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Encouraging Creative Ideas in the Engineering Design Process for Science Classes

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Abstract

One of the most challenging tasks for teachers in projects is to develop creative ideas. Due to the linear system perspective of education, fostering students' creativity is restricted. However, engineering design and scientific process skills that comprise creativity have an iterative structure. An iterative process-oriented education enables students to engage with questions. First, the current study includes a theoretical framework for the nature of engineering design and its transfer to classroom practices. Second, it provides examples of design-based activities that will contribute to the development of the engineering habits of the mind for teachers. In the study, a design of a future living environment activity that can be planned as a long-term student project is introduced. Then, a student design report and a design evaluation rubric for teachers are shared. In this section, engineering design-based projects are demonstrated in detail. These projects are based on the "One Item, One Material" project idea development strategy proposed by the authors. It is considered that such activities, which are carried out with the understanding of simple–complex science, can trigger the enthusiasm of discovery in students' minds.

Introduction

One of the most challenging tasks for teachers in projects is to develop creative ideas. Although the education system in Turkey has slowly begun to depart from the traditional approach in recent years, the fact that this system is based on a linear structure can be argued to hinder creativity. However, an iterative structure should be followed in teaching engineering design and scientific process skills that comprises creativity (Lucas, Claxton, & Hanson, 2014; Mursid, Saragih, & Hartono, 2022). Creativity mostly depends on the generation of new ideas. Thus, the presentation and evaluation of different ideas are associated with the ability to think in terms of variables. It may be possible that there are multiple solutions to a design-related problem (O'Byrne, Radakovic, Hunter-Doniger, Fox, Kern, & Parnell, 2018). In such cases, a solution that seems to be the best for one problem may not be so for another problem. Therefore, a linear approach to education distances students from such mental activities. An iterative, process-oriented education approach, on the contrary, constantly keeps students' minds busy with questions. Most students in science classes, workshops, or laboratories regard science as a field completely devoid of emotions. Our aim as the researchers is to encourage and reinvigorate students' feelings, such as passion, curiosity, excitement, pride, creativity, and will to explore and be productive, that, to this day, are either disregarded or overlooked. Our principle ought to be having a consistently and passionately innovative approach in the face of impossibilities, knowing that the dream of contributing under ideal circumstances may not always come true.

This study primarily presents a theoretical framework regarding the nature of engineering design and how it can be integrated into classroom practices. Then, a model for teachers on how to develop and carry out design-based classroom activities that will improve students' capacities of thinking like an engineer is proposed. Of these, the first is a project that can be carried out throughout the school year, in which the living environments of the future are designed. The second, on the contrary, is a sample design project developed by the researchers named "One Item, One Material," wherein the engineering design process is taught in detail. In the findings section of the study, examples from student projects are presented. Lastly, the activity template and design evaluation scale, which are created in accordance with the engineering design process proposed in this study, are presented.

The Nature of Engineering Design and How It can be integrated into Classroom Practices

In the most general terms, engineering is performing the act of designing under certain constraints (Wulf, 1998). However, this general definition actually encompasses many concepts and skills, such as creativity, determination, systematic thinking, and cooperation. These concepts and skills have developed over a period of 400 years (National Academy of Engineering [NAE] & National Research Council [NRC], 2009) and have formed the basis of modern engineering. Engineering has a direct relationship with designs. These designs can meet various needs and are classified according to the purpose of the design, as well as the type of knowledge and skills used in the design processes (Dieter & Schmidt, 2009; Haik & Shahin, 2011):

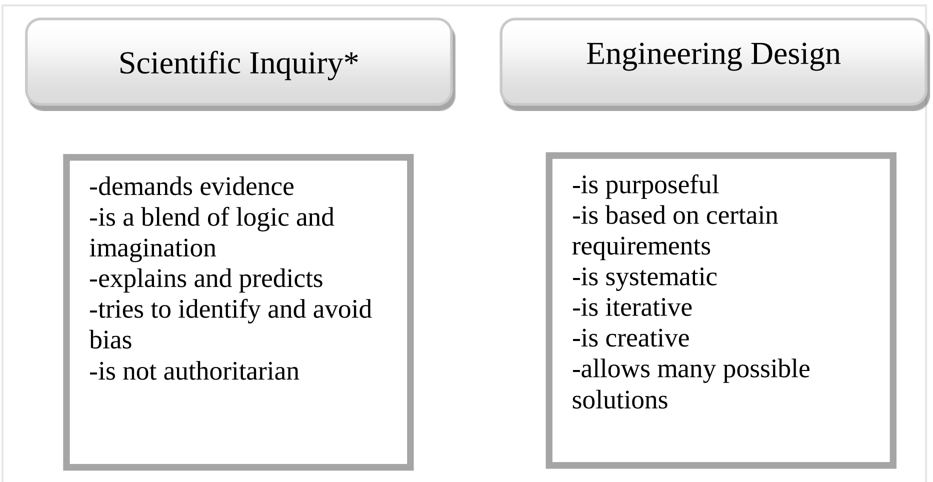
- *An original (new or innovative) design,* an invention such as the first automobile, the first airplane, or the wheel,
- *An adaptive design*, which is achieved when an existing solution is modified to meet a different need, such as the development of rapid prototyping machines based on the working principle of inkjet printers,
- *A development design,* which is achieved by taking an existing design as the point of departure but arriving at a significantly different design, such as developing a plasma television by taking cathode ray tube television as the starting point,
- *Redesign,* which refers to the objective of improving an engineered product by using alternative materials to reduce its weight or cost,
- *Selection design,* which refers to selecting standard components with the properties needed for the design, such as most electronic products, small electric motors, sensors, and conductive cables,
- *Industrial design,* which aims to develop products that appeal to the human senses (especially to the visual sense).

As can be inferred from the differences between the types of designs mentioned above, engineering design is much more comprehensive and complex than simply the transfer of certain components to a new product or the creation of a product based on a set of determined guidelines. Accordingly, engineering design is defined as a systematic process in which need- or problem-based solutions are developed (Eide, Jenison, Northup, &

Mickelson, 2017). The process of engineering design is shaped in line with the relevant engineering sub-discipline and the problem that the design is being developed to solve. Therefore, it is not possible to claim that there is a one-size-fits-all engineering design process. According to Dieter and Schmidt (2009), it is possible to talk about different engineering processes consisting of 5–25 steps. However, it is possible to argue that an average engineering design process consists of eight basic steps, namely, the identification of the problem or the need that the design is being developed to solve, the investigation of solutions developed to solve similar problems, the brainstorming of concepts for possible solutions, the selection of one of the proposed concepts to test, the development and testing of a prototype, the collection and analysis of the data obtained from the test, the redesign/improvement of a solution, and the communication of the solution (National Academies of Sciences, Engineering, and Medicine [NASEM], 2020).

Scientific Inquiry and Engineering Design

Engineering design integrates various approaches and perspectives, such as analytical and synthetic thinking, in-depth and holistic insight, planning and creativity, and procedural and conceptual knowledge for the development of a solution (NAE & NRC, 2009). Engineering design is generally associated with scientific inquiry due to its problem-solving nature. It will be beneficial for understanding the reason for the establishment of this association to reveal the distinctive characteristics of both the engineering design and scientific inquiry. The distinctive characteristics of scientific inquiry and engineering design are given in Figure 1.



* The presented definition of scientific inquiry in the figure represents the diverse ways in which scientists study the natural world rather than a research/investigation approach (National Research Council [NRC], 2000).

Figure 1. Characteristics of Scientific Inquiry and Engineering Design (International Technology Education Association [ITEA], 2000; NAE & NRC, 2009)

The characteristics laid out in Figure 1 are mostly valid for engineering design as well. For example, providing test- or analysis-based evidence is a prerequisite to determine the extent to which the design meets the need for which it was developed. Further, science is creative, systematic, and purposeful in nature as well. Some problems are easily solvable for both scientists and engineers. However, complex problems may require significant creativity from both groups. Engineers and scientists utilize similar cognitive tools such as brainstorming, reasoning, mental models, and visual representations in their solution development processes (NAE & NRC, 2009).

The main difference between science and engineering arises in the methods that are employed. An engineering design usually starts with a design or technological application offering a certain level of capability. This design or application encompasses scientific knowledge, devices, sub-components, methods of production, marketing methods, and economic variables. Rather than scientific curiosity, the main driving force of science is based on the needs of society, which are mostly associated with economic variables. After a need is identified, a solution model is developed. Here, unlike scientific models, this model aims to predict the performance of a design after it is materialized. The performance of a model, be it a mathematical or physical one, is subjected to an iterative viability analysis until an acceptable product is achieved or the project is abandoned. The design process of the product is completed when the design enters the production phase and is accepted as part of existing technology. In the future, this product can be regarded as a level of progress and the design process can be re-initiated (Dieter & Schmidt, 2009).

Method

Today, there is an ongoing transition to an educational approach that encourages interdisciplinary thinking. This transition can only be made possible through creating a participatory learning culture, because humans are open to influence from each other. An individual either adopts the mindset of the person with whom they are in communication with or transforms the mindset of that person. Imagine an educational environment where students learn, solve problems, design, and produce. Similar to Vygotsky's view that language is a tool facilitating mental development, the tools in such educational environments and knowing how to use them are of critical importance in the acquisition of certain skills by students. Another equally important variable is teaching natural and social science concepts to students, as these concepts are indispensable in producing scientific and quality design. Therefore, it is imperative to integrate into today's curricula the Science, Technology, Engineering, and Mathematics method, wherein the subjects of science, technology, engineering, and mathematics are taught in coherence rather than separately. In this part of the study, two methods will be proposed for developing new ideas on teaching engineering design in science classes. Of the two, the first is designing the future by engaging in scientific inquiry, and the second is making use of the "One Item, One Material" method in the classroom.

Developing New Ideas on Teaching Engineering Design in Science Classes

Designing the Future by Engaging in Scientific Inquiry

The students are asked to think of a scenario 30–35 years from now, wherein they are middle-aged people who are experts in areas of their choice, and try to imagine how their respective areas have developed in that period. Then, in light of their scientific knowledge, they are asked to write down their predictions about what will happen in their fields in the next 30 years. Students can create representations of what they imagine, such as a model or a simulation, or they can develop a prototype with a focus on one product. In addition, students should be given the opportunity to choose their own method of presentation. Examples of guiding questions to assist students are as follows:

- What do you think will change in classroom objects such as books, notebooks, pencils, erasers, boards, and desks in the next 30 years?
- What do you think will change in educational venues such as classrooms and school buildings in the next 30 years?
- Similar questions may be asked with a focus on health, daily life, home environment, entertainment venues, environmental issues, and professions of the future.

If wanted, a single theme can be selected, and environments and products related to this theme may be the point of focus. A design-oriented project can be planned on health care venues and products of the future. Future professionals are expected to have an innovative and questioning perspective that can produce practical solutions, as well as respond to the needs of the practice, innovation, and technological developments. Accordingly, students may be asked to choose other professions of the future, such as becoming a 3D software engineer, personal microbiome manager, biology and gene specialist, director of children's emotional and intelligence quotients, vertical farmer, drone technician, emotion designer, memory mechanic, memory enhancement specialist, climate analyst, human–machine hybrid environment designer/manager, crypto detective, nano-medical specialist, organ fabricator/designer, robot technician, pandemic safety officer, internet policeperson, sustainable business model specialist, artificial intelligence specialist, and time planner. Students may be asked to carry out research on these professions or have virtual or face-to-face conversations with people who have these or similar professions and come up with new designs. Thus, using the means at disposal, countless projects and design activities on the themes mentioned above can be developed.

One Item, One Material

This activity, which stands out as another type of alternative that can contribute to the development of students' engineering design skills, is carried out utilizing an item and a material. Students often have trouble developing and managing an original project. Indeed, a certain skill set and level of experience are needed to develop a qualified project. Accordingly, a number of strategies can be developed to be used by students who will work on a project for the first time. Students are asked to write down the first item that comes to mind on a piece of paper. These items can be anything from a table to a book, a clock, a lamp, a refrigerator, or a comb. Next, the papers are folded and collected in a box, and the same process is followed for materials. Students are asked to write down the first material (e.g., plastic, stone, paper, copper, or glass) that comes to mind on a piece of paper, and the papers are folded and collected in a box. Finally, students are asked to randomly select two papers, one from the items and the other from the materials box and design new products containing the item and material they have picked out.

Results

In this section, to lay out the engineering design process in detail, the steps that can be taken in developing students' design skills will be explored, starting from a case taken as an example. Accordingly, the engineering design process will be presented by focusing on a student's steps of brainstorming, developing, and materializing a project using "an item and a material." Next, other projects that are materialized by other students following the same pattern will be presented in a table. Finally, the Engineering Design Process Template and the Design Evaluation Scale will be given in Appendix.

The Method of "One Item, One Material" in Teaching Engineering Design Process

The item chosen by the student is a carpet and the material is flour. The first question that comes to mind is "What can be designed using a carpet and flour?" However, many products that were never thought of can be designed by following the methods used by scientists. First, variables such as types of carpets and their uses are listed; then, the same is done for flour. The lists are then compared, and some features of the item and the material are matched. For example, by combining the covering aspect of a carpet and flour's property of serving as a binding agent, a new type of natural animal food can be developed in order to meet the nutritional needs of stray animals and animals in nature in the winter months. In order to emphasize its components and function, this design can be named "Carpet Food." The engineering design process (National Aeronautics and Space Administration [NASA], 2011) follows the pattern below:

Ask: The questions asked at this stage help identify the problem and shape the solution. This is the stage where the need(s) that the product will be designed to meet is determined and limitations of the design are identified. These limitations can be related to cost, time, target audience of the design, or scientific principles. The question at the beginning of the design process is "How can a functional product be designed using a carpet and flour?" First, the needs that can be met by combining the item and the material are determined. In the example case, inspired by observations from daily life, the product to be designed from flour and a carpet is decided to meet the nutritional needs of stray animals and animals in nature who live in harsh conditions. Then, criteria regarding the design are determined. In the example case, the criteria of the product to be designed were determined to be a combination of one or more properties of the carpet and flour, low design cost, easily mass production, and nature friendliness. The design is intended to help stray animals and animals in nature that live in rough conditions.

Imagine: This includes brainstorming ideas on how to solve a given problem. This is the stage where the opinions of relevant stakeholders (for example, the target audience) can be taken, and similar designs are examined. The main goal of this stage is to come up with original solutions to the identified problem. In doing so, the first step is to examine in detail the relationship between the target audience of the product and the need the product is designed to meet. In the example case, research was conducted on the nutritional needs of stray animals and animals in nature, for which the product is designed. The research revealed that the General Directorate of Nature Conservation and National Parks of the Turkish Ministry of Agriculture and Forestry places feeding shelters on an annual basis to prevent the starvation of animals in nature in the winter months.

Next, the chemical and physical properties, uses, and types of the carpet and the flour were researched, and the obtained data were grouped and listed. Using these lists, the unique characteristics of the item and the material and their relationship with the needs of the target audience are identified. For example, different types of carpets were found to be floor rugs, wall rugs, kitchen rugs, play rugs for kids, and mats, while their uses were found to be surface coating, protection from the cold surface, and interior decoration. Flour, on the contrary, in addition to being a nutrient, helps arrange food consistency and serves as a binding agent. Accordingly, the solution the product to be designed will offer to the identified problem can be summarized as follows: Using the carpet to cover the ground of feeding shelters and making use of the binding and nutritive characteristics of flour to produce food, thus ensuring the survival of animals in nature that live in harsh conditions.

Plan: Designs are drawn up in line with the solution determined in the previous stage; if there are multiple possible solutions, the best is selected. Here, the best solution refers to the one that meets the determined criteria, as well as the need, the most efficiently. Next, the drawn designs are examined and compared, and one of them is selected as the prototype. The design developed to solve the problem in the example case is presented in Figure 2.

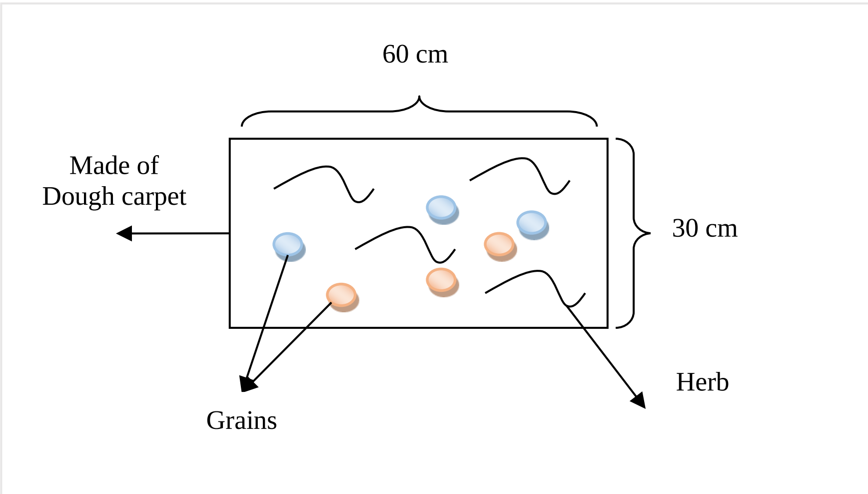


Figure 2. The Design developed to solve the Problem in the Example Case

The identified need is the prevention of starvation of animals in nature in harsh winter months, and the means of doing so is determined to be a combination of flour and carpet. The criteria of the product to be designed were determined to be a combination of one or more properties of the carpet and flour, low design cost, easily mass production, and nature friendliness. The developed prototype meets the identified need, as well as the criteria determined.

Create: A prototype that is compatible with the identified need (that the design is created to meet) and criteria is created (see Figure 3).

Improve: Based on the data obtained in the testing stage, the design is improved. This is the stage where the changes made to the product are justified based on the findings obtained in the testing stage that necessitated this improvement. The weaknesses of the design were reduced based on the data obtained during the testing stage. In doing so, to enable the feeding of the poultry animals in groups, the number of grains was increased, and they were distributed more homogeneously. In line with the finding that poultry animals mostly eat corn and wheat grains, different types of food were determined for different animals.

Lastly, the differences of the design from existing similar designs were listed, emphasizing its originality. The existing practices include leaving food in natural environments to prevent the starvation of wild animals in harsh winter conditions. However, these practices are carried out with a given type of food, which may not be suitable for the nutritional needs of all animals in the wild. The designed prototype, however, can be customized in line with the nutritional needs of relevant animals. Foods scattered around may be rendered inedible due to natural events, such as wind and rain. This problem is overcome owing to the binding property of flour. While the existing practices cause environmental pollution, the designed product is environmentally friendly, as it is made entirely from biodegradable materials.

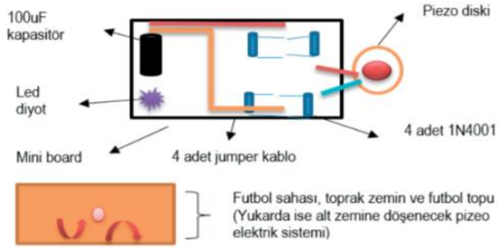
Figure 3. Prototype

Other Projects Designed by Following the "One Item, One Material" Method

In this section of the study, projects carried out by six pre-service science teachers will be presented in Table 1. Also, the items and materials picked out by students, the purposes of the designs made using these items and materials, and the photographs of the finished products are provided. By employing strategies and guidelines that activate students' creativity, each student can be encouraged to develop a project to the extent of their capacity.

Table 1. Other Projects Designed by Following the "One Item, One Material" Method

Item	Material	Purpose of the Project	Product
Pencil case	Wire	In order to add functionality to desks, a pencil case with a lamp and voice-command recognition was designed. In the design, the ability of pencil cases to store tools and items in an orderly manner and wire's flexibility and ability to string objects together were combined.	

Item	Material	Purpose of the Project	Product
Wallet	String	The purpose of the project is to design an easy-to-use and safe product with Braille inscriptions for visually impaired individuals. It is an adjustable product that can be easily used by individuals with vision impairment, with a fixed hanger, designed to be placed on the upper area of the left leg.	
Football	Soil	The project aims at electricity generation through the pressure exerted by solid objects on the ground and to store this electricity to meet the energy needs of areas such as football fields and tennis courts. With this system to be laid under the pitch, the pressure exerted by the athletes on the ground during games will be converted into electrical energy.	 *100uF capacitor *LED diode *Mini board *4 jumper cables *4 1N4001 *Piezo actuator disk Football field, dirt surface, football (Above is the piezoelectric system to be placed below the surface)
Glove	Sand	In this project, students were asked to design a planter with the aim of encouraging them to create artwork and grow and care for a plant.	
Pillow	Rubber	In this project, a travel pillow that provides safety/protection from external factors was designed using a pillow and soft rubber. The aim was to offer users a safe, comfortable, and peaceful sleep during their travels.	

Item	Material	Purpose of the Project	Product
Plastic bottle	Cotton	The aim of this project is to design a lamp that is easier and less costly to produce and more stylish than its expensive counterparts in the market.	

Discussion

It would be superficial to consider engineering, which is a standalone discipline, as merely a design and creation process that students only utilize to design simple products without taking into account the theoretical background. Basic engineering design knowledge can serve as a guide on how engineering can be integrated into teaching processes. NAE and NRC (2009) put forward three basic principles for the integration of engineering into the curricula of different levels of school education from pre-school to high school. These are (1) emphasizing the engineering design, (2) incorporation of important and developmentally appropriate mathematics, science, and technology knowledge and skills, and (3) promotion of engineering habits of the mind.

The most widely accepted approach to the integration of engineering design into the curricula is doing so in accordance with the education level of the students (Moore & Smith, 2014). In this study, the engineering design process developed by NASA (2011) was taken as a basis and adapted in line with the needs of the study. The said engineering design process is presented in Figure 4.

The concept of engineering as a habit of the mind refers to the values, attitudes, and thinking skills associated with engineering (NAE & NRC, 2009). This concept is defined as the ways of thinking and behaviors that engineers utilize in solving a problem (Lucas et al., 2014). The National Research Council (2010) put forward skills that align with engineering as a habit of the mind, namely, systems thinking, creativity, optimism, collaboration, communication, and attention to ethical considerations. In this study, students worked on these skills and gathered courage for their future projects. Systems thinking refers to a holistic perspective that acknowledges that the relationships among system components and between the components and the environment are as important as the whole structure (Monat & Gannon, 2018). An individual with the systems thinking skill focuses on repeated events and relationships between events, rather than on a specific situation in a series of events. In such cases, in the mind of the individual, patterns rather than snapshots are formed in the event flow, and it sees both the whole and the parts of the whole together (Senge, 1990).

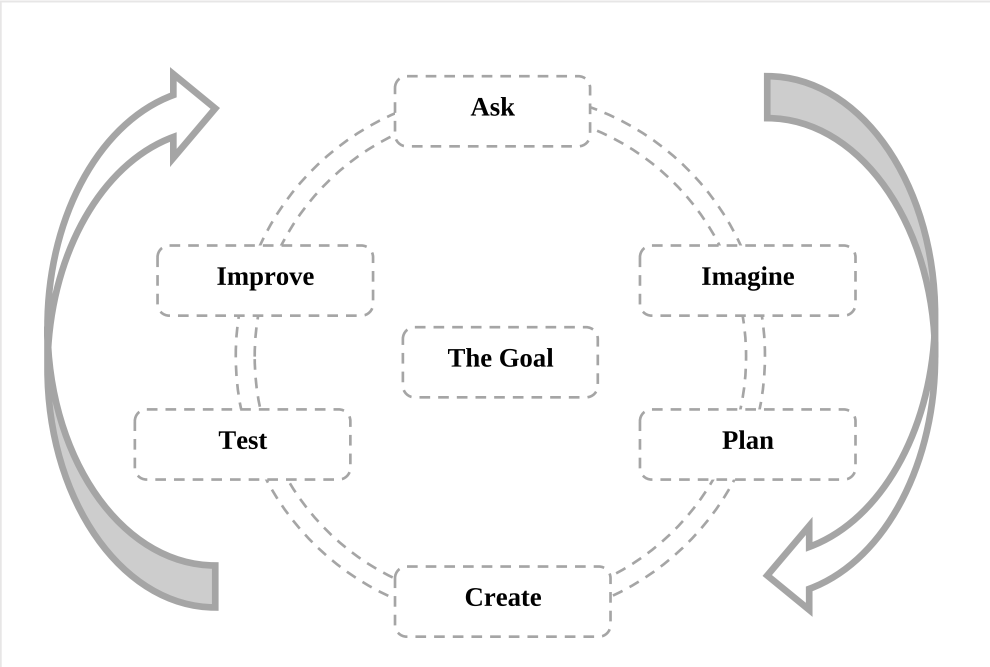


Figure 4. The Engineering Design Process used in the Study (adapted from NASA, 2011)

Conclusion

In this study, a theoretical investigation was carried out on the nature of engineering design and integrating in an effective manner the relevant concepts, skills, and practices into classroom activities. Then, techniques for carrying out engineering design-related activities with students were presented, and example applications that are compatible with the theoretical structure of engineering design were given.

In the integration of engineering design into classroom activities to encourage creativity, three principles are of critical importance: (1) the emphasis on engineering design, (2) the utilization of age-appropriate mathematics, science, and technology knowledge and skills, (3) and the incorporation of mental (minds-on) and physical (hands-on) activities into the curricula to support engineering as a habit of the mind and students' permanent acquisition of engineering concepts and skills. In ensuring the permanent acquisition of the said knowledge, it is important to make use of repetitive activities in the long term. The National Research Council (2012) conceptualized eight fundamental engineering practices in which students should be encouraged to engage, namely, asking questions and defining problems, developing and using models, planning and carrying out investigations, analyzing and interpreting data, using mathematics and computational thinking, constructing explanations and designing solutions, engaging in argument from evidence, and obtaining, evaluating, and communicating information—behavioral patterns in which concepts and information specific to each practice are used in concert (NRC, 2012). Engineering practices encompass building and learning, which go hand in hand (Mursid et al., 2022). In order to achieve competence in a field, repetitive activities that eventually turn into habits are carried out in time. For example, a violin virtuoso engages in many cognitive, affective, and psycho-motor behaviors through practice; with practice, they master and become capable of performing any piece without needing to look at a tab paper (Michaels, Shouse, & Schweingruber, 2007). Consequently, the development and utilization of teaching activities based on engineering practices help students understand the nature of engineering, internalize how engineers work, and identify the relationships between engineering and other disciplines (NRC, 2012).

Recommendations

Engineering design activities can be reinforced with subject-specific science concepts and scientific research methods. For example, in designing a lighting product that saves energy, relevant concepts such as current and voltage can be taught, or in the controlled experiments of the prototype, scientific methods can be emphasized. Similarly, certain mathematical concepts and computational methods can be used especially in the stages of model-prototype building and testing. Technology and technology-related concepts can be used to illustrate the outputs of engineering design. Technology can encourage the consideration of the social, environmental, and other impacts of design decisions. Measurement tools such as thermometers, various software for data collection and classification of data, graphing calculators, and computer design programs should be used appropriately to support engineering design (NAE & NRC, 2009).

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Appendix: Engineering Design Process Template and the Design Evaluation Scale

Engineering Design Process Template

First name, Last name		
Used in the design	*Item:*	*Material:*
Name of the project		
Purpose of the project		
Tools and other equipment used in design		
Implementation Process		
Ask (Problem is defined. This is the stage where the need(s) that the product will be designed to meet is determined, and the limitations related to the design are determined. These limitations can be related to cost, time, target audience of the design, or scientific principles.)		
Imagine (Brainstorming solutions for the identified problem. In this stage, the opinions of relevant stakeholders—for example, the target audience—can be taken). Similar designs are examined. The main goal of this stage is to demonstrate the unique nature of design solutions.)		
Plan (Designs are drawn up in line with the solution determined in the previous stage; if there are multiple possible solutions, the best is selected. The best solution refers to the one that meets the determined criteria, as well as the need, the most efficiently. Next, the drawn designs are examined and compared, and one of them is selected as the prototype.)		

Create (A prototype that is compatible with the identified need, that the design is created to meet, and criteria is created. Here, photographs from the different stages of production should be attached. These photographs should be in high resolution and have a white background.)	
Test (Evaluation of whether the prototype meets the identified need. At this stage, data on the design are collected and analyzed. In the testing stage, the strengths and weaknesses of the design are identified.)	
Improve (Based on the data obtained in the testing stage, the design is improved. In this stage, the changes made to the product are justified based on the findings obtained in the testing stage that necessitated this improvement.)	
Project Evaluation Process	
Difference of project product from existing ones (List in items)	
Photographs of the project product from different angles (high-resolution, from at least high different angles. The photographs should have a white background. During the homework submission, these photos should be submitted electronically in jpg, png, or gif format.)	

Design Evaluation Scale

Design and functionality		
A. Is it functional?	Yes	No
B. Is it durable?	Yes	No
C. Is it low-cost?	Yes	No
D. Is it safe?	Yes	No
E. Can it be used by an independent user?	Yes	No
F. Is it easy to use?	Yes	No
G. Is it easy to handle?	Yes	No
H. Is it easy to store?	Yes	No
İ. Does it have a long shelf life?	Yes	No