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RESEARCH ARTICLE

Teaching the topic of friction force using technology-supported design based instruction: an application example

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ABSTRACT

This study aimed to design, implement, and evaluate the applicability of activities enriched with technology-supported design-based instruction on the topic of friction force. The study was conducted with 20 fifth-grade students at a public middle school in a large city in western Turkey. The implementation process lasted 12 lessons. Students designed three- dimensional (3D) models using the Tinkercad program in line with engineering design processes to observe the effect of friction force and printed their designs using a 3D printer. Students' designs were evaluated using the Design Evaluation Rubric. Furthermore, data related to the teaching process was collected using the Activity Worksheet and Activity Evaluation Form, and the applicability of the activity was discussed. As a result, it was observed that the activity had positive results in learning the subject and developing students' skills such as engineering and design. In further studies, activities that support students' design skills can be carried out.

KEYWORDS

Friction force; technology; three-dimensional (3D) modeling; middle school students

Introduction

In today's rapidly advancing technological landscape, it is crucial for individuals to adapt to these technological advancements. Consequently, countries are making changes to their education systems to align with contemporary demands. The primary objective of these education systems is to cultivate individuals who possess scientific process skills, can organize information, think innovatively and creatively, and are proficient in technology and engineering design, thereby fostering scientifically literate individuals. Identifying the knowledge dimension components of science literacy is one of the goals of the Next Generation Science Standards (NGSS) (NRC, 2012). The Next Generation Science Standards (NGSS) represent one of the major reforms in science education in recent years (McComas and Nouri 2016). This reform is a change that focuses on science, engineering, and engineering practices (Achieve 2013). One of the goals of the new generation of science standards is to develop science literacy and cultivate individuals who understand the structure of scientific knowledge. The framework established in this context has introduced a new perspective on K-12 science education, learning, and teaching (NRC, 2015). This study focuses on STEM integration in K-12 science classrooms. Furthermore, not all science content can or should be taught using the STEM approach. In teaching science concepts, inquiry-based learning should be encouraged (NGSS, 2012). From this perspective, Inquiry-Based Science Education encourages students to think critically. Thus, students develop logic and evidence about the natural world to ask questions, conduct research, formulate arguments, create models, and communicate findings (Crawford 2014, p. 515). Additionally, this approach takes into account factors such as the guidance provided by the teacher and the cognitive and social activities in which students participate. This approach emphasizes the student's active role in constructing knowledge under the teacher's guidance. Thus, this model is defined as a student-led, discovery-based learning process (Furtak et al. 2012). This research aligns with the NGSS dimensions:

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Disciplinary Core Ideas (DCIs), Science and Engineering Practices (SEPs), and Cross-Cutting Concepts (CCCs). This framework will help students better understand the concept of friction.

Individuals need to be educated as individuals who develop comprehensive and well- equipped skills in order to be successful in their careers. In this context, educational institutions aim to increase the quality of human resources in parallel with scientific and technological developments (Rina, Murtini, and Indriayu 2019). Next Generation Science Standards (NGSS) are used in science education to enable individuals to acquire the skills necessary to compete globally. Furthermore, NGSS enables students to recognize how knowledge emerges through active participation in science and engineering practices (NRC, 2012).

The new generation science standards emphasize that engineering and design education should continue from preschool through high school. Design-based teaching forms the basis of the new generation science standards (Kim, Suh, and Song 2015). Technology plays a prominent role in helping students acquire engineering design skills. It can be quite a challenging process, particularly for students, to create three-dimensional drawings using pen and paper. Therefore, three- dimensional design programs today make it much easier for students to acquire these skills. In this regard, Web 2.0 tools and technological software have recently been integrated into the education and teaching process (Ürek, Sarıoğlan, and Akbay 2025). These tools have become an important part of the education and training process (Stefancik and Stradiotová 2020). Some of these tools include Tinkercad, Kahoot, Algodoo, and Canva. Among these tools, Tinkercad is a three-dimensional software tool used mainly in the field of design and engineering. This web design tool is seen as a web design tool that covers the fields of electronics and coding and aims to create innovative designs (Tinkercad, 2023). It is expected today that teachers and students integrate technology and engineering design processes into science education, particularly using technological software such as modeling and computer-aided design (Douglass and Verma 2022; White and Newby 2024). Considering that we live in the age of technology, the use of technological tools in education attracts the interest and attention of many students (Buzzard et al. 2011). It would be beneficial for teachers to receive adequate training in this area for the use of new technologies in education (Li et al.2023). Technology will help students gain different experiences and insights throughout their education (Herrington and Kervin 2007). In this context, although there are many computer-aided design (CAD) applications, the Tinkercad three-dimensional (3D) program was used in this study. This is because the Tinkercad platform is considered a suitable design program for middle school students in terms of its accessibility and ease of use (Eryilmaz and Deniz 2021).

Individuals need to possess engineering design skills and digital skills in order to solve science-related problems they encounter (Thibaut et al. 2018). Furthermore, individuals are expected to have engineering design skills, science, and mathematics disciplines before producing concrete materials. It is considered necessary for individuals to use and discover their design skills in response to the problems they encounter (Kelley and Knowles 2016). It is particularly important for individuals to reach a level where they can produce solutions by approaching the problems they encounter from an engineering perspective (Guzey et al., 2014). From an engineering perspective, one of the important issues is creating and presenting products (Bozkurt & Ercan 2016; Dekkers, Chang, and Kreutzfeldt 2013). In this context, converting designs into tangible materials by printing them with a 3D printer is an important issue in terms of revealing students' design skills in a practical way.

Purpose and importance of the activity

The purpose of this study is to design, implement, and evaluate the feasibility of a technology- supported, design-based teaching activity enriched with activities on the topic of friction force in science lessons for 5th-grade middle school students.

Today, countries have prioritized technology and engineering design processes in the reforms they have made in their education systems (Raja and Nagasubramani 2018). It has been stated that the use of engineering design is necessary to support teaching, especially in science education (Gao et al. 2020). Acquiring technology and engineering design skills is seen as an important factor in individuals becoming scientifically literate. The engineering design process has benefits such as explaining scientific theories and increasing the effectiveness of teaching. Engineering design has been found to be effective in helping individuals understand the subject by providing concrete examples through modeling (Greca and Moreira 2000). Furthermore, it ensures that individuals gain more experience and that teaching becomes more efficient through their active participation in this area (Harrison 2001). In this context, providing engineering education from an early age and during middle school increases individuals' interest in technology and ensures their success in disciplines such as science and mathematics (McDonald 2016). As learning through design emerges, individuals better understand the relationship between science and technology, thereby developing their engineering skills and enabling the creation of products (Kolodner 2002; Scott 2012). Thus, the learning process becomes more efficient and also facilitates the development of design and technological skills.

This study examines the engineering design process, technology integration into the process, the Tinkercad CAD application, 3D designs, and tangible outputs from a 3D printer, and technology and design models such as the Phet Colorado simulation program. When evaluated in terms of addressing current topics and ensuring students' active participation in the process regarding friction force, which is one of the science teaching applications, it is considered to be an important example in this field.

In line with the above explanations, this study seeks to answer the following questions.

- Are activities on friction force in a teaching process enriched with technology-supported design-based activities effective in teaching the subject?
- Are three-dimensional (3D) designs made with the Tinkercad program and concrete materials obtained from a three-dimensional printer effective when used in teaching the topic of friction force?

Materials and process

This section consists of five main parts. The first part covers the materials used in the activity, the second part covers the participants, the third part covers the data collection tools and their evaluation, the fourth part covers the pre-implementation of the activity, and the fifth part covers the implementation process of the activity in stages.

Materials

The materials in this activity are divided into virtual materials and concrete materials. Virtual materials are models designed by students in the Tinkercad program, while concrete materials are materials printed by students using a three-dimensional (3D) printer. Virtual materials are related to the Tinkercad program, and the general features of this program and its introduction to students are covered in the Introduction to Tinkercad section. This section is detailed below. Tangible materials are models taken from a three-dimensional printer, and images related to these models are shown in Figure 1.

Participants

The participants in this study consisted of a total of 20 students, including 9 male students and 11 female students in the 5th grade of a public middle school in the western region of Turkey. The participants' age range is between 10 and 11. The presence of a science laboratory, technology laboratory, and 3D printer at the school was a factor in selecting the school. One of the 5th grade classes at the school was randomly selected.

Data collection tools and evaluation

Two different data collection tools were used in this study. These tools, the "Activity Worksheet" and the "Activity Evaluation Form," were developed by the researchers. The validity and reliability of these tools were ensured by consulting four science teachers and two science educators with doctorates in

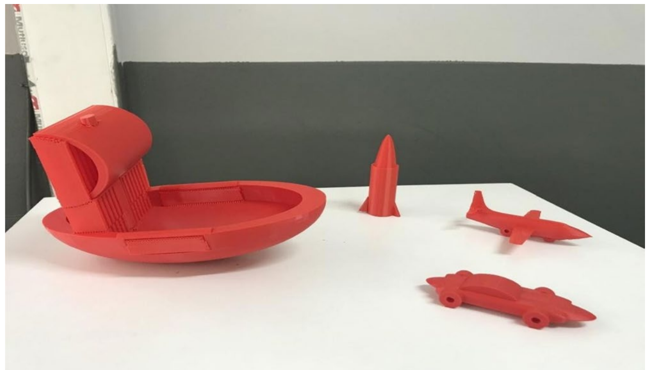

Figure 1. Physical materials obtained from a 3D printer.

Table 1. Design evaluation rubric.

Students' designs are evaluated at this stage by scoring them according to the rubric provided below.

1	2	3	4
Beginner	Advanced	Good	Excellent
Score		**Quality**	
…….		Design creation and originality	
……		Design suitability for purpose	
……		Creation of the design sketch and prototype	
…….		Incorporation of scientific concepts into the design (increasing/ decreasing friction force)	
…….		Usability of the design in daily life	

In addition, activity worksheets are distributed to students at this stage. Students are asked to complete these worksheets in groups. Apart from this, activity evaluation sheets are distributed to students regarding the activities they have done and they are asked to evaluate them.

science. In addition, the "Design Evaluation Rubric" tool used to evaluate the designs in the study was developed by the researchers, and its validity and reliability were ensured by obtaining expert opinions from a science teacher, a technology design teacher, and science education experts. The Design Evaluation Rubric criteria are given in Table 1 below.

The students' designs were scored by both researchers independently using a design evaluation rubric. The inter-rater reliability coefficient was calculated as 0.90 (Miles and Huberman 1994). The two designs on which agreement could not be reached were discussed by the researchers, and following a consensus, they were placed in the appropriate category.

Designing and planning the pre-application activity

In this study, the plan was developed in accordance with the activity lesson plan based on the technology-supported engineering design and entrepreneurship model. This plan was prepared in line with the Engineering Design and Entrepreneurship Model produced by Çakmakçı (in press, cited in Eres and Ecevit 2025), which includes the stages of Ask, Imagine, Plan, Produce, Develop, and Market-Become an Entrepreneur. This model is shown in Figure 2 below.

Introduction to Tinkercad

In this section, students were introduced to the Tinkercad program before the activity. Then, they were given general information on how to work with this program. Students were also introduced to basic features such as moving objects, resizing objects, viewing objects in three different dimensions, deleting unwanted objects, and changing the colors of their designs. Students were encouraged to discover features such as duplicating, copying, grouping, aligning, and viewing objects in the program on their own. Thus, before the event, students had the opportunity to practice using the Tinkercad program. The training session is shown in Figure 3 below.

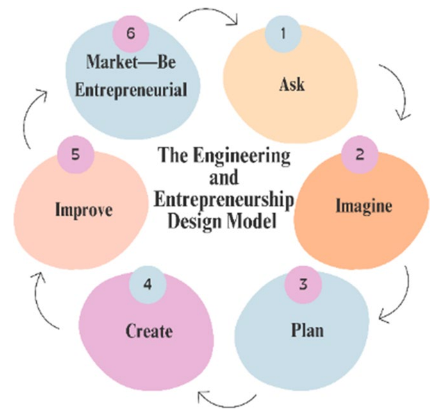

Figure 2. Engineering design and entrepreneurship model (Çakmakçı in press, cited in Eres and Ecevit 2025).

Implementation process of the activity

The activity was conducted over three weeks, with a total of twelve class hours, four hours per week. The research process of the study is presented in Table 2 below.

Asking step. During the first two class hours of the first week of the activity, students were presented with a problem from daily life as part of the activity preparation process to draw their attention to the topic and establish a connection. The teacher asked the students, "Mr. Ahmet wanted to change a broken light bulb in his bathroom by placing his plastic chair on the tile floor of the bathroom and climbing on it. However, the chair's legs slipped on the tile floor, the chair broke, and Mr. Ahmet fell to the floor. Mr. Ahmet only has one more plastic chair in his house and no other chairs, so if he tries the same thing again, he will encounter the same result." How do you think Mr. Ahmet will solve this problem? Students were asked to come up with ideas for a solution to this problem. In addition, the students' attention was drawn to the topic by asking them the following questions about events that occur in daily life.

> "How does friction force affect parachutists when they use their parachutes during landing?"
>
> "How does friction force affect the hinges of a door that is difficult to close and makes an annoying noise when hinges are lubricated?"

Imagination step. In the last two lessons of the first week, the teacher presented a problem from daily life to the students. The teacher pointed out to the students that "vehicles around schools, especially in cities, do not slow down during school hours, and this situation puts students in danger." The teacher then asked the students, "How do you think we can find a solution by changing the surface of the road outside the school perimeter?"

After receiving answers from the students, they worked individually using the Phet Colorado simulation program. During this process of interacting with the computer, the students observed the effect of different friction forces on different surfaces in the Phet Colorado simulation program. In this way, they tried to concretize abstract concepts with the simulation program. In this context, students were asked to imagine attachments that would increase or decrease the effect of friction force and to think of names for these attachments. Images of the work done are provided in Figure 3.

Planning step. At this stage, students plan their designs based on the ideas they have selected as most suitable for themselves. They create their plans by thinking about the designs they intend to make in stages. Students are asked to plan how they will design tools that increase or decrease friction. In particular, they are asked to plan how the tips, surfaces, or, if applicable, the surfaces of the tires of these tools should be. The work related to planning the designs the students intend to create is shown in Figure 3 below.

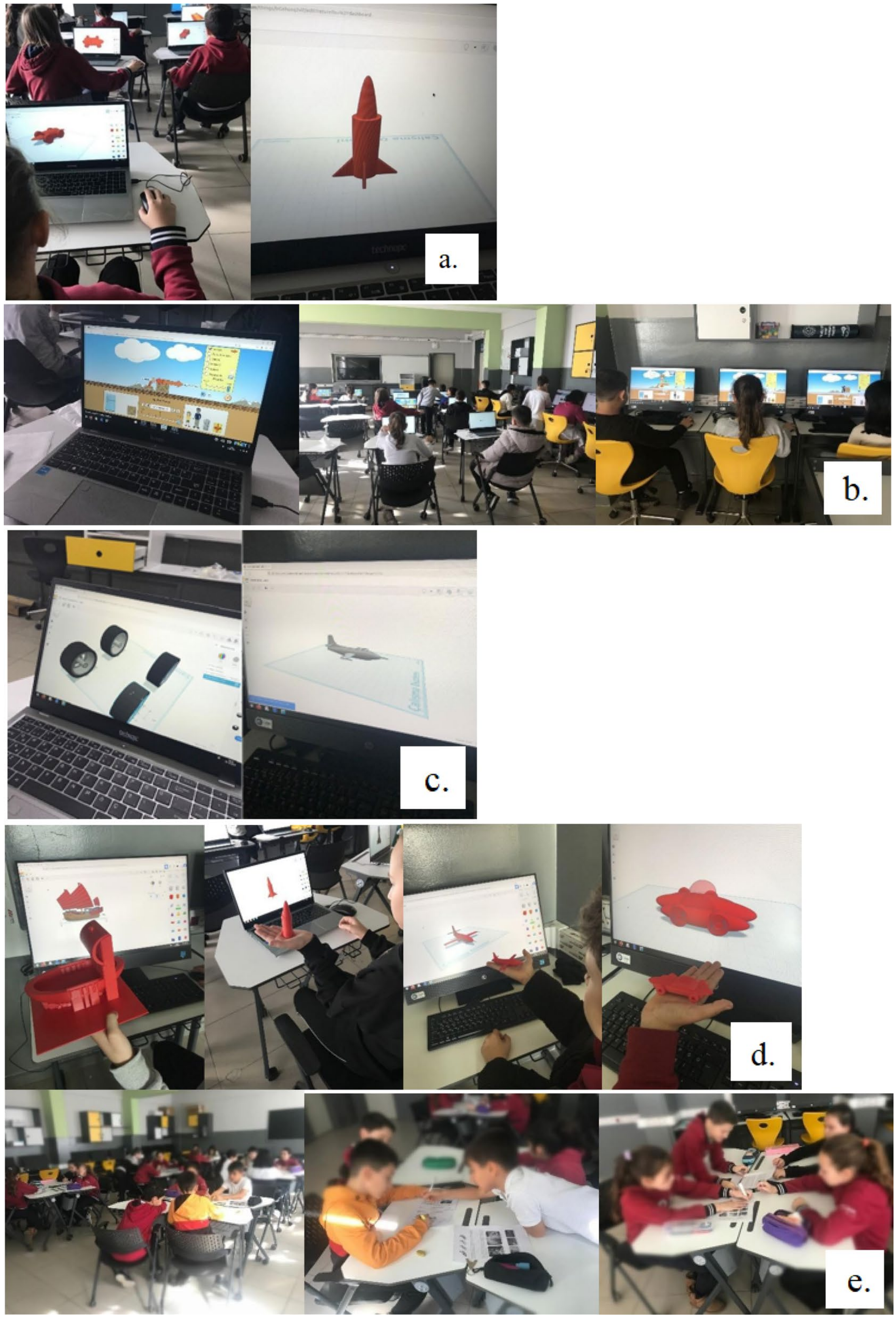

Figure 3. Implementation steps of activities: (a) introductory training session on the tinkercad program and the virtual design models created; (b) visuals from the phet Colorado simulation program study; (c) visuals of the designs students plan to create during the planning phase; (d) physical materials of the designs created; (e) group work done by students on the activity worksheets.

Creation step. In the second week of the study, students used simulation and design programs to concretize abstract concepts. Over a total of four class hours, students used the Tinkercad program

Table 2. Research process of the study.

Duration	Preparation and Implementation Process of the Activity	Evaluation of the Activity
Week 1: 2 class hours (80 min)	Introduction and training on the Phet Colorado simulation and Tinkercad design program	
Week 1: 2 class hours (80 min)	Individual work using the Phet Colorado simulation program	
Week 2: 4 class hours (160 min)	Creating three-dimensional (3D) designs using the Tinkercad design program	
Week 3: 2 class hours (80 min)	Printing from a three-dimensional (3D) printer	Evaluation of designs using a rubric scale
Week 3: 2 class hours (80 min)		Filling out Activity Worksheets and Activity Evaluation Forms

to design tools used in daily life that increase and decrease the effect of friction force. It was noted that the 3D models created by the students are related to the forces of friction in everyday life and that they should take this into account when creating the models. At this stage, after explaining that increasing or decreasing friction force in certain situations in daily life can make our lives easier, it was observed that the tools designed by the students in this section could reduce or increase the effects of air resistance and water resistance. Discussion regarding the shortcomings of the designs took place in the next stage.

Improvement step. During the first two class hours of the third week of the study, the students' Tinkercad designs were materialized by printing them on a 3D printer. At this stage, the students' designs were evaluated according to the Design Evaluation Rubric criteria, and the shortcomings of the designs were discussed with the students. Then, the designs with the shortcomings completed were printed on a 3D printer. Students carried out their designs by following the stages of the engineering design process. The design models created are shown in Figure 3.

Market-entrepreneurship step. In this section, students' ideas on how to bring their designs to the global market were gathered. In this context, students expressed the contributions their designs would make to us.

In the final section of the study, namely the measurement and evaluation stage, during the last two class hours of the third week, students were divided into groups and Activity Worksheets were distributed to the groups. Finally, Activity Evaluation Forms were distributed to the students to be filled out individually. Students were asked to evaluate the activity by answering the questions on this form. Below is Figure 3, which shows the group work in which the students answered the Activity Worksheet.

Evaluation of the activity

This section will be examined in three parts: the evaluation of the designs created and the evaluation of the Activity Worksheet, Activity Evaluation Forms and Design Evaluation Rubric.

Evaluation of the activity worksheet, activity assessment form and design evaluation rubric

The effectiveness of the activity carried out in this section was evaluated. At this stage, Activity Worksheets were distributed to each group, and students were asked to complete the activity worksheets in groups. The reason students are divided into groups is to facilitate collaborative learning by sharing the insights they gain from the design program they work on individually. When forming the groups, the distribution of female and male students was taken into account, and the groups were assigned randomly. There are five groups, each consisting of four students.

It was observed that students in the second group gave incorrect answers to item 1 on the activity worksheet. The answers given by the second group are shown in Figure 4(a) below. It was observed that the other groups answered the first item correctly. In addition, it was determined that all groups

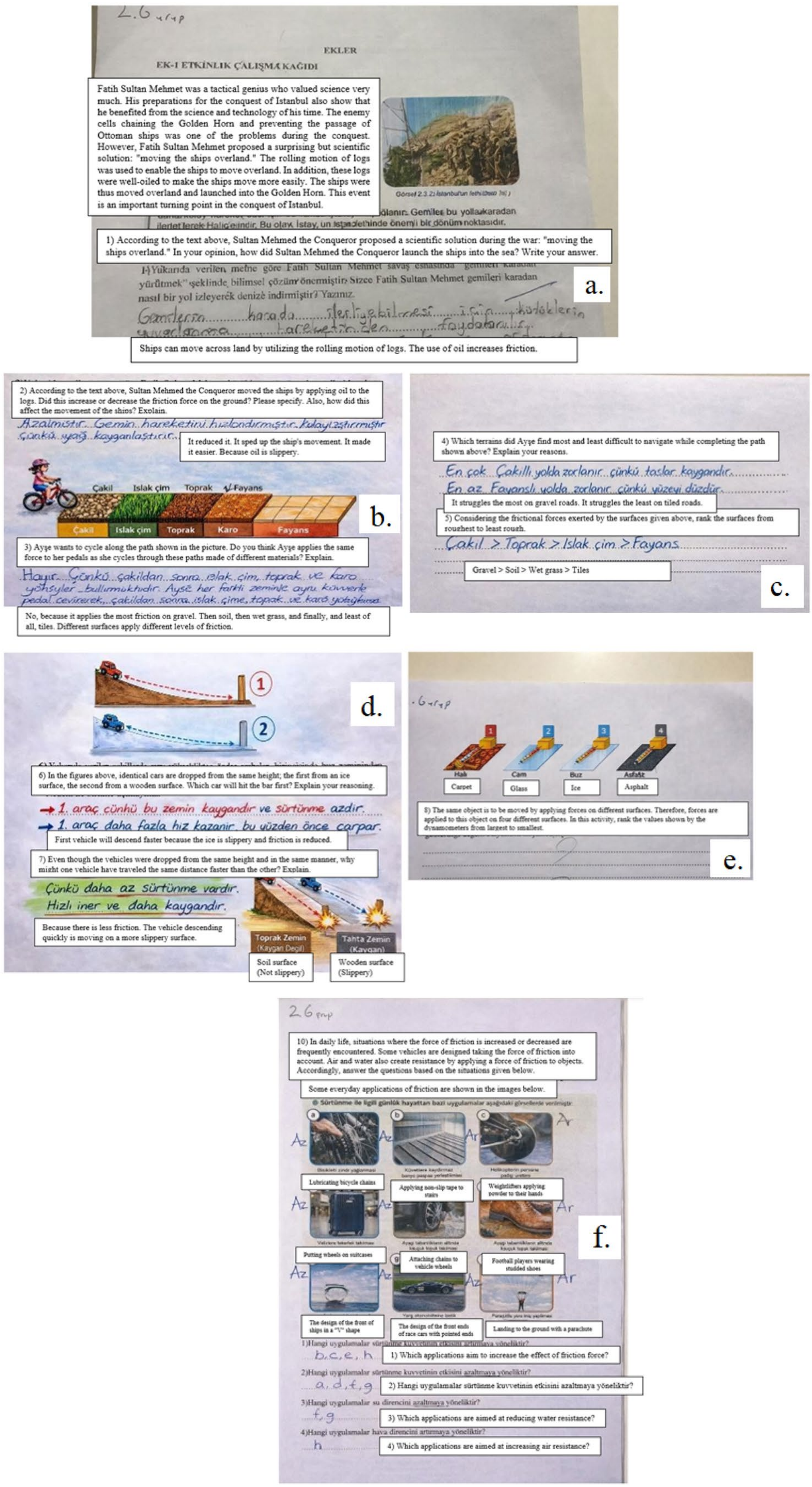

Figure 4. Students' responses on Activity Worksheet: (a) item 1; (b) item 2 and 3; (c) item 4 and 5; (d) item 6 and 7; (e) item 8; (f) item 10.

Table 3. Students' responses to the activity evaluation form.

Items	Student's Responses (f:20)
Item 1: What are your thoughts on this activity? Please explain.	It was very fun and very nice. (f:13) Interacting with the computer was educational. (f:2) Designing with Tinkercad and simulation activities with Phet Colorado were fun. (f:4) Did not express an opinion. (f:1)
Item 2: Were there any parts of the activity you found difficult? Explain the parts you found difficult.	Yes, I had difficulty while designing. (f:14) No, I did not have any difficulties while creating the designs. (f:6)
Item 3: Write your thoughts on whether the activity you did could be done in different topics of the Science class or in different classes.	I want it because it was fun and educational. (f:18) No, I don't want to. (f:2)
Item 4: What did you learn after this activity? Explain how the activity affected your learning.	Thanks to the simulation and design program, I understood the subject. Thanks to technological tools, I had the opportunity to test it as in real life. (f:20)
Item 5: What are your suggestions regarding this activity? Please specify.	I recommend applying it to different subjects and different courses. (f:16) I recommend group work when creating designs. (f:4)

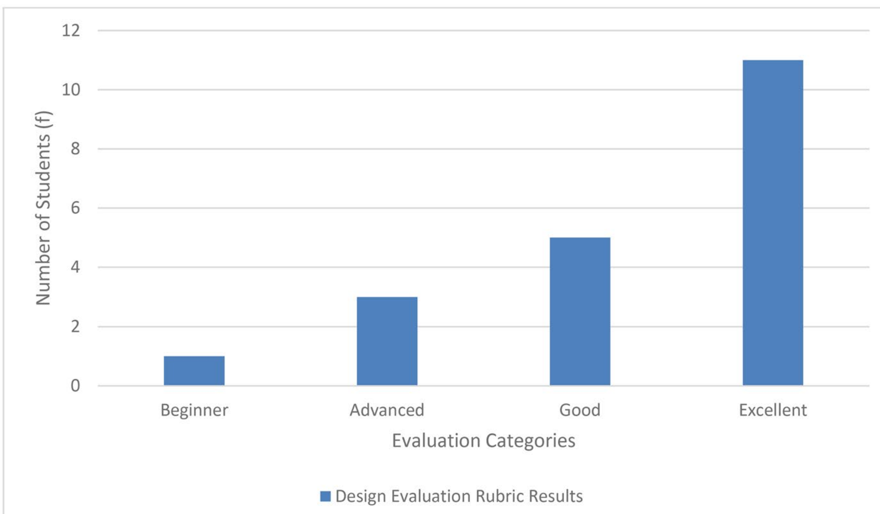

Figure 5. Design evaluation rubric results.

answered items 2, 3, 4, and 5 correctly. Similarly, it was determined that students in all groups answered items 6 and 7 correctly. The answers given by the students are shown in Figure 4(b–d). Looking at the answers given to the eighth item, it was seen that the students in the second group did not answer the question, while the other students gave the correct answer. The answers given by the students in the second group are shown in Figure 4(e) below. When the answers given to the ninth item were examined, it was seen that all groups gave the correct answer, while in the tenth item, it was determined that the students in the second and fourth groups gave the wrong answer. The visuals related to the evaluation are given in Figure 4(f).

The responses given by the students on the Activity Evaluation Form are grouped by similar expressions and presented in Table 3 below.

The Activity Evaluation Form was administered individually to all students. As seen in Table 3, when looking at the responses given, nineteen students stated that the activity was fun, educational, and that interacting with the computer, designing with Tinkercad, and simulation activities with Phet Colorado were educational and fun in response to the first question asking for their thoughts on the activity. One student did not express an opinion on this matter. Regarding item 2, which asked about the challenging aspects of the activity, fourteen students stated that they found it difficult to create designs. Six students stated that they did not find it difficult to create designs. Regarding item 3, which asked about their thoughts on conducting the activity in different courses or subjects, eighteen students stated that they would like it to be conducted, citing that it was educational and fun. The other two students stated that they did not want it to be done. Regarding the thoughts on the effect of the activity on learning the subject concepts, as stated in the fourth item of the activity, twenty students stated that they learned and even had the opportunity to test their understanding of the subject in real life thanks to the simulation and design program. They also stated that they had a practical and productive learning experience. Regarding the suggestions related to the activity in the final item, item 5, four students suggested that the design activity be done in groups, while sixteen students suggested that these activities be done in different topics and different lessons of science education.

The results of the design evaluation rubric used to assess the activity are presented in the graph below (Figure 5).

An analysis of the design evaluation rubric results revealed that most students produced designs of an excellent level ($f = 11$). Additionally, there were students whose designs were found to be of a good level ($f = 5$). In contrast, it was found that some students' designs required improvement ($f = 3$). Finally, there was one student whose design was at a beginner level ($f = 1$). Based on these results, it was observed that most of the designs created using the collected data were tailored to the event's objectives and had a positive impact on the event's efficiency.

Conclusion and discussion

This study aims to discuss the effects of simulation and design programs in teaching students about friction force. To this end, students were asked to design tools using the Tinkercad design program to observe the effects of friction force. Additionally, students printed their designs using a 3D printer, enabling more effective learning through tangible materials. Thanks to the Tinkercad program, students were able to easily transfer their designs from their minds to a digital environment. This enabled them to easily make the desired changes to their designs, such as color changes or dimensions. However, printing the designs on a 3D printer was found to be time-consuming and costly. Based on the results of the study, it can be concluded that the Phet Colorado simulation program and the Tinkercad design program were effective in helping students learn about the concept of friction. There are studies in the literature that parallel with this situation. In conclusion, there are studies indicating that computer simulations support meaningful learning (Fan, Geelan, and Gillies 2018; Ganasen and Shamuganathan 2017; Gunhaart and Srisawasdi 2012; Rutten, Van Joolingen, and Van Der Veen 2012; Smetana and Bell 2012). It can be said that this is an effective activity, especially because students have the opportunity to test the concept of friction force in their daily lives using technology and design-supported activities. When we look at the students' views about the activity, it is seen that most of them stated that these types of activities are educational, fun, and intriguing. Studies in the literature have also been found indicating that computer simulations and the Tinkercad program are interactive, interesting, educational, and motivating for students (Bl et al. 2024; Pranata 2024; Salame and Makki 2021). One of the results obtained is that this activity is effective in understanding the concept of friction force. Similarly, studies have shown that engineering design is effective in science education (Aranda et al. 2020; Havice et al., 2018; Hsu et al., 2011; Roth 2001). Furthermore, engineering design skills are necessary for solving problems in daily life (DiFrancesca, Lee, and McIntyre 2014; Thibaut et al. 2018). Students need science and mathematics disciplines to be able to solve the problems they encounter (Kelley and Knowles 2016). Similarly, Ugaldi et al. (2025) stated that prints made with a three-dimensional (3D) printer helped elementary school students better understand topics related to space science. Furthermore, Coşkunserçe (2025) found that materials produced by a three-dimensional (3D) printer increased the academic achievement of sixth-grade students in the subject of "Systems in Our Body." In a study by Spyros et al. (2021), which again used three-dimensional (3D) design and printer technology to determine friction force and the factors affecting this force, it was demonstrated that this technology is effective in conceptual understanding. In this regard, there are other studies that show similar results (Hsiao et al. 2019; Kostakis, Niaros, and Giotitsas 2015; Leduc-Mills and Eisenberg 2011; Şen, Ay, and Kiray 2020).

It can be said that this activity, by encouraging individuals to participate actively in the learning process, makes the process of learning and understanding the subject more effective. From this perspective, within the scope of the activity, students both actively participated and advanced their design skills by developing original designs. Considering today's conditions, it can be said that simulations, 3D software, and technological applications greatly facilitate the teaching of abstract concepts in science education. There are studies in literature that have obtained similar results (Smetana and Bell 2012; Petersen et al. 2020). In other words, digital technology and software have been shown to contribute to the development of engineering design skills (Kaya et al. 2019). When designing vehicles in real life, it is known that topics such as friction force, air resistance, and water resistance must be considered in order to achieve the necessary acceleration while also taking fuel costs into account. From this perspective, it has been concluded that students' understanding of this topic and the relevance of their designs to real life will also affect their future lives.

In summary, it can be said that this technology-supported and design-based activity has proven to be effective in helping students understand the concept of friction force. Furthermore, these activities, particularly the Tinkercad design program, have positively contributed to the development of students' engineering design skills and enabled them to create unique designs. From this perspective, it is seen that Web 2.0 tools have become an important part of the teaching process (Stefancik and Stradiotová 2020). Apart from these, the fact that students printed their designs from a three-dimensional (3D) printer and had concrete materials on this subject has also shown that it is extremely effective in helping students understand the subject. It has been found that integrating technology into the teaching environment positively affects learning and teaching environment (Buzzard et al. 2011). The fact that students find these activities fun, interesting, and educational also shows that the activity has a positive effect. Another finding is that students' understanding of the position of objects, the size of objects, and the relationship between them in their three-dimensional (3D) designs also involves spatial thinking (Lee and Bednarz 2012; Logan 2012; Uttal and Cohen 2012). It is extremely important for students to create the designs in their imagination on the computer and to print these designs.

Finally, there are some limitations to the study. In the study, limitations were identified, such as students struggling to create designs because they did not have sufficient knowledge of the Tinkercad program. To overcome this limitation, students were introduced to the Tinkercad program before the application and were informed about the application. It is believed that there may be some shortcomings in the teaching of the Tinkercad program to students due to limitations on the part of the teacher and time constraints. This is one of the limitations of the study. Another limitation of the study is that the teaching activities focused on a single topic for only four class hours. Additionally, it is possible that students provided the answers the researcher was looking for when evaluating the activity. For this reason, it may be helpful to add the necessary items to the activity evaluation form to allow students to conduct self-assessments, or to create a space where students can express their thoughts. This time constraint, however, has highlighted the limitations of applying design skills. The engineering design process and the task of printing the models designed during this process one by one on a 3D printer took a considerable amount of time in practice. Consequently, there was insufficient time during the project for students to test the models they had designed in an educational setting. This was determined to be a limitation in terms of time for the development of students' engineering skills.

Based on the results obtained in the study, the following recommendations are presented.

- In technology and design-based teaching, it may be more beneficial to develop these skills by performing simple 3D modeling activities before complex models. In schools without 3D printers, students should be encouraged to create engineering designs and model them with concrete materials.
- Conducting similar studies in different subjects and courses, as well as designing and printing different models, may also be effective in teaching different subjects.
- As this type of engineering work requires a significant amount of time, careful time management is essential. Plans can be made to incorporate testing of the products resulting from this work into the teaching process.
- In order to further develop students' engineering design skills, conducting similar studies in greater depth at different grade levels and monitoring students' progress in this area may make

the study more productive. These recommendations have been made for future research and applications.

- It was suggested that, in future studies, using not only an activity evaluation form but also an observer's form or recording the conversations among students would lead to more productive results.

Author contributions

CRediT: **Ayberk Bostan Sarıoğlan** & **Emrullah Sarıca**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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