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Research article

Exploring preservice primary teachers’ understanding of the engineering design process through integrated STEM laboratory activities

Umran Betul Cebesoy*

Department of Mathematics and Science Education, Usak University, 1 Eylul Campus, Usak, Türkiye

* **Correspondence:** Email: umran.cebesoy@usak.edu.tr; Tel: +90-276-2212121/2155.

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Abstract: Effective STEM (science, technology, engineering, and mathematics) education requires teachers who are well prepared to design and facilitate integrated learning experiences. However, traditional discipline-based segregated teaching continues to dominate many classrooms, limiting opportunities for meaningful integration across STEM fields. Engineering design offers a powerful pedagogical framework for bridging these disciplinary boundaries through deliberate engagement in problem-solving processes. This study examined how an engineering design–based STEM laboratory course enhanced preservice primary teachers' (PPTs) understanding and application of engineering design principles. Employing a basic qualitative research design, a 14-week course was developed in which PPTs collaborated in 10 groups to create prototypes addressing real-life problems. Data were collected through 50 reflective laboratory sheets completed by 10 participants and analyzed deductively. Findings revealed that participants initially struggled with applying the engineering design process; however, their understanding and design thinking skills improved progressively throughout the course, though this improvement was not consistent across all cases. Overall, the results highlight the potential of engineering design pedagogy in teacher education for fostering integrated STEM competencies among preservice teachers. The gradual improvement observed in participants' design thinking suggests that iterative engagement with engineering design stages supports the development of interdisciplinary connections in STEM learning. These findings position engineering design as a critical framework for building PPT’s integrated STEM competencies.

Keywords: design-based learning, engineering design process (EDP), integrated STEM education, preservice primary teachers, teacher education

1. Introduction

In recent decades, there has been a growing recognition of the need to reform STEM (science, technology, engineering, and mathematics) education toward a more integrated and transdisciplinary approach [1–3]. Supporting this, recent worldwide educational reforms also confirmed the need for integrated STEM education [1,4]. Although there is no widely accepted definition of integrated STEM education, there are several definitions that are frequently cited in the literature. For instance, Moore et al. [3] defined integrated STEM education as “an effort to combine some or all of the four disciplines of science, technology, engineering, and mathematics into one class, unit, or lesson that is based on connections between the subjects and real-world problems” (p. 38), whereas Sanders [5] (2009) defined it as “approaches that explore teaching and learning between/among any two or more of STEM subjects” (p. 21). Bybee [6] also provided a comprehensive perspective on integrated STEM education by outlining eight different approaches that highlight varying degrees and purposes of STEM integration.

Building upon these conceptualizations, researchers have sought to operationalize what “integration” means in practice by developing models that describe different levels of disciplinary connection in STEM education. Rather than teaching science, mathematics, and technology as isolated subjects resulting from disciplinary separation [7–9], STEM education researchers have proposed several integration models to overcome this fragmentation [8]. In general, three forms of cross-disciplinarity—multidisciplinary, interdisciplinary, and transdisciplinary—are used to describe the levels of integration in STEM education [1,10,11]. Compared to multidisciplinary STEM education, which typically employs “inspired” or “simplified” real-world problems, transdisciplinary STEM education represents a deeper level of integration as it engages learners with “complex” real-world problems [10,11]. Integrated STEM education emphasizes the use of authentic, real-world problems that require the application of knowledge and skills across multiple disciplines [3,9,10,12,13]. This approach encourages students to develop essential 21st-century competencies such as problem-solving and critical thinking, while applying scientific and mathematical concepts through hands-on, design-based learning experiences [14,15]. As a result, students’ awareness of their own learning processes, as well as their interest and engagement in STEM subjects, increases [2,16]. One of the most effective ways to achieve such meaningful integration and engagement is through the engineering design process (EDP), which has emerged as a central pedagogical strategy that anchors interdisciplinary STEM learning.

Design is more than simply creating physical objects; it also involves formulating interventions that transform existing circumstances into desired outcomes [13]. Design constitutes one of the fundamental engineering practices, denoting an organized and iterative process of decision-making [17,18]. In this sense, design serves as an essential tool for integrated STEM education [1,19]. One of the most effective pedagogical approaches to engage students in such processes is design-based learning (DBL), which immerses learners in authentic design challenges that mirror real-world engineering practices [13]. Within this context, defining the EDP, which operationalizes DBL, becomes even more essential. Engineering design does not have a single, universally agreed-upon definition; however, several widely accepted definitions exist in the literature. For instance, Dym et al. [20] defined engineering design as a structured and purposeful problem-solving process in which designers conceive, evaluate, and refine ideas for systems, devices, or processes. The primary goal of this process is to develop a functional solution that meets users' needs while adhering to a defined set of constraints and limitations. Similarly, the Accreditation Board for Engineering and Technology (ABET) characterizes engineering design as an iterative and creative decision-making process aimed at developing systems, components, or processes that satisfy specific needs and requirements within given constraints by applying engineering sciences, mathematics, and basic sciences [21].

Although these definitions share common characteristics—such as being iterative, systematic, and goal-oriented and operating under real-world constraints—engineering design pedagogy differs in its primary focus. Engineering design pedagogy refers to the instructional use of the engineering design process to support student learning. Rather than emphasizing the quality of the final product, this pedagogical approach highlights how students engage in scientific inquiry, collect and analyze data, justify design decisions, and construct design artifacts while working on authentic, ill-structured, real-world problems by adopting persistence, collaboration, and reflection skills through teamwork [e.g., 2,9,22]. Since engineering design is a highly complex process, it requires a definition of the skills required for the effective engineering design process. While there is no set of predetermined skills adopted in engineering design, different research operationalizes different skills. For instance, high-order skills such as observing, modeling, modifying, analyzing, and evaluating a project were determined as required skills in engineering design in Fan and Yu's [16] study, and analytical skills (such as fundamental understanding of mathematics and science) and open-ended problem-solving skills (such as identifying and formulating problems and solving problems) were characterized as demanded skills for engineering design [23].

In this study, we embraced this pedagogical perspective by conceptualizing engineering design skills as preservice primary teachers' ability to engage in EDP-based problem solving, articulate and justify design decisions using scientific reasoning, and iteratively revise their solutions through reflection and evaluation. Thus, engineering design skills are examined not as technical design proficiency or curriculum planning competence, but as reflective design reasoning enacted during EDP-based STEM activities.

Building on this pedagogical framing, the EDP is recognized as one of the most fundamental concepts and practices for helping students develop engineering habits of mind and authentic problem-solving skills [24,25]. Therefore, EDP plays a crucial role in K–12 education by fostering the cross-disciplinary knowledge and methods needed to address real-life challenges [3,26]. Several studies also emphasize that even younger students are capable of engaging meaningfully in early engineering experiences [14,27]. Research has further demonstrated that integrating engineering design into STEM instruction enhances students' conceptual understanding, promotes 21st-century skills such as higher-order thinking, computational thinking, and creativity, and increases their motivation, interest, and engagement [14,16,28,29]. Through iterative cycles of design and reflection, students learn to connect theoretical knowledge with practical application—an essential step toward scientific literacy and innovation. Studies further indicate that even very young learners are capable of engaging in the EDP [27,30,31]. Thus, from the early grades onward, students should be introduced to the EDP as a foundation for meaningful STEM learning.

However, the effective implementation of EDP in classrooms largely depends on teachers' understanding, preparation, and ability to facilitate design-based learning experiences. Despite the increasing emphasis on integrated STEM education and engineering design, many teachers lack adequate preparation and sufficient content knowledge to design and implement such learning environments [2,8,26,32–34]. Teachers need additional opportunities to deepen their understanding of the EDP and to develop the skills necessary to integrate STEM disciplines effectively through design [8,35]. Continuing professional development (PD) programs have been shown to be effective in enhancing and supporting teachers' abilities to implement integrated STEM education through the EDP [28,33,34,36,37].

Given this need for professional competence among in-service teachers, it is equally important to ensure that preservice teachers are equipped with strong foundations in engineering design and integrated STEM pedagogy before entering the profession. Studies also indicate that teacher education programs often provide limited exposure to engineering concepts and the design process [34,38]. Consequently, preservice teachers may struggle to implement integrated STEM lessons effectively or to recognize how engineering can serve as a context for meaningful science and mathematics learning. To overcome this challenge, engineering has recently been introduced into many teacher education programs [39]. Research has shown that preparing preservice teachers with adequate experiences in the EDP equips them to design and implement integrated STEM education in their future classrooms [33,40–43]. Elementary classrooms offer a particularly powerful setting for implementing STEM education [33]. Preparing preservice teachers with knowledge and experiences related to the engineering design process is, therefore, crucial. Through explicit engagement in design-based STEM tasks, preservice primary teachers can develop a deeper understanding of how to connect disciplinary content, foster inquiry and creativity among their future students, and design classroom environments that mirror authentic scientific and engineering practices.

Despite the growing body of research on integrated STEM education and the engineering design process, existing studies have largely centered on preservice or in-service science teachers, often within discipline-specific (e.g., [37]) or secondary-level contexts (e.g., [40]). However, preservice primary teachers are systematically underrepresented in STEM and EDP research. This oversight fails to acknowledge their critical role in shaping students' earliest encounters with engineering design thinking and iterative problem-solving processes.

This distinction is substantively important. Unlike preservice science teachers, preservice primary teachers teach multiple subjects to younger learners and often have limited disciplinary depth in science and engineering. Consequently, the implementation of engineering design–based integrated STEM activities in primary teacher education programs prepares them to teach design-based integrated STEM activities. Equipping preservice primary teachers with these competencies is essential for building future generations of learners who are capable of thinking critically, solving complex problems, and creating innovative solutions to real-world challenges. Moreover, while prior research has documented positive outcomes of EDP-based STEM instruction, fewer studies have qualitatively examined how preservice primary teachers develop an understanding of engineering design over time, particularly with respect to the iterative nature of the process and the integration of multiple disciplines in authentic design contexts. Addressing this gap, the present study investigated preservice primary teachers' evolving engagement with engineering design during a 14-week integrated STEM laboratory course, offering insight into how engineering design thinking emerges within a generalist teacher education context.

This study was designed to develop preservice primary teacher candidates' (PPTs) understanding of engineering design–based STEM activities. The main research question that guided the present study is:

How effective was an engineering design–based STEM laboratory course in developing PPT's engineering design skills?

1.1. Importance of the study

The integration of engineering design into STEM education has been widely recognized as a powerful approach to enhancing student learning, fostering creativity, and promoting the application of knowledge to real-world problems [3,27]. However, the successful implementation of such pedagogies in schools largely depends on teachers' understanding, confidence, and ability to design meaningful interdisciplinary learning experiences. Research shows that many teachers—particularly preservice teachers—face significant challenges in translating integrated STEM principles into classroom practice due to their limited exposure to engineering and the design process [32–34,38]. Consequently, teacher preparation programs must provide opportunities for preservice teachers to experience, reflect on, and implement integrated STEM learning through engineering design–based activities.

Focusing on preservice primary teachers is particularly important because they play a foundational role in shaping young learners' attitudes and understandings toward science, technology, and engineering. Previous studies have shown that even very young students are capable of engaging in engineering design tasks. For instance, Elkin et al. [31] found that young learners were eager to participate in design activities, while English et al. [13] demonstrated that they could design sketches and connect them to everyday problems. Similarly, English and King [27] reported that fourth-grade students successfully applied disciplinary knowledge during the design evaluation and redesign phases of engineering design, and Estapa and Tank [33] confirmed that including engineering design in early years enhances students' understanding of engineering concepts. Collectively, these findings highlight that primary classrooms offer ideal contexts for introducing STEM through engineering design, as it enables students to use disciplinary knowledge to solve real-life problems.

Nevertheless, research indicates that teacher education programs provide limited exposure to engineering design. Many recent studies have called for the inclusion of integrated STEM education through the engineering design process (EDP) in teacher education programs [e.g., 2,8,39]. Capobianco et al. [39] noted that engineering has only recently been introduced into science teacher education programs. Recent efforts have aimed to integrate EDP into chemistry teacher education [4,40], elementary teacher education [39,44], technology teacher education [42], and science teacher education programs [41,45]. However, to the best of our knowledge, integrating EDP within primary teacher education through an explicitly designed STEM framework remains an area yet to be explored. Engaging preservice primary teachers in integrated STEM education through EDP allows them to experience engineering design as a process of inquiry, testing, and redesign, thereby aligning their pedagogical thinking with contemporary STEM education frameworks.

2. Methodology

2.1. Research design

A basic (generic) qualitative approach was utilized in the study. This method does not follow the accepted presumptions of other popular qualitative approaches like grounded theory, phenomenology, or ethnography [46]. Using this method, the researcher focuses on "(1) how people interpret their experiences, (2) how they construct their worlds, and (3) what meaning they attribute to their experiences" [47], (p. 23). In this way, we investigated how PPTs interpreted their experiences after engaging in engineering design–based STEM laboratory activities and how their interpretations changed after each STEM activity.

2.2. Participants

This study was conducted in a compulsory Science Laboratory course offered in the second year of the primary teacher education program in a mid-sized public university in the Western Anatolian region of Türkiye. The participants consisted of 40 preservice primary teachers (PPTs) who were all enrolled in this course during the data collection period. The participants were selected using convenience sampling, as the researcher was the course instructor and had direct access to the instructional setting. This group was considered appropriate for the purpose of the study because the course was centrally regulated by the Higher Education Council of Türkiye [Yüksek Öğretim Kurumu (YÖK)] and followed a standardized curriculum implemented across primary teacher education programs nationwide [48]. Therefore, the participants represent a typical cohort of preservice primary teachers following a series of compulsory courses like biology, chemistry, physics, science laboratory courses (run for two consecutive semesters in the third and fourth semesters), and science teaching method courses (run for two consecutive semesters in the fifth and sixth semesters) during their undergraduate education in addition to other core courses. After graduation, they will be primary teachers who will teach from grade 1 to grade 4. They will teach life sciences and primary science courses to students aged six to ten years old, besides courses like mathematics, Turkish language, foreign language, and music.

To conduct laboratory activities, PPTs formed small groups on a voluntary basis. A total of 10 different groups were created, each consisting of four participants (mixed-gender or female-only groups). None of the participants had any prior experience with STEM and had not taken any STEM-related elective or compulsory courses before this laboratory course. Each participant completed an individual laboratory activity sheet (4–6 pages) for each of the five STEM activities implemented during the semester. These sheets included written reflections, design explanations, sketches, and photos of the final prototypes. In total, 200 laboratory sheets were collected (40 participants × 5 activities). Given that the focus of this study was to examine shifts in design reasoning within the instructional context, a typical purposeful sampling strategy [47] was employed. Since group members collaboratively worked on a single shared design during each activity, their written reports largely documented a collective design process. Therefore, one activity sheet from each group was selected for each activity to represent the group-level reflection. Selection was based on completeness and clarity of documentation to ensure analytic consistency. Accordingly, 50 laboratory sheets (10 groups × 5 activities) were included in the data analysis. The analysis therefore reflects group-level reflective narratives rather than individual developmental trajectories.

2.3. Intervention

The present study was conducted within the Science Laboratory course, which is a two-credit course held for two lesson hours each week (each lesson hour lasts for 50 minutes). Our initial aim was to explore the development of PPTs' understanding of the engineering design process. For this purpose, a 14-week engineering design–based STEM laboratory course was designed. The content of the course is presented in Figure 1.

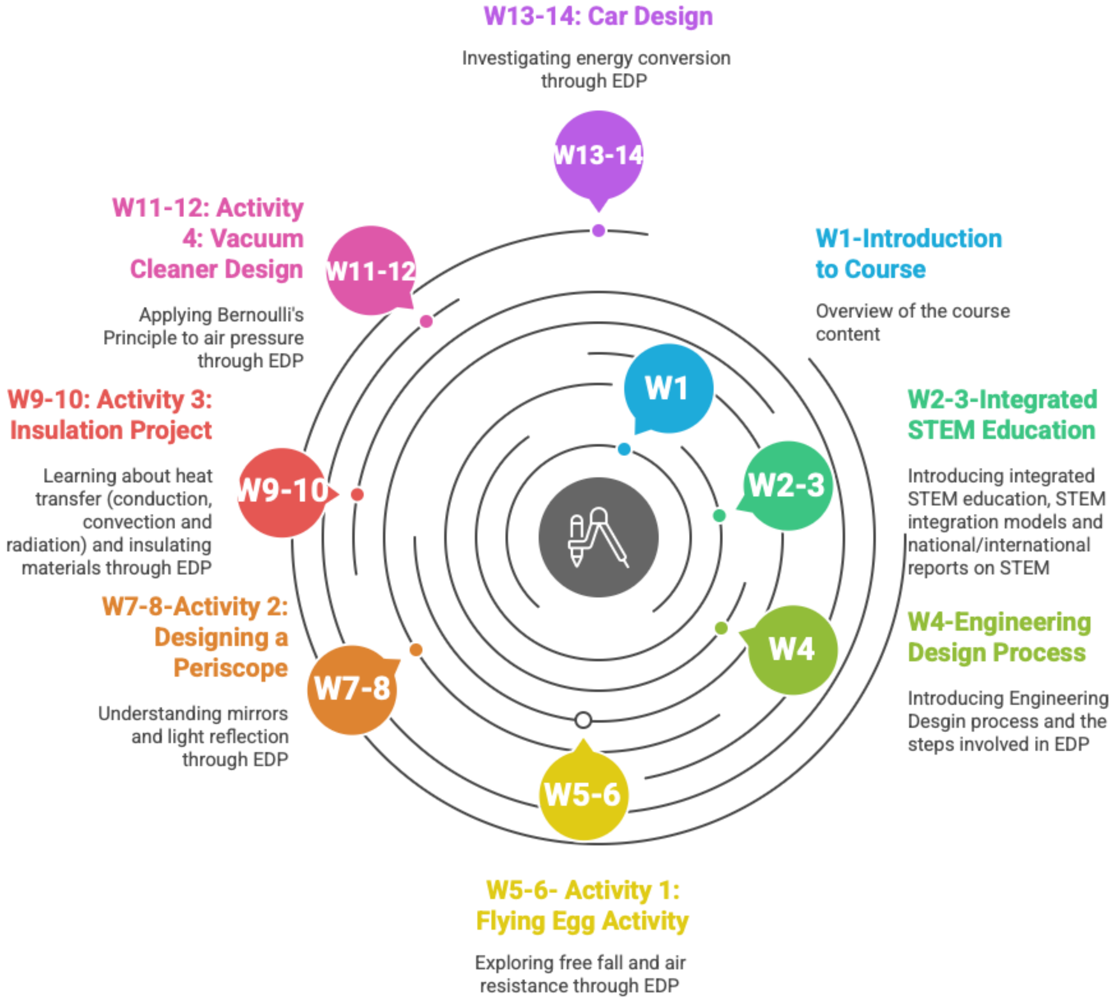

Figure 1. The content of the course.

The first week was devoted to introducing the content and purpose of the course to the participants. The syllabus of the course was presented, and the participants were invited to join the study. Signed informed consent forms were gathered from each participant. The integrated STEM education strategy, its development, and the national reports on STEM were presented in the following two weeks (weeks 2–3). In the fourth week, the engineering design process was presented. Since the course was predominantly science-related, science was the major STEM discipline during the laboratory activities. Following the course's theoretical part, the PPTs participated in five different STEM activities, each of which required them to integrate scientific, mathematical, and technological knowledge using an engineering design–based methodology.

Each activity was designed by following Hynes et al.'s [25] engineering design phases, which are presented in Figure 2.

Figure 2. Engineering design process (adapted from Hynes et al. [25]).

The model starts with presenting a daily life problem as a first step. This step is essential, as it enables participants to define and identify a problem clearly, which in turn helps them come up with their own solutions. Participants investigate potential ideas that cross their minds in the second step. Participants work in pairs to generate solutions while considering the limitations and criteria in the third step. They generate a wider range of design concepts while working in pairs and during brainstorming sessions. The team members evaluate the potential solutions they produced in the previous stage in order to ultimately choose the best option from among all initial ideas in the next step (choose the best solution). Then, the groups build a prototype (a physically working model) by using their scientific and mathematical knowledge (fifth step). Testing and assessing the solutions is the next step. The team members evaluate the success of their prototype by taking their requirements and limitations into account. At this point, the team members acknowledge that the prototype is not the final product. In subsequent stages, they might rework and retest their prototypes, illustrating the iterative nature of engineering design. A crucial part of the engineering design process is sharing the solution with other teams. Each team presents its prototype in this step, complete with written reports and PowerPoint presentations. A crucial step in helping teams optimize their designs is redesigning them. Every team makes an effort to produce a final product that satisfies the requirements and limitations. The team finalizes their product in the last step [25].

We designed STEM activities according to the design-based pedagogical approach, which builds on problem-based learning (PBL). During PBL sessions, students work in collaborative groups to solve a proposed problem that has multiple solutions [49]. Smith et al. [50] proposed that PBL is a suitable setting that offers genuine STEM subject integration. Every activity began with the introduction of a problem from everyday life. For example, Activity 1 started with the introduction of Felix Baumgartner's famous story and how he could arrive safely at the world's surface. There is a series of questions probing students' previous understanding, and the groups were asked to design a model that would land on the surface safely. Each group designed their model by using an egg. The challenge was not cracking a raw egg that was dropped from a certain height. Money (it must be reasonably cheap) and a certain height of 20 m were constraints in this activity. During testing, if their model was unable to land safely without cracking the raw egg, the group needed to redesign their model, showing the iterative nature of engineering design. During the activity, the PPTs used scientific content knowledge of free fall and air resistance. They needed to make calculations while designing the models. The whole process is based on the engineering design process. In this manner, the activities were designed by considering the transdisciplinary STEM integration model, which calls for utilizing knowledge or abilities from two or more disciplines to solve practical problems [1].

2.4. Data collection tools

To investigate participants' understanding of engineering design and how their understanding was developed throughout the course, we collected data by using reflective laboratory narratives. During the course, each participant prepared five reflective laboratory narratives. A total of 50 narratives were included in the data analysis.

2.4.1. Reflective laboratory narratives

PPTs' individual reflective laboratory narratives were used as the main data source in this study. Reflective narratives are frequently used in teacher education programs, as they enable participants to examine and articulate their ideas based on their experiences and observations (Capobianco et al., 2022). In this study, the reflective laboratory narratives were designed to capture PPTs' initial concrete experiences with engineering design–based laboratory activities. These narratives were structured according to the engineering design steps proposed by Hynes et al. [25]. The content of Activity 1 is presented in Table 1.

Table 1. Content of Activity 1: Flying egg activity.

Steps of the engineering design process	Directions and probing questions
1. Identify the need/problem	How did Felix Baumgartner manage to land on Earth safely? How does an object that is dropped from space land safely on the ground? What is free fall? Why do objects fall?
2. Research need/problem	As an engineer, design a product that will allow an egg thrown from a certain height to land on the surface without breaking it.
3. Develop possible solutions	As an engineer, how would you design it? Draw your initial design. What kind of materials would you use in this design? Discuss the train design you are planning to design using the information you

		have learned from your group members.
4.	Select the best solution	Draw the design that all the group members agree on. Show the materials you would use while designing your model in your drawing. What are the criteria (material, durability, etc.) of the materials you are planning to use? Please specify. What are the limitations of the materials you are planning to use? Please specify.
5.	Construct a prototype	Was the prototype you designed your first design? Do you have trials before the latest prototype?
6.	Test and evaluate the solution	Design your prototype and test it. In this step, check whether the product you have designed worked or not. Did it work? Why? What can be done to improve your design?
7.	Communicate the solution	Present your design to other classmates. Do they have any suggestions to further improve it? If so, what are they?
8.	Redesign	Did you redesign your prototype? If you did, what were the missing points in your initial design? If you redesign the final train design, what would you change? What materials would you plan to use in this redesigned train?

2.5. Researcher's role/positionality

In this study, the author adopted a researcher–practitioner role, simultaneously serving as the course instructor and the researcher. This insider position allowed for prolonged engagement, pedagogical sensitivity, and a nuanced understanding of the instructional context. It also entails potential bias arising from the influence of the researcher's perspectives [51]. Nevertheless, the study would not have been feasible without the author's position as the course instructor. Accordingly, reflexivity was maintained throughout the research process to acknowledge and critically examine the researcher's positionality.

2.6. Research ethics

This study gathered approval from the relevant university's administrative boards. The research adhered to the Declaration of Helsinki with no deception or harm to the human participants by fully informing them about the contents of the study. The participants voluntarily participated in the study. Participants were informed about the content of the research, and each participant signed an informed consent form that acknowledged the structure of the study. Each participant was given a pseudonym to protect their identity. Their quotes are provided in double quotation marks.

Data analysis

To understand how the intervention catered to the participants' understanding of engineering design, we employed a four-level analytic rubric previously developed and validated in earlier studies [32,52,53]. However, during initial readings of the data, minor refinements were made to clarify category boundaries and improve the operational clarity of level descriptors. These refinements did not alter the overall four-level structure of the coding book but enhanced its applicability to the specific context of this study, resulting in a deductive–iterative coding process. The coding book is presented in Table 2.

Table 2. Coding book used in assessing participants' understanding of the engineering design process (adapted from Ozkıcılcık & Cebesoy [52] and Ozkızılcık [53]).

Level	Definition	Characteristics of solution/design/product
Underdeveloped	The product/design did not meet the predetermined criteria and limitations, or the ultimate product did not work or provide a sufficient solution to the problem. PPT did not follow the engineering design steps.	No working model.
Partially developed	The product/design was working and functional considering the criteria and limitations. However, PPT did not mention the iterative process of engineering design.	PPT either used exact materials they found during their internet research or did not provide any suggestions for redesign and stated that "I would not change anything at all" if redesigning their initial product/design.
Developed	The PPT followed the phases of the engineering design process step-by-step, producing a comprehensive and functional product or design (design, test, redesign, and improve). The product met the predetermined requirements and limitations while suggesting improvements.	PPT developed a working solution/product/design that has distinctive features that could not directly be reached from an internet search and that has creative solutions/materials, etc. The ultimate product/design has redesign suggestions, but these suggestions only include small modifications in the initial model.
Well-developed	The PPT developed a comprehensive and functional product or design and meticulously followed each phase of the engineering design process (design, test, redesign, and enhance). The product met the predetermined requirements and limitations while having unique characteristics. Furthermore, the PPT suggested creative recommendations and ideas (tools, apparatus, models, and designs) for enhancing and developing the ultimate product.	PPT developed a working solution/product/design that has distinctive features that could not directly be reached from an internet search and that has creative solutions/materials, etc. The redesign suggestions and drawings include new features and innovative ideas that could be used, such as new materials and improvements in design.

According to Table 2, if the ultimate design/model was not working or did not include the criteria and limitations, this model was labeled as *underdeveloped*. If the design/model was functionally working and constituted a solution to the problem addressed by considering the criteria and limitations, but the iterative nature of engineering was not followed, the design was labeled as *partially developed*. Uniqueness is a distinctive character that delineates partially developed and developed designs. We were looking for designs that had an iterative nature of engineering (e.g., the designs should have suggestions for improvement). Lastly, if the design included creative recommendations and ideas (tools, apparatus, models, and designs) for enhancing and developing the ultimate product, this design was labeled as *well-developed*.

The unit of analysis was the whole laboratory narrative (including sketches and redesign explanations) produced for each activity. Each narrative was read multiple times to identify evidence of engineering design phases, iterative improvements, and the nature of redesign suggestions. Coding was conducted in three stages: (1) independent initial coding by two researchers, (2) comparison and discussion of discrepancies, and (3) refinement of coding decisions through peer debriefing sessions. Inter-coder agreement was calculated using Cohen's kappa coefficient, yielding a value of $\kappa = 0.80$, which indicates substantial agreement. Discrepancies were discussed until consensus was reached, thereby enhancing the dependability and reliability of the findings. Rather than treating each activity as a static classification, we traced the progression of each group's rubric level across the five STEM activities to examine developmental patterns over time. This longitudinal comparison enabled us to identify shifts from underdeveloped or partially developed designs toward developed and well-developed understandings of the engineering design process.

2.7. Trustworthiness of the study

The trustworthiness of a qualitative study can be ensured by using multiple measures such as triangulation, self-reflection, prolonged engagement, peer debriefing, or audit trail [54]. Creswell [55] suggested the use of at least two measures to confirm the trustworthiness of a qualitative study. In this study, the researcher used *prolonged involvement* to get more in-depth knowledge about the participants and stayed on the site before and after the study, as she was the course instructor of other science-related courses offered in the department. Thus, the researcher knew the participants, who were not complete strangers to the researcher. In another attempt to increase the study's credibility and ensure external validity, *thick description* was adopted in the study. The researcher explained in detail the intervention used during the study, giving the weekly syllabus and explaining the content of each STEM activity and the structure of laboratory sheets. One last measure was *peer debriefing*. An experienced qualitative researcher with more than six years of experience in designing and implementing science laboratory courses, and who was not involved in this study, served as both a peer debriefer and an independent coder. As the peer debriefer, she checked the research methodology and examined emerging interpretations during data analysis. Inter-coder agreement was established through independent coding of 15 laboratory sheets (three samples from five different activities; approximately 30%). She coded the selected data by using the coding book created by the authors [52,53]. In addition, inter-coder reliability procedures were conducted as part of the data analysis process (see Data analysis section).

3. Findings

To explore how participants' understanding of the engineering design process evolved throughout the engineering design–based STEM laboratory course, the selected laboratory sheet (representing group work) was analyzed sequentially across the five activities using the established coding book. The unit of analysis was the whole laboratory narrative for each activity. Participants' developmental trajectories across activities are mapped in Table 3 to visualize shifts, continuities, or regressions in their understanding. Following this trajectory mapping, *partially developed*, *developed*, *well-developed*, and *non-working-design* cases were examined in depth to identify qualitative differences in design reasoning and iterative thinking. Rather than aiming to demonstrate linear progression, the analysis focused on tracing patterns of change over time.

Table 3. Change in participants' engineering design understanding in each activity.

Participant (Pseudonym)	Activity number				
	Activity 1	Activity 2	Activity 3	Activity 4	Activity 5
Ali	Partially developed	Partially developed	Developed	Developed	Developed
Bahar	Developed	Developed	Well-developed	Developed	Developed
Canan	Developed	Developed	Developed	No working design*	Developed
Dilek	Partially developed	Partially developed	Partially developed	No working design*	Partially developed
Esra	Well-developed	Developed	No working design*	Well-developed	Developed
Fatih	Developed	Developed	Developed	No working design*	Partially developed
Gaye	Developed	Developed	No working design*	Well-developed	Developed
Hasan	Developed	Developed	No working design*	Developed	Well-developed
Inci	Partially developed	Developed	Developed	No working design	No working design*
Jale	Developed	Developed	No working design*	Developed	Developed

*The first round ended with no working design. The second iteration was concluded in working designs that were coded as *developed*.

3.1. Nonlinear development and contextual differences

Following the individual trajectory mapping presented in Table 3, a cross-case distribution of design quality levels across the five activities was examined (see Table 4). This distribution provides a class-level pattern that complements the individual narratives and allows the reader to situate the presented cases within the broader developmental landscape.

Table 4. Distribution of participants' design quality across activities.

	Underdeveloped	Partially developed	Developed	Well-developed
Activity 1	0	3	6	1
Activity 2	0	2	8	0
Activity 3	4	1	4	1
Activity 4	3	2	4	1
Activity 5	1	2	6	1

As shown in Table 4, the distribution of design levels indicates a gradual shift from partially developed toward developed and well-developed levels across activities. While partially developed designs were more common in the first activity, later activities showed an increase in developed and well-developed designs. Although Activities 3 and 4 initially included several non-working designs due to task complexity, these were revisited through subsequent iterations and later resulted in working designs coded as *developed*. This shift indicates the role of iterative engagement in supporting the improvement of design functionality.

Overall, the distribution does not suggest a linear shift from underdeveloped toward well-developed design solutions across activities. Instead, it reveals a fluctuating pattern in which development coexisted with moments of stagnation and regression. For instance, while Activities 1 and 2 were dominated by *developed* designs (6 and 8 cases, respectively), Activities 3 and 4 marked a noticeable increase in *underdeveloped* designs (n = 4 and n = 3, respectively), indicating that design performance was sensitive to task-specific demands rather than reflecting cumulative progression. However, these *underdeveloped* scores were replaced by *developed* designs after iterations. By Activity 5, *developed* designs again became the most frequent category (n = 6), suggesting recovery and adaptation rather than steady advancement. Importantly, *well-developed* designs remained relatively limited across all activities (n = 1 in most cases), reinforcing the interpretation that participants' engagement with iteration and optimization was still emerging. Taken together, this pattern supports the argument that participants' understanding of engineering design evolved in a nonlinear manner. Rather than demonstrating uniform improvement, the cohort exhibited episodic development shaped by task complexity and iterative engagement with failure and redesign. Overall, the findings indicate that development in engineering design understanding was nonlinear and context-dependent rather than cumulative.

3.2. Iterative thinking and redesign suggestions

Redesign attempts served as a key indicator of engineering understanding. Participants differed substantially in how they engaged in iteration. An analysis of participants' individual design iterations revealed varying levels of development across cases. There was no evident or systematic progression in participants' understanding of engineering design across the activities (i.e., from *underdeveloped* to *well-developed*). Nevertheless, several participants (e.g., Ali, Bahar, İnci, and Hasan) demonstrated noticeable enhancement in their engineering design skills over the course of the semester-long implementation. For example, in the initial activities (Activities 1 and 2), Ali did not offer any suggestions for redesign (e.g., "The design was effective, as the egg landed softly without breaking. Overall, the outcome met the design goals, and no modifications were deemed necessary", Activity 1). In subsequent activities, however, he began to propose minor yet meaningful modifications, which can be interpreted as evidence of development in this regard. Sample excerpts from Ali's laboratory sheets are provided below:

> "We couldn't stick the materials properly with packing tape. This caused heat loss in the hot water we put inside the box. Our design was successful in terms of the model, but not in terms of the adhesive we used. If I were to redesign it, I would change the adhesive, as I do not think it provided effective insulation. We covered the outside of the shoe box with rock wool and XPS. Because the adhesive was ineffective, we used Styrofoam on the inside of the shoe box. By improving the adhesive, I would attach the Styrofoam to the outside of the XPS to enhance insulation performance. (Ali, Activity 3)

> Actually, our design worked as planned. However, since the body we cut out of cardboard was too close to the ground, the car's wheels could not move properly. We completed the car's circuit system, but it was not functioning well in terms of movement. If I were to redesign it, I would modify the body structure, as its close contact with the wheels prevented the car from moving smoothly." (Ali, Activity 5)

Unlike Ali, Canan always provided redesign suggestions for her prototype in all activities. Sample excerpts from her reflective laboratory narratives are provided below:

> "Our design was successful in terms of meeting the specified criteria. Our goal was to see the opposite side through reflection by using mirrors, and we achieved this objective. The binoculars in our design were intended to have the shape of a rectangular prism; however, due to measurement errors we made, they acquired a slightly curved appearance and could have been smoother. This issue occurred because the cardboard from the shoe box we used was thick, which made it difficult to cut and assemble precisely. Consequently, distortions occurred, affecting the clarity of the image. In a redesign, I would definitely change the type of box we used. (Canan, activity 2)
> Our design provided thermal insulation. However, heat loss could have been measured more accurately. Additional materials could have been used: by using more insulation material, we could have reduced heat loss to near zero. If we were to do it again, I would use additional insulation materials alongside the materials we used. Because I would want to minimize heat loss." (Canan, activity 3)

Both Ali and Canan perceived their models as effective in achieving the intended purpose. Nevertheless, they proposed redesign suggestions, such as replacing the adhesive or incorporating additional insulation materials to reduce heat loss. These suggestions, however, reflected only minor refinements rather than substantial improvements to their initial designs.

3.3. Stability without iteration

Some participants (e.g., Dilek and Jale) consistently reported satisfaction with their initial prototypes and did not propose modifications across multiple activities. Their designs were generally categorized as either *partially developed* (as in Dilek's case) or *well-developed* (as in Jale's case) in most of the activities (four out of five activities completed). These reflections suggest a performance-based conception of design success—where meeting criteria was equated with design completion—rather than an iterative view of engineering as continual optimization. This pattern reflects limited engagement with refinement as an epistemic practice. As illustrated in Dilek's case, participants' reflections indicated satisfaction with their initial designs rather than a need for further refinement or modification. For instance, Dilek's responses across four activities, presented below, suggest that her group's prototype performed well and did not necessitate any revisions, including minor adjustments.

> "There was nothing missing from our design. I wouldn't change anything. (Activity 1)
> Our design was successful; we made a periscope at a low cost. (Activity 2)
> There was nothing missing from our design. Our design was successful. At the end of the given time, the water temperature dropped from 71 to 62 ℃. (Activity 3)

> Our design was successful. We designed a vehicle using minimal and economical materials. There were no shortcomings in our design because it performed very well.” (Activity 5)

3.4. Sketch–prototype alignment and design creation

Creating initial design sketches and subsequently using them to construct prototypes was considered an important component of the engineering design process. In several cases, sketches closely aligned with final prototypes, indicating coherent translation from conceptual representation to material construction. In other cases, sketches were revised during prototyping, demonstrating adaptive decision-making. For instance, Jale provided two initial sketches for her group’s design (Figure 3). In her initial sketches, she indicated the materials to be used and later decided, based on the group’s collective discussion, which design to construct.

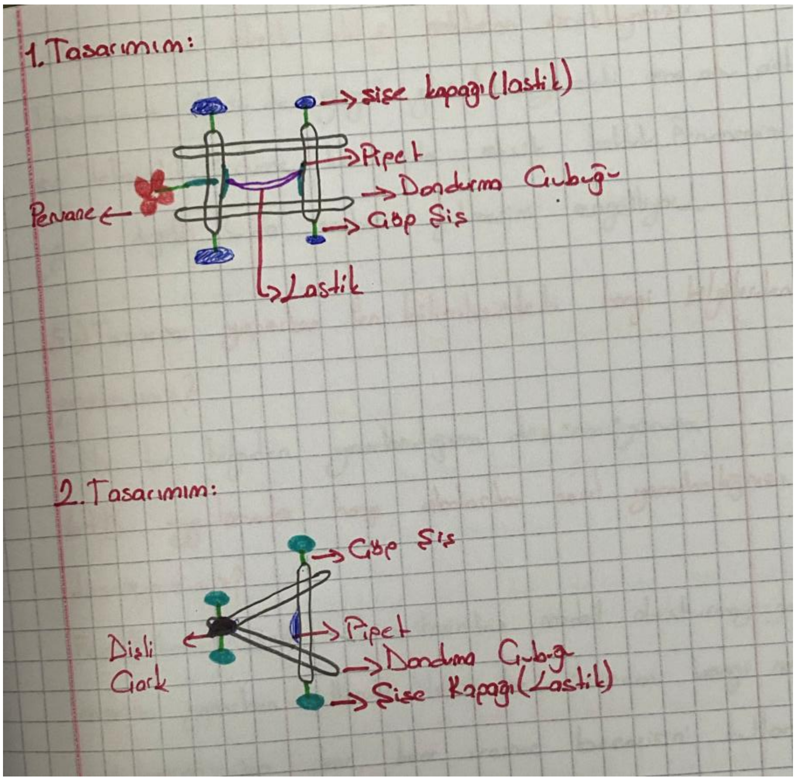

Figure 3. Jale’s two initial drawings in “Let’s do our car” (Activity 5).

In some cases, participants’ sketches closely mirrored their final prototypes, demonstrating a clear alignment between their initial ideas and implemented designs (see Figures 4 and 5).

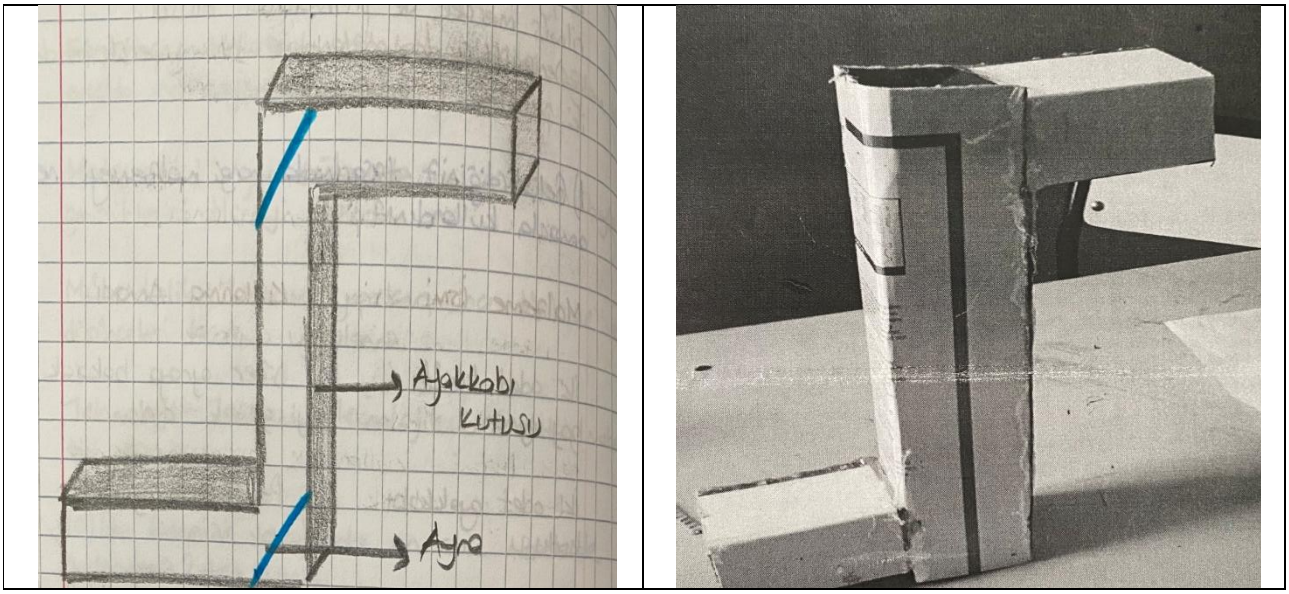

Figure 4. Gaye's sketch (left) and final product (right).

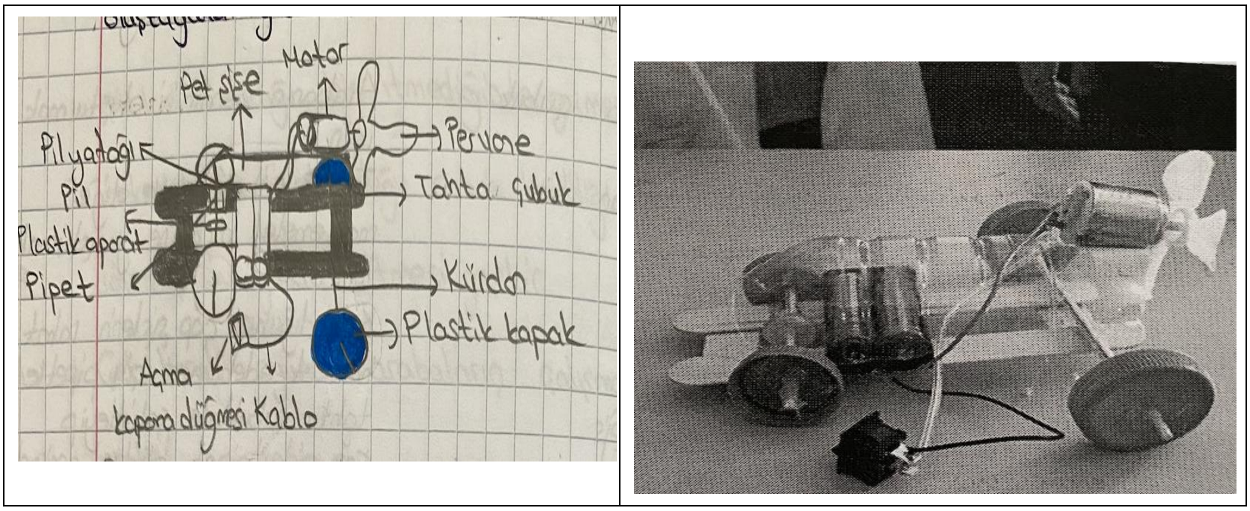

Figure 5. Bahar's sketch (left) and final product (right).

We also observed instances where participants revised their sketches during the prototype construction process (see Figure 6). These patterns suggest varying levels of engagement in pre-construction planning and iterative visualization, both central to engineering design epistemology.

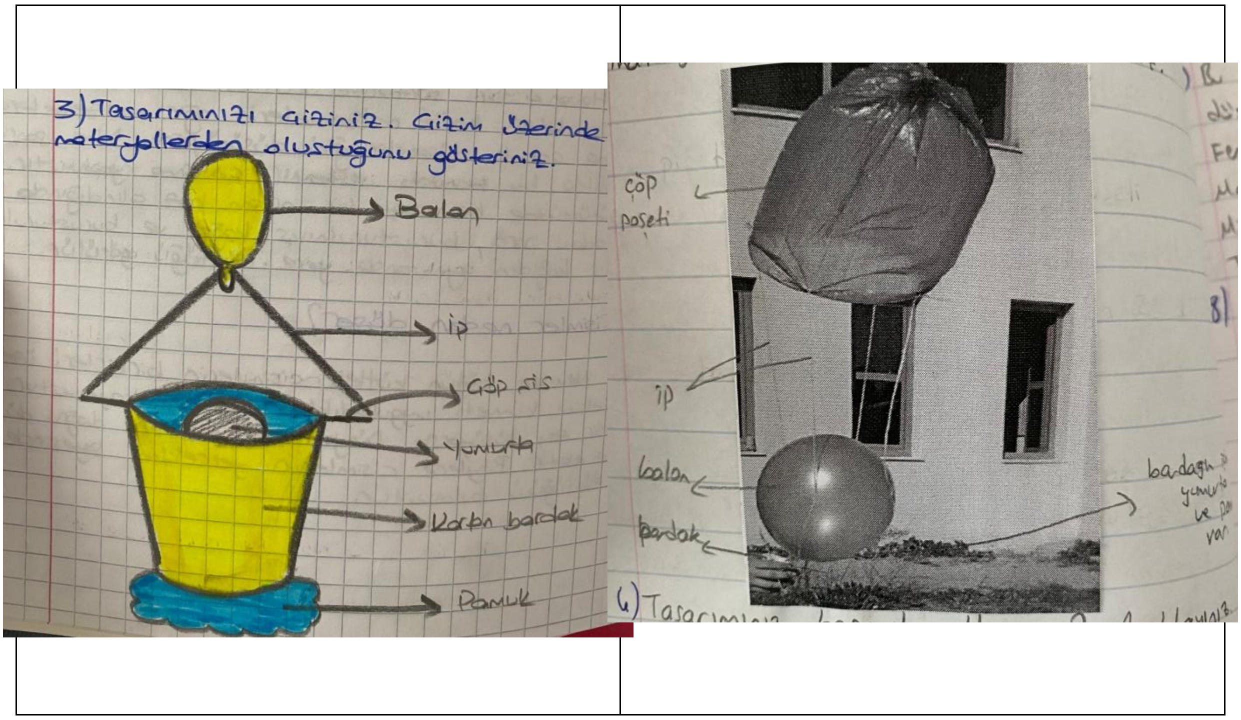

Figure 6. Dilek's sketch (left) and final product (right).

3.5. Iterative nature of engineering design

It is worth noting that Activity 4 required particular attention, as 4 out of 10 groups were unable to produce a functioning design by the end of the activity. The preservice teachers' reflections indicated that they were aware of and able to articulate the reasons why their designs did not work. For instance, Canan and Fatih's reflections below illustrate their understanding of the causes of failure:

> "My design was not successful. Our vacuum cleaner did not work. The propeller we used in the design was too big, so the motor may not have functioned properly. We had difficulty starting and selecting suitable materials." (Canan)
>
> "Our design was not successful. We failed for two reasons: first, we bent the propeller upside down. Second, we connected the current in reverse, so the motor was pushing the air instead of pulling it. That's why the vacuum was blowing instead of sucking in." (Fatih)

Moreover, Fatih proposed potential redesign improvements: "If I redesigned this again, first, we would position the fan blades more neatly on the body. Then, we would connect the current correctly, not in reverse."

These reflections suggest that participants were able to recognize the technical flaws in their designs and propose feasible corrective actions, demonstrating an emerging understanding of engineering reasoning and problem-solving within the design process. As the engineering design process continued until the students were able to create a working product, the groups returned their initial models to apply their suggestions to further revise their products.

3.6. Innovative approaches for redesign attempts

Lastly, we identified several design features that demonstrated innovative approaches, which were coded as *well-developed*, particularly in the use of alternative materials aimed at improving design performance. Sample excerpts are provided below:

> "If I redesigned the same model, I would inflate the balloons with helium gas instead of air. Because helium gas is much less dense than air, it would allow the egg to descend more slowly." (Esra, Activity 1)
> "Our design provided thermal insulation; however, we could have prevented heat loss more effectively. We could have used more suitable insulation materials (such as glass wool) to minimize heat loss." (Bahar, Activity 3)
> "I would change the material forming the broom's frame. I would choose a body design that makes it easier to place the fan and battery inside." (Esra, Activity 4)

These reflections illustrate participants' growing capacity to propose creative and material-based improvements to their prototypes, indicating an enhanced understanding of how design modifications can optimize functionality.

Redesign attempts play a crucial role in the engineering design process. While we expected the PPTs to select appropriate materials for their designs and construct prototypes using those materials, we also anticipated that they would engage in iterative improvements before arriving at a final product or prototype to be shared with the whole class. Hülya's excerpt below illustrates her group's earlier attempts to identify suitable materials:

> "Our first design was unsuccessful because we hadn't chosen the right materials. But when we made it again with different materials, our car worked. We struggled to understand why the car didn't work at first. If I *were* to redesign it, I would change the propeller, as it hit the pipette and prevented it from turning. That's why the car didn't work at our first try. I would choose a more suitable propeller."

This reflection demonstrates that participants recognized the importance of material selection and iterative testing in achieving a functional design, highlighting their developing understanding of the redesign process as an integral part of engineering practice.

4. Discussion

This study examined how preservice primary teachers' (PPTs) understanding of engineering design evolved throughout a 14-week compulsory engineering design–based STEM laboratory course. Rather than demonstrating a simple linear progression from novice to expert-like understanding, the findings reveal a more complex and context-sensitive developmental trajectory.

While several PPTs began to incorporate redesign suggestions over time, this development was neither uniform nor cumulative. Participants' engagement with iteration fluctuated across activities, suggesting that engineering design understanding is not automatically strengthened through repeated exposure alone. Instead, the epistemic demands of specific tasks appeared to shape the depth of iterative reasoning. These challenges implicit assumptions in parts of the literature that participation in design-based STEM environments naturally leads to increasingly sophisticated design thinking.

Even in these refinements, PPTs applied disciplinary knowledge, such as adjustments in measurement, characteristics of rectangular prism, angles, and thickness, with ideas from science (e.g., reflection of light, etc.). These examples indicate that, although the activities were framed as integrated or transdisciplinary STEM experiences, science remained the dominant discipline, while mathematics and technology were primarily used in supportive and instrumental ways during the design process. This asymmetry highlights a potential tension within integrated STEM implementation: exposure to engineering design does not necessarily guarantee balanced disciplinary integration. Instead, participants may revert to their strongest disciplinary identity—science—when engaging in complex design tasks. This finding extends previous work by illustrating how disciplinary dominance can persist even within explicitly integrated instructional contexts. Nevertheless, participants were able to draw on multiple disciplinary resources when engaging in engineering design tasks.

This finding is consistent with previous research demonstrating that students can apply disciplinary knowledge through engineering design processes [e.g., 8,22,27,28,33–35]. In the same vein, Donna [22] stated that engineering design activities can promote connections within and between STEM disciplines, and Kelly and Knowles [9] reported that students were able to construct new knowledge in science and mathematics disciplines through EDP. Findings from professional development studies with science teachers similarly suggest that engineering design can support disciplinary integration [28]. They reported that a professional development program was effective in supporting science teachers' integration of engineering design components. The need to support preservice teachers' engagement with engineering design through integrated STEM education has also been highlighted by Kuvac and Koc [41]. However, it should be noted that this study did not aim to explicitly assess how each STEM discipline contributed to the design process or the extent to which PPTs consciously recognized and articulated connections among disciplines beyond task completion. Evidence of interdisciplinary understanding was inferred from participants' design actions and reflections rather than from targeted assessment tools. This aligns with the primary qualitative focus of the study but also points to an important direction for future research.

This finding supports the initial aim of the study, which was to foster preservice teachers' engineering design skills prior to entering the profession. Early encounters with integrated STEM education and EDP are particularly important for developing future teachers' awareness of the role of engineering in STEM learning contexts. Indeed, Capobianco et al. [39] emphasized the importance of providing preservice teachers with explicit and early opportunities to develop and apply engineering design and design pedagogy. Such experiences may also promote deeper understanding of STEM education and yield to an increased motivation to implement integrated STEM instruction in future classrooms, as reported by Berisha and Vula [4].

There were several noteworthy cases in our findings. For instance, some PPTs did not show clear progression in their understanding of engineering design across the five activities. In these cases, participants stated that their models were "working as intended" and therefore did not require further redesign, suggesting that redesign was conceptualized primarily as fixing a problem rather than as an iterative process based on systematic evaluation and optimization. This tendency indicates that some participants initially understood engineering design as a technical revision process rather than as a cyclical and reflective design practice. This finding is consistent with previous research demonstrating that preservice teachers often experience difficulties in recognizing the iterative nature of engineering design, even after participating in STEM-related coursework. [e.g., 32,40,42]. Similar challenges have also been reported for in-service science teachers when integrating engineering into their instruction [32], highlighting a persistent and ongoing need for support in understanding the relationship between science and engineering.

Given that the participants in this study had no prior exposure to engineering design processes or integrated STEM education before this course, their focus on surface-level modifications can be interpreted as characteristic of novice engagement with engineering design rather than a lack of effort or interest. These findings underscore the importance of sustained and repeated encounters with integrated STEM education through EDP to support preservice teachers in developing a more sophisticated and iterative understanding of engineering design.

In several cases, participants' initial prototypes did not work. For instance, in Activity 4, several groups were unable to produce a functioning prototype in their initial attempt. In this activity, participants were able to identify the underlying reasons for their prototype's initial failure and subsequently revise their prototype based on these insights, resulting in functional prototypes. This is particularly noteworthy, as identifying and revising their prototypes is a crucial component of EDP. Indeed, design evaluation and redesign stages are especially significant because they require students to apply disciplinary knowledge from different disciplines, as highlighted by English and King [27]. Consistent with this, PPTs in our study were able to identify the reasons why their initial prototypes did not work properly by applying their knowledge in science and mathematics; then, they successfully produced functional designs during the redesign phase. Such interventions have been shown to be fruitful in enhancing both preservice teachers' [e.g., 40,41,43] and in-service teachers' [e.g., 28,32,33,36] understanding of engineering design pedagogy. Therefore, it is crucial to create opportunities for preservice teachers to engage in engineering design through integrated STEM activities. Preparing future teachers who are competent and confident in implementing integrated STEM education has been emphasized in previous research [4,56]; the findings of the present study reinforce this importance.

Sketches are important in EDP. Investigating PPTs' sketches showed that in some cases, participants were able to produce more than one sketch and choose one to construct their prototypes. Close examination of the PPTs' sketches showed that participants were able to draw annotated sketches that showed the materials to be used and then build the prototypes. This finding is in line with English and King [27], who indicated that most participants were able to design a plane based on their annotated sketches. In a similar manner, Sulaeman et al. [57] also found that Japanese students were able to enhance their design skills through EDP.

In some instances, participants provided design suggestions that were categorized as *well-developed*. In these cases, participants proposed creative and material-based improvements in order to optimize their prototypes' functionality, indicating an enhanced understanding of engineering design. This finding aligns with previous research [e.g., 2,39,44] that highlights the importance of introducing engineering design in teacher education programs. While earlier research has shown preservice teachers' limited exposure to engineering during teacher education programs [e.g., 38], recent efforts have increasingly aimed to integrate engineering design concepts into the teacher education curricula [e.g., 40,44,52]. Moreover, current research continues to call for a greater inclusion of engineering within undergraduate teacher education programs [e.g., 2,8,13]. Capobianco et al. [39] further argued that incorporating engineering design earlier and more explicitly in teacher education programs represents a powerful way to prepare future teachers to integrate engineering design pedagogy within integrated STEM teaching practices.

4.1. Limitations and implications for further research

In this study, we aimed to develop preservice primary teachers' engineering design skills through a semester-long engineering design–based STEM laboratory course. The results indicated improvement in PPTs' understanding of engineering design, although there remains room for further development. First, the intervention lasted for 14 weeks (one semester). Future research should consider a longer implementation period, as Capobianco et al. [39] highlighted the importance of embedding engineering design throughout teacher education rather than within a single semester.

Second, although 200 laboratory sheets were collected, the analysis was conducted on one representative reflective narrative from each group for each activity. While this strategy enabled an in-depth qualitative examination of group-level design reasoning, it may have limited the visibility of individual differences within groups. Including multiple group members' reflections in future studies could provide a more comprehensive understanding of group interactions and meaning-making processes. In addition, the study relied primarily on retrospective written reflections, which may be subject to recall bias or socially desirable responses. The absence of triangulation through observations, interviews, or process-based artifact analysis constitutes another limitation. Therefore, the findings should be interpreted as context-bound insights into participants' evolving reflections on the engineering design process rather than as definitive evidence of measurable skill development.

Third, reflective narratives were used as the sole data source in this study. Although narratives are a powerful tool for capturing participants' experiences, collecting them solely in written form might provide limited insights into their actual development. Therefore, future research could benefit from employing more diverse data collection methods, such as classroom observations or focus-group interviews with group members. Moreover, further research could adopt mixed-methods or design-based research approaches to triangulate qualitative insights with quantitative measures of design thinking, problem-solving, or STEM integration efficacy. Such approaches would allow researchers to examine not only how preservice teachers experience engineering design–based learning but also the magnitude and patterns of change across larger samples.

One limitation of this study is that, although rubric-based evaluations of the developed products were included, these data were used descriptively and were not subjected to statistical analysis. Consequently, the study does not provide quantitative evidence of preservice teachers' learning outcomes or allow for comparisons across participants or activities. Future research may address this limitation by adopting mixed-methods designs that integrate systematically analyzed rubric scores and additional quantitative measures alongside qualitative analyses.

A further limitation of this study is that the depth and quality of the participants' redesign processes were not systematically evaluated. While participants engaged in multiple design cycles, many focused on surface-level or technical modifications, and the study did not include specific assessment tools to examine whether redesign decisions were grounded in systematic evaluation or conceptual rethinking. Future research may address this limitation by incorporating analytic rubrics, design journals, or mixed-methods approaches to more closely examine the development of iterative engineering design thinking.

Another limitation of this study concerns the author's role as a researcher–practitioner. While this dual role enabled prolonged engagement, pedagogical sensitivity, and a nuanced understanding of the instructional context, it may also have introduced potential bias related to the influence of the researcher's perspectives and positionality [51]. Further research could adopt different data collection tools to triangulate the results. One last limitation of this study is that the instructional process was guided by an engineering design model rather than a comprehensive instructional design framework. Although this approach aligns with the nature of engineering design–based learning, future research may benefit from integrating instructional design models and formal expert reviews to enhance the robustness and transferability of the instructional design. Further studies should employ longitudinal and mixed-methods designs to explore how preservice teachers' understanding of engineering design develops over time and transfers into classroom practice. Such research would strengthen theoretical and empirical insights into engineering design–based STEM teacher education. Despite these limitations, this study represents one of the first attempts to integrate engineering design–based STEM education into primary teacher education programs, whereas most previous studies have been conducted either with science, technology, or chemistry teachers.

Use of Generative-AI tools declaration

The author declares she have used Artificial Intelligence (AI) tools in the creation of Figure 1 and 2. Napkin.ai tool was used to create both Figures. The author prepared and approved the content of figures.

As the author is not native speaker of English, Gen-AI (Chat GPT) was used for assistive reasons (e.g., to improve the clarity, grammar, and academic tone). All the ideas belong solely to the author. The author reviewed, edited, and approved all the content to ensure accuracy and intellectual integrity.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Ethics declaration

This study gathered approval from the relevant university's administrative boards. The research adhered Declaration of Helsinki with no deception or harm to the human participants by fully informing them about the content of the study. The participants voluntarily participated in the study. Participants were informed about the content of the research and each participant signed an informed consent form which acknowledged them about the structure of the study.

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Author’s biography

Dr. Umran Betul Cebesoy is an Associate Professor of Science Education at Usak University, Türkiye. She specializes in socioscientific issues, decision-making in complex controversial issues, and engineering design-based STEM education. Her research interests mainly focus on how preservice teachers make decisions regarding socioscientific issues and on engineering design-based STEM laboratory applications.