Chapter 9
Using Engineering Design in Technology Education

Euisuk Sung and Todd R. Kelley

Abstract In contemporary technology education, engineering design is becoming an essential component to connect technology with Science, Mathematics, and Engineering. The engineering design process is an iterative process of devising a system, component, or strategy to meet desired needs. Still, there are many unanswered questions: "Why do we use the engineering design process?" "How do we use the design process?" and "How do students use the engineering design process to solve technological problems?" This chapter will review the existing engineering design process models presented by textbooks and researchers. Then, the author considers contemporary learning theories that align with the engineering design process in terms of design cognition. Next, the author will present a design process model derived from an experimental pattern study. This chapter will explain how students perceive and undertake the engineering design process in an authentic problem-solving setting, based on the research findings. Finally, this chapter contains practical suggestions on the use of the engineering design process in the classroom.

Keywords Engineering design · Sequential analysis · Engineering and technology education · STEM education · Design cognition

9.1 The Questions I Asked and Why They Are Important

With the integrative movement of Science, Technology, Engineering, and Mathematics (STEM) education, engineering design is positioned as an essential component of technology and engineering education. The International Technology and Engineering Educators' Association (ITEEA) released the new standards, named Standards for Technological and Engineering Literacy (STEL; ITEEA, 2020), which

E. Sung (✉)
New York City College of Technology, New York, USA
e-mail: ESung@citytech.cuny.edu

T. R. Kelley
Purdue University, West Lafayette, USA

P. J. Williams and B. von Mengersen (eds.), *Applications of Research in Technology Education*, Contemporary Issues in Technology Education,
https://doi.org/10.1007/978-981-16-7885-1_9

include engineering literacy as one of the core components of technology education. STEL described engineering as using scientific principles and mathematical reasoning to optimize technologies to meet needs defined by criteria under given constraints. The adoption of engineering in technology education can be considered in terms of two functions of engineering: (1) as noun engineering means a discipline, artifacts, and careers; (2) as verb engineering refers to engineering actions such as designing, developing, researching, and applying of engineering habits of mind. In technology education, the two aspects have been implemented through the engineering design process. The Standards for Technological Literacy (STL; ITEEA, 2000/2003/2007) stated that "Engineers [...] use a particular approach called the engineering design process. [...] The engineering design process demands critical thinking, the application of technical knowledge, creativity, and an appreciation of the effects of design on society and the environment" (p. 99). The use of engineering design helps students develop the engineering habits of mind and consider engineering a possible future career.

However, little is known about the engineering design process, particularly for K-12 education. Many technologies and engineering textbooks introduce engineering design as a technological problem-solving process and present numerous design process models. Still, little emphasis is given to how educators and students use the process models. One of the most prevalent misconceptions about the engineering design process is the belief that it provides an optimal problem-solving process. Mosborg et al. (2005) studied the authenticity of engineering design processes where the researchers asked engineers how their practices compare to a design process model shown in technology and engineering textbooks. Their study revealed that most engineering practitioners disagreed with the design process model because the actual engineering design process contains complex iterations that vary depending on the types of problems and contexts. Another misconception about the engineering design process is that it is a linear or single path. The volume of design studies confirmed that there is no single correct procedural pathway of the design process (Chan & Schunn, 2015; Dorst & Cross, 2001; Jin & Chusilp, 2006; Kim & Kim, 2015). Instead, the researchers agreed that design processes are highly iterative and vary in type, context, designer expertise, and other factors (Adams, 2002; Dorst, 2004; Harfield, 2007; Jonassen, 2000; Kruger & Cross, 2006). Therefore, in this study, the author attempted to identify how students perform design tasks focusing on the engineering design process resulting in two research questions.

1. What are the characteristics of the engineering design process of elementary students when solving engineering challenges?
2. What are the patterns of the problem-solving strategies in the engineering design process?

9.2 How I Answered the Questions

The context of this study was the National Science Foundation (NSF)-funded Math Science Targeted Partnership (MSP) Science Learning through Engineering Design (SLED). The project was conducted for five academic years, from 2011 to 2016. The SLED project built collaborative partnerships with four colleges within a large, research-intensive university and four school corporations located in the Midwest of the USA. The project's overarching goal was to enhance science learning by integrating the engineering design approach into the elementary classroom. Throughout the five-year project, the research project videotaped 48 engineering design team challenges, and each team consisted of three elementary students. The total number of participants was 144, and the entire duration of video and audio recording was 13 h 52 min. The SLED research team developed the engineering design challenges used in this study. This project used eight engineering design challenges, as listed in Table 9.1.

This study adopted a sequential analysis method to detect the patterns of the design process in engineering challenges (Bakeman & Gottman, 1986). The author observed students' behaviors when the elementary students responded to the engineering design challenges and found repeating patterns of design strategies. For example, students often start an engineering challenge with identifying problems and then move to the analysis process, where they research the constraints and criteria of the challenge. Also, when generating design solutions, they tended to move back and forth between questioning, predicting, and drawing stages of the engineering design process. The underlying idea of this study was the repeated design strategies form clusters of design patterns, and the collection of the clustered patterns characterize the design behaviors. The author believed that identifying patterns not only helps identify how students perform the engineering design but also provides a fundamental understanding of how students solve engineering problems. Therefore, this study sought the statistical significance of repeating design behaviors using a pattern detection methodology presented by Bakeman and Gottman (1986). The adoption of

Table 9.1 Engineering design challenges

Grade	Lesson title	Engineering and science concepts
Grade 3	Musical instrument	Sound, pitch, waves
	Simple machine	Force, gears, lever, pulley, wedge, fulcrum
Grade 4	Canal	Erosion, drainage, slope, runoff
	Door alarm	Electrical power, open- and closed-circuits, load
Grade 5	Prosthetic leg	Mass, volume, kinetic energy
	Water filter	Filtration, purification, water quality
Grade 6	Roller coaster	Potential energy, kinetic energy, gravity, friction
	Solar tracker	Earth rotation, direct versus indirect lights, ball bearings, linkage

Table 9.2 Engineering strategy coding scheme

Design strategy (Code)	Description
Defining problem (s) (DF)	stating or defining a problem which will enhance the investigation leading to an optimal solution
Analyzing (AN)	identifying, isolating, or breaking down to clarify the essential components of the problem
Predicting (PR)	prophesying or foretelling something in advance; anticipating the future based on special knowledge
Questions (QH)	asking, interrogating, challenging, or seeking answers related to a problem
Designing (DE)	conceiving, creating, inventing, contriving, or planning
Managing (MA)	planning, organizing, directing, coordinating, and controlling the inputs and outputs of the system
Modeling (MO)	presenting ideas graphically in the form of a sketch, diagram, or equation

the pattern detection technique allowed the researcher to present the results through statistical significance.

This study used the Concurrent Think-Aloud (CTA) protocol, a research method that asks the participants to speak aloud while performing specific tasks. The research team videotaped the participants' design strategies and coded them using Halfin's (1973) codes. Halfin developed 17 cognitive strategies commonly used by engineers and scientists in his dissertation study. This study revised his codes and adopted seven of the initial codes, as shown in Table 9.2.

9.3 What I Found Out

To characterize the process of problem-solving in engineering design, the author presents the pattern analysis results using average time percentages, the frequency, and the duration of design strategies used in the 48 CTA sessions. Based on the coding results, the author conducted a sequential pattern analysis to detect the cognitive patterns of the design process. The coded raw data were exported to a string of sequential events and analyzed using GSEQ software (Bakeman & Quera, 2015).

9.3.1 Use of the Engineering Design Process

To identify the features of design strategies used by elementary students in engineering design challenges, the author analyzed the 48 engineering design sessions. Table 9.3 and Fig. 9.1 illustrate how elementary students utilized design strategies

Table 9.3 Time usages in 48 engineering design sessions

Design strategy	Mean	SD	Min	Median	Max
Analyzing (AN)	01:09.7	01:04.2	00:00.0	01:01.4	05:05.2
Designing (DE)	08:01.4	03:13.6	00:39.5	08:26.0	14:18.2
Defining Problems (DF)	02:03.3	00:31.4	01:07.3	01:53.1	03:19.8
Managing (MA)	00:50.5	00:38.4	00:00.0	00:49.6	02:21.8
Modeling (MO)	03:15.9	01:52.2	00:15.6	03:16.9	06:49.3
Predicting (PR)	01:05.2	00:44.2	00:00.0	01:08.3	03:38.7
Questioning (QH)	00:54.1	00:43.0	00:01.1	00:40.5	02:56.2
Total	17:20.2				

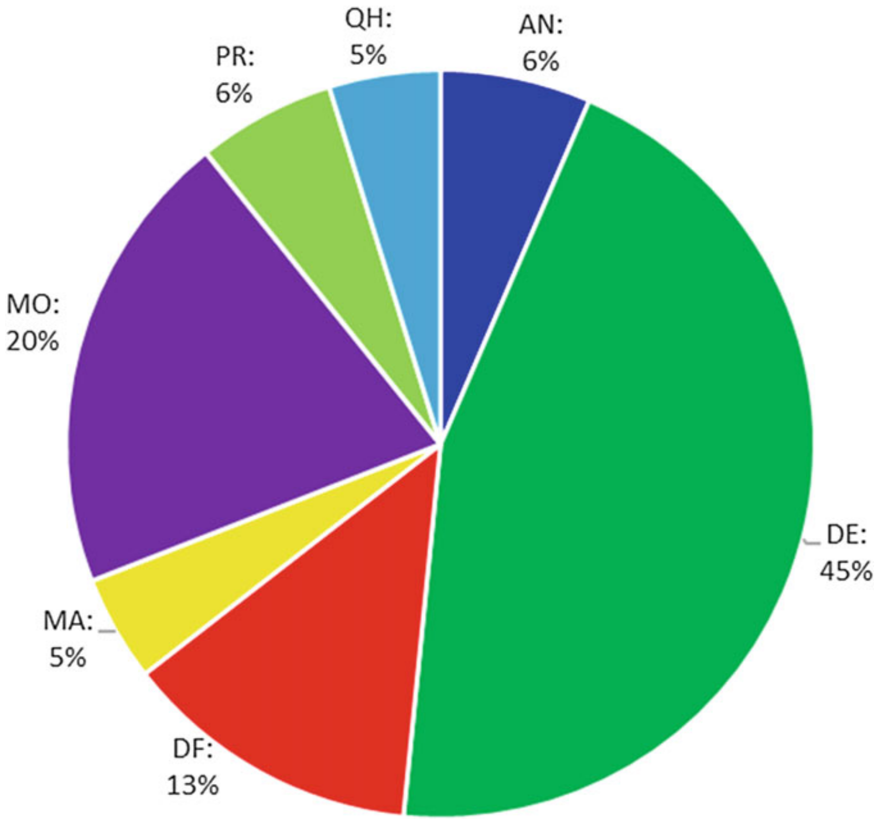

Fig. 9.1 Mean time percentages of 48 CTA sessions

with their time usages. The average duration of the engineering design session was 17:20.2 (17 min and 20.2 s). The shortest session was 5:35.4, and the most extended session was 28.03.6 min. The overall statistics indicate that the participants spent most of their time Designing (DE, duration (d) = 08:01.4) and minoring in Managing (MA, d = 00:50.5), Predicting (PR, d = 01:05.2), or Analyzing (AN, d = 01:09.7).

The author presented the time usages in each design challenge to understand how the different design challenges shape other design behaviors. Because each engineering design challenge had different time lengths, the researcher converted the measured time into the relative duration per 10-min interval.

The results show that almost half of the time in the engineering challenges was dedicated to Designing while Predicting, Questioning, Managing, and Analyzing were relatively small. For example, the individual charts in Fig. 9.2 indicate that students spent longer in Designing in the Simple Machine challenge, which required designing a physical device to save a wolf from a trap. Also, students spent more time Analyzing design strategies in the Water Filter and Canal design challenges which had longer design statements with complex design requirements.

9.3.2 Common Design Patterns of the Engineering Design Process

This study conducted a sequential pattern analysis to identify the patterns of the sequential process of the engineering design strategies. The pattern analysis relies on the sequential order of design strategies and their frequencies. Table 9.4 shows the overall statistics of design strategy frequencies with their sequences. For example, the number 198 (212.52) in the cell crossing AN and DE implies the transitions from Analyzing to Designing occurred 198 times. Accordingly, the expected frequency of 212.52 indicates that the expected statistical number of shifts from Analyzing to Designing was 212.52 based on the AN row (355) and DE column (1,939).

Based on the numbers of observed and expected statistics, the author obtained statistical possibilities of the sequential transitions with z-scores and p-values shown in Table 9.5. For example, the p-value crossing AN and MA was 0.047 ($z = 1.99$), which implies the transitions from Analyzing to Managing were statistically significant compared to other sequential events. The bold values in Table 9.5 indicate the patterns statistically significant at the 0.05 level.

The author visualized the results in Table 9.5 by illustrating statistically significant transitions with their sequential orders in Fig. 9.3. Figure 9.3 reflects that most of the engineering design sessions started with reading the design brief, so the patterns begin with Defining Problems (DF, $n = 167$). There exist two pathways from Defining Problems to the next stages of Analyzing (DF → AN, $p < 0.001$, $z = 16.02$) and Managing (DF → MA, $p < 0.001$, $z = 6.81$). The Analyzing (AN, $n = 355$) stage had two significant paths to Questioning (AN → QH, $p = 0.007$, $z = 2.72$) and Managing (AN → MA, $p = 0.047$, $z = 1.99$). Questioning (QH, $n = 636$) also had

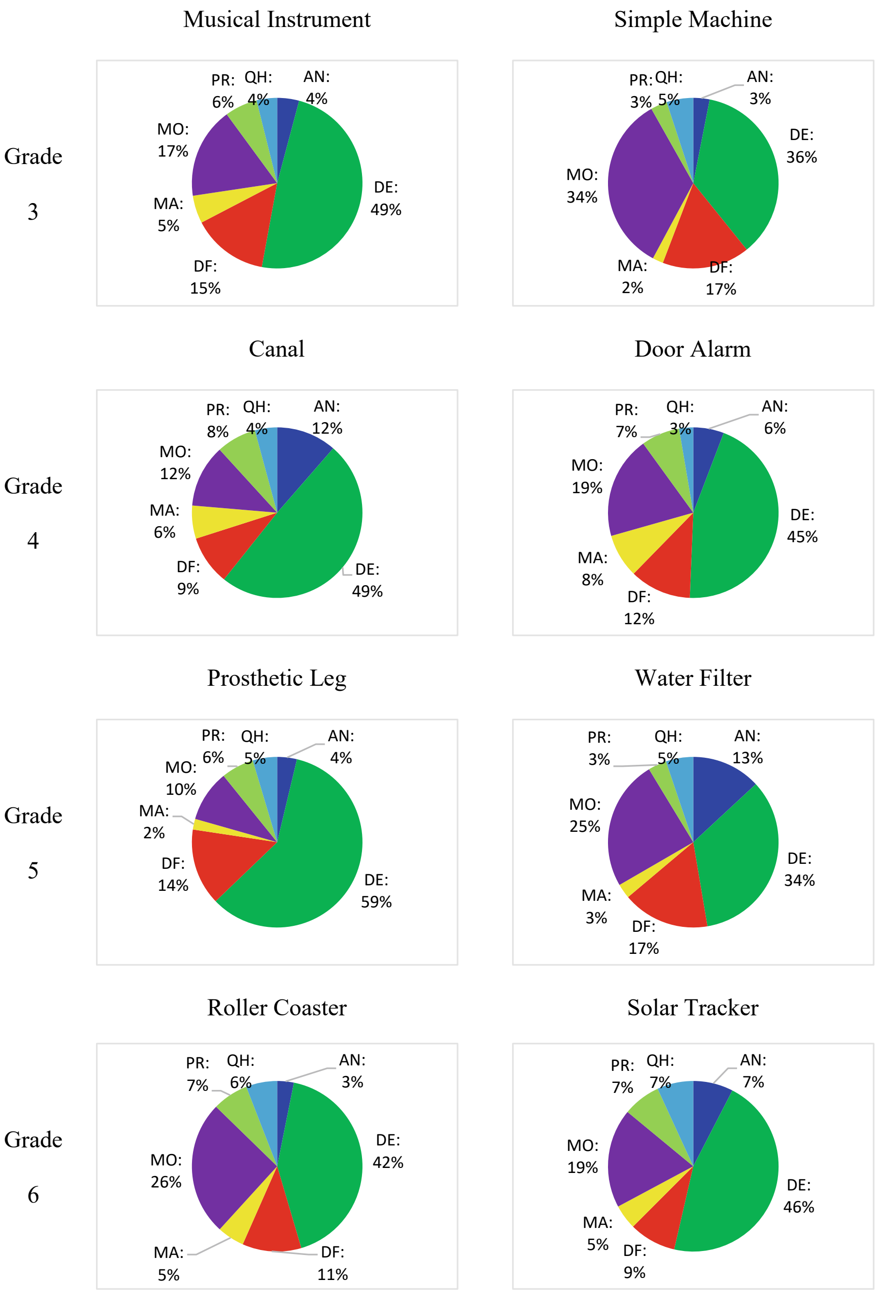

Fig. 9.2 Mean percentages of design strategies by engineering design challenges

Table 9.4 Observed and expected frequencies of design strategies in 48 engineering design sessions

Observed (Expected)	Given								
		AN	DE	DF	MA	MO	PR	QH	Total
Target	AN		198 (212.52)	24 (05.75)	33 (24.04)	34 (56.08)	19 (23.65)	47 (32.96)	355
	DE	152 (212.01)		52 (69.20)	209 (289.52)	805 (675.42)	367 (284.87)	343 (397.00)	1,928
	DF	51 (08.01)	68 (96.75)		32 (10.94)	7 (25.53)	0 (10.77)	9 (15.01)	167
	MA	36 (22.57)	250 (272.54)	23 (07.37)		86 (71.92)	9 (30.33)	43 (42.27)	447
	MO	36 (55.89)	646 (674.79)	11 (18.24)	127 (76.32)		42 (75.10)	143 (104.66)	1,005
	PR	18 (23.56)	293 (284.42)	1 (07.69)	57 (32.17)	47 (75.05)		51 (44.11)	467
	QH	62 (32.96)	484 (397.97)	8 (10.76)	20 (45.01)	30 (105.01)	32 (44.29)		636
	Total	355	1,939	119	478	1,009	469	636	5,005

Table 9.5 z-scores and p-values of sequential design strategies

P-value (Z-score)	Given							
		AN	DE	DF	MA	MO	PR	QH
Target	AN		0.187 (−1.32)	**<0.001**[a] **(8)**	**0.047**[a] **(1.99)**	0.001 (−3.42)	0.298 (−1.04)	**0.007**[a] **(2.72)**
	DE	<0.001 (−5.45)		0.008 (−2.67)	<0.001 (−6.35)	**<0.001**[a] **(7.12)**	**<0.001**[a] **(6.52)**	<0.001 (−3.7)
	DF	**<0.001**[a] **(16.02)**	<0.001 (−3.8)		**<0.001**[a] **(6.81)**	<0.001 (−4.17)	<0.001 (−3.51)	0.091 (−1.69)
	MA	**0.002**[a] **(3.07)**	0.067 (−1.83)	**<0.001**[a] **(6.11)**		0.051 (1.95)	<0.001 (−4.26)	0.897 (0.13)
	MO	0.002 (−3.09)	0.114 (−1.58)	0.055 (−1.92)	**<0.001**[a] **(6.82)**		<0.001 (−4.49)	**<0.001**[a] **(4.49)**
	PR	0.211 (−1.25)	0.497 (0.68)	<0.010 (−2.56)	**<0.001**[a] **(4.83)**	<0.001 (−3.81)		0.242 (1.17)
	QH	**<0.001**[a] **(5.62)**	**<0.001**[a] **(5.9)**	0.363 (−0.91)	<0.001 (−4.2)	<0.001 (−8.77)	0.038 (−2.08)	

Note [a] Right-tailed at 0.05 level

two significant sequential patterns to Analyzing (QH → AN, $p < 0.001$, $z = 5.62$) and Designing (QH → DE, $p < 0.001$, $z = 5.9$). The Designing (DE, $n = 1{,}928$) strategy resulted in two significant transitions to Predicting (DE → PR, $p < 0.001$, $z = 6.52$) and Modeling (DE → MO, $p < 0.001$, $z = 7.12$).

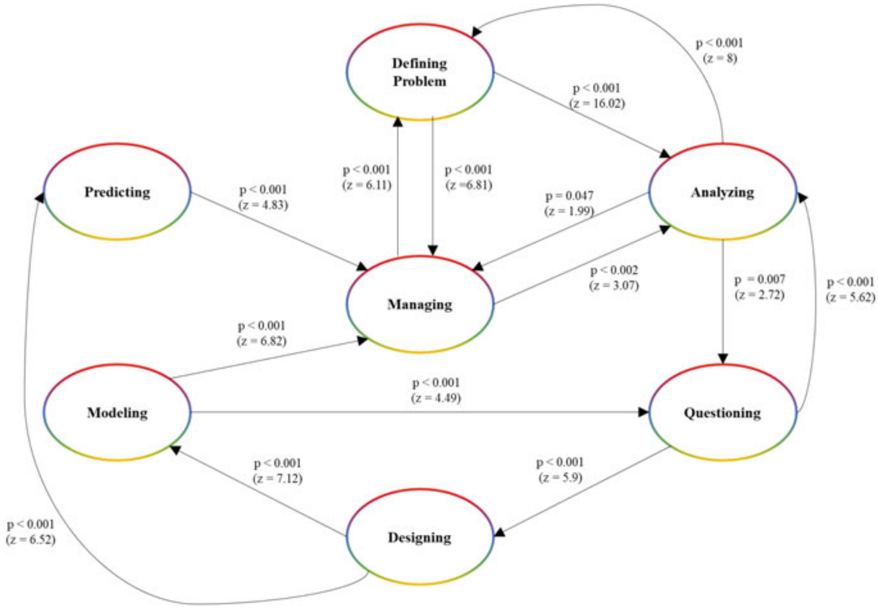

Fig. 9.3 Pattern diagram of design strategies with statistical significance

The model shows the recursive patterns of all design stages. There exist bidirectional patterns between Defining Problems and Analyzing, Analyzing and Questioning, Analyzing and Managing, and Defining Problems and Managing. The researcher also found cyclical patterns between Questioning, Designing, Predicting, Modeling, and Managing. After Questioning, the model shows two subsequent design pathways: (1) Questioning → Designing → Modeling → Questioning or Managing, and (2) Questioning → Designing → Predicting → Managing. These results indicate that the Designing (DE) strategy relates to Modeling and Predicting, which externalizes mental representation by drawings (MO) or predicts the consequences of design ideas (PR). Another finding from the pattern diagram is that Managing (MA) was a mediator of Design strategies. The Managing was associated with problem identification strategies (MA ↔ DF, MA ↔ AN) and solution strategies (MO → MA, PR → MA). The Managing coding scheme contained control assertions such as "What's next?" "What would we do?" "Let's do this." Using Managing cognition, the participants iterated their design strategies from solution strategies to problem strategies.

9.4 How Can This Research Be Used to Improve Teaching and Learning?

9.4.1 Concentration on Designing and Modeling

The results identified that the participant students spent more than half of their time in *Designing (45%)* and *Modeling* (20%). The high percentage of the two design strategies illustrates that vital engineering design elements are generating solutions and expressing ideas to share, implement, and test the solution. There is no clear evidence that the high percentages of design and modeling represent a good design strategy. However, Atman and her colleagues (2007) found that engineering experts tend to spend more time designing than novices. Mentzer et al. (2015) compared the use of problem-solving strategies between high school and college students and concluded that college students are prone to spend more time on solution strategies (designing, modeling, and predicting) while high school students tend to focus on problem strategies (problem identification and analyzing). In summarizing the findings of this study and literature research, *Designing* and *Modeling* are the heart of engineering design, and expert engineers tend to focus on these stages more than other strategies. While there is no guarantee staying in Designing and Modeling longer produces a quality design, this result may imply that technology and engineering educators will need to provide appropriate and effective strategies to identify the design problem and focus on ideations, modeling, and designing.

9.4.2 Use of Modeling as a Mental Tool

The use of modeling strategies in engineering design prompts a rethink of the engineering design process in terms of design cognition. Goldschmidt (1991) noted that engineers use sketching as a tool to display mental images, which informs us that students similarly need to learn the way to visualize their mental ideas as a form of realization (Goldschmidt, 1991). Sung et al. (2019) showed that the use of informed sketching techniques with schematic symbols and strategic approaches led to quality design sketches and creative ideas. In this study, the research found *Designing* and *Modeling* occurred sequentially after *Questioning* strategies. For example, many triad design teams started designing with guiding questions such as “how can we improve this solution?” and then generated ideas and stored them as a form of sketching. Cognitive scientists argued that the mental capacity of a human is limited to holding a certain amount of information so that it can process only a few pieces of information at a time, and only a few are transferred to long-term memory (Bruning et al., 2011). However, this study indicates that engineering design helps students expand their mental capacity through sketching, an externalized device for modeling mental images. This result implies a critical point that engineering and technology educators should not overlook the power of sketching in engineering design, including rough freehand sketching.

9.4.3 Problem Versus Solution-Oriented Approaches

This study confirmed that the participants emphasized problem identification more diminutive than the other design strategies. The mean percentages of Defining Problem and Analyzing were 13% and 6%, respectively. This study showed that the use of Defining Problems and Analyzing varied by design task. The percentages of Defining Problem ranged from 9% of Solar Tracker to 17% of Simple Machine. The rates of Analyzing varied from 3% of Simple Machine to 13% of Water Filter. The results show that the participants heavily focused on problem identification (see Fig. 9.2). Several design studies have investigated the relationship between problem identification and the quality of the design. Atman and Bursic (1998) investigated the relationship between the ratio of problem-scoping and solution quality. They confirmed that more emphasis on problem-scoping yielded a quality design solution. Kruger and Cross (2006) compared the outcomes of problem-driven and solution-driven designs. Their study demonstrated that the design strategies focused problem-driven resulted in low creativity scores and high overall design quality. Meanwhile, solution-driven strategies yielded high creativity and lacking overall quality. Although there is no clear evidence which approach is dominantly excellent or bad, technology and engineering educators need to consider a balanced problem- and solution-driven design strategies depending on students' prior knowledge and skills in engineering design.

9.4.4 Stressing the Iterative Design Process

Most design process models illustrate the engineering design process as a sequential procedure. For example, one of the well-known design process models, French's design process model (1999), depicted design process as a sequential process of (1) Identifying the need, (2) Analysis of problem, (3) Statement of the problem, (4) Conceptual design, (5) Selected schemas, (6) Embodiment of schemas, (7) Detailing, and (8) Working drawings. While this model stresses the recursive nature of the design process, many students and teachers misunderstand by thinking that the design process is a strict procedure that they should follow to achieve the best results (Crismond & Adams, 2012; Mosborg et al., 2005). Koen (2003) noted that engineers want to produce the best solution to their problems. The notion of the best solution is often called *optimization* in engineering. However, authentic engineering design problems do not have the best solution to all problem types. A design process model is a shortcut to a solution that meets the design criteria under certain constraints, not an approach to reach the best solution. As shown in the pattern-based design process model in Fig. 9.3, the author confirmed multiple pathways in the engineering design process. Nowadays, many engineering problems require creative and innovative solutions. However, fixed, and inflexible design processes yield uniform design solutions and do not offer creative solutions. The findings of this study confirmed that students did not follow a fixed design pathway. Instead, they tended to iterate several design strategies to explore solutions to the problem. This may imply that educators need to avoid forcing students to follow a fixed design process and encourage them to iterate design steps to find better solutions.

9.4.5 Engineering Inquiry

Burks (1946) defined inquiry as an activity of resolving authentic doubt to achieve a stable belief. Crismond and Adams (2012) noted that informed designers use inquiry to collect, organize, and analyze evidence that provides rich resources for engineering design devices and systems. Engineers' inquiry is comparable with scientific inquiry. Junginger (2007) argued, "to arrive at good design today, designers have to get involved in a systematic inquiry beyond aesthetics and functions" (p. 59). Lewis (2006) claimed that inquiry facilitates convergent and divergent thinking in engineering design. This study showed that questioning was a critical stage that bridged problem and solution domains. Also, questioning was an entry point to the solution strategies such as designing, predicting, and modeling. Based on these results, the researcher encourages educators to value the inquiry of engineering design as they make the scientific inquiry of science learning (NRC, 2000, 2012). The researcher promotes engineering and technology educators to develop effective questioning strategies to encourage the inquisitive habit of mind by raising inquiry questions such as "what is the problem?" "who is the client?" "how will your team create the prototype, model, or solution?" "how will you record results?" "how will you improve your solution?" or "how will you use your design solution?".

9.5 Conclusion

The ability to solve problems in creative and innovative ways is becoming more critical than ever (Friedman, 2012). Many companies face global competition in producing creative products and services; therefore, our students need to develop creative problem-solving abilities. To support these demands, the educational curricula in the U.S. and other countries focus on building creativity, communication, design, and innovation (Brown, 2008). In the last two decades, many K-12 STEM educational standards have attempted to integrate multiple disciplines using engineering design as a platform to foster students' problem-solving abilities (Common Core State Standards Initiative, 2010; ITEA/ITEEA, 2000/2003/2007; the NGSS Lead States, 2013). When adopting the engineering design approach in schools, appropriate instruction about the engineering design process must build these practical problem-solving abilities.

The journey of this study began with the simple question, "How do students solve engineering problems?" As a technology teacher, the author experienced when students solve engineering problems in the classroom. They tended to show a specific type of behavioral or cognitive pattern. This study attempted to identify the cognitive patterns of problem-solving in young students using Halfin's codes (1973) and sequential analysis (Bakeman & Gottman, 1986). While doing this research, the most exciting moment was when the author checked the statistical results, which were similar to what the study had witnessed in his technology and engineering classes. When teaching technology and engineering, the author met many engineering design process models from textbooks or other teaching materials but often used them without considering why they were created and how to use them. This study does not intend to provide which model is the best or the correct answer but to reflect on the practice of engineering design in the technology and engineering classroom.

One of the biggest takeaways of this study is that engineering design is not just solving a problem, it makes students cognitive thinker, and technology and engineering education plays a significant role in building the ability. Contemporary research from cognitive and learning science indicates that students are active learners, and the primary function of educators is to facilitate student learning by building educative learning environments (McCaslin & Hickey, 2001). As this study indicated, students use various cognitive strategies, including framing problems, analyzing and formulating questions, ideations, modeling, and self-regulation, and managing the group performance in the process of engineering design. With the adoption of engineering into technology education (STEL, 2020), it is important to investigate where the focus of technology and engineering education should reside and what educational outcomes we want to bring into K-12 education. The results of this study will help engineering, technology, and more significant STEM education communities improve understandings of how students undertake engineering design challenges and problem-solving pathways.

References

Adams, R. S. (2002). Understanding design iteration: Representations from an empirical study. In *Common Ground: Proceedings of the Design Research Society International Conference at Brunel University* (pp. 1151–1161). Staffordshire University Press.

Atman, C. J., & Bursic, K. M. (1998). Verbal protocol analysis as a method to document engineering student design processes. *Journal of Engineering Education, 87*(2), 121–130. https://doi.org/10.1002/j.2168-9830.1998.tb00332.x

Atman, C. J., Adams, R. S., Cardella, M. E., Turns, J., Mosborg, S., & Saleem, J. (2007). Engineering design processes: A comparison of students and expert practitioners. *Journal of Engineering Education, 96*(4), 359–379. https://doi.org/10.1002/j.2168-9830.2007.tb00945.x

Bakeman, R., & Gottman, J. M. (1986). *Observing interaction: An introduction to sequential analysis*. Cambridge University Press.
Bakeman, R., & Quera, V. (2015). *GSEQ: Generalized sequential 5.1.22*. http://www2.gsu.edu/~psyrab/gseq/
Brown, T. (2008). Design thinking. *Harvard Business Review, 86*(6). https://hbr.org/2008/06/design-thinking
Burks, A. (1946). Peirce's theory of abduction. *Philosophy of Science, 13*(4), 301–306. https://doi.org/10.1086/286904
Bruning, R. H., Schraw, G. H., & Norby, M. M. (2011). *Cognitive psychology and instruction* (5th ed.). Pearson.
Chan, J., & Schunn, C. (2015). The impact of analogies on creative concept generation: Lessons from an in vivo study in engineering design. *Cognitive Science, 39*(1), 126–155. https://doi.org/10.1111/cogs.12127
Common Core State Standards Initiative. (2010). *Common core state standards for mathematics.* National Governors Association Center for Best Practices and the Council of Chief State School Officers.
Crismond, D. P., & Adams, R. S. (2012). The informed design teaching and learning matrix. *Journal of Engineering Education, 101*(4), 738–797. https://doi.org/10.1002/j.2168-9830.2012.tb01127.x
Dorst, K. (2004). On the problem of design problem-problem solving and design expertise. *Journal of Design Research, 4*(2), 126–139. https://doi.org/10.1504/JDR.2004.009841
Dorst, K., & Cross, N. (2001). Creativity in the design process: Co-evolution of problem–solution. *Design Studies, 22*(5), 425–437. https://doi.org/10.1016/S0142-694X(01)00009-6
French, M. J. (1999). *Conceptual design for engineers* (3rd ed.). Springer, London.
Friedman, K. (2012). Models of design: Envisioning a future design education. *Visible Language, 46*(1), 132–153. https://search.proquest.com/docview/1019963104?accountid=13360
Goldschmidt, G. (1991). The dialectics of sketching. *Creativity Research Journal, 4*(2), 123–143. https://doi.org/10.1080/10400419109534381
Halfin, H. H. (1973). *Technology: A process approach.* Doctoral dissertation, West Virginia University. *Dissertation Abstracts International, 11*(1), 1111A.
Harfield, S. (2007). On design 'problematization': Theorising differences in designed outcomes. *Design Studies, 28*(2), 159–173. https://doi.org/10.1016/j.destud.2006.11.005
International Technology and Engineering Education Association (ITEA/ITEEA). (2000/2003/2007). *Standards for technological literacy: Content for the study of technology.* Author
International Technology and Engineering Education Association (ITEEA). (2020). *Standards for technological and engineering literacy: The role of technology and engineering in STEM education.* Author
Jin, Y., & Chusilp, P. (2006). Study of mental iteration in different design situations. *Design Studies, 27*(1), 25–55. https://doi.org/10.1016/j.destud.2005.06.003
Jonassen, D. H. (2000). Toward a design theory of problem solving. *Educational Technology Research and Development, 48*(4), 63–85. https://doi.org/10.1007/BF02300500
Junginger, S. (2007). Learning to design: Giving purpose to heart, hand, and mind. *Journal of Business Strategy, 28*(4), 59–65. https://doi.org/10.1108/02756660710760953
Kim, E., & Kim, K. (2015). Cognitive styles in design problem solving: Insights from network-based cognitive maps. *Design Studies, 40*, 1–38. https://doi.org/10.1016/j.destud.2015.05.002
Koen, B. V. (2003). *Discussion of the method: Conducting the engineer's approach to problem solving*. Oxford University Press.
Kruger, C., & Cross, N. (2006). Solution driven versus problem driven design: Strategies and outcomes. *Design Studies, 27*(5), 527–548. https://doi.org/10.1016/j.destud.2006.01.001
Lewis, T. (2006). Design and inquiry: Bases for an accommodation between science and technology education in the curriculum? *Journal of Research in Science Teaching, 43*(3), 255–281. https://doi.org/10.1002/tea.20111

McCaslin, M., & Hickey, D. T. (2001). Educational psychology, social constructivism, and educational practice: A case of emergent identity. *Educational Psychologist, 36*(2), 133–140.

Mentzer, N., Becker, K., & Sutton, M. (2015). Engineering design thinking: High school students' performance and knowledge. *Journal of Engineering Education, 104*(4), 417–432. https://doi.org/10.1002/jee.20105

Mosborg, S., Adams, R., Kim, R., Cardella, M., Atman, C., & Turns, J. (2005, June). Conceptions of the engineering design process: An expert study of advanced practicing professionals. Paper presented at *2005 Annual Conference*, Portland, OR. https://peer.asee.org/14999

National Research Council. (2000). *Inquiry and the national science education standards: A guide for teaching and learning*. National Academies Press.

National Research Council. (2012). *A framework for K12 science education: Practices, cross cutting concepts, and core ideas*. National Academies Press.

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. National Academies Press.

Sung, E., Kelley, T. R., & Han, J. (2019). Influence of sketching instruction on elementary students' design cognition: A study of three sketching approaches. *Journal of Engineering Design, 30*(6), 199–226.

Euisuk Sung is an assistant professor of Career & Technology Teacher Education at New York City College of Technology. He studied computer science for his bachelor's degree and worked in a start-up company as a software engineer. After years of working in computer science, he decided to become an educator, which was the most valuable work for his career. He taught in public high schools for nine years and authored several technology education textbooks. He completed his Ph.D. degree in engineering and technology teacher education, and his research interest includes the maker movement, computational thinking, and design thinking.

Todd R. Kelley is an Associate Professor in Technology Leadership and Innovation and joined Purdue University in 2008 upon completion of his Ph.D. at the University of Georgia. His dissertation research was on teaching and learning engineering design in secondary education. Prior to graduate school, Kelley was a high school and middle school technology education teacher for nine years teaching in three school districts in New York state and Indiana. Todd's research focus is in design and cognition seeking to better understand how young students learn design and how design improves STEM education. He joined a team of researchers to create a program to improve learning STEM in elementary grades, and the team was awarded an NSF Math and Science partnership called Science Learning Through Engineering Design (SLED). Todd is currently the PI on an NSF I-Test project called Teachers and Researchers Advancing Integrated Lessons in STEM (TRAILS). TRAILS prepares science and technology education teachers to integrate STEM content through biomimicry inspired engineering design within the context of entomology.