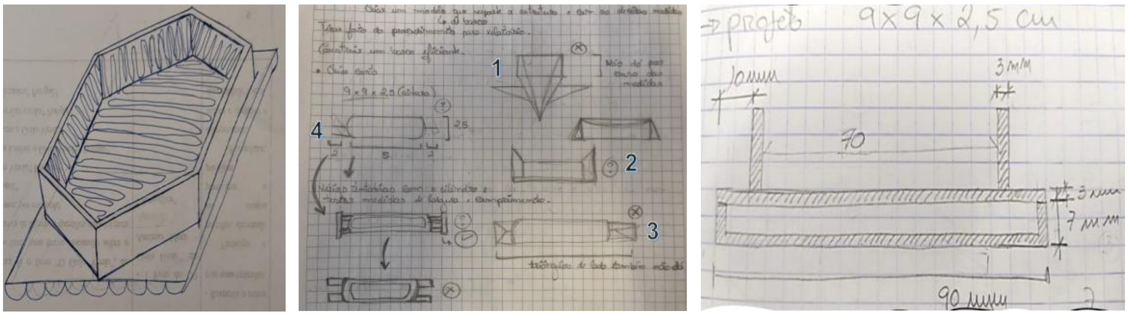

Figure 7. Clear sketches of the new model.

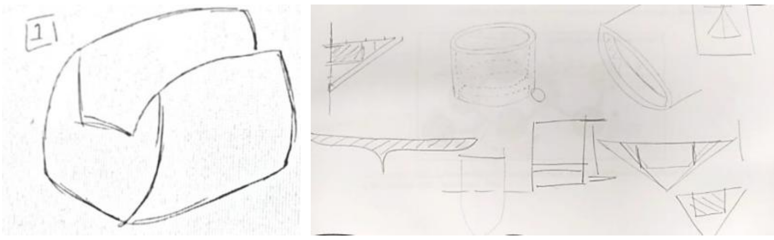

Figure 8. Unclear or not feasible sketches for Tinkercad.

Since there was no specific indication of the roles of each member of the group, the participants decided what each person would do. The sketches were made by one or more students, but the modelling in Tinkercad was only performed by one of the members of each group, incorporating suggestions from the colleagues. Regardless of who was carrying out the task in question, every participant in each group was involved in the same action rather than taking on parallel tasks.

4.1.3. Build, test/evaluate, and redesign

After imagining and designing the boat, the participants moved on to building the 3D model using Tinkercad (see Figure 9). As part of the didactical experience, the pre-service teachers previously explored this CAD environment, becoming familiar with its main functions (e.g., drag and drop, resizing, rotating, changing views, grouping), so they would feel comfortable using this tool to solve the problem.

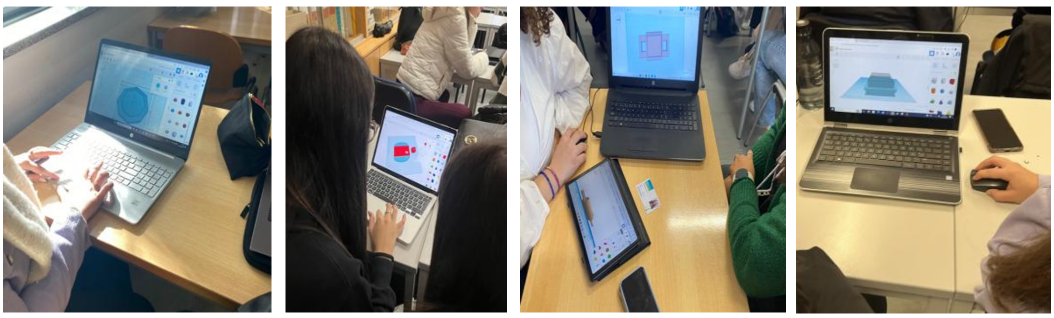

Figure 9. Building the models in Tinkercad.

Most groups tried to build the model that they initially planned in Tinkercad, however, not all of them were able to implement the chosen idea due to different reasons, such as, while using the CAD software, they found a way to make the model more effective (e.g., applying holes; mixing shapes) or more creative, in the sense of being original, or the planned model was difficult to create with Tinkercad due to its complexity in terms of construction (e.g., the shapes, the grouping, the holes needed). During the construction of the new model, and as they used Tinkercad, most of the groups also applied Redesign, making room for improvements applied through successive iterations even before the testing and evaluation step of the ED process. Not all of the participants had thought about the model's measurements in the planning phase, only the shape, but while working with Tinkercad, this need emerged. So, it was not until this stage that they thought about the measurements and also tried to optimize them to ensure more space for the coins. Another reason for the redesign was related to the use of cavities/holes, which in the virtual environment was not always easy to build due to the needed rigor, having to combine solids, measurements, aspects related to symmetry, and the attention to the depth of the cavity as to not puncture the model. In these cases of redesign, the groups globally mentioned the importance of taking into account factors such as depth (e.g., creating space for the coins, and using a height that compensates for the movement of the water), stability, and balance of the model (e.g., considering the base) that were not so well-planned.

After completing the project in Tinkercad, they saved it as an STL file and then used Ultimaker Cura to slice the model before printing it. After the 3D printing, the models were observed and compared. Figure 10 illustrates some of the results.

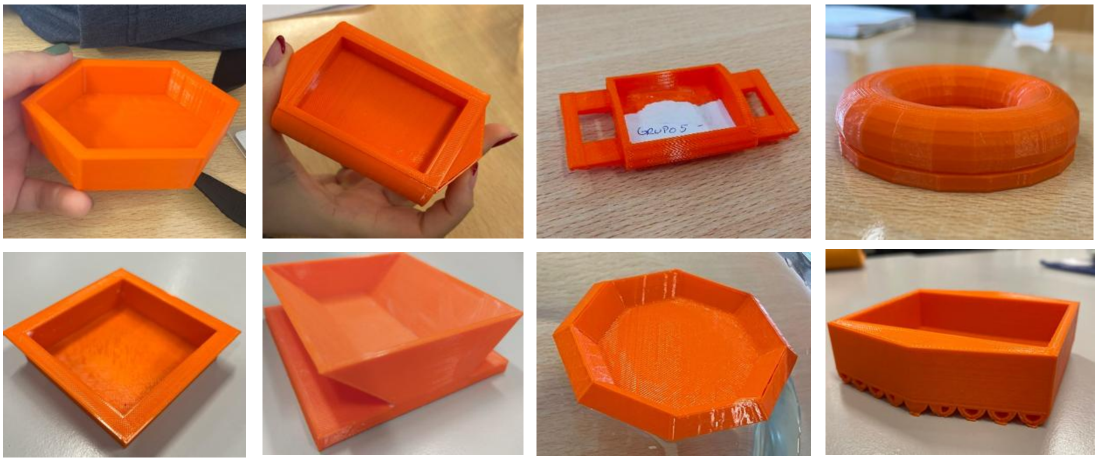

Figure 10. Examples of some of the printed models.

Overall, we can categorize the models in three groups in terms of diversity: 1) models mostly recurring to prisms, with similarities to the initial boat; 2) models resulting from the combination of prisms with non-polyhedral solids; and 3) most original constructions (unusual or unique models, revealing divergent thinking). Five groups presented models recurring to prisms, with similarities to the initial boat (e.g., the 1st and 5th photos in Figure 10), showing lower levels of creativity. Seven groups have built models that included a combination of prisms with non-polyhedral solids (e.g., the 2nd and 8th photos in Figure 10), displaying an attempt to include novel ideas. Six groups stood out for presenting unusual models compared to the others (e.g., the 3rd and 4th photos in Figure 10). Two of the models designed did not correspond to what the respective groups expected due to construction errors in Tinkercad, related to incorrect groupings (see Figure 11) or to the level of detail and accuracy of the printer (e.g., partitions with low thickness).

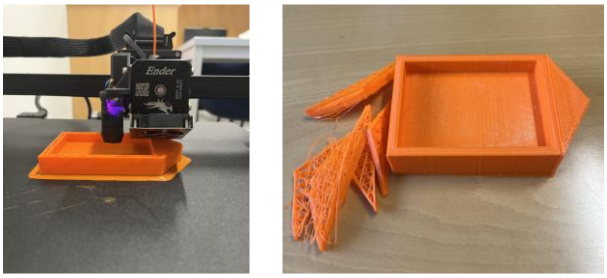

Figure 11. Model with construction errors.

After this discussion, each group tested the respective model (see Figure 12) in light of the problem conditions, having in mind the results from the tests made with the initial boats.

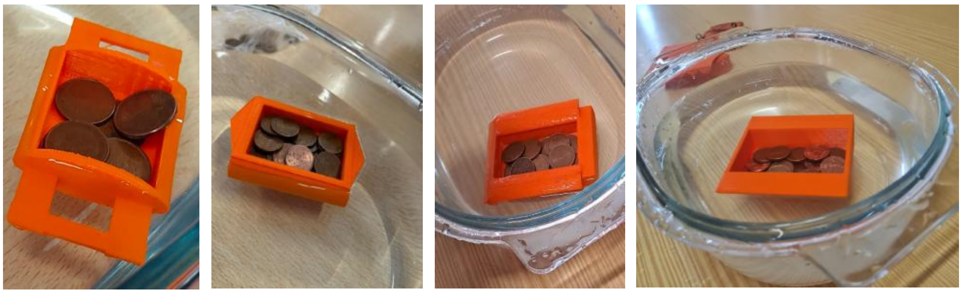

Figure 12. Testing the designed models.

Of the eighteen groups, nine concluded that their model was less effective compared to the boat from the initial step, since it supported a smaller number of coins. In particular, two of these models only supported 5 or 6 coins (e.g., the 1st photo in Figure 12) due to the fact that they did not consider the real dimensions of the model in Tinkercad and were influenced by the virtual environment, focusing only on the shape.

4.1.4. Solution

The last stage of the didactical experience corresponded to the writing of the report in which the groups had to describe and discuss, among other aspects, how they solved the problem following the ED process. Through this report, it was possible to access more detailed ideas about the results. Each group organized and presented the data collected throughout the experience, although with different levels of depth in the argumentation.

In general, every group compared the efficacy of the three boats, the two initially presented and the one they had built, in terms of the number of coins sustained, trying to reflect on the behavior of each one, particularly the designed model. With this evaluation, they were able to think about the strengths and weaknesses of their work and what they would do differently, particularly the groups that did not succeed, in the sense that their model sustained a smaller number of coins. The most common ideas were to adjust the measurements in Tinkercad, assuming that they did not take into account the transition from the virtual model to the real object; to be more rigorous in the use of

Tinkercad's functions, namely the grouping function that was not always considered; and to optimize the model's measurements, using cavities with greater depth in order to dispose more coins. Other arguments were used with the intent of improving the product, although with less frequency, such as the possibility of designing a more creative model and also the usefulness of being able to experiment a physical representation of their prototype before using Tinkercad.

4.2. Perception of the role of the STEAM disciplines

The written report also gave us information about the participants' perceptions of the role of the STEAM disciplines while solving this particular problem. The majority identified the role of the STEAM disciplines (see Table 2), however they found it easier to analyze the presence of science (physics) and mathematics, possibly because these areas have a more evident presence in the school curriculum, particularly in elementary education.

Table 2. Concepts associated to each STEAM discipline.

Science	Technology	Engineering	Art	Mathematics
Forces, weight, mass, balance, fluctuation, stability, density, surface tension, Archimedes' Law	Construction of a model in a virtual environment, 3D printing of the model, the possibility to try different models	ED process Association to technology	Design, creativity, sketches	Geometric concepts used in the model construction, symmetry, measurements, calculations, problem solving

Despite being able to refer to the abovementioned concepts, the arguments frequently showed a lack of rigor in the language used, namely related to geometric concepts—"roof", "tips", "hollow", "half cylinder", "pyramid" instead of "triangular prism", "triangle" instead of "triangular prism", "straight side"—as well as physics concepts, such as the confusion between weight and mass, "uniform" or "sustenance" instead of "stability" or "balance". Also, most of the groups were not able to deepen their argumentation in terms of the role of physics, focusing mainly on fluctuation, stability, and balance.

Although these future teachers have prior scientific knowledge regarding these disciplinary areas, they still have difficulties in showing awareness of their application to authentic problems, which leads us to believe that more experiences of this type are necessary.

4.3. Potentials and challenges of the used technology

Solving this problem required the use of specific technology, namely a CAD software (Tinkercad) and a 3D printer. The participants received technical training focused on the use of these resources on the second stage of the didactical experience and then applied them in the following stage (the ED process). After solving the problem, they were asked to comment on the potentials and challenges identified in the use of Tinkercad and the 3D printer in their written report. Globally, they recognized the importance of contacting with both resources as a way of keeping up with the technological developments of two tools that they did not know and whose value they recognized. The training stage was considered fundamental by the participants, preparing them for future interventions, but also for demystifying the complexity of the use of a 3D printer.

They considered Tinkercad to be an intuitive and easy-to-use tool, with a simple interface, mainly due to the integration of familiar shapes, with explicit menus and a simple manipulation. Being future elementary education teachers, they valued the possibility of building a variety of objects starting from a set of solids that can be grouped, cut, and/or have holes, promoting creativity. They were able to easily experiment with different possibilities, redesigning their models as often as they saw fit, and valued the process of trial and error. Some difficulties were also identified that, in the participants' opinion, may also be experienced by their future students, such as navigating the camera angles (changing views in Tinkercad) and in making sure that the grouping was made correctly by selecting the adequate shapes (an aspect that, in some cases, was only identified when the model was printed). Although some groups showed difficulties related to scaling, neglecting the measures of the model in the virtual environment, they recognized the importance of this feature in a CAD software to promote more robust learning. Overall, Tinkercad was considered a useful tool that these pre-service teachers declared to apply in future projects, not only in mathematics, due to its potential regarding the learning of geometric concepts and the development of spatial thinking, but also in interdisciplinary work.

Regarding the 3D printer, the participants reacted positively to the possibility of virtually building an object and converting it into something tangible, despite that in two cases (due to problems in the creation phase in Tinkercad or printer limitations) the model did not correspond to the expected result. The only challenge some of the groups mentioned was related to time constraints in the classroom, concerning the duration of the printing and the need to print several projects. The overall reaction of the future teachers to the printing process (by layers/slices) and to the model itself was of enthusiasm and satisfaction. They agreed that 3D printing can be a useful tool to create opportunities for students to be designers themselves and make concrete the projects that they develop.

5. Conclusions

This study intended to provide some insights about the approach to STEAM education through engineering design (ED), resorting to 3D printing, in the context of teacher education. It specifically focused on the ED process steps, the perceived role of the STEAM disciplines, aiming an integrative perspective, and on the technical and pedagogical components underlying the use of CAD and 3D printing. It is extremely pertinent to access (future) teachers' perceptions about practices of this nature, which are valued and recommended in the current curricular trends, and also provide them experiences that use the same teaching and learning principles that teachers are expected to use with their own (future) students [13,36]. This study involved the participation of 72 future teachers of elementary education who went through a didactical experience that contemplated sequential stages including moments of theoretical introduction and technical training in the use of technological tools (Tinkercad and 3D printing), as well as implementation and evaluation, based on the resolution of an ED problem. The main conclusions of the study were presented and organized according to the research questions, based on the triangulation of the collected data, supported by the theoretical framework.

The participants were presented with an authentic problem that required the application of multidisciplinary concepts in the scope of STEAM education, which they had to solve using the ED process. The ED model presented was that of Vale et al. [15], adapted from Hester and Cunningham [3] (see Figure 2), and was composed of seven steps (Problem, Imagine, Design, (Re)Build, (Re)Test and Evaluate, Redesign, Solution). The engagement with the problem was well achieved, with the participants identifying the conditions and limitations of the presented situation. The fact that they had the opportunity to test the behavior of previous models from a hands-on perspective and through collaborative work was essential, following active learning principles, with the emergence of the cognitive, physical, and social dimensions [10,36]. In this step, they made comparisons and formulated conjectures based on the experiments conducted, which influenced the following steps of the ED process, applying these ideas to the brainstorming step. The discussion of alternative solutions was fundamentally based on everyday references they already knew, additional research on the internet, and the adaptation of the tested models, so there was a concrete component that was emphasized on the basis of previous knowledge. Not all groups valued the Design step, moving immediately to the Building step using Tinkercad. The groups that used sketches showed different levels of performance, ranging from clear and intentional sketches, with a deep level of detail, to sketches that were barely perceptible or not feasible in Tinkercad. In the Building step, the majority tried to construct the chosen solution in Tinkercad, which happened in a few cases. Most of the groups merged this step with Redesign by experimenting in the CAD environment, identifying ways of achieving a more effective or creative model, or because they found it impossible to build their model due to the level complexity or because they had not planned the dimensions of the boat. In this step (Building), a small number of participants neglected the dimensions of the model and focused just on the shape, only realizing this constraint after printing, and two groups reported problems in the printing process because they did not get the designed model, due to mistakes made when using Tinkercad (groupings and unrecognized partitions by the printer for being too thin). When they tested the models, only half of the groups came up with a more effective solution that could hold more coins than the initial boat. Although this is a significant failure rate, we associate this scenario with it being their first experience and the fact that they have built the model in a virtual environment they had only just learned about. It would have been easier if the model had been built from scratch in a hands-on perspective, with commonly used materials, as one of the groups suggested in their reflection. The level of abstraction required and the competences of spatial thinking involved may help explain this performance [40,46]. As previously stated, some of the participants did not follow the ED cycle as it was presented (see Figure 2), skipping the Design step or merging Building and Redesign steps, a common aspect to other studies conducted with different ED problems [15,32,54]. Although the results fell a little short, it is worth noting that sharing the solutions through the written report was a key moment for these future teachers to identify the strengths, weaknesses, and aspects to improve in their work. They were able to realize what they could change in the solution, both in terms of planning and design, but especially in the Building step in Tinkercad.

The use of the ED process in education can be considered an asset in the context of the development of problem-solving abilities. This approach has natural connections to STEAM education and is known for providing the ideal STEAM content integrator with a more balanced role of the involved disciplines [14,15,29]. Focusing on (future) teachers, it is important for them to be aware of this potential and, above all, to be able to recognize the contribution of each discipline along the ED process and the level of interdependence between them [2]. The future teachers who took part in this study were able to reflect on these issues based on the didactical experience, particularly the implementation phase where they solved the boat problem. The majority were able to identify concepts associated with all of the STEAM subjects, although they found it easier to refer to mathematics and science (physics) concepts. This result can be related to the tendency of emphasizing these two disciplines due to their statute or for being in the curricular matrix of compulsory education [15,24].

The use of a CAD environment and 3D printing were introduced in this study, in an attempt to keep up with technological developments and current educational trends in straight connection with the ED process [37,42]. These resources have been recommended in education, as a support to the development of ideas and problem solving, and it is therefore necessary for teachers to be proficient in their use. As a result of the didactical experience, the participants were able to identify some potentials and challenges in using these technologies. Overall, they reacted positively to the contact with Tinkercad and 3D printing, which they did not know about, as part of their training. Tinkercad was considered easy to use, very intuitive and interactive, a promotor of the trial-and-error approach, and with potential for the exploration of geometric concepts, along with the possibility of building models, ideas also stated in the literature [4,39]. The challenges mentioned were related to operating the views and executing certain groupings due to the complexity of certain models. All subparts (solids) of a model must be created with separate encodings and then grouped [38], and if we are dealing with a lot of subparts, it is likely that one or more are forgotten. The 3D printing generated an expected enthusiasm among the participants given the opportunity of seeing their virtual project turned into something tangible [5,41,42,45]. As a challenge, the future teachers focused on the time constraints related to the duration of the printing [47]. Two groups were disappointed with the outcome of the printed object, which did not correspond to their design, but they recognized that it was due to mistakes committed during the construction in Tinkercad.

In light of the study's findings, we propose some recommendations for future research in the field of STEAM education, engineering design, and 3D printing, aiming to facilitate the development and advancement of knowledge in these matters. Some of the participants did not follow the ED model exactly as it was presented, skipping or merging steps. Considering these results, but also results from prior studies [15], we think it is necessary to review the ED model used and adapt it to make it clearer and more functional to the users. Sketching is basic for ED, to help represent concepts and ideas, however this practice is almost totally displaced by the use of computer-aided tools. This leads to sketching being seen as an old drawing method, replaced by new computer drafting interfaces, and consequently to the lack of proficiency in these skills [54]. Given the importance of sketching in the design process, we need to reinforce and pay more attention to this step of the ED process in future interventions. This approach has helped the future teachers to realize the presence of the various STEAM disciplines, but we feel that there is still some work to do in terms of promoting a greater awareness of the overlaps and a more equitable disciplinary attention. Although 72 participants were involved, this was a qualitative study of exploratory nature. It would be important to apply this didactical experience to other participants, for example, in-service teachers whose contribution could be of extreme relevance to the literature.

Author contributions

Ana Barbosa: Conceptualization, Methodology creation, Investigation, Resources, Validation, Formal analysis, Data curation, Writing - original draft, Writing – review & editing, Supervision; Isabel Vale: Conceptualization, Methodology creation, Investigation, Resources, Validation, Formal analysis, Data curation, Writing – review & editing; Dina Alvarenga: Conceptualization, Methodology creation, Investigation, Writing – review & editing. All authors have read and approved the final version of the manuscript for publication.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

We declare that there are no conflicts of interest.

Ethics declaration

The ethics principles for conducting research in education have been followed.

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