Education and Information Technologies
https://doi.org/10.1007/s10639-024-12489-2

Failure analysis and continual improvement in the engineering design process: Teacher roles in children's problem-solving processes

Ahmet Erol[1]

Received: 9 February 2023 / Accepted: 16 January 2024

Abstract

STEM education, which means integrated thinking, attracts the attention of early childhood educators and researchers. Engineering education, which naturally serves STEM integration, contributes to children's problem-solving skills with failure analysis and continual improvement habits of mind. Children need adult support in this process due to their developmental characteristics. This study focuses on the roles of teachers in situations where children fail to solve the problems they encounter in the engineering design process. In this direction, the research was carried out with a case study. The participants were 17 preschool teachers working in southwestern Turkey and 255 children in their classes. The data for the study were collected through observation and a semi-structured interview protocol. The data were analyzed by content analysis. According to the results, teachers facilitated failure analysis and continual improvement processes in the problems faced by children by encouraging them to rethink the problem, encouraging them to persist, and inviting communication and cooperation with friends. The findings highlight teacher encouragement as important in children's failure analysis and continual improvement processes.

Keywords Early childhood · Teachers' roles · Failure analysis · Continual improvement · Problem-solving

✉ Ahmet Erol
ahmete@pau.edu.tr

[1] Department of Preschool Education Program, Pamukkale University, Denizli, Turkey

Published online: 23 January 2024

1 Introduction

With the beginning of the twenty-first century, the world is transforming fields such as education, trade, economy, technology, and social structure. Increasing globalization with scientific innovations, labor demands, and economic competition in new fields pushes the competencies and skills expected from individuals into question (Wilmarth, 2010). At this point, two skill sets that continue to attract the attention of researchers in the literature are highlighted: 21st-century and life skills (Kennedy & Odell, 2014; Papacharisis et al., 2005; Wagner, 2008). 21st-century skills refer to the skills an individual needs to cope with difficulties and contribute to the progress and development of society (Kennedy & Odell, 2014; Lai & Viering, 2012). Wagner (2008) stated that 21st-century skills such as critical thinking, cooperation, problem-solving, leadership, adapting to the environment, entrepreneurship, taking initiative, effective oral and written communication, analyzing information, curiosity, and imagination are essential.

Life skills are another set of skills as crucial as 21st-century skills. Life skills are the ability to function under pressure, solve problems, set goals, communicate, cope with success and failure, work in a group, and receive feedback (Pacharisis et al., 2005). Life skills are adaptive and positive behaviors that enable individuals to deal effectively with the demands and challenges of daily life. UNESCO (2008) defines life skills as "psycho-social skills that can be learned and applied, such as self-awareness, problem-solving, critical thinking, and interpersonal skills." Life skills are competencies that facilitate an individual's physical, mental, and emotional well-being.

Problem-solving is considered within the scope of both 21st-century skills and life skills (UNESCO, 2008; Wagner, 2008). This skill refers to individuals' mental, emotional, and behavioral ability to adapt to daily changes (Shewchuk et al., 2000). Problem-solving skills help people constructively solve problems in their daily lives. This process has a dynamic structure, and solving one problem can often lead to another problem. Therefore, patience and persistence are essential in the problem-solving process. In this context, adults will encourage children to be patient and persistent. Due to their developmental characteristics, children need professional adults to master problem-solving processes (The Early Childhood STEM Working Group, 2017). As educational professionals, teachers are essential components of this process.

Teachers play a crucial role in helping children overcome obstacles they encounter in problem-solving (Brenneman et al., 2019). Their guidance and support help children develop problem-solving skills and enable them to cope with the challenges they will face in the future (Zan, 2016). At this point, learning environments need to be organized to support problem-solving to support children's problem-solving skills. Engineering design-based activities attract attention by offering problem-solving opportunities to children (Lange et al., 2019; Lippard et al., 2019). When children fail in the design process, they can solve problems by trying to design, test, and improve. In this process, they use error analysis and continual improvement methods.

1.1 Engineering design process (EDP)

People must develop tools, machines, materials, and processes to solve problems (Bers et al., 2013). Engineers collaborate to solve a problem that people need (Lange et al., 2019) and define their work as "designing within limitations" (Cunningham, 2018; Cunningham & Hester, 2007). Engineering design is the planning, organization, development, testing, production, and operation of products that fulfill a desired function within the specified criteria and constraints through scientific and mathematical principles (Lange et al., 2019). Due to the rise of STEM education in early childhood education, in recent years, researchers have focused on integrating engineering into preschool classrooms and supporting children's engineering habits of mind (EHoM) (Bagiati & Evangelou, 2015; Lippard et al., 2018; Van Meeteren & Zan, 2010).

Children encounter problem-solving and engineering design in their daily activities and use their innate thinking methods in their engineering design experiences (Moore et al., 2018). They naturally change their environment in line with their curiosity and motivation to explore. These changes form the basis of engineering thinking. From an early age, they bring objects together to solve their problems, establish relationships, examine what they combine, and explore by taking them apart again (Cunningham, 2018; Lange et al., 2019; Lippard et al., 2019). In this process, they experience spaces, shapes, dimensions, and gravity (Texley & Ruud, 2018) and find opportunities to collaborate and communicate (Stone-MacDonald et al., 2015; Isabelle et al., 2021). This natural process helps children develop early engineering thinking, problem-solving, and creative thinking skills.

Regarding learning, engineering practices refer to the iterative design process cycle that can be used with children (NRC, 2012). The EDP, which helps children's problem-solving processes, is a concept we hear frequently in the context of STEM education. This process encourages children to solve problems and continuously improve their designs (Lippard et al., 2018; Portsmore & Milto, 2018). In this process, children solve problems using their EHoM (Katehi et al., 2009). There are many different models of the EDP. However, they all share specific components: defining a problem, brainstorming possible solutions, designing and creating a solution, testing and evaluating, developing the design, and sharing results (Zan, 2016).

The engineering design cycle for children usually begins with "problem identification" and continues exploring that problem. Next, the children "imagine" the solution to this problem and brainstorm the solution. In the third step, they "plan" possible solutions to the problem. In this process, children follow their plans and test their solutions in order to choose the appropriate solution to the problem. In the final stage, children analyze what aspects of their design they can improve and redesign as necessary. The process continues until the design is successful (Bustamante et al., 2018). Children use two fundamental concepts in this process: failure analysis and continual improvement.

1.2 Failure analysis and continual improvement: Habits of minds

Failure analysis and continual improvement are essential parts of the EDP. Children reflect on these skills while using their EHoM. EHoM is reflected in children's design processes and games. Of these habits, optimism is related to children's perseverance and self-motivation. It is about continuing to try even if you fail the first time. It reflects a worldview where possibilities and opportunities can be found in every challenge (Lippard et al., 2018; NAE & NRC, 2009). Collaboration can increase children's understanding of various tasks and support learning from multiple perspectives. Communication is a fundamental skill for problem-solving, learning, and academic success. Expressing what he thinks while learning is a way for teachers to assess children's understanding and integration of new information. Children benefit from these habits in the failure analysis and continual improvement processes they follow while solving problems.

Failure is generally an undesirable event or situation (Shipley et al., 2022). On the other hand, failure analysis is a systematic and critical process for determining the physical root causes of problems. The process is complex, draws on many different technical disciplines, and includes a variety of observational and review techniques (Shipley et al., 2022). One of the critical factors in adequately performing failure analysis is to develop a clear and unbiased view of failure, keep an open mind, and collaborate with experts in other disciplines when examining and analyzing evidence. Correctly performed failure analysis is a critical step in the problem-solving process. It is the key ingredient for correcting and preventing errors, achieving higher levels of quality and reliability, and ultimately increasing customer satisfaction (Shipley et al., 2022; Scutti & McBrine, 2002). Children encounter failure analysis in their daily lives while busy with something. They try to find solutions to these problems by engaging in a series of cognitive activities.

Failure in the EDP refers to failing to meet the specified criteria and constraints (Shipley et al., 2022). Constraints and criteria are determined before the EDP, and whether the design is successful is evaluated by meeting these criteria. Children who cannot achieve these expectations look for solutions by performing failure analysis, a mental activity. In this process, they engage in continual improvement activities to improve their designs according to the determined expectations. Continual improvement is an iterative process to increase the ability to meet the requirements needed for the design. Continual improvement processes are very similar to problem-solving activities. The main difference is that improvement activities are planned and usually organized as part of a more extensive program; problem-solving occurs more frequently and unplanned (Plura, 2000). Henry Petroski states: "It is an apparent paradox in science and engineering that more is learned from failures than from successes." Failure is an inherent element of engineering design because children will inevitably experience moments of design failure when solving open-ended problems, developing prototypes, and designing solutions.

Naturally, children get many opportunities for continual improvement during the EDP. In this process, if children's optimistic habits of mind are supported, they can succeed in continual improvement. At this point, children need teachers who support their EHoM. These teachers can help children positively evaluate their failures while encouraging them to continually work on development and improvement in their design processes. These skills increase children's problem-solving abilities but also support them in coping with the challenges they will encounter throughout their lives. These processes provide children with valuable skills they can use throughout their lives and encourage continuous learning and development.

1.3 Teachers ' facilitator role in thinking processes

In an EDP, children ask questions but can quickly abandon them when they cannot find the answers. They may give up when their solutions fail the first time. Since optimism and persistence are essential in engineering education, teachers must motivate children and support their attendance (Dorie & Cardella, 2014; Jones & Gearns, 2016). At another point, there is a need for teachers who encourage the use of failure analysis and continual improvement cycles when children encounter problems in the design process. Teachers help children identify a problem they can solve and expand children's curiosity, interest, and thinking by encouraging them to think about the problem and persist even when their design fails. In addition, the language teachers use and the experiences they provide encourage children to think, calculate, and design like scientists, mathematicians, and engineers (The Early Childhood STEM Working Group, 2017).

Although EHoM is a natural inclination in children, they need adult help when demonstrating failure analysis and continual improvement skills. When teachers encourage problem-solving in children and ask open-ended questions for reflection, they provide opportunities for assumption and prediction and support children's skills to succeed in school and life (Jones & Gearns, 2016). This support is an essential context for failure analysis and continual improvement, called "habit of mind." At another point, teachers can provide children with learning opportunities through engineering concepts and skills, and they can help children get to know engineers and develop positive attitudes toward it as a career field (Dorie & Cardella, 2014; Gunning et al., 2016).

1.4 Current study

Scientists and engineers widely use failure analysis and continual improvement when solving problems (Shipley et al., 2022). These terms can often seem foreign to children. However, it has been observed that children exhibit these habits when observed in play, activities, or design processes (Lippard et al., 2019; Van Meeteren, 2018). Especially in EDP, children may encounter many failures when creating their designs. Although they usually try to solve the problems they encounter independently, they need the guidance of teachers who encourage them to think. Teachers support children's discovery and learning by providing rich, high-quality learning environments (Ruzzi et al., 2017). By encouraging children to see failure as a learning opportunity, teachers can improve their problem-solving, critical thinking, and creativity (Moore et al., 2018; Isabelle et al., 2021). They can also increase children's confidence and motivation for their designs. Teachers' facilitating roles in children's problem-solving processes and the strategies they use in this process can help children use the failure analysis and continual improvement process more efficiently and effectively (Gunning et al., 2016). A study emphasized that teachers use the EDP to provide children with problem-solving skills and support the development of EHoM (John et al., 2018). However, many teachers still give less space to engineering and mathematics in their programs (Monkeviciene et al., 2020). In this respect, it is meaningful that this study focuses on teachers.

At another point, teachers who support children's EHoM in early EDP serve to develop their problem-solving skills (Kewalramani et al., 2020; Lippard et al., 2019). These habits of mind serve the cycle of failure analysis and continual improvement and significantly impact the design's success. Children begin to develop EHoM using failure analysis and continual improvement processes for their problems. These skills help children develop their abilities to cope with difficulties, think analytically, and find alternative solutions (Moore et al., 2018; Stone-MacDonald, 2015). As planners of the learning process, teachers play an essential role in planning and implementing a developmentally effective engineering process (Soylu, 2016). In this context, it will be essential to examine the strategies used by teachers who will support children in problem-solving, failure analysis, and continual improvement. Therefore, this study focuses on the facilitating roles of teachers in the failure analysis and continual improvement processes that children apply while solving the problems they encounter in early EDP.

2 Methods

2.1 Research design

This research was conducted in the tradition of the qualitative case study. A case study is an in-depth description and examination of a limited system (Merriam, 2009; Patton, 1990). According to Yin (1993), a qualitative case study is suitable to cover the contextual conditions of the phenomenon under study. This study examined the failure analysis and continual improvement habits of mind that children use while solving problems in the EDP in the context of teachers' facilitator roles.

2.2 Participants and research context

In this study, participants were determined by the criterion sampling method, one of the purposeful sampling types. According to Patton (1990), critical situations can be a source for criterion sampling because they are rich in information. In this study, the critical situation consists of teachers who apply the EDP, observe the children during the activity, and support them in the problem-solving processes they encounter. Agreeing to participate in professional development (PD) in early engineering education and integrating their practice with children in early engineering education were accepted as criteria for participation in the research. After explaining the purpose and process of the research, 17 early childhood teachers voluntarily participated in the study. The participants work in a public preschool in a province in southwestern Turkey. Descriptive data about the participants is explained in Table 1.

Table 1 Teachers and Children Distribution of Demographic Information

	Demographic Variables		F	%
Teachers	Gender	Female	17	100
		Male	0	0
	Age	20–24 years old	8	47.06
		25–29 years old	3	17.65
		30–34 years old	4	23.53
		35–39 years old	2	11.75
	Professional Experience	1–5 years	9	52.94
		6–10 years	5	29.41
		11–15 years	3	17.65
Children	Gender	Girl	132	51.77
		Boy	123	48.23
	Age	6-year-olds	87	34.12
		5-year-olds	115	45.10
		4-year-olds	53	20.78
	Number of years in early childhood institutions	First year in preschool	193	75.67
		Second year and above in preschool	62	24.33

As seen in Table 1, all the participants were women. Participants are predominantly between 20 and 24 ($N=8$). Most participants have 1–5 years of professional experience ($N=9$). In addition, an average of 15 children are in the participants' classrooms. Three teachers have 16 children in their classroom, five have 15 children, seven have 17 children, and two have 13 children. The participating children comprised 132 girls and 123 boys aged between 4 and 6 years. The majority of children (45.10%) are in the 5-year-old group. Two hundred nine participating children attend a half-day preschool, and 46 follow a full-time preschool. None of the children received special education or mainstreaming. All of the children came from families where their parents lived together.

2.3 Professional development

The teachers in this study also participated in the early engineering education Professional Development (PD) process. One reason was that the purpose of the study was to focus on the context of failure analysis and continual improvement in the EDP. However, in the region selected, no teacher applied engineering education to early childhood. Within the framework of this need, a PD process was first planned. The PD process took five days. The PD process is as follows:

1. *Presentations and discussions.* PowerPoint presentations included conceptual information such as the EDP, models, and application examples. In this regard, four presentations were made to teachers. A small group and extensive group discussions followed each presentation. Discussions about early engineering education were planned during and after the presentation process. A sample discussion was as follows: Based on what we discussed today, think about your practice

with children; how is it similar and different? The presentations aimed to inform teachers about early EDP and prepare them for workshops. The presentations lasted four days.

2. *Workshops*. Workshops are planned to deepen and discuss the information conveyed through presentations. Implementation of the workshops with teachers lasted three days. Three workshops were prepared for teachers' PD processes. Each workshop focused on integrating the EDP into early childhood classrooms. The first workshop was for introducing early engineering design models and examining sample activities; the second workshop evaluated the process and asked practical questions during the design process; and the third workshop was for teachers to create original engineering design activities. The researcher prepared the workshops. For example, the content of the first workshop was as follows: to start the design process (engineering education with children's picture books), activities were aimed at starting the story, reading stories, writing scenarios for engineering education, and developing STEM vocabulary in children.

   In the third workshop, each participant worked individually to create an EDP activity for their class, considering three steps: (1) plan, (2) implement, and (3) evaluate. The activities were prepared in the EDP specified by Stone-McDonald (2015): think about it, try it, fix it, and share it. Additionally, teachers prepared an analytical rubric to evaluate the EDP. These activities also formed action plans that teachers would implement in their classrooms. Participants set goals for themselves and identified the adjustments and changes needed in their classrooms and practices with children. They designed an event in this context. The findings of this study include the fact that teachers facilitate children's problem-solving processes during the implementation of activity plans. Teachers prepared an activity and implemented it with children for two weeks.

3. *Evaluation*. The evaluation was made after presentations and workshops. For this purpose, evaluation forms, analytical rubrics, and reflective diaries were used. Participants provided feedback on the PD process using the evaluation form. The researcher evaluated the teachers' learning processes through an analytical rubric. These evaluations were related to the PD process and were not the study's primary purpose. Therefore, the data obtained from these evaluations were not included in the findings of this study.

2.4 Data collection

The teachers who participated in the PD process implemented the activities they prepared during the process with the children. In this study, data were collected during engineering design activities with children. Observation and interviews were used to collect data by qualitative research designs (Merriam, 2009).

2.4.1 Observation protocol (OP)

The observation protocol developed by Lippard et al. (2019) was used to examine the engineering mindset exhibited by children during activities. OP is an observation measure that captures behaviors that indicate the engineering habits of the mind in early childhood classrooms. OP includes various items such as the EHoM exhibited by children, the area in which they play, and the roles of teachers. The researcher made a Turkish adaptation of the OP. In this process, opinions were obtained from three experts fluent in English and Turkish to ensure language validity. In addition, the opinions of two early childhood experts were received during the adaptation process of the form. After the observation protocol was finalized, the children in the classes of three teachers who implemented STEM education in their classrooms were observed, and the observation protocol was filled out. Following the implementation, the OP was finalized.

The observation for this study was carried out by 17 preschool teacher candidates who received training on OP. There was an observer in each teacher's classroom. Observers attended a four-hour training session on the observation protocol provided by the researcher. Within the scope of the pilot study, each observer observed the children during the free-play process and filled out the protocol. At the end of the observation, the researcher and the observers came together and discussed the application. These discussions were about how observers would transfer similar situations they would encounter during the actual implementation process into the protocol. Following the pilot study, observers observed the teachers' implementation of the EDP. Observers recorded the children's behavior during the engineering education process. Teacher candidates transcribed the children's statements verbatim into the protocol. At the end of the application process, 17 observation notes were taken by 17 teacher candidates.

2.4.2 Semi-structured interview protocol (SSIP)

Semi-structured interviews were conducted with the teachers participating in the study. Expert opinion was consulted during the preparation of the interview protocol. The experts comprised three researchers in early childhood education and two teachers. The form was given its final shape with the recommendations of experts. In addition, a pilot interview was held with a teacher not included in the study group to clarify the questions. As a result of the pilot interview, the observation protocol for the actual application was re-examined. The researcher conducted interviews with teachers in two stages on two different days. The first stage interview was held before the teachers implemented the EDP activities they designed. During this process, the interviews with the teachers focused on how they would react to children who had problems during the design process and their expectations from the process. The first stage interview was conducted individually with the teachers for approximately 14–16 min. The second stage interview took place at the end of the teachers' practices. First, teachers chatted about their children's difficulties in this process. The interviews lasted 17–28 min and were held in the schools where the teachers worked. Sample questions: How do you react if children fail during the activity? Have you observed that children display patience and optimism in the failures they encounter during a design process? Can you tell us about it? How do you motivate children who experience failure to solve the problem? Can you tell us a memory of your support for children in problem-solving? Interviews were conducted individually with teachers.

2.5 Data analysis

The data obtained in this study were analyzed using the content analysis method. Content analysis is expressed as a dimension such as screening qualitative texts in line with repetitive words and themes and reducing and interpreting qualitative data to determine their essential consistency and meaning by taking the voluminous qualitative material (Patton, 1990). In line with the content analysis, all the data was read and monitored, and this process was applied repeatedly. In the second stage, the data were coded, and the themes were reached by associating the codes related to each other (Merriam, 2009). In this context, the data analysis was carried out in four stages. In the first stage, the researcher repeatedly read each participant's interview transcripts and observation notes. In the second stage, an independent researcher was asked to code the transcripts and observation notes. In the third stage, the differences were reviewed by comparing their codes and categories. The emerging themes were identified in the final stage, and consensus was reached with the independent coder. Independent coders and researchers also selected representative quotes and identified categories within themes (Seidman, 2006). In the data collected from the interviews and observations, the teachers were coded as "T1, T2, T3, …. T17," and their observation notes were coded as "O1, O2, O3, …. O17." For the transferability of the study findings, rich and detailed descriptions were created, and participant quotations were provided. Besides word processors, no other software was used in the qualitative analysis.

2.6 Trustworthiness

Attention was paid to points showing the validity of credibility, such as ensuring participant control over the findings, making observations throughout the research process, the researcher's statement of bias, spending time with the participants in their environment for a certain period, and checking the research data by a different researcher (consensus). Expert opinion was sought for the semi-structured interview protocol used in the study. The transferability of the study findings to different situations was checked. The study's coding and themes were cross-checked with an independent researcher during the analysis process. The findings were handled with rich and detailed descriptions and supported with examples. At this point, the themes obtained were evaluated and discussed within the literature framework. Information about the determination of the focus of the study, the environment in which the research was carried out, and the participants were given.

2.7 The role of the researcher and ethical considerations

The researcher has published articles on engineering education in early childhood. In addition, the author wrote her doctoral dissertation on the STEM PD of early childhood teachers. Therefore, it is meaningful to do this work. In this study, the researchers were directly involved in the data collection process and data analysis and acted as a tool (Creswell, 2008). During the data collection process, the researchers took care to be as objective as possible, not judging the behaviors and words of the participants and not creating expectations in them. Before beginning the study, the ethics committee's approval was obtained. Afterward, both written and verbal approvals were obtained from the administrator of the institution to be researched and the participating teachers. It was shared with the families that they could withdraw from the research if they encountered applications other than those specified in the data collection tools, the contents of the educational activities, and the research process. The results of the research were shared with the teachers. In the study, legal permissions were obtained within the framework of ethical principles, the participants were selected from among volunteers, their identities were kept confidential, and questions that would put the individual in trouble were avoided.

3 Findings

The teachers guided the children to overcome the challenges during the EDP. The encouragement of the teachers made it easier for the children to look at problems from different perspectives and solve them. Teachers seem to assist children in failure analysis and continual improvement, taking on three key roles: (1) encouragement to rethink the problem; (2) encouragement of patience and persistence; (3) an invitation to communication and collaboration.

3.1 Encouragement to rethink the problem

Teachers emphasized that when children experience failure in their designs, they try many ways to motivate them to solve problems. According to teachers, these ways encouraged children to think about the problem again and try the solutions they produced. Additionally, teachers asked the children to share the solutions they found. According to teachers, the sharing process led children to make new experiments, think, and find creative solutions. T4 emphasized her thoughts on this issue as follows:

> I tell the child to think so that he can notice the part of his work that has failed. I want him to consider the reasons for the failure and share the solutions he discovered. As children come up with ideas, they are very willing to experiment (T4).

The teachers first observed the children to understand the problem they were experiencing: *I did observe to understand where the child had problems* (T3). *If a child has* *a problem, I watch what they do first* (T17). Another purpose of the observations was to understand the feelings and emotions of the children: *I try to understand the feelings and emotions of the child by observing* (T3). Teachers seem to use two strategies to motivate children to think about the problem: (1) using protective questions and (2) organizing the learning environment.

3.1.1 Using protective questions

According to the analysis of interview transcripts, teachers used questioning in two ways: (1) to encourage children to rethink the problem and (2) to encourage persistence and optimism. After the observation, teachers encouraged children to think about the problem by asking protective questions. At this point, teachers' approaches to motivating children with their questions and encouraging them to try alternative ways also attract attention. Teachers said they tried to activate children's thought processes by asking them open-ended questions such as "*What are you planning to do?* (T3)." For example, as seen in T4's statement, teachers tried to help children learn from their mistakes and keep trying without giving up, with questions: "*Where did we make a mistake? How can we fix it?*". Such questions helped children develop their ability to cope with failure while increasing their self-confidence. E.g.

> Where did we go wrong? With questions such as how we can fix it, I ensure that children do not give up in the face of failure and do not give up trying (T4).
> By asking open-ended questions, I make the child realize where his failure stems from. I encourage the child to try different and alternative ways by increasing his motivation (T1).
> I support children's awareness by asking questions and chatting with them about their reasons (T3).
> I try to give a new perspective to the problem by asking questions. Then I encourage him to try the new solution he finds (T8).

As seen in the statements above, teachers frequently use open-ended questions to make it easier for children to solve problems. These questions seem to activate children's thinking processes. T15 emphasized: *"I say to the child, "What can you do differently?" and the child immediately begins to come up with ideas to achieve design success." I think asking questions creates a movement.*

3.1.2 Organizing the learning environment

At another point, teachers stated that they prepared an environment for failure analysis and continual improvement by restructuring the learning process and learning centers to serve children and solve problems. According to the teachers, organizing the learning environment strengthened the children's failure analysis and continual improvement habits: *When I see children who have too many problems, I immediately organize the learning center; the children are positively affected by this change, and they are more willing* (T14). At this point, the clues and materials placed by the teachers in the learning center encouraged the children to solve problems. T1 and T3 emphasized this situation as follows:

> I support the learning environment or learning process by rearranging it according to the child's interests and skills. Thus, the materials and clues that children can use when they encounter a problem guide them (T1).
> When children have difficulties solving a problem, I organize the learning center and put new materials there; these are the materials that they can use to solve the problem, and they also give clues to the children (T13).

3.2 Encourage patience and persistence

When teachers realize that they are failing in the design process, they seem to make it easier for them to solve the problem by encouraging them to persist. Teachers stated that they observed that children can give up immediately in the face of difficulties: "*I have observed that children often have difficulties with patience and give up quickly*" (T1). Some teachers emphasized individual differences.

> While some children leave the activity without completing it, others persistently want to continue (T5).
> Some of the children show optimism, some cannot, they leave the activity because it did not happen (T3).

Teachers encouraged children to be patient and persistent, helping them reflect on their failures. These roles of teachers were reflected in the children's failure analysis and continual improvement habits. E.g.

> I give him the opportunity to try, saying that sometimes attempts may fail, but we can fix it by working on it. By encouraging patience and persistence, I motivate children to succeed in their designs. These conversations allow children to insist on problem-solving (T5).
> I support the "failure is an opportunity for us to achieve better results" mentality in children. I activate their motivation to work tirelessly in the face of failure. I can see that children analyze the failed parts of their designs and make efforts to improve them (T8).

As a result of the teacher's encouragement, the insistence of the children in solving the problems was also reflected in the observation notes: *I do not want to move on to the next activity before my teacher completes it* (O7). At some point, the children asked the teachers for help: *"My teacher, can you help me?"* (O9). After the encouragement of the teacher, the child's insistence on the design was observed as follows:

> The child was designing a package for the rabbit. However, he could not make a package that could carry enough weight, so the teacher asked him to think about

> the materials he used. He said he could have done things differently. After that, the child tried to improve the design using different materials (O13).

3.3 Invitation to communication and collaboration

Teachers seem to encourage failure analysis and continual improvement in the problem-solving process by inviting children to communicate and collaborate. The strategies used by the teachers were conceptualized into two sub-themes. (1) an invitation to communication, and (2) an invitation to collaboration.

3.3.1 Invitation to communication

The teachers expressed that the children are willing to communicate with their peers: "*The children are very open about this; the children help each other." They are in constant communication and observe each other* (T3). However, children were not always successful in communicating, and they needed the teacher's encouragement: *Sometimes it is necessary to motivate children because they can solve the problem if they talk to their friend, they cannot talk, and if they try to talk, they deviate from the focus of the subject* (T16). Teachers stated that they encourage children to communicate with their peers and to get information about their problem-solving methods: *"I encourage them to get peer support"* (T5). *I want them to communicate with their peers and understand how they solved the problem* (T11). These incentives made failure analysis and continual improvement of children's designs possible. E.g.

> Even when we encourage children to communicate with their friends, they start solving the problems they face for their designs, and we understand the importance of even just supporting communication (T11).
> It is very exciting for children who communicate with their peers to constantly improve their designs by observing them; I did not think that there would be such a difference (T15).

3.3.2 Invitation to collaboration

To the teachers, the children were not willing to cooperate: *"I encourage the children to cooperate, but they still want to make their own ideas independent"* (T12). When teachers observed children, they realized that they had not previously created cooperative learning opportunities: *When I started to implement the action plans, I realized that I did not encourage the children to cooperate* (T7). As the process progresses, teachers have stated that they are providing more opportunities for cooperation to children: *Over time, I saw that children began to work together* (T11). Teachers emphasize that they motivate children who have problems in design to get support from their peers: *"I see that there is a problem. You can ask your friends for help to solve the problem."* (T13) These incentives prompted children to seek peer support in failure analysis and continual improvement. E.g.

> When I tell the children that you can succeed if you work with your friend, the children start to work together after a while, and when they solve the problem, they are more willing to work together in the next activity (T17).

Teachers' invitations to children's cooperation supported cooperation in problem-solving. Children's understanding of the division of labor has improved: *"My task is to bring materials"* (O6). In addition, teachers emphasized that they use various strategies to encourage children to cooperate. Restricting the materials given for problem-solving was one of them. [*A child wanted to build a tower, but he did not have enough materials to build it; they realized that they could solve the problem by combining the materials]. My teacher, we built this tower with Buket* (O17). T9 highlights this situation as follows:

> Especially when I put limited material in the learning center, the children realized that they needed to work together to solve the problem. Otherwise, they would not be able to solve problems with the materials given to them (T9).

4 Discussion and implication

This study focuses on the roles of teachers in failure analysis and continual improvement processes while solving problems that children encounter in engineering design activities. Children participating in the EDP already acquire many skills (Bustamante et al., 2018; Stone-MacDonald et al., 2015; Moore et al., 2018). However, the significance of teacher encouragement in failure analysis and continual improvement of children is emphasized to deepen these skills (Dorie & Cardella, 2014; Jones & Gearns, 2016). At this point, the aim of the study is meaningful. As seen in the findings, the teachers invited the children to rethink the problem, be patient and insistent, and communicate and cooperate with their peers to motivate them to solve it. These strategies empower children in the face of problems through failure analysis and continual improvement. The zone of proximal development (ZPD) within Vygotsky's social constructivist understanding sheds light on the subject. The ZPD represents the possible learning a child can achieve when appropriate educational conditions are provided (Schunk, 2014). In addition, it refers to many tasks that the child has not yet accomplished but can achieve with the help of talented people (Vygotsky, 1978). Within the scope of this study, teachers encouraged children to solve problems through their roles in the ZPD in children's early engineering learning.

Teachers tried to support failure analysis and continual improvement by encouraging children to think again about the problem. In this process, they used protective questions and organized the learning environment. It has been determined that these strategies teachers use encourage children to do failure analysis and continual improvement while solving problems. Using accurate and effective questions in the STEM education process encourages children to deepen their learning and learn more (Bredekamp, 2020). In addition, the materials in the learning centers provide children with the opportunity to develop EHoM by providing opportunities to examine relationships. These opportunities force children to think about the properties and functions of various materials and encourage them to solve problems (Lippard et al., 2018). Rethinking the problem can help us find potential failings. In the literature, it is emphasized that teacher support in the early STEM and engineering education process provides children with the opportunity to test, develops children's problem-solving skills, and directs children to cooperate (Lippard et al., 2018; Simoncini & Lasen, 2018). Therefore, our findings are consistent with the literature.

According to another theme, teachers tried to facilitate failure analysis and continual improvement by encouraging patience and persistence in children. Patience and persistence in problem-solving are related to optimism, one of the EHoM (Lippard et al., 2018). Teachers extended optimism by asking children about their designs, using different methods and techniques, and acting as models for children. Encouraging teachers' optimism helped children with failure analysis and continual improvement. As a result of the teacher's encouragement, the children insisted on seeing the good side even when faced with obstacles, tried different ways in the design process, and reflected the habit of optimism. Optimism impacts how children perceive and respond to problems, their ability to shape their learning, and how they deal with the following problem (Pawlina & Stanford, 2011). Therefore, it is meaningful to support it in the early childhood years.

Teachers sought to assist children's failure analysis and continual improvement processes by promoting communication and collaboration. The children reflected on their collaborative habits by helping their friends and sharing tasks during the design process. In addition, they exhibited their communication habits by expressing their thoughts clearly and explaining their designs to their teachers and other friends during the activities. When teachers encourage collaboration in the design process, it is seen that children are more successful in failure analysis and continual improvement. Stone-MacDonald et al. (2015) emphasized that children find many opportunities for cooperation and communication during the EDP. Although design processes naturally allow children to communicate and collaborate, children often need teacher support. Teachers encourage children to think more deeply about materials through communication and assist in problem-solving processes. Communication facilitated by the teacher is a necessary skill for collaborative problem-solving. At this point, communication goes beyond knowing vocabulary and includes understanding the needs and wishes of others (Loveland & Dunn, 2014). Studies indicate that teacher support in the EDP contributes to cooperation and communication skills in children (Cunningham et al., 2018; Hatzigianni et al., 2020; Isabelle et al., 2021).

Similarly, scientists and engineers collaborate to solve a problem that people need (Lange et al., 2019). In this respect, it is meaningful for teachers to invite children to cooperate in solving problems. The findings of the study are similar to the literature. Additionally, studies indicate that collaborative learning environments support children's problem-solving skills (Trujillo-Leon et al., 2022; Zisopoulou, 2019). Another study shows that cooperative learning significantly affects young children's mathematical problem-solving skills (Tarim, 2009). In this respect, the findings of this study are supported by learning approaches accepted in the literature.

4.1 Limitations and future directions

This study has some limitations. First, this study is limited due to the small number of participants. The small number of participants creates a problem for the generalizability of the data obtained. This limitation is mitigated by the fact that this study is qualitative and does not seek to generalize. However, based on this limitation, future quantitative and qualitative studies can be conducted with more prominent participants. Also, before the study, the teachers were involved in a PD process. Therefore, the data obtained were shaped more by the post-PD experiences of teachers than by their routine practices. In order to better capture the current situation, future studies can focus on children's problem-solving processes without raising any awareness among teachers. In this study, it was determined that the questions asked by the teachers to the children helped with problem-solving. Future studies can be carried out to support teachers' questioning skills. The findings of this study support EHoM. PD programs can be prepared through which teachers can raise awareness on this issue. The findings suggest that fostering optimism in children plays a crucial role in failure analysis and continual improvement. At this point, it is recommended to organize teacher PD. This study focused on teachers' strategies to encourage children to solve problems encountered during the EDP process. Future studies can focus on children's problem-solving strategies in the EDP process.

5 Conclusion

This study highlights teachers' strategies to support children's failure analysis and continual improvement habits of mind during the EDP. As seen in the findings, teachers tried to help children in their problem-solving processes by encouraging them to rethink problems, showing patience and determination, and supporting them in communicating and collaborating with their peers. These strategies helped children make sense of problems and empowered them to engage in failure analysis and continual improvement. Therefore, the findings reveal how teachers contribute to children's development of problem-solving skills by using EDP in their classrooms. Additionally, this study highlights the importance of teachers' role in supporting students' failure analysis and continual improvement processes. These findings highlight the importance of engineering education in early childhood and provide perspectives on how teachers can play an influential role in this process.

Support and acknowledgment No financial support was received from any institution for this research.

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).

Data availability The data that support the findings of this study are available on request from the corresponding author [AE]. The data are not publicly available due to ["them containing information that could compromise research participant privacy/consent"].

Declarations

Conflict of interest There is no conflict of interest between the authors or other persons/institutions/organizations in the study.

References

Bagiati, A., & Evangelou, D. (2015). Engineering curriculum in the preschool classroom: The teacher's experience. *European Early Childhood Education Research Journal*, *23*(1), 112–128. https://doi.org/10.1080/1350293X.2014.991099.

Bers, M. U., Seddighin, S., & Sullivan, A. (2013). Ready for robotics: Bringing together the T and E of STEM in early childhood teacher education. *Journal of Technology and Teacher Education*, *21*(3), 355–377.

Bredekamp, S. (2020). *Effective practices in early childhood education: Building a foundation (4th ed)*. *Upper Saddle River*, NJ: Pearson.

Brenneman, K., Lange, A., & Nayfeld, I. (2019). Integrating STEM into preschool education; designing a professional development model in diverse settings. *Early Childhood Education Journal*, *47*, 15–28. https://doi.org/10.1007/s10643-018-0912-z.

Bustamante, A., Greenfield, D., & Nayfeld, I. (2018). Early childhood science and engineering: Engaging platforms for fostering domain-general learning skills. *Education Sciences*, *8*(3), 1–13. https://doi.org/10.3390/educsci8030144.

Creswell, J. W. (2008). *Educational research planning, conducting, and evaluating quantitative and qualitative research*. International Pearson Merril Prentice Hall.

Cunningham, C. M. (2018). *Engineering in elementary STEM education: Curriculum design, instruction, learning, and assessment*. Teacher College Press. New York.

Cunningham, C. M., & Hester, K. (2007). *Engineering is elementary: An engineering and technology curriculum for children* Presented at the ASEE Annual Conference and Exposition, *Honolulu*, HI.

Dorie, B., & Cardella, M. E. (2014). Engineering at home. In Ş. Purzer, J. Strobel, & M. Cardella (Eds.), *Engineering in pre-college settings: Research in synthesizing research, policy, and practices*, (pp. 254–265). *Indiana*, IN: Purdue University Press.

Gunning, A. M., Marrero, M. E., & Morell, Z. (2016). Family learning opportunities in engineering and science. *Electronic Journal of Science Education*, *20*(7), 1–25.

Hatzigianni, M., Stevenson, M., Bower, M., Falloon, G., & Forbes, A. (2020). Children's views on making and designing. *European Early Childhood Education Research Journal*, *28*(2), 286–300. https://doi.org/10.1080/1350293X.2020.1735747.

Isabelle, A. D., Russo, L., & Velazquez-Rojas, A. (2021). Using the engineering design process (EDP) to guide block play in the kindergarten classroom: Exploring effects on learning outcomes. *International Journal of Play*, *10*(1), 43–62. https://doi.org/10.1080/21594937.2021.1878772.

John, M. S., Sibuma, B., Wunnava, S., Anggoro, F., & Dubosarsky, M. (2018). An iterative participatory approach to developing an early childhood problem-based STEM curriculum. *European Journal of STEM Education*, *3*(3), 1–12. https://doi.org/10.20897/ejsteme/3867.

Jones, K. L., & Gearns, D. K. (2016). *Preschoolers investigating STEM science - technology - engineering – math a classroom and family STEM project book project ideas contributed by members of the early childhood care and education group Bremerton school district*, *Bremerton*, WA, www.bremertonschools.org/ecce.

Katehi, L., Pearson, G., & Feder, M. (2009). *Engineering in K-12 education: Understanding the status and improving the propects*. The National Academies Press.

Kennedy, T. J., & Odell, M. R. L. (2014). Engaging students in STEM education. *Science Education International*, *25*(3), 246–258.

Kewalramani, S., Palaiologou, I., & Dardanou, M. (2020). Children's engineering design thinking processes: The magic of the ROBOTS and the power of BLOCKS (electronics). *EURASIA Journal of Mathematics Science and Technology Education*, *16*(3), 1–14. https://doi.org/10.29333/ejmste/113247.

Lai, E. R., & Viering, M. (2012). *Assessing 21st century skills: integrating research findings. paper presented at the annual meeting of the national council on measurement in education*, Vancouver, B.C., *Canada*.

Lange, A., Brenneman, K., & Mano, H. (2019). *Teaching STEM in the preschool classroom exploring big ideas with 3- to 5-year-olds* Teachers College Press: *Colombia*.

Lippard, C. N., Riley, K. L., & Lamm, M. H. (2018). Encouraging the development of EHoM in prekindergarten learners. In L. English, & T. Moore (Eds.), *Early engineering learning* (pp. 19–36). Springer.

Lippard, C. N., Lamm, M. H., Tank, K. M., & Choi, J. Y. (2019). Pre-engineering thinking and the EHoM in preschool classroom. *Early Childhood Education Journal*, *47*, 187–198. https://doi.org/10.1007/s10643-018-0898-6.

Loveland, T., & Dunn, D. (2014). Teaching engineering habits of mind in technology education. *Technology and Engineering Teacher*, *73*(8), 13.

Merriam, S. B. (2009). Qualitative research: Designing, implementing, and publishing a study. *Handbook of research on scholarly publishing and research methods* (pp. 125–140). IGI Global.

Monkeviciene, O., Autukeviciene, B., Kaminskiene, L., & Monkevicius, J. (2020). Impact of innovative STEAM education practices on teacher professional development and 3–6-year-old children's competence development. *Journal of Social Studies Education Research*, *11*(4), 1–27.

Moore, T. J., Tank, K. M., & English, L. (2018). Engineering in the early grades: Harnessing children's natural ways of thinking. In *Early engineering learning* (pp. 9–18). Springer, *Singapore*.

NAE & NRC (National Research Council) (2009). *Engineering in K–12 education: Understanding the status and improving the prospects*.

National Research Council (NRC). (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. National Academies Press.

Papacharisis, V., Goudas, M., Danish, S. J., & Theodorakis, Y. (2005). The effectiveness of teaching a life skills program in a sport context. *Journal of Applied Sport Psychology*, *17*(3), 247–254.

Patton, M. Q. (1990). *Qualitative evaluation and research methods*. SAGE Publications, inc.

Pawlina, S., & Stanford, C. (2011). Preschoolers grow their brains: Shifting mindsets for greater resiliency and better problem solving. *YC Young Children*, *66*(5), 30.

Plura, J. (2000). Continual improvement within the quality management systems. *Kvalita Inovácia Prosperita*, *1*, 13–22.

Portsmore, M., & Milto, E. (2018). *Novel engineering in early elementary classrooms. In Early engineering learning* (pp. 203–223). Springer, *Singapore*.

Ruzzi, B. L., Eckhoff, A., & Linder, S. M. (2017). Growing in STEM: STEM resources and materials for engaging learning experiences. *National Association for the Education of Young Children NAEYC*, *72*(1), 90–93.

Schunk, H. D. (2014). *Learning theories from an educational perspective* (Trans. Ed. Şahin, Muzaffer). Nobel Academic Publications. *Ankara*.

Scutti, J. J., & McBrine, W. J. (2002). *Introduction to failure analysis and prevention*. ASM International.

Seidman, I. (2006). *Interviewing as qualitative research: A guide for researchers in education and the social sciences*. Teachers College Press.

Shewchuk, R. M., Johnson, M. O., & Elliot, T. R. (2000). Self -appraised social problem-solving abilities, emotional reactions, and actual problem-solving performance. *Behavior Research and Therapy*, *38*(7), 727–740.

Shipley, R. J., Miller, B. A., & Parrington, R. J. (2022). Introduction to failure analysis and prevention. *Journal of Failure Analysis and Prevention*, *22*(1), 9–41.

Simoncini, K., & Lasen, M. (2018). Ideas about STEM among Australian early childhood professionals: How important is STEM in early childhood education? *International Journal of Early Childhood*, *50*(3), 353–369.

Soylu, Ş. (2016). STEM education in early childhood in Turkey. *Journal of Educational and Instructional Studies in the World*, *6*(1), 38–48.

Stone-MacDonald, A., Wendell, K., Douglass, A., & Love, M. L. (2015). *Engaging young engineers: Teaching problem solving skills through STEM*. Brookes Publishing.

Stone-MacDonald, A. S., Wendell, K., Douglass, A., & Love, M. L. (2015). *Engaging young engineers teaching problem-solving skills through STEM*. Paul H. Brookes Publishing Co. Baltimore.

Tarim, K. (2009). The effects of cooperative learning on preschoolers' mathematics problem-solving ability. *Educational Studies in Mathematics*, *72*, 325–340.

Texley, J., & Ruud, R. M. (2018). *Teaching STEM literacy: A constructivist approach for ages 3 to 8*. Published by Redleaf Press.

The Early Childhood STEM Working Group (2017). *Early STEM matters: Providing high-quality STEM experiences for all young learners*. A policy report by Early Childhood STEM working group. http://ecstem.uchicago.edu.

Trujillo-León, U., Delgado-Arenas, R., Delgado-Corazao, S., Corazao-Marroquín, N., & Farfán-Pimentel, J. F. (2022). Cooperative learning and its effects on the development of problem-solving skills in secondary school students, Callao. *NVEO-Natural Volatiles & Essential Oils Journal NVEO*, 1109–1121.

UNESCO (2008). *Gender-responsive life skills-based education advocacy brief gender-responsive life skills-based education*

Van Meeteren, B., & Zan, B. (2010). Revealing the work of young engineers in early childhood education. *Early Childhood Research and Practice*, *12*(2).

Van Meeteren, B. D. (2018). The importance of developing EHoM in early engineering education. In L. D. English, & T. Moore (Eds.), *Early engineering learning* (pp. 37–52). Springer.

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Harvard University Press.

Wagner, T. (2008). *The global achievement gap: Why even our best schools don't teach the new survival skills our children need-and what we can do about it*. Basic Books.

Wilmarth, S. (2010). Five socio-technology trends that change everything in learning and teaching. In H. Hayes, & Jacobs (Eds.), *Curriculum 21: Essential education for a changing world* (pp. 80–96). Association for Supervision and Curriculum Development.

Yin, R. (1993). *Applications of case study research*. Sage.

Zan, B. (2016). Introduction: Why STEM? Why early childhood? Why now? (Counsell. In S. Escalada, L. Geiken, R. Sander, M. Uhlenberg, Van J. Meeteren, B. Yoshizawa, & S. Zan, B., (Eds.),) In *STEM learning with young children: Inquiry teaching with ramps and pathway* (pp. 23–30). Teachers College Press.

Zisopoulou, E. (2019). Collaborative learning in kindergarten: Challenge or reality? *Journal of Early Childhood Studies*, (2), 335–351. https://doi.org/10.24130/eccd-jecs.1967201932113.