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Article

Solving Problems through Engineering Design: An Exploratory Study with Pre-Service Teachers

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Abstract: A possible pathway to achieve disciplinary integration is through the use of the Engineering Design (ED) process, starting with problems in a real context that enable the mobilization of concepts from various disciplinary areas. The study reported in this paper aims to analyze the performance underlying the use of the ED process in solving authentic problems in a STEAM perspective, with future teachers of elementary education. We adopted a qualitative and interpretative methodology, with an exploratory design, where data were collected through participant observation, documents, artefacts and photographic records. The results are discussed, taking into account previous research and the data collected throughout the classes, where future teachers solved a problem task and created an artefact and a poster. Preliminary results show that the participants valued the experience and were actively engaged, showing persistence and motivation in solving the problem in a collaborative way, through the different steps of the ED cycle. This approach constituted an opportunity to favor the establishment of connections between different areas, such as mathematics, sciences or arts, detecting the possibility of integrating previously learned concepts. Difficulties were evidenced in the identification of some underlying mathematical and physical sciences concepts, particularly in the mobilization of an adequate scientific language while arguing and making decisions, or in accurately justifying the need to improve the designed plan.

Keywords: engineering design; problem solving; authentic problem tasks; hands-on activity; connections; mathematics education; STEAM education



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1. Introduction

There is a growing emphasis on encouraging creative thinking in education, innovating pedagogies and developing connections among subjects. Tasks focusing on creative processes, rather than concentrating only on achieving solutions for proposed problems, are more relevant nowadays. Therefore, this kind of task is being designed and experienced in school more frequently by innovative teachers around the world. In this scenario, STEAM Education and the disciplinary integration it may provide has been gaining momentum, but the way in which its disciplines should be articulated is still an open debate [1]. A promising approach to attain this integration could be the use of authentic problems, solved through an Engineering Design (ED) process, that require a hands-on (and minds-on) activity, involving students in active learning [2–5].

Taking previous ideas into consideration, in this paper we report an ongoing study, carried out with elementary education pre-service teachers (6–12 years old), that intends to understand and characterize the performance underlying the use of ED in solving authentic problems in a STEAM perspective, during their Didactics of Mathematics classes. In particular, along this didactical experience we want to identify the main difficulties and the main contents mobilized by the participants in solving the proposed problems. To this end, we stated the following research questions: (Q1.) How can we characterize

the pre-service teachers' performance in solving the problem using the ED process?; (Q2.) What were the main STEAM contents and skills identified during the didactical experience?; and (Q3.) How can we characterize the pre-service teachers' engagement along the didactical experience?

2. Theoretical Framework

2.1. The Teaching and Learning of Mathematics: Current Trends

Changing education standards reflect the need for increasingly complex skill development. Although memorizing rules, facts and procedures is an important part of learning, in particular learning in mathematics, it is not enough to achieve proficiency and students must also develop conceptual knowledge and understanding, as well as higher-order skills. In this scope, many educational organizations [6,7] frequently refer to the importance of mastering four skills (4Cs), that support deeper learning and knowledge transfer, to tackle the challenges of a rapid and dynamic world development: Critical thinking (including problem solving)—Make informed decisions or judgements, to achieve the best solution; Communication—Understand and share ideas, thoughts and solutions with others; Collaboration—Provide opportunities for working together to make decisions in favor of a common goal; Creativity—Provide opportunities for new and efficient approaches. It is fundamental to develop these skills by themselves, but by combining all of them, through the use of adequate tasks and methodologies, students are empowered to solve more complex problems, work together and come up with creative solutions.

These current educational trends demand the use of instructional methods that involve learners in the learning process, in other words, demand the use of active learning [8]. Active learning contemplates strategies that focus more on developing students' skills and knowledge than transmitting information, requiring them to solve tasks that imply higher-order thinking, which contrasts with the so-called traditional classroom, where the teacher uses tasks to introduce new concepts, or procedures associated with a certain concept, and then the students practice using similar tasks, passively acquiring the information conveyed by the teacher [5]. An instruction guided by active learning principles encompasses several approaches that presupposes the interconnection between intellectual/cognitive, social and physical engagement [2–4]. The direct interaction between these dimensions (Figure 1) contributes to most lasting learning outcomes, leading students to gather information, think and solve problems collaboratively.

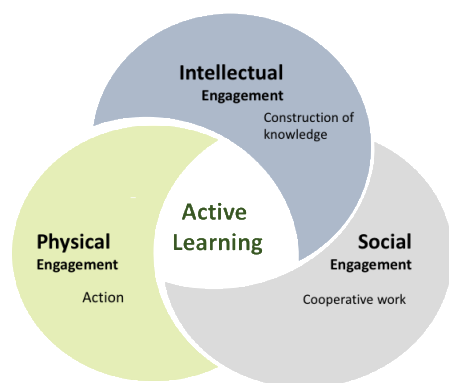


Figure 1. Dimensions of active learning [5], adapted from Edwards [2].

To be successful in solving a task, students must be intellectually engaged with the underlying contents, showing intrinsic motivation to establish relationships, develop conceptual knowledge and use critical thinking, going beyond memorization or a more basic understanding [2]. In the context of mathematics education, problem solving tasks are the most adequate choice, since they foster reasoning and communication, helping students attain a deeper understanding [2,5,8]. However, intellectual engagement may not be

enough for students to succeed (in mathematics). Communication has an important role in classroom interactions, between teacher and students and between students themselves. So, in an active learning context, we should also consider the students' engagement in a socially mediated learning, highlighting social interactions as one of the good practices in the mathematics classroom [4,9], by promoting small group activities and/or collective discussions. This type of collaboration facilitates the sharing and development of mathematical concepts and meanings and it is up to the teacher to foster a sense of community, making students feel safe and confident enough to take risks and express their ideas, either among peers or with the teacher. Adding to these principles, and according to Hannaford [10], thinking and learning are not just in the mind; quite the contrary, the body plays a decisive role in the entire cognitive process. Intelligence depends more on the body than we normally realize. Students who move can learn more effectively than those who attend typically sedentary classrooms, regardless of the activity. On the other hand, creating opportunities for students to move during lessons allows them to be more involved, improving attention levels and hence their comprehension [2]. The use of kinesthetic teaching and learning strategies, which include hands-on tasks or walking around the surrounding space are, therefore, more effective in improving students' attention and engagement levels, especially in younger students, breaking with the routine of sitting in the classroom just listening to the teacher. In terms of active learning, movement can assume many forms in different educational settings, but overall students are expected to construct, modify and integrate ideas, interacting with the physical world, materials and their peers [2,4].

Active learning does not merely constitute the implementation of certain instructional practices, but it also denotes learners' meaningful engagement, at different levels, in the learning process, which instructors facilitate through specific techniques [8]. Student engagement is a complex concept that encompasses multiple variables. One of the most common perspectives involves the consideration of three levels of engagement: cognitive, affective and behavioral [11,12]. These dimensions, and the respective specificities, have to be considered as part of the learning process in the context of the activity related to a particular task. Cognitive engagement involves the idea of investment, recognition of the value of learning and a willingness to go beyond the minimum requirements. It refers to aspects such as concentration, motivation, effort, ability to self-regulate, mastering knowledge and skills and the use of strategies to overcome challenges [11,13]. Affective engagement includes students' reactions to school, teachers, peers and academics, influencing their willingness to become involved in schoolwork. This level of engagement is associated with emotional reactions (affections), either positive or negative, such as acceptance, interest, enthusiasm, sense of belonging and attitude towards learning, which will influence the predisposition to carry out a task [11,13]. Behavioral engagement refers to the active participation in academic, social and extracurricular activities, and is considered crucial for the achievement of positive academic outcomes. This dimension of engagement includes the compliance with rules and classroom aspects related to the duration of a task, persistence, attention, posing questions and participation in collective discussions [11,13].

Kong and colleagues [12] developed a set of descriptors to characterize these three levels of engagement in the context of mathematics (Table 1), which contribute to analyzing in greater detail the relationship between student engagement and the learning outcomes.

Table 1. Engagement levels and descriptors.

Levels of Engagement	Descriptors
Cognitive	Surface strategy (memorization; procedural knowledge; handling tests) Deep strategy (understanding; establish connections; justification) Reliance (pose questions; follow the teacher's instructions)
Affective	Interest (joy; pleasure; sense of satisfaction; curiosity; excitement) Achievement orientation (effort to get good results; focus on finishing a task) Anxiety (nervous, worried; afraid of poor results) Frustration (uncomfortable; tired; dislike for the task)
Behavioral	Attentiveness (listen; take an active part in the discussion; make an effort; concentration) Diligence (effort to understand; try again; persistence) Time spent (on out-of-class learning)

Active learning environments may be implemented through the use of several methodological strategies but we cannot neglect the relevance of the tasks used to trigger students' activity. Tasks play a central role in the activity carried out in the classroom and in achieving an effective teaching and learning of mathematics. We can find clear suggestions in the literature that highlight the value and potential of rich and challenging tasks [14–16] to engage students in productive struggle and widen their understanding [9]. Good mathematical tasks give students the opportunity to learn meaningfully, using mathematical and non-mathematical concepts, ideas and abilities, in an integrated way [16]. Multiple-solution tasks, that can be solved by the use of different strategies, may help accomplish this goal, meeting the diversity of students' learning styles, encouraging the development of mathematical knowledge, flexibility and creativity [14,17]. Another important feature of good tasks is their potential to promote the use and understanding of interconnected knowledge, aiming to help students build a sound content knowledge and see the structure of the domain and also transfer their knowledge to new situations [18]. Rather than teaching students isolated concepts, hoping they will connect them together to solve a task, students should be incited to recognize the need to develop interconnected knowledge in the context of challenging and authentic tasks [18]. The authenticity of a task can be related to different perspectives, particularly in mathematics education. We consider that an authentic task is a meaningful, purposeful and goal-directed situation that simulates real-world problem solving [19], that has occurred or that might very well have happened. The task also has to be truthfully described and the conditions under which it would be solved in the real situation are simulated, with some reasonable fidelity, in the school context [20]. Hence, authentic tasks are based on situations which, while sometimes fictional, represent the kinds of problems encountered in real life, meaning that they are designed with the intention of mirroring reality [21,22]. Considering these principles, the teacher should focus on selecting tasks that highlight connections between core concepts and representations, connections with real contexts and between different disciplines [18,23]. Several institutions and programs [9,24] accentuate the importance of providing students with experiences solving authentic tasks, because they foster the development of mathematical content and procedural knowledge, prepare them to apply mathematics in real-life contexts and increase their motivation by familiarizing them with daily uses of mathematics.

2.2. Perspectives about STEAM Integration

International recommendations suggest and support students' preparation for an adequate integration in a society that is becoming more and more scientifically and technologically advanced. This is one of the reasons for STEM education to be widely recognized. To delimit the concept, English [25] states that STEM education is used to identify activities involving any of the four areas (Science, Technology, Engineering, Mathematics), a STEM-related course, or an interconnected or integrated program of study. Some educational trends call for the integration of Arts, in the sense of the liberal arts and humanities, advocating an approach associated with creativity, aesthetics and innovation, generating the acronym STEAM [26].

Much ambiguity still surrounds STEAM education and how it can be most effectively implemented [27]. The perspectives on STEAM integration vary from a disciplinary approach to a multidisciplinary/interdisciplinary/transdisciplinary approach [28,29], respectively learning concepts and skills: separately in each discipline; separately in each discipline but within a common theme; from two or more disciplines in a closely linked manner, aiming to deepen knowledge and skills; from two or more disciplines through their application to real-world problems.

So STEAM education may be carried out through the adoption of different models but, considering the traditional curricular matrix and the inexistence of a STEAM discipline in the majority of the curricula, it can be easier for teachers to adopt an approach where some disciplines prevail, rather than embarking on a STEAM program per se. In fact, over recent decades, STEAM Education has mostly been focused on improving science and mathematics as isolated disciplines, with little attention given to the other areas [27,30]. However, the interdisciplinary and transdisciplinary approaches are gaining endorsement [28,31], making connections more transparent, through an effective integration of procedural, conceptual and attitudinal contents within STEAM subjects. This perspective is in line with the need to promote the development of students' abilities to solve real-world problems, which are not fragmented in isolated disciplines; quite the contrary, to solve these problems students need skills that cut across different disciplines [32].

An idea or concept is better understood if it can be connected to previously known ideas or concepts [33], a fact that reinforces the importance of interdisciplinary/transdisciplinary teaching practices. We may even state that the low performance and lack of motivation shown by students in certain disciplines might be related to a teaching practice focused on isolated themes/contents, without articulation with previous knowledge or other curricular areas. Therefore, some concerns have been expressed in the adoption of a more dynamic model where STEAM Education emerges in the context of active learning, highlighting the establishment of connections, but also aiming for an equitable representation of all the STEAM disciplines in an integrated approach [27,34]. For some researchers, Mathematics and Engineering appear in need of an increased recognition [27,35], having little expression in the proposed activities or merely an instrumental role, which is quite reductive, and there is a tendency to emphasize technology or to guide the proposed problems towards the science strand [36].

How can we emphasize the role of Mathematics and Engineering in STEAM integration? According to English [34], the focus on mathematical literacy in the sense of meeting life needs, using mathematics to make informed judgements, understanding its usefulness and its applications, can provide core foundations and promote learning in the other disciplines. As for Engineering, it can be highlighted through components like ED and thinking, foundational processes of this area that can be extended to all the STEAM disciplines [37,38], through posing problems, generating artefacts and evaluating and optimizing solutions.

Despite the controversy of this debate of practically opposing ideas, the perspective of an effective articulation between STEAM disciplines has begun to prevail, building on content knowledge developed within and across disciplines, to prepare students to solve real-world problems, as part of the requirements for the development of 21st century skills, which imply multidisciplinary knowledge and approaches. Faced with this context, the challenge relies in achieving a more balanced content representation of the STEAM disciplines. ED is one of the possible pathways to accomplish this goal, providing the ideal STEAM content integrator, through the creation of opportunities to identify commonalities and establish connections among the involved disciplines [39].

2.3. Engineering Design in STEAM Education

To understand the contingencies of an increasingly demanding and complex world, it is crucial that engineering and technological literacy are meaningfully developed by all [40]. Contrary to what might be thought, engineering is accessible to everyone; in fact, students are born engineers, showing innate enthusiasm towards designing and making their own

creations, taking things apart and figuring out how things/phenomena work [40]. As discussed in the previous section, the principles of engineering make sense if we draw on students' curiosity to provoke the need to be engaged in open-ended, authentic real-world problem solving, that allows for multiple approaches and solutions, ultimately searching for understanding, through hands-on activities [28,40,41]. Through this type of approach, students might be more aware of identifying and understanding concepts of traditional curricular areas, like science or mathematics, applying these in an integrated way, which translates the way knowledge is expected to be used in a real context. "Student perceptions of engineering and technology, their understanding of engineering, and their understanding of relevant science are greatly improved by participation in engineering activities" [40] (pp. 15–16).

Due to its principles, ED promotes a bridge between mathematics and science concepts, as well as the arts, starting from real-world problems that foster creativity, collaboration, decision-making, critical thinking, communication and reasoning, generating a natural STEAM integration [28,42,43]. Yet despite being recognized as one of the most significant contexts in which to work with real-world problems at any age level, it is still an underrepresented field in early education. We may find many frameworks for integrating ED in school but they are not yet prolific in the early grades, and we should not ignore children's abilities to solve engineering-based problems. This is an age in which they are naturally curious, have questions, have a need to explore everything that surrounds them (objects, phenomena) and enjoy creating artefacts. It is also a means to introduce children to technology, not only in what concerns digital media, but other aspects also, such as computational thinking. Being exposed to the foundations of engineering, through the ED process, they naturally develop and apply core knowledge of STEAM subjects, especially mathematics and sciences, whilst also developing the 4Cs skills [30].

An integrated STEAM instruction grounded on ED uses the practices of engineering as the context and/or as an intentional component of the content to be learned, acting as an 'integrator' that brings together different parts in a way that requires them to work together as a whole [38]. The ED process should entail different iterative steps, among which we can highlight the definition of the engineering problem, the design of engineering solutions, the implementation of a solution, and testing, evaluating and optimizing this solution [38,44]. Furthermore, throughout the design process, while solving the problem, students must manage risk and uncertainty, consider their prior experiences and learn from failure [38,45], adjusting their reasoning and actions. In addition, a final requirement for qualitative ED is the incorporation of design justification [37,43]. Students should be able to evidence what they have learned during the design process, justifying their design decisions, based on the used and newly acquired knowledge, and make recommendations about the design, based on the results of their tests [38,44]. This design justification serves as an effective mechanism to reveal the students' development, facilitating conceptual change [43].

There are several frameworks for ED but most of them [35,45] are supported in the model proposed by Cunningham and Hester [46], an iterative model composed of five-steps: ask; imagine; plan; create and improve. Grounded on the ideas of those proposals, we adapted the design process of Cunningham and Hester [46], changing the terminology of some steps and, to make the process cycle clearer, after the testing and evaluation phase, we introduced the possibility of more iterations in case students need to improve the prototype or recomplete the design process (Figure 2). The adapted ED cycle 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).

ED can help engage students and facilitate the learning of STEAM contents [28,35,47], because it gives them the opportunity to solve challenging and authentic problems, with

multiple solutions, using various resources and representations, to produce a specific product. Considering STEAM disciplines, we may add that mathematics, science and technology provide the content knowledge to make sense of the problems to solve through ED processes. Many of the concepts introduced in the classroom, for example through traditional Science subjects, present engineering opportunities [48], such as the properties and motion of objects or the analysis of specific phenomena. Students need to use the acquired knowledge about the central concepts involved and apply a variety of procedures that clearly show natural relations among STEM/STEAM subjects, while trying to reach a solution [48]. The use of authentic tasks leads to experimental activities that simulate technological, technical and scientific processes, including mathematical ones, and tends to strengthen ED as a credible STEAM approach [49]. ED can be associated to the general paradigm of Maker Education, as a particular methodology that highlights the systematic steps of a problem solving method [50]. This parallel is established through constructivism, due to the need to learn by doing or think how to make something, undergoing a ‘hands-on’ approach, manipulating/creating physical objects to develop new knowledge, sharing it and reflecting on it with others [50]. The hands-on/minds-on activity perspective facilitates the acquisition of new skills and knowledge and the gaining of experience through the active participation of learners. These instructional strategies are very effective for the teaching and learning process, since experimental activities generate student’s motivation, making them remember easily and desire to learn (mathematics), preparing them to integrate new challenges through the development of important skills [51].

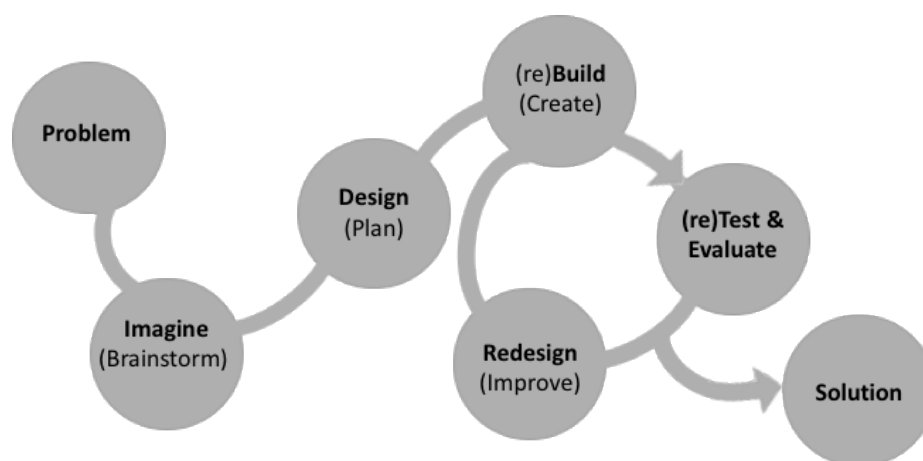


Figure 2. Engineering Design Cycle (adapted from Cunningham and Hester [46]).

2.4. Summarizing

Given that the ideas discussed in the previous sections ground our study, we considered it pertinent to summarize them in Figure 3.

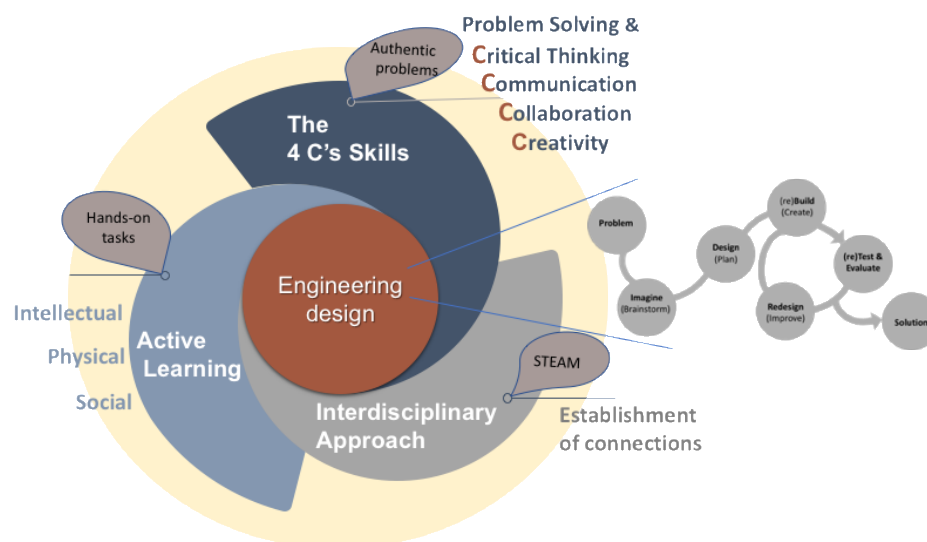


Figure 3. Theoretical Framework.

We decided to conduct this study, believing that the use of authentic and challenging tasks with multiple-solutions, through hands-on activities, are needed in mathematics classes, encouraging creativity, critical and flexible thinking. The predominant use of routine tasks is still a common practice in many countries, devaluing active learning and the development of essential skills demanded by society (e.g., problem solving, collaborative work, creativity and communication—4Cs). In this perspective, STEAM education may have a relevant role, also emphasized by international recommendations that state its importance in preparing students to deal with complex and diverse challenges. This is a teaching and learning approach in which students build and demonstrate knowledge and/or understanding through their engagement in a design process in which Science, Technology, Engineering, Arts and Mathematics work together. To pursue these ideas we use ED, as a vehicle that bridges the gap between mathematical and sciences concepts, as well as the arts, starting from real-life problems through a cyclical design process.

3. Method and Procedures

3.1. Context and Participants

As previously discussed, we designed a didactical experience for future elementary education teachers (6–12 years old) with the aim of understanding and characterizing their performance regarding the use of ED in solving authentic problems in a STEAM perspective. In particular, through this didactical experience, we wanted to identify the main difficulties and the main contents mobilized by the participants in order to solve the proposed problems. This led us to use a qualitative and interpretative approach [52,53]. The choice of the paradigm was sustained by the fact that the main goal was to understand the perspective and reactions of the participants to a particular situation. We adopted an exploratory design [54,55] because not much is known about the problem that we want to examine, which means that it is at a preliminary stage, and we have reasons to believe it contains elements worth discovering to inform future research. For a better comprehension of the problem we defined the following research questions: (Q1.) How can we characterize the pre-service teachers' performance in solving the problem using the ED process?; (Q2.) What were the main STEAM contents and skills identified during the didactical experience?; and (Q3.) How can we characterize the pre-service teachers' engagement along the didactical experience?

We conducted this research with 45 pre-service teachers attending the first semester of the 3rd year of an Undergraduate Course in Primary Education, with a three-year duration (six semesters), that precedes a Master's Course qualifying them for the teaching of

pre-school and primary education. This Undergraduate Course is composed of subjects related to the areas of didactics, general education, content knowledge and practice in formal and non-formal educational contexts. This group had 42 women and 3 men, with an average age of 22 years and, among other subjects, they were enrolled in a curricular unit of Integrated Mathematics, within the scope of didactics of mathematics, that served as the context for the data collection. The work developed during the semester followed the current curricular guidelines for the teaching and learning of mathematics, focusing on fundamental transversal 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 (Figure 4) on problem solving (types of problems, problem posing, problem solving/posing strategies, multiple-solution tasks), creativity (fluency, flexibility, originality), mathematical connections (internal and external), reasoning (inductive, deductive) and communication (oral, written).

This curricular unit, as others in teacher education programs, included experiences to stimulate the pre-service teachers' knowledge and skills, particularly by solving the same tasks and using the same teaching and learning principles that they are expected to use with their future students. It was with this purpose in mind that we posed the problem discussed in this paper, asking them to solve it in accordance with the knowledge potentially used by elementary school students.

As the participants also attended a curricular unit in didactics of science in the same semester, taught by one of the researchers, we considered that it could be an asset to adopt a co-teaching perspective, having the two teachers, of mathematics and sciences, present during the work developed. This option was grounded on the fact that co-teaching can be an effective strategy to enhance student STEAM experiences, having two teachers actively engaged, working together with groups of students, sharing the planning, organization, implementation and assessment of instruction, as well as the physical space [56]. It is also important to clarify that, during the 1st and 2nd year of the course, these future teachers attended two Science curricular units (corresponding to 96 h + 64 h) and three Mathematics curricular units (corresponding to 96 h + 64 h + 64 h), with the aim of introducing and/or deepening their content knowledge about relevant topics.

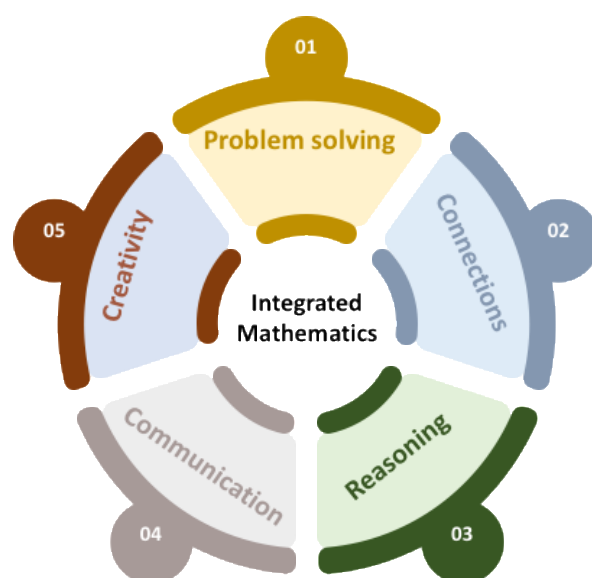


Figure 4. The teaching modules.

3.2. The Moments in the Didactical Experience

We carefully prepared this didactical experience, divided into four main moments, that the participants/students went through during the classes, summarized in Figure 5.

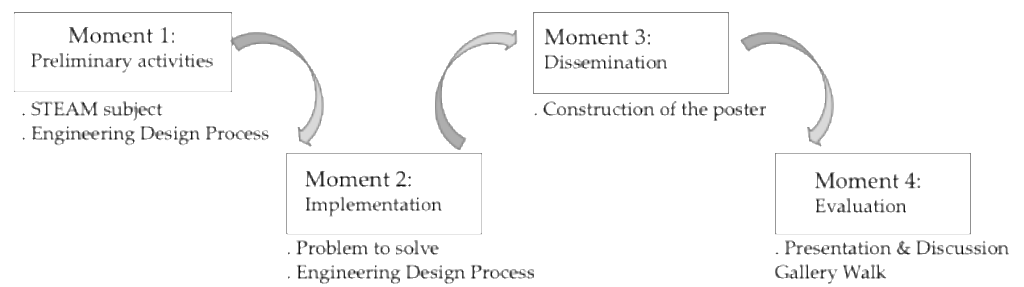


Figure 5. Main moments in the didactical experience.

3.2.1. Moment 1—Preliminary Activities

This moment served as an introduction to the main ideas of ED in STEAM integration, in order to prepare students for the subsequent work on the problem. Therefore, we began to characterize STEAM education and its relation to interdisciplinarity and the establishment of connections. Our purpose was to introduce the ED process that lies at the core of engineering, as a pathway for STEAM integration, using the cycle presented in Figure 2.

The ED process can improve students’ problem solving skills in a different way from the traditional teaching of mathematics through problem solving. As this experience was conducted during the Problem Solving module of the curricular unit, it was important to analyze, compare and discuss these two processes with the participants: the new approach (ED) with the one they already knew (Polya’s Model). The two processes are in fact very similar, since the basic steps are similar [57–59]. The main differences rely on the nature and goals of the problem, i.e., designing a product (ED) or solving a mathematical problem (Table 2).

Table 2. Similarities between Engineering Design Process and Problem Solving Process.

Engineering Design Process	Problem Solving Process (Adapted from Polya [59])	
The problem	Understand the problem	Did I understand the problem? What is asked?
Imagine (Brainstorm)		What do I need to know about the problem? Do I have enough information to solve the problem?
Design (Plan)	Devise a plan	Collect all the available information. Do I know a related problem? Did I use all the conditions? Can I use know strategies, like look for a pattern; draw a Figure?
(re)Build (Create)	Carry out the plan	Carry out the previous plan. Select a strategy to solve the problem. Solve the problem
(re)Test & Evaluate	Look back	Examine the solution. Does the answer/solution make sense? Does the solution fit the conditions? Does it work?
Redesign (Improve)		Does the solution work? If not redesign it. Check each step. Can I find a simpler or better solution?
Share the Solution		Share the solution.

3.2.2. Moment 2—Implementation

This was the main moment of the four identified in the didactical experience, as it corresponded to the presentation and solution of the STEAM-based problem. For this study, we focused on a particular kind of problem, that emerged in the context of this curricular unit to highlight the potential of the ED process to trigger integrated learning, while solving challenging real-world situations—The Paper Table Problem (Figure 6).

Build a table strong enough to support a heavy book.
 The table top should be about A4 format and the table legs will be made of paper and should have approximately 20 cm long.



Figure 6. The Paper Table Problem.

The experience was implemented in two classes, with a total of four hours, where the participants, the student teachers, worked in groups of three or four. To solve the problem, we provided the following materials: 1 cardboard sheet (for the tabletop); eight publicity leaflets; one masking tape; one heavy book; one white sheet of paper (A2); paper/notebook; scissors; and drawing supplies. They did not have access to more materials, even if they were needed. Students had some instructions and conditions on how to build the table, particularly the implementation of the ED process cycle (Figure 2). They had access to some guiding questions associated with each step of the ED process cycle and adapted to the paper table problem, to help them achieve a prototype (Table 3). Students could only start building the prototype after making a sketch of the table they decided to make within the group. To conclude, we appealed to the students’ creativity and aesthetic sense in all their productions.

Table 3. Questions to clarify the steps of the ED process cycle.

Design Process	Description
Identify the Problem	Can I build a table that supports a book, without breaking down?
Imagine	What kind of tables can I build?
Design (plan)	Choose one table type. Draw a sketch of the table.
(re)Build (create)	Did you follow the plan to create a model/prototype?
(re)Test & Evaluate	Did the table support the book?
Redesign (Improve)	Modify the table if it doesn’t fit the conditions or improve the model. Did you confirm the strength of the table legs? Did you build a table prototype?
Share Solutions	Communicate your product. Create a poster where you summarize the used process and the STEAM contents.

While planning the didactical experience, we had some expectations about the STEAM contents and skills students would need to use during the construction of the table, which we summarize in Table 4.

Table 4. Expected contents and skills of STEAM areas in the paper table problem.

Engineering	Science	Mathematics	Art	Technology
Engage in the ED process. Identify and compare different basic types of tables (e.g., one, three, four legs), table support legs (e.g., triangular, cross, cylindrical) and discuss how these structures enhance stability and strength. Create, develop and communicate design ideas and processes. Build and share at least one paper table prototype that is able to hold a book for a minute.	Develop an understanding of the center of mass. Identify forces acting on different table types, including tension and compression. Understand how different table types support a book. Understand the resistance of the available materials.	Apply measurement skills and geometry concepts: polygons; solids; symmetries; ... Identify the properties of polygons or solids correctly; ... Apply spatial reasoning in working 2-D and 3-D shapes. Draw sketches using 2-D and 3-D representations. Use mathematical language correctly. Use problem solving strategies.	Show flexibility and divergent thinking. Show originality in design. Construct the artifact with aesthetic sense and perfection.	Look for types of tables in webpages. Consult webpages about tables’ resistance.

3.2.3. Moment 3—Dissemination

The third moment of the didactical experience began after the students had solved the problem and built a prototype of the table. It was intended that, within the groups, they discussed and reflected on the work developed and shared the results with their peers. To do so, they had to create a poster, on an A2 sheet of paper, following some guidelines, which would be accompanied by the prototype. They had to decide how to display their ideas in the poster, therefore using their originality and aesthetic sense. This is an important aspect, since aesthetic elements of handicraft may promote understanding of mathematical concepts, by exposing students to concrete space/figures/shape experiences.

The poster should specifically contain a characterization of each step followed in solving the problem, according to the proposed ED cycle (Figure 2), including: different sketches of the table; chosen model; mathematics and physics concepts and procedures involved; specification of what was done to strengthen the table if the initial plan did not work, also mentioning the main difficulties along the whole solution process. This written production should also include some reflections based on the following questions: What did you consider most important in building the table? Did you follow all the steps in the cycle? Why? Which was the most complicated step in the cycle? What did you learn from the experience?

3.2.4. Moment 4—Evaluation

This last moment was implemented after the elaboration of the posters and was analyzed and discussed through a Gallery Walk [5,60]. To clarify the dynamics, a Gallery Walk (GW) follows four stages: (1) Presentation and observation of posters—posters were placed on the walls of the classroom for observation; (2) Analysis and elaboration of comments—Each student went through the different posters to analyze the different solutions and, after their evaluation, wrote, on post-its, their personal comments, doubts, questions, possible errors, etc. While students analyzed their colleagues' solutions, we circulated the classroom, monitoring students' observations and discussions; (3) Group discussion—After this round, each group analyzed the feedback to the poster, making a small report; (4) Collective discussion—with all the posters placed again on the wall, the groups orally presented the solutions and reacted to the comments of their peers. This step enabled us to highlight some of the ideas expressed, making connections between the different approaches, making syntheses, clarifying doubts, concepts and errors; to give feedback on the content of each poster, which all students already knew about, after commenting and discussing, based on what we observed. The dynamics of a GW focuses on the creation of posters, encouraging students to share and reflect on learning during collaborative work, and facilitates the contact with other students' ideas [5]. During this moment, the participants also had the opportunity to evaluate their peers' prototypes. In this manuscript, we chose not to describe this moment because of its extension and also because the information gathered would not affect the research problem.

3.3. Data Collection and Analysis

Data was collected in a holistic, descriptive and interpretative manner, during the classes of a unit course on which one of the researchers was also the teacher. Several sources of data collection were undertaken, including: naturalistic participant observation, recording free-flowing notes, focusing on the future teachers' reactions, interactions, conversations, discussions and interpretations, having the problem in mind, that included a record of facts but also the researchers' commentaries about those facts; documents, namely individual records and the groups' posters, with the synthesis of the ED cycle and comments; artefacts (prototypes of the table); and photos.

To analyze the data, we used a qualitative and inductive approach, returning to content analysis [53], relying on the written productions, the artefacts, the observations made, the field notes and the photos. We used an iterative process of writing, reading, reviewing, rewriting and consulting the collected data, that led to a refinement of the information [61].

We proceeded to an inductive categorization to systematize the data and facilitate the interpretation of the results. In this process, starting from the problem, the research questions, the theoretical framework and the collected data, we organized our analysis related to the paper table problem/didactical experience, according to the following dimensions: (1) participants' performance, during the solution of the table problem, the use of the ED cycle and the creation of the poster; (2) STEAM contents and skills identified by the participants, according to the subjects of the STEAM anagram Sciences, Technology, Arts and Mathematics (Table 4); and (3) participants' engagement during the didactical experience, focusing on cognitive, affective and behavioral engagement (Table 1).

4. Results from the Implementation of the Paper Table Problem

To report the main findings, we used the information from the observational notes of the future teachers' conversations, reactions and interactions; the individual records and the groups' posters, with the synthesis of the ED cycle and comments; artefacts (prototypes of the table); and photos. In this manuscript we centered our attention on the second and third moments of the didactical experience, related to the construction of the table and the poster.

4.1. The Participants along the Engineering Design Cycle

To present the results during the ED cycle, instead of going through each of the seven steps, we grouped them into three clusters, because we detected that some steps could not be distinguished due to the nature of the work done, as they involved a forward and backward movement. Therefore, we considered: Part 1. Exploring and designing the problem (steps 1–3); Part 2. (Re)building, (re)testing and redesigning (steps 4–6); and Part 3. Group results (step 7). Along the ED process, students had access to some guiding questions to help them confront the different steps.

4.1.1. Part 1. Exploring and Designing the Problem

The participants had to follow the ED cycle to solve the problem (Figure 2). After reading, the students initially reacted to this challenge with some doubts, because they had never solved a task of this nature. However, they quickly began to identify the type of table they could build, talking to each other about tables they knew and which would be a better model to support the load of a book. Some consulted the smartphone to have some ideas of table examples; others did not feel the need to search the internet, since it was a current object of daily life (Figure 7).

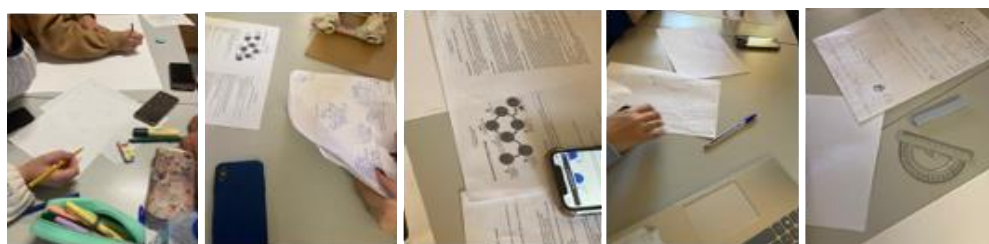


Figure 7. Participants following the ED cycle.

There were moments of brainstorming, discussion and drawing of many types of tables, with different supports for the tabletop. The justifications for their choices indicate that they were aware of the main ideas in mind: strong enough to support a book, have stability and an easily built structural support. One group had concerns about making a different and "prettier" table (Figure 8) in order to be original, leading them to change the first sketch, which was too simple and fragile. These concerns were raised and were most evident during the construction step.

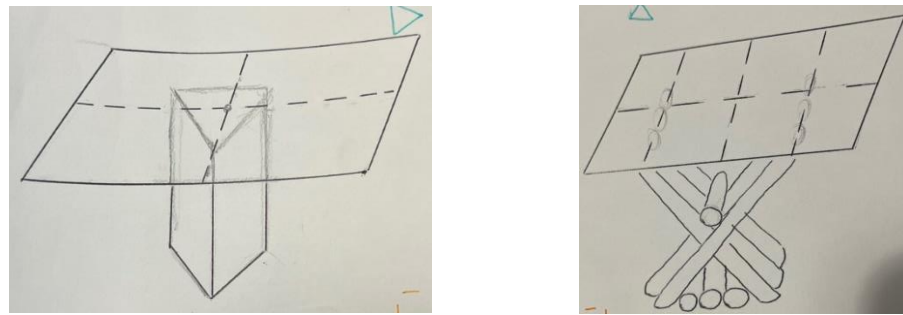


Figure 8. The two tables' sketches.

The discussions focused mainly on the shapes to use for the table legs, identifying some properties of figures and shapes that could make them stronger. They were asked to start building the prototype only after making a sketch of the table and deciding which model to choose. Unexpectedly, the drawing of the table model revealed itself to be of great difficulty, which led to some frequently made comments: “Do we really have to draw, teacher? Can't we start building? I don't know how to draw, I have never been good at drawing (. . .) Me neither!?”.

After overcoming some of the initial discussions, they began to draw the sketch of the table, chosen from the different proposals presented by the elements of each group, trying to break away from some of the difficulties experienced with the drawings. Let us see some examples. For instance, in Figure 9 we can observe that two groups drew 2D-models because they could not represent them in 3D (images from the poster). The first image shows that the first two sketches in 2D are not clear enough to understand how the legs or the support of the table will be built. The second shows a top view of three 2D-drawings, in which we can clearly identify the position of the table legs. In addition, they explained what each drawing meant (a table with eight cylindrical legs, a table with six cylindrical legs; table to be tested).

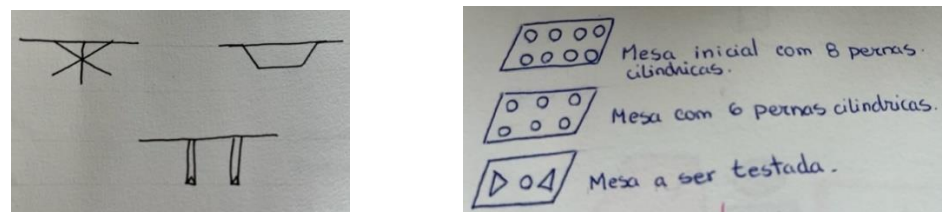


Figure 9. 2D-Drawings presented by two of the groups.

On the other hand, in the groups who drew 3D-Figures, some were not able to present a sketch that clearly illustrated the arrangement of the legs (first drawing of Figure 10), but there were also those who did this clearly (second drawing of Figure 10).

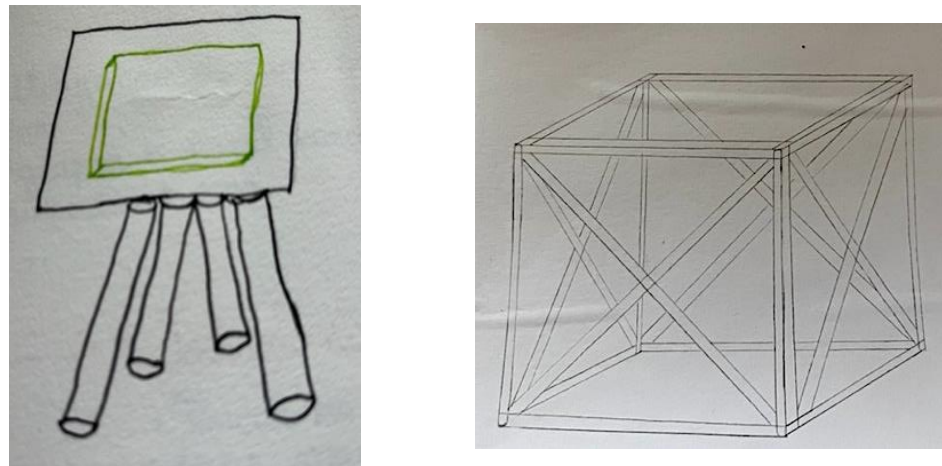


Figure 10. Two 3D-Drawings.

Although the redesign occurred after building the table, Figure 11 shows some sketches of one group that redesigned the table even before building it (images that appear in the students' notebook).

The first model (on the left) was abandoned because the group concluded, before beginning the construction, that it was complicated to build due to the number of legs (eight). Having so many legs would imply deciding how to dispose them and, also, they thought that they would not need them all, changing it for another model (on the right).

We also observed many models that used triangles. One specific group, using analogy, discussed that many bridges are composed of triangles, because triangular arrangements increase strength and stability. Another group that decided to use triangles, while joining them to support the table, faced many difficulties and decided on another type of model.

After this exploration, which we can consider more at the level of ideas, they moved on to the next steps, starting to work with the materials provided.

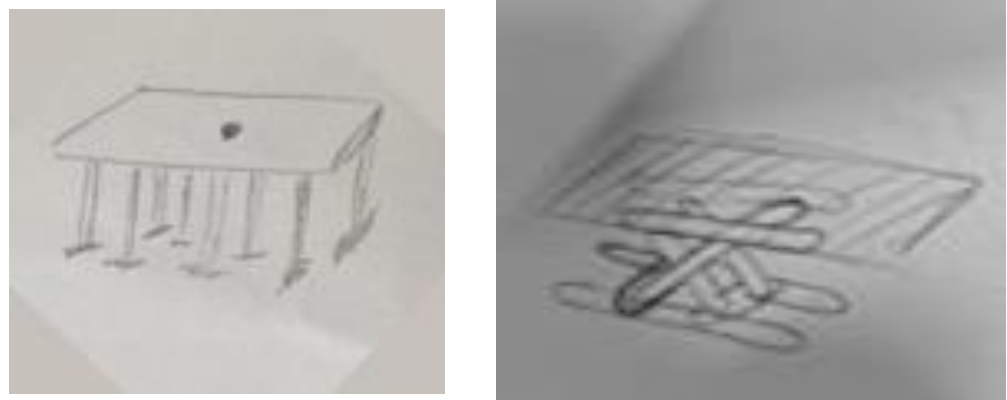


Figure 11. Redesigning the table model.

4.1.2. Part 2. (Re)Building, (Re)Testing and (Re)Designing

This problem does not involve many complex concepts and calculations, just simple geometric concepts and measurements. This was translated into concerns about the legs' measurements, because this was a condition. There were also students who used a set square or a protractor to see if the legs were perpendicular. Others concluded that the legs should have an inclination of 60° for a good balance of the table. The test and the redesign, in order to improve or rebuild the model, required the application of mathematics and science concepts and scientifically sound explanations, which contributed to the high cognitive demand of the task. It was during these steps of the ED process that students

experienced more difficulties, because they demanded decision making, planning and justifying actions.

After deciding the table model, they began to look for ways to use the paper to build the table's legs. They made many attempts to fold the paper. Most of them rolled the paper to make tubes (cylinders); others chose to construct solids, mainly prisms. When they finished the tubes, some began to test their resistance (e.g., standing it on the table and pressing on it to see if it tilted or twisted) and, according to their observations, rebuilt it: by rolling the paper, so that it would be a tighter tube, or by inserting other tubes tightly rolled inside the cylinder to make it more resistant. Then, after getting these elements ready, they began to use them as isolated legs or combined some to achieve a structure to support the top of the table, using the tape to tie the paper. The ones who constructed prisms, pyramids or cubes used the tubes to build the shapes and the edges of the solids, taping the ends together to maintain the shape. Then they decided where to place the legs' supports. For many groups, this was the most difficult part of the construction. Figure 12 shows students folding the paper and assembling the legs.



Figure 12. Students building their prototypes.

When the structure that supports the tabletop was concluded, they tested the table's strength and stability using the book's weight. In some cases, at the first attempt, the table stood for some seconds and then fell down. Then, these students revised the chosen model or the way the paper was rolled/tied to obtain the tubes or the way they connected the elements; others, built a solid prototype table at the first attempt. Figure 13 shows some of the participants testing the tables. Some were curious to test the maximum height the table could hold. In the first image participants were expectant to check if the table would collapse; in the second, they carefully tested one book and succeeded; in the last two images, an attempt with five books shows that the first table was not strong enough to hold the weight and the other was robust.



Figure 13. Participants testing the strength of their table.

One of the groups used a structure in the form of a triangular Indian tent. When testing the model, placing the book, they observed that the legs began to tilt and twist. When asked about their option for that structure and what they could do to improve it, one of the students said, "I remember, from math, that the triangle is the more rigid shape". Therefore, they decided to triangulate the table legs (Figure 14, from poster). Previously, when they had imagined the table, they didn't expect that it would collapse.

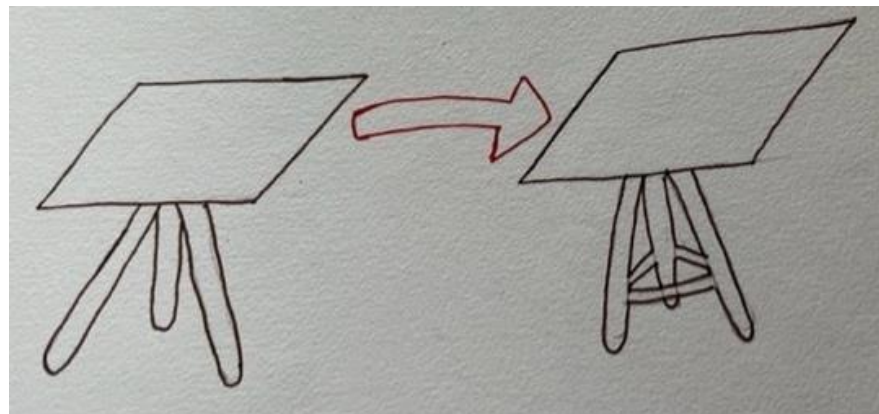


Figure 14. Improvement by triangulation.

We identified another group that revealed difficulties with the stability and balance of the tabletop. After testing the model they had sketched, the table collapsed, even when trying to place the book in different positions to distribute the load of the forces. “And now what are you going to do? Another table? No teacher, we will just make another cylinder and put one here and take this one out and put it here (pointing to the new place of the cylindrical legs)”. So they reinforced the weak area, adding a new leg and rearranging the two legs (cylinders) to balance the table (Figure 15, from the poster).

These participants explained that “the prisms better support the weight if they were lengthwise in a symmetrical position, and they must be placed in a symmetrical position”. They also stated that “the book must be placed in the center of the tabletop, for better stability and better support of the weight”.

Most of the students made their structures stronger using intuition, daily know-how or the trial and error strategy, but they weren’t able to identify certain concepts or principles underlying the strength of the table. Even those who tried to provide an explanation did not use adequate concepts or terminology. Despite these difficulties, everyone managed to build a table.

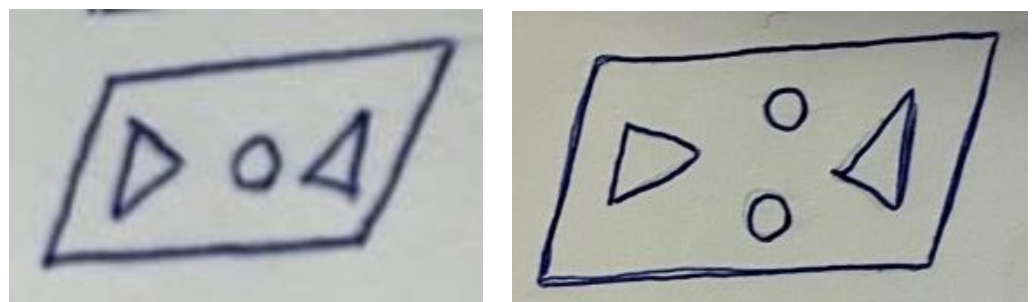


Figure 15. Improvement by reinforcing the model.

4.1.3. Group Results

The products of these didactical experience were the tables’ prototypes and the posters. The students were able to be successful in building a table, even if they used too much tape to reinforce the prototype, and creating a poster, following the given instructions. Several different tables emerged, some of them different from the previous designs, derived from the unsuccessful tests with the book. So, instead of making a new table model, they tried to combine the structure they already had with others to make it stronger. For instance, Figure 16 shows a prototype that uses legs in the shape of a square Indian tent that was not stable enough, and the group decided to introduce a cylinder in the center to reinforce it.



Figure 16. Table after reinforcement.

Table 5 summarizes the types of tables built, according to the support structure used for the tabletop, and Figure 17 shows some of the final prototypes.

Table 5. Types of paper tables.

Solids (38%)	Isolated/Simple Legs (46%)	Combined (16%)
Cubes	I-legs	Prism + legs
Triangular prisms	V-legs	Cylinder + square Indian tent
Square pyramids	X-legs	
Cylinder	Legs in triangle Indian tent	
Mixed solids	Legs in square Indian tent	



Figure 17. Some table prototypes.

After the construction of the table, the participants began to create their poster, following the instructions. In this step they discussed how to organize the information via the poster, and revisited the ED cycle, thinking back on the work developed to describe their thoughts and processes in each of the ED steps. With the prototype in front of them, they began to look for the ideas, concepts and procedures used in the scope of mathematics and physical sciences. They had some aesthetic concerns with the poster construction. To finalize, they described their reaction to this experience (Figure 18).



Figure 18. Some posters.

4.2. Participants' Engagement in the Didactical Experience

To analyze the participants' engagement, we mainly relied on data related to observation, observational notes and the written productions. Given the description presented in the previous section, some aspects will not be exhaustively analyzed as they have already been addressed.

4.2.1. Cognitive Engagement

The incorporation of active learning principles in the classroom tends to enhance students' engagement and promote deeper learning. At the same time, the nature of the problem posed also implied a series of abilities and the use of integrated knowledge from different content areas. Therefore, we expected that the use of surface strategies would not be helpful in reaching a solution. This type of strategy implies the memorization of information and procedures and the unreflective association of concepts and facts and, normally, tasks are seen as an imposition or a hurdle to be overcome. Although the ED cycle was previously introduced to the future teachers, requesting the implementation of each of its steps, the underlying procedures are not in line with rote learning. We may state that all the groups undertook a series of tests during the didactical experience, but demanded evaluation and understanding of the changes to be made to the model. Hence, we can assume that this didactical experience prompted the use of deep strategies.

All the participants understood the problem and its conditions, including the material restrictions. The fact that it mimics a "real-context situation" gave them insights into the problem and led them to look around and observe tables or search the internet for other table models to help with the brainstorming. This didactical experience constituted an opportunity to favor the establishment of connections through the integration of disciplinary areas (mathematics, sciences, art), as well as the fundamentals of engineering, occasionally resorting to technology. In general, sciences, in particular physics, contributed to justifying the stability, balance and strength of the table and the materials used. Technology was used in a spontaneous way in the Imagine step, during brainstorming. Engineering contributed, through the design cycle, to solve the problem. Arts contributed to the creative strand, the aesthetics/design of the created artefact and in the elaboration of the poster. Mathematics was also important in solving the problem, through the use of problem solving strategies (e.g., guess and check; logical reasoning; simulation) and to realize the effect of using some geometric shapes, as well as the idea of symmetry.

The future teachers had to summarize what they applied while solving the paper table problem, mentioning aspects such as contents and actions/skills used in reaching the solution. Table 6 presents the main ideas drawn from their reflections:

Table 6. Integrated STEAM contents and actions/skills for building a paper table.

Disciplinary Area	Contents and Actions for Building Paper Table
Science	Develop basic understandings of centers of mass and forces Contribute to justify the balance and resistance of the table and the materials used Contribute to understand how different tables support a load
Technology	Used spontaneously in the Imagine step, during brainstorming to discover types of tables Contribute to recognize basic table types (e.g., one foot; four feet) and table structures (e.g., triangulation of the table legs)
Engineering	Engage participants in its design model to address and solve the problem (arrive at a consensus, test and retest) Recognize how the structures constructed enhance stability and strength
Art	Contribute to creativity with the aesthetics features of the prototype of the table created (design, structure, design, overall look) Contribute to creativity with the aesthetics features in the elaboration and organization of the poster (e.g., disposition of the cycle and the sketches of the table, use of colors)
Mathematics	Contribute to solve an authentic hands-on problem, using problem solving strategies (e.g., guess and check; logical reasoning, simulation) Construct arguments in group's design and criticize their peers' designs Understand the effect of using some concepts (e.g., shapes; pyramids; prisms, cubes; symmetry; estimation and measurements; perpendicularity; angles; weight) Spatial reasoning in recognizing, drawing and working with different 2-D and 3-D shapes and their representations

All the contents needed to solve the paper table problem were revisited and consolidated in curricular units the participants had attended in previous years; most of them are basic and part of the elementary school curriculum. Thus, we expected that some of these concepts would be more easily identified and mobilized by the participants in their arguments, but this did not always happen, especially with the science concepts. In addition to this, the participants also had difficulties in using scientific language to justify their decisions. In relation to mathematics, we detected the use of incorrect designations/terminology, for example, when transforming a shape to test its resistance (distinguishing quadrilaterals, confusing rectangles with rhombuses). Another aspect had to do with spatial orientation, related to the sketches representing 3D-Figures; although we did not expect an artistic work, only a sketch, there were students who showed and verbalized their inability to do this. One reason they pointed out was that they had never been asked to draw 2D or 3D-shapes and real images. Difficulties of the same nature were identified in the building stage, while manipulating the paper, folding, rolling and taping, showing that their motor skills are underdeveloped; which they justified by stating that they were not accustomed to use folding and cutting in mathematics classes. As for reliance, we can say that, in general, the groups sought for validation from the teachers in the different steps of the ED cycle. This was more frequent in the evaluation stage, to check the solution, and in disseminating the results with the poster construction. They evidenced some insecurities in organizing their ideas to express the different steps of the ED cycle and even more in identifying the underlying mathematics and science concepts and scientifically justifying their options.

4.2.2. Affective Engagement

The majority of the participants expressed interest during the didactical experience, which included solving the problem collaboratively to achieve the desired artefact, that "would not be so efficient and rich if done individually". They were compelled and excited by the opportunity of "building something from scratch" and "resorting to crafts", valuing the hands-on dimension of the proposal. Initially they were curious and even intrigued or surprised by the proposal of building a table that could sustain a heavy book using the given materials, mainly by the fact that the structure should be made from leaflets,

described as being “thin and not very resistant”. However, at the end, they valued the experience, stating that they “were surprised that such thin paper could support so much weight, varying its shape and the spatial arrangement of the table’s structure”, and with the fact that “with this problem it was possible to apply different knowledge, from different areas, making it more interesting than the current disciplinary problems”.

As they designed, built and tested their ideas, we observed different reactions, depending on the outcome. We noticed some anxiety, especially when they were about to try the resistance of the table in holding the book, reflected on the expectation of the result; and frustration, particularly in the design step, with the need to make a sketch, an aspect that some attributed to “difficulties in making 3D drawings”; in the building step, too, some groups manifested frustration when they observed that when they assembled all the parts of the support, these did not fit. However, the moment when they achieved a solution that met the requirements, and verified that the constructed table sustained the book, was translated into a generalized sense of satisfaction. The inevitable comparison between the groups’ outcomes (achieving (or not) a durable resistant table; an aesthetic/creative artefact; clarity of the description of the ED cycle on the poster) made some participants worried about the possibility of poor results: “we used too much tape”; “our poster is a bit confusing”; “our table is a little bit tilted”; “we could have done better”; “I would improve the aesthetics of the table”.

Although this group of pre-service teachers revealed different levels of performance, either in the mathematics or science curricular units, there was no significant impact in their affective engagement. In general, we observed a genuine effort from the majority of the participants to solve the problem and finish the task, questioning each other, thinking out loud, asking about the what-ifs, helping with all the procedures needed to build the table (folding and rolling paper, applying tape, assembling and holding all the parts together) (Figure 19).



Figure 19. Collaborative work.

This dimension of achievement orientation was crucial, giving them drive and motivation to make an effort. Globally, it was considered a “challenging problem” that brought the participants “satisfaction”, having the opportunity to “work as a team” and realize that “from such a fragile material it is possible to build resistant models”.

4.2.3. Behavioral Engagement

Behavioral engagement is closely related to student participation in the classroom and, in this case, given the nature of the didactical experience, it can be analyzed through aspects of Attentiveness and Diligence.

Despite listening attentively to the teacher’s instructions while presenting the problem and the ED cycle, some of the participants tended to skip the Design step, that is, they brainstormed some ideas and quickly picked up the material, trying to create a model. It was clearly stated that they should apply all the steps of the ED cycle, making a sketch before attempting to build the artefact, in order to carefully plan their actions. Through the participant observation, these situations were identified and discussed with the participants, who understood the teachers’ point of view and adjusted their actions. In our view, this behavior was not related to lack of attention but mainly with the need to materialize their

ideas via physical representations. Some of these participants also assumed “low drawing competencies” and that it was “easier to experiment with the paper”. Most groups had more than one idea in the brainstorming stage, but also recognized that they had some difficulties in coming up with feasible proposals. In this step of the ED cycle, we mostly observed intense discussions within the groups, with the participation of the majority of the respective elements (none thought individually), trying to listen to each other and reach a common agreement about the best decision to proceed to the next step.

The test and evaluation of the created model allowed the participants to collaboratively evaluate the validity of their solution. In most cases there was a need to improve, redesign and rebuild the table, making the necessary adjustments (“level the legs”, “strengthen the structure with more paper”, “add more legs”, “ensure balance”, “change the shape of the legs”). Everyone made an effort, looking at the conditions of the problem to be fulfilled, making as many attempts as necessary. They showed persistence, channeling their effort towards the main goal: “Not everything is perfect at the first attempt, but if we think, give ideas and listen to the colleagues in the group, a positive result can be obtained with extra work”. Although not all students were completely satisfied with the result, mentioning that they would “change aesthetic aspects to have a more appealing table”, they also recognized that “the most important thing was to get a robust table”, channeling all their efforts and attention to that purpose.

5. Conclusions

The challenges of today’s society bring added responsibility to schools, so teachers can provide learning opportunities for all students to “do the math”. Many authors advocate the importance of cognitively challenging tasks through which students make decisions and choices, plan actions and explain and justify their options [62]. This didactic experience constituted an opportunity to favor the integration of some disciplinary areas (mathematics, science, art), as well as the fundamentals of engineering, occasionally resorting to technology [31,46]. The paper table problem was proposed with the aim of increasing these student teachers’ interest in mathematics and letting them recognize that engineering has many links to the mathematics that they study and use in class. It was also an opportunity to motivate them, as future teachers, to develop and use the ED process with their own pupils, providing a rich source for creating learning experiences that reflect the features of real-life problems. On the other hand, this didactical experience constituted a chance to overcome some negative attitudes, like the teachers’ lack of confidence or knowledge in undertaking new challenges [1,28,57].

Following this study, we can summarize some conclusions. Addressing the first research question, we noticed that all the groups were able to reach a solution that satisfied the conditions of the problem. Some groups made more attempts than others, redesigning and rebuilding the structure, and we can also state that, comparing the artefacts, some tables were more stable than others. The implementation of the paper table problem evidenced that these future teachers were able to use the ED cycle, imagining, designing, building, testing and redesigning/rebuilding, and if needed sharing their product. However, some groups tried to skip the Design step, experimenting with the materials after the brainstorm, due to their difficulties in drawing 3D shapes or the need to make their ideas concrete through physical representations. Despite revealing difficulties in using correct terminology or sound scientific arguments, the shared ideas expressed the awareness of the use of multidisciplinary knowledge, prompted by the nature of the problem. The need to test and evaluate the strength and stability of the constructed table led to a more in-depth analysis of the impact of the choice for certain shapes, of the spatial distribution of the table’s legs, the importance of symmetry and the relation to center of mass and forces. Given that some of the participants did not follow the ED cycle as it was presented, skipping or merging steps, it will be necessary to review this model and adapt it to make it clearer and more functional. In order to do this, we need a reflection supported by more empirical studies of this nature.

Reviewing the second research question, it appears that this experience was thus seen as an opportunity to simultaneously develop abilities such as problem solving, communication, creativity, cooperative work, but also integrate disciplinary knowledge, establishing connections of different kinds [6,7,25,26]. While solving the problem the pre-service teachers did not intentionally reflect on the contents and skills applied. Knowledge was used in an integrated manner, especially the topics related to mathematics and science, analyzing simultaneously the effect of the shapes of the legs, their spatial orientation, the distribution of the forces and the idea of center of mass. They were able to verbalize these ideas in their discussions and some of them expressed these concepts in the poster. Others were not very accurate in their justifications. We did not formally ask the participants to identify and articulate a list of STEAM contents, aspect that will be considered in future experiences, making them intentionally reflect about this issue, as presented in Table 6.

Concerning the third research question, we concluded that this didactical experience allowed the identification of different types of engagement: cognitive, affective and behavioral [12]. Considering the different levels of cognitive engagement, we noticed that, to solve this problem, the participants had to apply deep strategies, having the need to reflect about concepts and procedures and understand the effects of the underlying procedures. The reliance on the teacher in specific moments of the process of solving the problem was also noticeable, particularly in the evaluation step and also in sharing the solution, since they were asked to scientifically justify their options. In the affective domain, the participants expressed interest in the authenticity of the problem and the procedures underlying the ED cycle, which were new to them. Depending on the outcomes, we also observed anxiety (expectation of the test), frustration (inability to draw), concern (comparison with other groups), and satisfaction (achieving a solution). In general, the elements of the several groups revealed achievement orientation, working together to reach a common goal, and making an effort in the several steps of the ED cycle to solve the problem. The behavioral engagement was translated through observable indicators like attentiveness and diligence. The participants actively took part in solving the problem, listening to the teachers and to each other, making collective decisions when needed (brainstorm, choose an idea, how to build the model and divide tasks). The test and evaluation step, that in several cases led to the need for redesign and retesting multiples times, showed the persistence of the participants, who automatically discussed and analyzed possible adjustments to the tables.

To conclude, teacher education programs should include experiences that stimulate pre-service teachers' knowledge, particularly solving the same tasks and using the same teaching and learning principles that they are expected to use with their own future students [15,17,60].

6. Limitations

Looking back on this didactical experience, both from the perspective of the participants and the teachers involved, despite the positive outcomes, there are some aspects to improve and limitations to overcome. The first was the difficulty in finding appropriate problems/projects with the intended characteristics: be authentic; involve hands-on work; expressing technological ideas; and using elementary knowledge of mathematics and physical sciences. The second set of difficulties was related to the materials that we need to provide the students to solve the problem. When we have too many students, we may have logistical problems. The third limitation was not expecting to find so many difficulties with the design and redesign of the sketches, especially with future teachers from elementary education. We also identified as a limitation the need for audio and video recordings of the groups' interactions in designing and building the tables, as well as interviews to access a more in-depth clarification of some individual and group ideas and perspectives. Concluding, we did not expect that the pre-service teachers had such narrow concepts of sciences, much of them common sense; so, these findings highlight the need for further scaffolding to prompt participants to use both sound scientific and mathematical knowledge [1].

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References

- English, L.D.; King, D. STEM integration in sixth grade: Designing and constructing paper bridges. *Int. J. Sci. Math. Educ.* **2019**, *17*, 863–884. [CrossRef]
- Edwards, S. Active learning in the middle grades. *Middle Sch. J.* **2015**, *46*, 26–32. [CrossRef]
- Edwards, S.; Kemp, A.; Page, C. The middle school philosophy: Do we practice what we preach or do we preach something different? *Curr. Issues Middle Level Educ.* **2014**, *19*, 13–19.
- Nesin, G. Active Learning. In *This We Believe in Action: Implementing Successful Middle Level Schools*; Association for Middle Level Education: Westerville, OH, USA, 2012; pp. 17–27.
- Vale, I.; Barbosa, A. Movement & learning: The gallery walk strategy. In *Improving Children's Learning and Well-Being*; Carvalho, G.S., Palhares, P., Azevedo, F., Parente, C., Eds.; UM-CIEC: Braga, Portugal, 2020; pp. 7–22.
- Fadel, C.; Bialik, M.; Trilling, B. Four-Dimensional Education: The Competencies Learners Need to Succeed. Center for Curriculum Redesign, 2008. Available online: <https://curriculumredesign.org/our-work/four-dimensional-21st-century-education-learning-competencies-future-2030/> (accessed on 10 September 2022).
- World Economic Forum. New Vision for Education: Fostering Social and Emotional Learning through Technology. 2016. Available online: http://www3.weforum.org/docs/WEF_New_Vision_for_Education.pdf (accessed on 12 September 2022).
- Prince, M. Does Active Learning Work? A Review of the Research. *J. Eng. Educ.* **2004**, *93*, 223–231. [CrossRef]
- National Council of Teachers of Mathematics. *Principles to Actions: Ensuring Mathematical Success for All*; NCTM: Reston, VA, USA, 2014; pp. 9–11.
- Hannaford, C. *Smart Moves: Why Learning Is Not All in Your Head*, 2nd ed.; Great River Books: Salt Lake City, UT, USA, 2005; pp. 15–16.
- Fredricks, J.A.; Blumenfeld, P.C.; Paris, A.H. School Engagement: Potential of the Concept, State of the Evidence. *Rev. Educ. Res.* **2004**, *74*, 59–109. [CrossRef]
- Kong, Q.P.; Wong, N.Y.; Lam, C.C. Student engagement in mathematics: Development of instrument and validation of construct. *Math. Ed. Res. J.* **2003**, *15*, 4–21. [CrossRef]
- Attard, C. Engagement with mathematics: What does it mean and what does it look like? *APMC* **2012**, *17*, 9–13.
- Leikin, R. Interplay between creativity and expertise in teaching and learning of mathematics. In Proceedings of the 40th Conference of the International Group for the Psychology of Mathematics Education, Szeged, Hungary, 3–7 August 2016; Csíkos, C., Rausch, A., Sztányi, J., Eds.; PME: Szeged, Hungary, 2016; Volume 1, pp. 19–34.
- Sullivan, P.; Clarke, D.; Clarke, B. *Teaching with Tasks for Effective Mathematics Learning*; Springer: New York, NY, USA, 2013; pp. 13–21.
- Vale, I.; Barbosa, A. Visualization—A pathway to mathematical challenging tasks. In *Mathematical Challenge for All*; Leikin, R., Christou, C., Karp, A., Pitta-Pantazi, D., R. Zazkis, R., Eds.; Springer International Publishing: Cham, Switzerland, 2022, *in press*.
- Vale, I.; Pimentel, T.; Barbosa, A. The power of seeing in problem solving and creativity: An issue under discussion. In *Broadening the Scope of Research on Mathematical Problem Solving: A Focus on Technology, Creativity and Affect*; Carreira, S., Amado, N., Jones, K., Eds.; Springer International Publishing: Cham, Switzerland, 2018; pp. 243–272.
- Fries, L.; Son, J.Y.; Givvin, K.B.; Sligler, J.W. Practicing Connections: A Framework to Guide Instructional Design for Developing Understanding in Complex Domains. *Educ. Psychol. Rev.* **2021**, *33*, 739–762. [CrossRef]
- Jurdak, M. Contrasting Perspectives and Performance of High School Students on Problem Solving in Real World Situated, and School Contexts. *Educ. Stud. Math.* **2006**, *63*, 283–301. [CrossRef]
- Palm, T. The Realism of Mathematical Schools Tasks—Features and Consequences. Ph.D. Thesis, Umea University, Umea, Sweden, 2002.
- OECD. *Education at a Glance 2011: OECD Indicators*; OECD Publishing: Paris, France, 2011.

22. Vos, P. What Is 'Authentic' in the Teaching and Learning of Mathematical Modelling? In *Trends in Teaching and Learning of Mathematical Modelling: International Perspectives on the Teaching and Learning of Mathematical Modelling*; Kaiser, G., Blum, W., Borromeo, R., Stillman, G., Eds.; Springer: Dordrecht, The Netherlands, 2011; Volume 1. [CrossRef]
23. National Council of Teachers of Mathematics. *Principles and Standards for School Mathematics*; NCTM: Reston, VA, USA, 2000.
24. OECD. PISA 2018 Results. Combined Executive Summaries, Volume I, II & III. OECD, 2019. Available online: https://www.oecd.org/pisa/Combined_Executive_Summaries_PISA_2018.pdf (accessed on 25 July 2022).
25. English, L.D. Advancing elementary and middle school STEM education. *Int. J. Sci. Math. Educ.* **2017**, *15* (Suppl. S1), 5–24. [CrossRef]
26. Quigley, C.F.; Herro, D.; Shekell, C.; Cian, H.; Jacques, L. Connected learning in STEAM classrooms: Opportunities for engaging youth in science and math classrooms. *Int. J. Sci. Math. Educ.* **2020**, *18*, 1441–1463. [CrossRef]
27. Breiner, J.M.; Harkness, S.S.; Johnson, C.C.; Koehler, C.M. What Is STEM? A Discussion about Conceptions of STEM in Education and Partnerships. *Sch. Sci. Math.* **2012**, *112*, 3–11. [CrossRef]
28. English, L.D. Learning while designing in a fourth-grade integrated STEM problem. *Int. J. Techno Des. Educ.* **2018**, *29*, 1011–1032. [CrossRef]
29. Vasquez, J.; Sneider, C.; Comer, M. *STEM lesson Essentials, Grades 3–8: Integrating Science, Technology, Engineering, and Mathematics*; Heinemann: Portsmouth, NH, USA, 2013.
30. Bybee, R. Advancing STEM education: A 2020 vision. *Technol. Eng. Teach.* **2010**, *70*, 30–35.
31. Martín-Páez, T.; Aguilera, D.; Perales-Palacios, F.J.; Vílchez-González, J.M. What are we talking about when we talk about STEM education? A review of literature. *Sci. Educ.* **2019**, *103*, 799–822. [CrossRef]
32. Thibaut, L.; Ceuppens, S.; De Loof, H.; De Meester, J.; Goovaerts, L.; Struyf, A.; Boeve-de Pauw, J.; Dehaene, W.; Deprez, J.; De Cock, M.; et al. Integrated STEM Education: A Systematic Review of Instructional Practices in Secondary Education. *Eur. J. STEM Educ.* **2018**, *3*, 1–12. [CrossRef]
33. Hiebert, J.; Carpenter, T.P.; Fennema, E.; Fuson, K.C.; Wearne, D.; Murray, H.; Olivier, A.; Human, P. *Making Sense: Teaching and Learning Mathematics with Understanding*; Heinemann: Portsmouth, NH, USA, 1997.
34. English, L.D. STEM: Challenges and Opportunities for Mathematics Education. In Proceedings of the 39th Conference of the International Group for the Psychology of Mathematics Education, Hobart, Australia, 13–18 July 2015; Beswick, K., Muir, T., Wells, J., Eds.; PME: Hobart, Australia, 2015; Volume 1, pp. 4–18.
35. English, L.D.; King, D.T. STEM learning through engineering design: Fourth-grade students' investigations in aerospace. *Int. J. STEM Educ.* **2015**, *2*, 14. [CrossRef]
36. Honey, M.; Pearson, G.; Schweingruber, H. (Eds.) *STEM Integration in K-12 Education: Status, Prospects, and an Agenda for Research*; Academies Press: Washington, DC, USA, 2014.
37. Bryan, L.A.; Moore, T.J.; Johnson, C.C.; Roehrig, G.H. Integrated STEM education. In *STEM Roadmap: A Framework for Integration*; Johnson, C., Peters-Burton, E., Moore, T., Eds.; Taylor & Francis: London, UK, 2015; pp. 23–37.
38. Lucas, B.; Claxton, G.; Hanson, J. *Thinking Like an Engineer: Implications for the Education System*; Royal Academy of Engineers, 2014. Available online: www.raeng.org.uk/thinkinglikeanengineer (accessed on 31 August 2022).
39. Kelley, T.R.; Knowles, J.G. A conceptual framework for integrated STEM education. *Int. J. STEM Ed.* **2016**, *3*, 11. [CrossRef]
40. Cunningham, C.M. Engineering is elementary. *Bridge* **2009**, *30*, 11–17.
41. Shahali, E.H.; Halim, L.; Rasul, M.S.; Osman, K.; Zulkifeli, M.A. STEM learning through engineering design: Impact on middle secondary students' interest towards STEM. *Eurasia J. Math. Sci. Techno Educ.* **2017**, *13*, 1189–1211. [CrossRef]
42. Fan, S.; Yu, K. How an integrative STEM curriculum can benefit students in engineering design practices. *Int. J. Techno Des. Educ.* **2017**, *27*, 107–129. [CrossRef]
43. Wells, J.G. PIRPOSAL Model of Integrative STEM Education: Conceptual and Pedagogical Framework for Classroom Implementation. *Techno Eng. Teach.* **2016**, *75*, 12–19.
44. Guzey, S.S.; Moore, T.J.; Harwell, M. Building up STEM: An analysis of teacher-developed engineering design-based STEM integration curricular materials. *J. Pre-Coll. Eng. Educ. Res.* **2016**, *6*, 2. [CrossRef]
45. Education Department at WGBH. Design Squad Global Inventing Green 12-Week Club Guide. WGBH, 2019. Available online: https://pbskids.org/designsquad/pdf/parentseducators/DSG_Inventing_Green_Club_Guide_6_Week.pdf (accessed on 3 September 2022).
46. Cunningham, C.M.; Hester, K. Engineering is Elementary: An Engineering and Technology Curriculum for Children. In Proceedings of the ASSE Annual Conference and Exposition, Honolulu, HI, USA, 1 January 2007; pp. 12.639.1–12.639.18.
47. Kelly, G.J.; Cunningham, C.M. Epistemic tools in engineering design for K-12 education. *Sci. Educ.* **2019**, *103*, 1080–1111. [CrossRef]
48. Mann, E.L.; Mann, R.L.; Strutz, M.L.; Duncan, D.; Yoon, S.Y. Integrating engineering into K-6 curriculum developing talent in the STEM disciplines. *J. Adv. Acad.* **2011**, *22*, 639–658.
49. Carreira, S.; Baioa, A.M. Mathematical modelling with hands-on experimental tasks: On the student's sense of credibility. *ZDM Math. Educ.* **2018**, *50*, 201–215. [CrossRef]
50. Dougherty, D. The maker movement. *Innovations* **2012**, *7*, 11–14. [CrossRef]
51. García-Molina, R. Ciencia recreativa: Un recurso didáctico para enseñar deleitando. *Rev. Eureka Enseñ Div. Ciencias* **2011**, *8*, 370–392. [CrossRef]

52. Erickson, F. Qualitative Methods in Research on Teaching. In *Handbook of Research on Teaching*; Wittrock, M., Ed.; MacMillan: New York, NY, USA, 1986; pp. 119–161.
53. Miles, M.B.; Huberman, A.M. *Qualitative Data Analysis*; Sage Publications: Thousand Oaks, CA, USA, 1994.
54. Given, L.M. (Ed.) *The SAGE Encyclopedia of Qualitative Research Methods*; Sage Publications: Thousand Oaks, CA, USA, 2008; Volume 1–2.
55. Yin, R.K. *Case Study Research: Design and Methods*; Sage Publications: Thousand Oaks, CA, USA, 2003.
56. Bacharach, N.; Heck, T.; Dahlberg, K. Researching the use of co-teaching in the student teaching experience. In *Moving forward and Broadening Perspectives: Coteaching in International Contexts*; Murphy, C., Scantlebury, K., Eds.; Springer Publishing: New York, NY, USA, 2013.
57. Enderson, M.C.; Grant, M.R. Emerging engineers design a paper table. *Math. Teach. Middle Sch.* **2013**, *18*, 362–369. [[CrossRef](#)]
58. Stoner, M.; Stuby, K.; Szczepanski, S. The engineering process in construction & design. *Math. Teach. Middle Sch.* **2013**, *18*, 333–338.
59. Polya, G. *How to Solve It?* Princeton University Press: Princeton, NJ, USA, 1945; pp. 27–42.
60. Vale, I.; Barbosa, A. Promoting mathematical knowledge and skills in a mathematical classroom using a gallery walk. *Int. J. Res. Educ. Sci.* **2021**, *7*, 1211–1225. [[CrossRef](#)]
61. Creswell, J.W. *Research Design: Qualitative, Quantitative and Mixed Methods Approaches*, 3rd ed.; Sage Publications: Thousand Oaks, CA, USA, 2009.
62. English, L.D.; King, D.; Hudson, P.; Dawes, L. The aerospace engineering challenge. *Teach. Child. Math.* **2014**, *21*, 122–126. [[CrossRef](#)]