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Elementary Students' Engineering Design Process: How Young Students Solve Engineering Problems

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Abstract

With the increasing importance of teaching STEM to young students, the engineering design process (EDP) has become a popular learning platform in K-12 STEM education. The engineering design process guides students in solving engineering problems, but there is a lack of understanding of how students utilize this process. In this study, we explored how iterative design activities form procedural patterns of the engineering design process using sequential analysis. We videotaped 48 engineering design sessions via the Concurrent Think-Aloud (CTA) protocol from elementary students grades 3-6 in the USA. The data was coded using Halfin's codes. The sequential analyses identified the statistical significance of patterns from the repetitive design activities. The results indicate: 1) there were two iterative recursions in the problem and solution phases, 2) questioning was a gateway to designing, 3) modeling and predicting occurred with designing, and 4) managing bridged the problem and solution phases. The study also found that different design contexts yield distinctive procedural patterns. This result implies that engineering educators need to understand the proper use of the design process model.

Keywords: design process, design pattern, engineering design, sequential analysis, elementary STEM education

Introduction

With the increasing significance of teaching science, technology, engineering, and mathematics (STEM) to young students, teaching engineering in elementary schools is becoming important to expand the STEM-capable workforce and increase STEM literacy for all students (Garry et al., 2020; Kelley & Knowles, 2016). Research has found that characteristics of engineering design include iteration and collaboration (Wynn & Eckert, 2017; Jin & Chusilp, 2006), the co-evolution between problem and solution domains (Dorst & Cross, 2001), complex cognitive processes (Dym et al., 2005), reflective decision-making (Wendell, Wright, & Paugh, 2017), dealing with "wicked problems" (Buchanan, 1992), and learning through failure (Jackson et al., 2021; Maltese, Simpson & Anderson, 2018). In K-12 engineering education, the engineering design process (EDP) guides students and educators in engineering learning (Arık & Topçu, 2020; Yu, Wu, & Fan, 2020). However, little is known about how young students manage engineering problems in terms of their cognitive processes.

As Engineering Design became the centerpiece of technology, design, and engineering education, there came to be a long and intense debate surrounding the engineering design process. Johnsey (1995) questioned whether the engineering design process is a uniform process that students must follow. He reviewed several published process models but found that there was little research evidence. Meanwhile, some researchers have attempted to characterize the engineering design process based on contextual factors. Lawson (1979) studied the differences between the design processes of architectural engineers and scientists. He found that architectural engineers were more likely to use solution-oriented strategies while scientists focused on problem-focused strategies. Lu (2015) investigated the relationship between problem-solving strategies and design quality and found the solution-driven approach resulted in more creative design outcomes. Dorst and Cross (2001) investigated the relationship between the design process and creativity and claimed that iterations in the design process were crucial to generating creative design solutions. To identify the recursive engineering design process, Clarkson and Eckert (2004) claimed that the repetitive activities of engineers can form patterns and that these patterns can characterize engineering problem-solving. However, little is known about the shape of the iterative patterns of EDP. Therefore, this study prompts two critical questions: What are the specific processes of EDP? What are the key strategies of EDP that lead to the design solutions? We believe that studying patterns of EDP will contribute to understanding learning mechanisms in STEM education.

Research questions

1. What EDP patterns does sequential analysis identify in elementary students in grades 3-6?
2. What are the cognitive strategies of elementary students in grades 3-6 that lead to the solution phase?
3. Are there differences in EDP patterns by design tasks? If so, how do EDP patterns vary?

Literature review

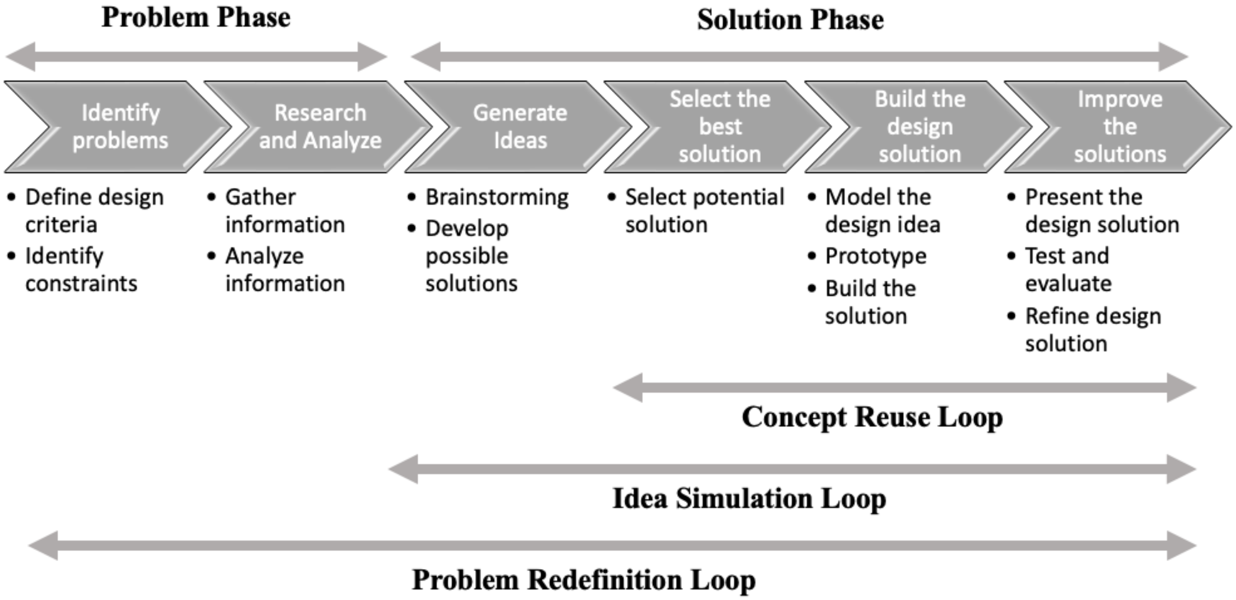
Types of the engineering design process models

Several publications have presented EDP models to identify the best engineering design practices; however, these models have varied depending on their goals, context, and emphasis. Two major pillars of EDP studies have been prescriptive and descriptive models (Cross, 2021; Johnsey, 1995). Both types of models are commonly expressed as procedural flows, such as charts, recursive diagrams, and decision-making trees; however, there is a major difference in their objective and approach: Prescriptive models illustrate core elements of the design process to guide the designers in efficiently solving a given problem. Although some prescriptive models are similar to a sequential flow, their goal is to conceptualize the major tasks for each design step. For example, March (1984) presented a design process model that adopted the prescriptive approach focusing on explaining the tasks and methodologies of each step rather than showing a sequential design process. On the other hand, descriptive models have a *solution-focused* nature, emphasizing successful engineering design procedures. For example, French's (1999) model consists of eight steps: 1) need; 2) analysis of the problem; 3) statement of the problem; 4) conceptual design; 5) selected schema; 6) embodiment of schemes; 7) detailing, and 8) working drawings. The model describes an optimal procedure to accomplish a given design task.

The engineering design process clusters each design activity element and shows different levels depending on the point of view. Clarkson and Eckert (2004) described EDP on the macro level with the identification of need, conceptual design, detailed design, preparation for production, production, and delivery. Hubka (1980) introduced a structural design cycle that is comprised of conceptual design, layout design, detail design, and managing by analyzing the specific operations accompanied by designers. Meanwhile, Dorst and Cross (2001) conceptualized EDP as a symmetrical model, which categorizes design processes into problem and solution phases. The problem phase involves identifying the problem and analyzing design elements, while the solution phase includes devising, selecting, building, and improving the solution. Additionally, some design models have sub-iterations, such as concept reuse, idea simulation, and problem redefinition loops (Jin & Chusilp, 2006). Those loops and design cycles can be illustrated as a graphical model shown in Figure 1.

Figure 1

Problem and Solution Phases and Cognitive Loops in EDP



Cognitive operations in the engineering design process

In recent discussions, a critical argument has focused on the cognitive strategies involved in the engineering design process (Cross, 2021; Hay et al., 2017). Jin and Benami (2010) proposed the cognitive operational model to illustrate the relationships between cognitive processes and design operations using information processing theory (Atkinson & Shiffrin, 1968). Their model holds that designers gather ‘chunks’ of information from an external device through design operations such as sketching, talking, writing, and simulating. The design operations stimulate internal design cognitions, such as computing, questioning, supposing, and declaring. Next, designers determine whether the information is meaningful, relevant, divergent, emergent, or incongruous. The ‘chunks’ are delivered to mental operations and are processed through memory retrieval, association, and problem-solving.

Previous studies have indicated that the engineering design process is related to research on general problem-solving theories. Halfin (1968) studied what cognitive strategies engineers and scientists frequently use to solve problems and identified 17 strategies. The cognitive strategies are similar to the engineering design process; therefore, this study adopted Halfin’s codes to categorize students’ design activities. Several researchers have also attempted to identify a general model of problem-solving. For many years, there have been controversial discussions about whether problem-solving is domain-specific or general. Some have claimed that problem-solving strategies in young students are less sophisticated than adults (Brown, Collins, & Duguid, 1989; Jonassen, 2000). For example, Meadows (2006) suggested that experts use more sophisticated strategies and planning than novices because experts have a well-rounded mental structure optimized for solving problems. Robson (2006) claimed that young children tend to use trial and error strategies, while older children are more likely to use higher-order thinking skills. Furthermore, Elio and Scharf (1990) argued that novices are prone to oversimplify problems and hastily start ideation processes, while experts aim to understand challenges before proceeding with the design process. Thornton (2002) claimed that, although experts and novices have similar cognitive capacities regarding information handling, the mental processes of novices are less efficient in planning, organizing, associating, and retrieving information. Finally, Flavell et al. (1993) asserted that elementary students' problem-solving strategies are not fundamentally different from those of professional engineers, except that students have limited experience and lower levels of sophistication. According to the literature presented here, it is important to understand how students engage in the engineering design process, as it will contribute to a better understanding of how children use cognitive strategies to solve problems.

Research Methods

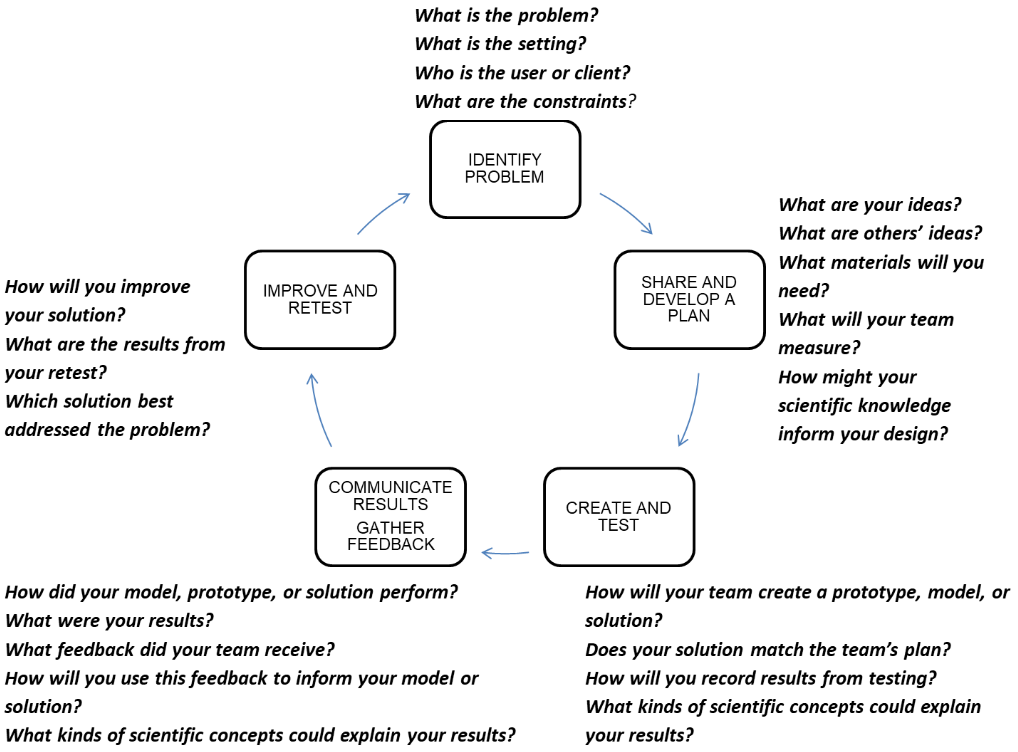
Context of study

This study was conducted in the SLED project funded by National Science Foundation. The SLED project built on collaborative partnerships with four colleges within a large, research-intensive university and four school corporations in Indiana, USA. The project's overarching goal was to enhance science learning by integrating the engineering design approach into elementary science classrooms. Over 100 pre-service teachers, 200 in-service teachers, and 5,000 students participated in the SLED project throughout the five-year period.

The SLED project recruited elementary teachers from the partnerships' district schools and delivered engineering lessons during a two-week summer intensive professional development workshop. During these professional development workshops, the SLED leadership team provided instructions for how to implement the engineering design lessons. The instructions included design-based learning, scientific inquiry, design sketches, and EDP. The SLED project developed the EDP model shown in Figure 2 based on the K-12 Science Education Framework and Next Generation Science Standards (National Research Council, 2012; The NGSS Lead States, 2013). The research team emphasized that teachers need to implement engineering design with its recursive nature; therefore, we recommended that the participant teachers avoid directly presenting the sequential chart of the EDP model but instead use it with the inquiry questions shown in Figure 2, as NGSS suggests (The NGSS Lead States, 2013).

Figure 2.

The SLED EDP Model and Guiding Prompts



What is the problem?
What is the setting?
Who is the user or client?
What are the constraints?

What are your ideas?
What are others' ideas?
What materials will you need?
What will your team measure?
How might your scientific knowledge inform your design?

How will your team create a prototype, model, or solution?
Does your solution match the team's plan?
How will you record results from testing?
What kinds of scientific concepts could explain your results?

How did your model, prototype, or solution perform?
What were your results?
What feedback did your team receive?
How will you use this feedback to inform your model or solution?
What kinds of scientific concepts could explain your results?

How will you improve your solution?
What are the results from your retest?
Which solution best addressed the problem?

Engineering design lessons and design task

The SLED project developed various engineering lessons for elementary students from grades three to six. The SLED lessons aligned with the Indiana Academic Standards for Science (Indiana Academic Standards, 2010) and Common Core State Standards for Mathematics (CCSSM; Common Core State Standards Initiative, 2010). When developing the lessons, the SLED team used two primary strategies: 1) the integration of multiple subjects, including science, technology, engineering, and mathematics (STEM), and 2) the adoption of the engineering design approach as a tool for science learning. Table 1 shows the SLED lesson titles and the addressed engineering and science concepts. For the sake of data collection, we developed additional "transfer problem" design tasks to assess students' science and engineering learning. The transfer problems featured the same science and engineering concepts but had slightly different contexts. For example, the *Door Alarm* lesson asked students to design a complete alarm circuit that sounds when a door opens, as shown in Figure 3. The transfer problem for the *Door Alarm* was entitled *Doggie Door Alarm*, shown in Figure 4, which had a slightly different design context and required students to design a door alarm to detect when a dog enters or exits. All instructional materials used in this study can be found on https://stemedhub.org/.

Table 1

SLED Lessons and Transfer Problems.

Grade	Lesson Title	Engineering and Science concepts
3	Musical Instrument	Sound, Pitch, Waves
	Simple Machine	Force, Gears, Lever, Pulley, Wedge, Fulcrum
4	Canal	Erosion, Drainage, Slope, Runoff
	Door Alarm	Insulator, Conductor, Open and Closed Circuits
5	Prosthetic Leg	Mass, Volume, Kinetic Energy
	Water Filter	Filtration, Purification, Water Quality
6	Roller Coaster	Potential Energy, Kinetic Energy, Gravity, Friction
	Solar Tracker	Earth Rotation, Direct Versus Indirect Lights, Ball Bearings, Linkage

Figure 3

Door Alarm Design Task (Designed by SLED Project Team, 2014)

Designing a Door Alarm

Someone has been sneaking into your classroom when the class has been at art. Your teacher needs help in designing an electric door alarm prototype with an open and closed circuit. This alarm should make noise when the door is opened and will turn off when the door is closed.

Criteria

- The door alarm should ring when the door is opened
- The door alarm should turn off after the door is closed
- The alarm should sound even if the door is slightly opened

Constraints

- Only use materials provided.
- There is no lock on the door
- The door opens on only one side in the room

Figure 4

Doggie Door Alarm Design Transfer Problem

Doggie Door Alarm

The Problem

Your grandma's dog Rex uses his doggie door often, and she wants to know when Rex is going outside. Grandma isn't always in the room when the door is used. She wants some kind of alarm signaling when the door is opened. You remember what you learned in the *Door Alarm* lesson, so you want to help design a doggie door alarm.

Criteria

- The door alarm should buzz when the door is opened.
- The door alarm should turn off after the door is closed.
- The alarm should sound even if the door is slightly opened.

Constraints

- Must use an alarm buzzer, a switch, wire, and batteries.
- Any other materials found in the typical classroom can be used.
- There is no lock on the door.
- The door only opens to the outside of the room.

Your Task

Describe how you would design a circuit to make a doggie door alarm that uses what you know about the design process in a fun and creative way.

Please describe aloud how you would start the design task - where would you begin?

What types of tests would you do to make sure that your circuit works?

Data collection

This study adopted the Concurrent Think-Aloud (CTA) protocol to capture students' cognitive strategies based on verbal reports while solving the design problem. The CTA protocol features concurrent verbalization, which collects real-time verbal data while students perform design tasks. After the teachers implemented an engineering unit, we contacted the teachers and arranged the data collection schedule. Groups of three students participated in a CTA session to facilitate collaborative problem-solving and verbal communication in the team (Sung & Kelley, 2019; Mentzer, Sutton, & Becker, 2015).

This study used criterion sampling (Gall, Gall, & Borg, 2007) with the three selection criteria: 1) able to express themselves verbally, 2) showed regular performance in the unit, and 3) assented to participate in this study. The participant triads formed a group and solved a transfer problem collaboratively. Each CTA session had a different duration because it lasted until the team determined that they had completed the given engineering task. All CTA protocol sessions were recorded using high-quality video and audio in the experimental setting shown in Figure 5.

Figure 5

Data Collection Setting for CTA Protocol

Sample size and participants

The research team collected 48 CTA sessions from 144 elementary students ages eight to eleven in grades three to six. The demographics of the participants are presented in Table 2. Although the researchers acknowledge that the disparity in the gender ratio might cause differences in collaboration and group dynamics (Schnittka & Schnittka, 2016), this study used gender-mixed groups to encourage group communication and collaboration (Mentzer, Sutton, & Becker, 2015).

Table 2

Sampled Participant Demographics.

	Gender		Ethnicity					
Grades	Male	Female	White	Black	Hispanic	Asian	Other	Total
3	22 (61.1%)	14 (38.9%)	33 (91.7%)	1 (2.8%)	2 (5.6%)	0 (0.0%)	0 (0.0%)	36
4	16 (44.4%)	20 (55.6%)	24 (66.7%)	3 (8.3%)	1 (2.8%)	4 (11.1%)	4 (11.1%)	36
5	18 (50.0%)	18 (50.0%)	23 (63.9%)	6 (16.7%)	5 (13.9%)	1 (2.8%)	1 (2.8%)	36
6	15 (41.7%)	21 (58.3%)	24 (66.7%)	8 (22.2%)	2 (5.6%)	1 (2.8%)	1 (2.8%)	36
Total	71 (49.3%)	73 (50.7%)	104 (72.2%)	18 (12.5%)	10 (6.9%)	6 (4.2%)	6 (4.2%)	144

Data analysis

CTA data coding

We used Halfin's codes (1973) to determine which cognitive strategies students used in the engineering design process. Halfin identified 17 predominant cognitive strategies used by engineers in the problem-solving process. In the SLED project, we identified seven codes frequently used by elementary school students in conceptual design and applied them to this study (see Table 3).

Table 3

Coding Scheme for CTA Protocol Data Analysis

Code	Definition	Example
Defining problem (DF)	Stating or defining a problem that will enhance the investigation leading to a solution.	"The criteria say we don't have to make the switch but need to use it to work."
Analyzing (AN)	Identifying, isolating, taking apart, and breaking down to clarify the essential components of a phenomenon or problem.	"We have to know which materials we can use to solve this problem."
Predicting (PR)	Prophesying or foretelling something in advance or anticipating the future.	"When the door opens, the wire will go up."

Questioning (QH)	Asking, interrogating, or seeking answers related to a phenomenon, problem, opportunity, or event.	"How does this wire connect to the other side of the battery?"
Designing (DE)	Conceiving, creating, inventing, contriving, or proposing a goal to meet needs, desires, problems, or opportunities to do things better.	"Doggy door is here, and we can have a copper here or some metal plate."
Managing (MA)	Planning, organizing, directing, coordinating, and controlling.	"So we could use some of our ideas and put them into your sketch."
Modeling (MO)	Producing or reducing an act or condition to a generalized construct may be presented graphically in a sketch, diagram, or equation.	"Let's draw the background framework we used in the classroom."

Note: Modified from Halfin's (1973) Cognitive Strategies.

The researchers used NVivo software to code the CTA sessions. While watching a recorded CTA video, we segmented video footage into meaningful chunks based on the appearance of transition cues, such as pauses, intonation, contours, and syntactical markers (Ericsson & Simon, 1993). For example, during a series of design discourses, when there was a pause or a change in topic, we separated them into two individual segments and assigned a code to each. To measure the reliability of our coding, an independent coder analyzed the same data and conducted a Kappa interrater reliability test. Based on Hruschka et al. (2004), the researchers randomly selected 11 sessions from the 48 CTA sessions to meet the 20% minimum requirement for the reliability test. The Kappa test showed 97.22% overall agreement and a weighted Kappa coefficient of .86, indicating almost perfect agreement based on Landis and Koch's (1977) criteria.

Sequential analysis

This study adopted sequential analysis to identify the patterns of EDP (Bakeman & Gottman, 1986). The basic algorithm of sequential analysis involves searching two-event sequences from a string of sequential codes. For example, if a group of students engaged in a design task with the series of events such as designing, modeling, questioning, designing, modeling, designing, questioning, designing, modeling, questioning, and modeling, then we coded this series as a string of codes with DE-MO-QH-DE-MO-DE-QH-DE-MO-QH-MO. Using the code string, we created a sequential frequency matrix, shown in Table 4.

Table 4

An Example of Sequential Frequency Matrix

		Target (Second) Code			
		DE	MO	QH	Sum
Given (First) Code	DE	0	3	1	4
	MO	1	0	2	3
	QH	2	1	0	3
	Sum	3	4	3	10

Table 4 shows the transition frequency for cognitive strategies. For instance, the table indicates the transition from *Designing* (DE) to *Modeling* (MO) happened three times in the sequence. Based on the string codes of the sessions, we ran sequential analysis to detect the statistical significance of two-sequential events using the expected frequency equation presented below (Bakeman & Gottman, 1986; Haberman, 1978, see Equations 1 and 2). The researchers analyzed sequential patterns of EDP using GSEQ 5.1 software developed by Bakeman and Quera (2015). The significance level for the sequential analysis test was set at 0.05.

$$Expected\ Frequency(\mathrm{e}_{rc}) = \frac{f(r)}{\mathrm{N}} \times \frac{f(c)}{N - f(r)}$$ *Equation 1*

Where $f(\mathrm{r}) = sum\ of\ the\ counts\ in\ the\ r^{th}\ column, Given\ code$

$f(\mathrm{c}) = sum\ of\ the\ counts\ in\ the\ c^{th} row$, Target code

N = sum of the total count

$$\mathrm{Adjusted\ residual(Z-score)} = \frac{x_{rc} - e_{rc}}{\sqrt{e_{rc}(1 - f(c)/N)(1 - f(r)/N)}}$$ *Equation 2*

$$x_{rc} = observed\ frequency$$

Results

Descriptive Statistics: Common Cognitive Strategies

We investigated the sum and average frequencies of the strategies used in 48 CTA sessions to identify common cognitive strategies. The average total duration was 17 minutes and 20 seconds, and the total number of cognitive strategies was 5,053. The results show that the elementary students dedicated a significant amount of time to *Designing* (45%), while little time was dedicated to *Managing* (5%), *Predicting* (6%), and *Analyzing* (6%) (see Figure 6).

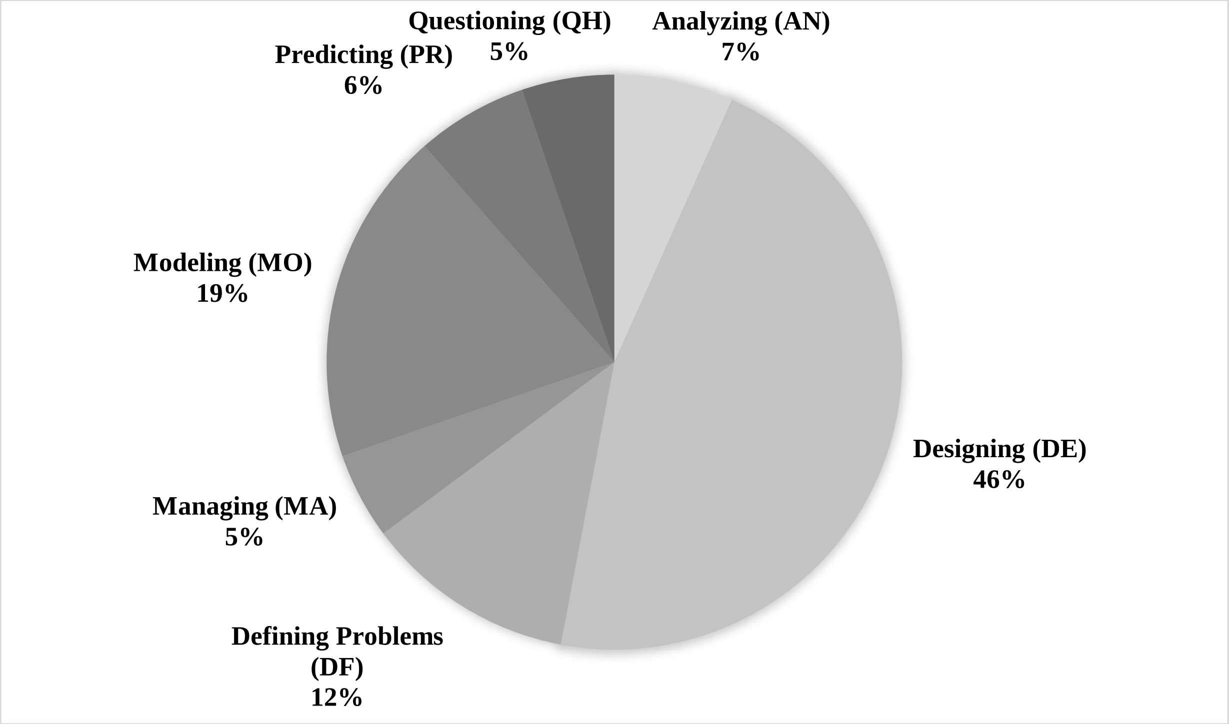
Table 5

Overall Percentages and Frequencies of Cognitive Strategies in 48 Design Sessions

Cognitive Strategy	Time usage			Frequency		
	Sum	Mean	SD	Sum	Mean	SD
Analyzing (AN)	0:55:46	01:09	01:04.2	355	7.40	5.42
Designing (DE)	6:25:07	08:01	03:13.6	1,939	40.40	19.40
Defining Problem (DF)	1:38:38	02:03	00:31.4	167	3.48	2.56
Managing (MA)	0:40:24	00:51	00:38.4	478	9.96	5.58
Modeling (MO)	2:36:43	03:16	01:52.2	1,009	21.02	13.43
Predicting (PR)	0:52:10	01:05	00:44.2	469	9.77	6.80
Questioning (QH)	0:43:17	00:54	00:43.0	636	13.25	9.69
Total	13:52:05	17:20		5,053		

Figure 6

Time Percentages of Cognitive Strategies



EDP Patterns from Sequential Analysis

To find the answer to research question 1, we pooled the 48 CTA sessions and analyzed EDP patterns using sequential analysis. In Table 6, the observed frequency indicates the number of transitions we coded from the data. The expected frequency represents the statistically expected value based on the sum of the row and column of each cell. For example, the cell crossing AN and DE shows 198 and 212.52 as observed and expected frequencies, respectively. The transition from *Analyzing* (AN) to *Designing* (DE) occurred 198 times, while it was statistically expected to occur 212.52 times. Using Equation 2, the researchers analyzed the statistical significance of the patterns at the 0.05 level in a right-trailed approach because the study aimed to examine repeated patterns of two-sequential events in EDP. The analysis identified 14 significant sequential EDP patterns.

Table 6

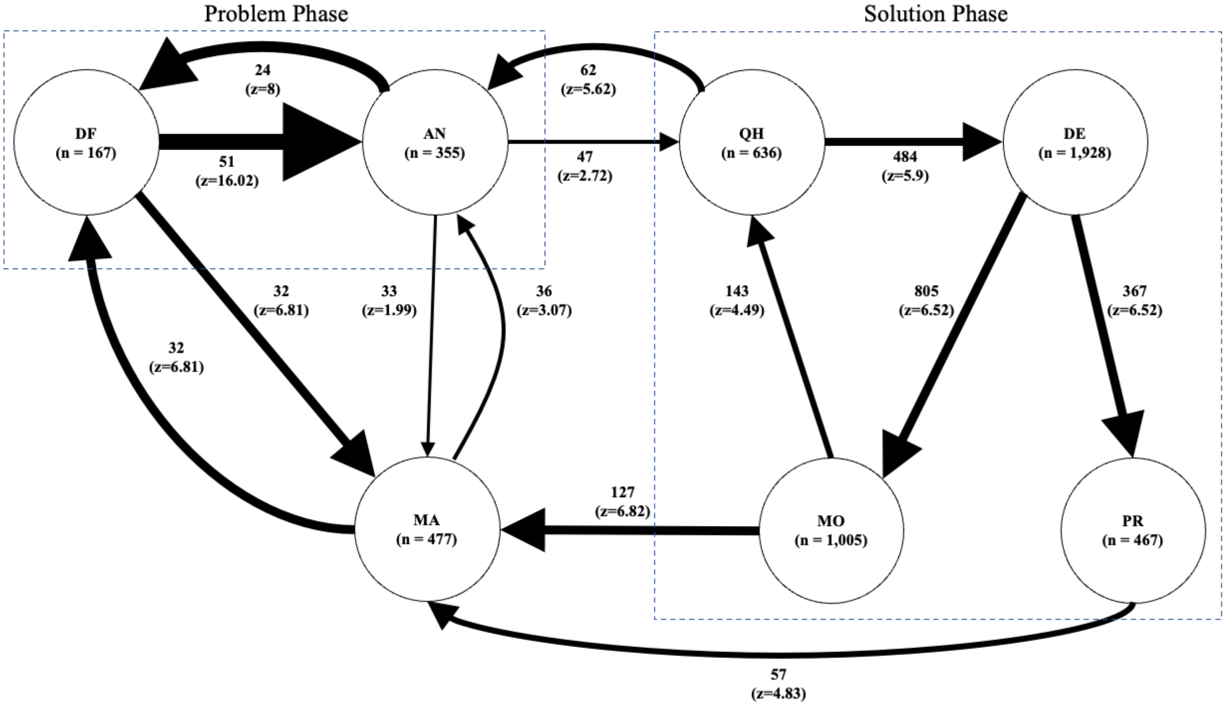
Observed Frequencies and z-scores of the Sequential Analysis Pooled 48 Sessions.

Observed frequency (z-score)		Target (Second) Code							
		AN	DE	DF	MA	MO	PR	QH	Sum
	AN		198	24	33	34	19	47	355
			(-1.32)	**(8*)**	**(1.99*)**	(-3.42)	(-1.04)	**(2.72*)**	
	DE	152		52	209	805	367	343	1,928
		(-5.45)		(-2.67)	(-6.35)	**(7.12*)**	**(6.52*)**	(-3.7)	
	DF	51	68		32	7	0	9	167
		(16.02*)	(-3.8)		**(6.81*)**	(-4.17)	(-3.51)	(-1.69)	
Given	MA	36	250	23		86	9	43	447
(First)		**(3.07*)**	(-1.83)	**(6.11*)**		(1.95)	(-4.26)	(.13)	
Code	MO	36	646	11	127		42	143	1,005
		(-3.09)	(-1.58)	(-1.92)	**(6.82*)**		(-4.49)	**(4.49*)**	
	PR	18	293	1	57	47		51	467
		(-1.25)	(.68)	(-2.56)	**(4.83*)**	(-3.81)		(1.17)	
	QH	62	484	8	20	30	32		636
		(5.62*)	**(5.9*)**	(-.91)	(-4.2)	(-8.77)	(-2.08)		
	Sum	355	1,939	119	478	1,009	469	636	5,005

*Note. * indicates the p-value is lesser than 0.05 right-tailed*

Figure 7

Statistically Significant Engineering EDP Patterns Pooled from 48 Sessions.



Notes. 1) n indicates the frequency of the cognitive strategy. 2) The numbers next to the arrow indicate the frequency and z-score between the two strategies. 3) The thickness of the arrows represents the z-scores between the two strategies.

We illustrate the results from the sequential analysis in Figure 7. The graphical illustration shows how the iterative patterns are shaped, with their intensity indicated by z-scores. While most EDP models emphasize the sequence of problem identification to analysis or research, this result shows that *Defining Problems* is statistically related to *Managing*. Also, the sequential analysis identified reversed sequential patterns, such as *Defining Problems* after *Analyzing* ($z = 16.02$; $p < 0.001$) or *Managing* ($z = 6.11$; $p < 0.001$). As previous studies have identified the iterative nature of EDP (Jin & Chusilp, 2006; Wynn & Eckert, 2017), this study also confirms that EDP is highly iterative, particularly with respect to recursions within the problem phase, including problem identification, analyzing, and managing. Another significant finding was the *Analyzing* to *Questioning* pattern ($z = 2.72$; $p = 0.007$). This pattern shows that questioning is important in transitioning from the problem to the solution phase. There has been a recent emphasis on questioning, also known as “engineering inquiry” (Estapa & Tank, 2017).

EDP Patterns Leading to the Solution Phase

Perhaps the primary goal of most EDP models is to guide students to find a solution to engineering problems. Therefore, we proposed research question 2-what are the cognitive strategies leading to the solution phase? In Figure 1, we defined the solution phase as designing, modeling, and predicting. Interestingly, the sequential analysis found only one statistically significant pattern leading to designing: *Questioning* (QH) to *Designing* (QH) ($z = 5.9$; $p <0.001$). As stated earlier, this shows that questioning was a unique strategy leading to *Designing* (DE). The adjacent strategies surrounding *Designing* were *Modeling* and *Predicting*. The *Designing* to *Modeling* ($z = 7.12$; $p < 0.001$) pattern indicates that designers externalize design ideas through drawing. Also, the *Designing* to *Predicting* ($z = 6.52$; $p < 0.001$) pattern shows that generating an idea and predicting its consequences are closely associated. Another interesting finding from the sequential analysis is that *Managing* was a mediator in EDP. *Managing* was associated with problem identification strategies, such as *Defining Problems* and *Analyzing*, and solution strategies, such as *Modeling* and *Predicting*. The *Managing* code represents controlling assertions, such as “What’s next?”, “What would we do?”, and “Let’s do this.” The result indicates that the managing strategy is vital in bridging the problem and solution phases.

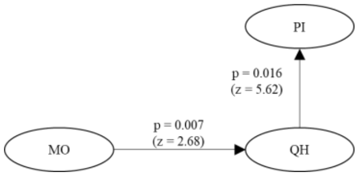
EDP Patterns by Design Tasks

To answer research question 3, we analyzed the EDP patterns by design task. We conducted a sequential analysis after pooling the CTA sessions by design task to see how the EDP patterns varied. The number of events required to identify statistical significance was insufficient to perform sequential analysis. Therefore, we combined two adjacent codes, *Defining Problems* (DF) and *Analyzing* (AN), into a new code, *Problem Identification* (PI) to represent the problem phase (Pleasant & Olson, 2019). Figure 8 illustrates the EDP patterns by design task. The results indicate that lower grades tend to produce limited numbers of significant EDP patterns. For example, *Musical Instrument*, performed by 3rd graders, led to only two significant sequential patterns: 1) *Modeling* (MO) to *Questioning* (QH) and 2) *Questioning* (QH) to *Problem Identification* (PI), and we were not able to run the sequential analysis for *Simple Machine* because the frequency of cognitive strategies in the design task was insufficient. However, the design tasks given to grades five and six produced more diverse and intense EDP patterns with higher z-scores. In particular, the *Roller Coaster* and *Solar Tracker* tasks assigned to the 6th graders showed more iterative problem-solving patterns.

Figure 8

Engineering Design Process Patterns by Design Problems

Musical Instrument

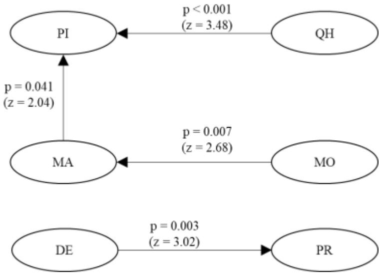


Simple Machine

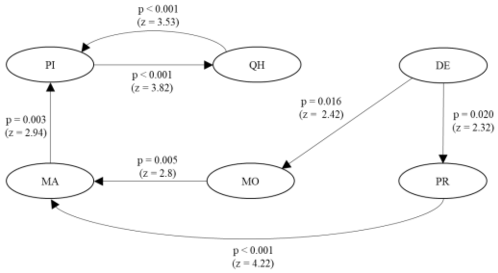
N/A

(due to low frequency, the sampled data was not sufficient to detect statistical significance)

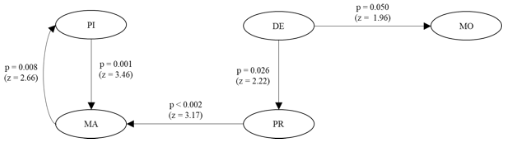
Canal



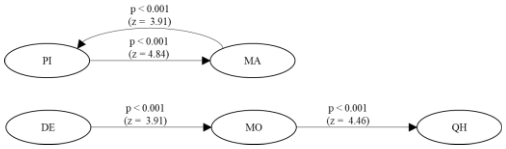
Door Alarm



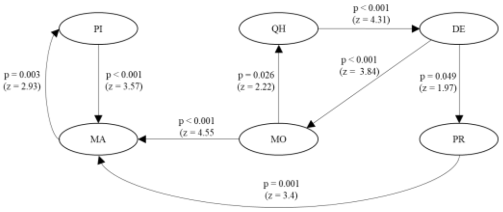
Prosthetic Leg



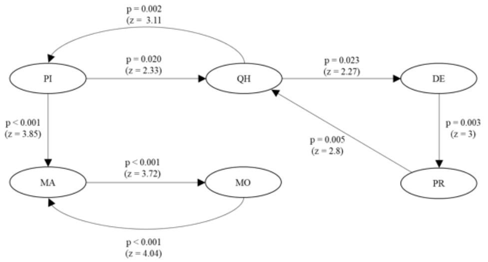
Water Filter



Roller Coaster



Solar Tracker



When designing a design task in the SLED project, the task's difficulty, the length of the design passage, and the complexity were adjusted considering the student's cognitive abilities. Thus, it is not clear if the complexity of the different EDP patterns is the result of the students' cognitive maturity or the complexity of the design task. For example, the Musical Instrument design task shown in Table 7 asked students to design a device that makes different pitches of sound. The analysis of sequential patterns of this design task produced only two significant patterns: *Modeling* to *Questioning* ($p = 0.007$, $z = 2.68$) and

Questioning to *Problem Identification* (p = 0.016, z = 5.62). These design patterns show that students sketched solutions (MO), and then asked questions (QH) to identify problems (PI), as shown in Figure 9. Interestingly, there were no patterns related to *Predicting* and *Managing*. This result implies that the students have not yet harnessed these strategies with other key design elements.

Table 7

Musical Instrument Design Task for Third Graders

Design Task	
You have built a tree fort out in your backyard. Your neighbor Pete is jealous and keeps trying to claim it for himself. You wish you had some way of knowing when he was coming! Your little sister says she will warn you from the house when she sees Pete in the backyard but wants to use a secret signal. You remember that you learned about different pitches in the Musical Instrument lesson. You decide to design a device that makes different pitches your sister can use to signal you that Pete is coming!	
Science Concepts	Design Requirements
• Sound • Volume • Pitch • Wavelength • Vibration • Instrument • Sound wave	• Make two different pitch sounds using vibrations. • The device must be made of materials found in your house. • The device should be no bigger than the length of a textbook. • The device should be heard from 10 meters away

In Figure 8, Door Alarm was given to fourth graders. Remarkably, the EDP patterns in this design task show more formalized iterations, similar to Solar Tracker given to six graders. As shown in Table 8, the scientific principle embedded in *Door Alarm* was electricity and electronic circuits, which was a challenging concept for fourth graders because it required the design of an electrical circuit and a physical device to function as the door opened and closed (Moodley & Gaigher, 2019). The *Door Alarm* design task produced seven significant recursive patterns. The EDP patterns contain two iterative design cycles in the problem and solution phases. The iteration cycle within the problem phase contains *Problem Identification* from/to *Questioning* (PI -> QH, p = < 0.001, z = 3.82; QH -> PI, p < 0.001, z = 3.53). This iterative pattern shows that students used the questioning strategy to identify the problem and design requirements. The iterations in the solution phase include *Designing* to *Modeling* (DE -> MO, p = 0.016, z=2.42) and *Designing* to *Predicting* (DE -> PR, p = 0.020, z =2.32). These EDP patterns indicate that recursive design strategies such as sketching and predicting occur after designing ideas. Figure 9 is an example of a Door Alarm design task solution.

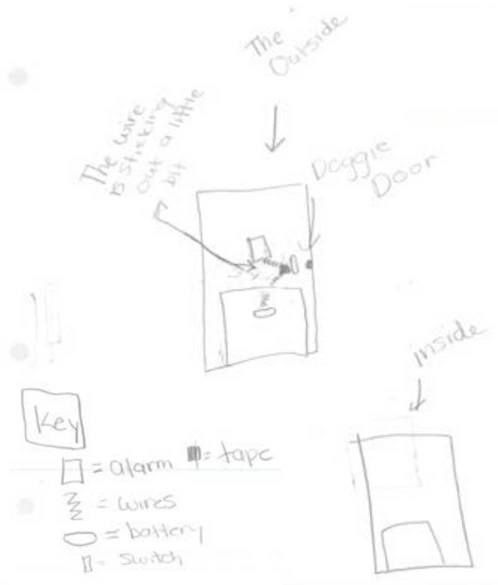
Table 8

Door Alarm Design Task for Fourth Graders

Design Problem	
Your grandma's dog Rex uses his doggie door often, and she wants to know when Rex is going outside. Grandma isn't always in the room when the door is used. She wants some kind of alarm signaling when the door is opened. You remember what you learned in the Door Alarm lesson, so you want to help design a doggie door alarm.	
Science Concepts	Design Requirements
• Electricity • Electronics • Electric Current • Battery • Resistance • Circuit • Load • Conductor • Insulator	• The door alarm should buzz when the door is opened. • The door alarm should turn on and off after the door is closed or opened. • Must use an alarm buzzer, a switch, wire, and batteries. • Any other materials found in the typical classroom can be used. • The door only opens to the outside of the room.

Figure 9

A Sketch from Door Alarm Design Solution



For the fourth grader's design task, Prosthetic Leg asked them to design a kicking machine using their knowledge of physics and engineering. The design requirements in Table 9 show that the solution demanded a mechanism with high numerical accuracy. *The Prosthetic Leg* yielded five significant sequential patterns. The data analysis indicates that *Problem Identification* formed two significant patterns: *Problem Identification* to *Managing* (PI → Ma, $p = 0.001$, $z = 3.46$) and *Managing* to *Problem Identification* (MA → PI, $p = 0.008$, $z = 2.66$). Also, the *Designing* strategy tended to move to *Modeling* (DE → MO, $p = 0.05$, $z = 1.96$) and *Predicting* (DE → PR, $p = 0.026$, $z = 2.22$). *Managing* had one significant pattern, formed with *Predicting* (PR → MA, $p = 0.002$, $z = 3.17$). Compared to *Door Alarm,* this design brief was more straightforward and presented detailed design guidelines, such as the distance capabilities of the solution.

Table 9

Prosthetic Leg Design Task for Fifth Graders

Design Problem
Your younger brother Joey is the Recess Paper Football Champion of his grade, but he's bummed he can't play since he broke his right index "kicking" finger playing basketball. Joey's friends say that if he can come up with something that flicks the football for him, they'll let him keep playing, but Joey knows he can't kick paper footballs with his opposite hand for accuracy. Joey heard you talking about

<table>
<tr><td colspan="2">learning about prosthetic legs, so he thinks you can help him by designing a device that will kick the paper football.
The Recess Paper Football game is played using two goal posts – one 3 feet away and one 5 feet away – so your device must be accurate to these varying lengths. Your brother Joey is looking for the following design features for this paper football kicker.</td></tr>
<tr><th>Science Concepts</th><th>Design Requirements</th></tr>
<tr><td>• Weight
• Mass
• Volume
• Density
• Prosthetic
• Lever
• Hinge Joint</td><td>• Hinge like a real-jointed finger that is flicking the paper football.
• Be designed to strike a paper football and propel it far enough to go through the goalposts.
• Be accurate at various distances (3 ft. to 5 ft.).
• Take up the floor space no larger than a typical textbook.</td></tr>
</table>

For the sixth grader's design task, Solar Tracker contains theoretical scientific concepts such as the earth's inclination, the position of the Sun, and direct and indirect rays (see Table 10). The students were required to design a solar tracking device for a violet plant.

Table 10

Solar Tracker Design Task for Sixth Graders

<table>
<tr><th colspan="2">Design Problem</th></tr>
<tr><td colspan="2">Your Aunt Sue has a rare African violet plant out on her patio. The patio is the only place Aunt Sue can put the violet, so it gets sunlight throughout the day. Aunt Sue's problem is that the violet needs sunlight, but it cannot be in direct Sun because the intensity of the Sun's rays could kill it. Aunt Sue remembers you talking about learning about tracking the Sun in your science class. She has asked for your design team's help in designing a system that will follow the Sun so that the Sun's direct rays won't hurt the flower. Aunt Sue is looking for the following design features to solve her problem.</td></tr>
<tr><th>Science Concepts</th><th>Design Requirements</th></tr>
</table>

• The inclination of the earth • Solar Panel • Direct Rays • Indirect rays • Position of Sun	• Track the Sun as it moves across the sky. • Allow sunlight to get to the flower – just not the direct rays. • Monitor the intensity of sunlight to ensure the intensity is not harmful to the plant.

The sequential analysis showed eight significant patterns. *Problem Identification* had two adjacent sequential patterns: *Managing* (PI → MA, $p < 0.001$, $z = 3.85$) and *Questioning* (PI → QH, $p = 0.02$, $z = 2.33$). The *Questioning* strategy also had two outgoing patterns: *Problem Identification* (QH → PI, $p = 0.002$, $z = 3.11$) and *Designing* (QH → DE, $p = 0.023$, $z = 2.27$). *Solar Tracker* did not produce the pattern of *Designing* to *Modeling*, unlike other design tasks. Instead, there was a one-directional pattern between Designing, Predicting, and Questioning (DE → PR, $p = 0.003$, $z = 3$; PR → QH, $p = 0.005$, $z = 2.8$).

Overall, each EDP pattern drawn from each design task had some similarities and differences, but commonly all models showed one or two iterative cycles in the problem and solution phases. When we developed the design tasks, different topics and difficulties were considered depending on the grade level, so it is unclear whether the different patterns resulted from the nature of design task, design skills, or the students' cognitive abilities. However, there was a general tendency that higher grade levels produced more diverse and repetitive patterns.

Discussion and Conclusions

Engineering design involves numerous design factors, including mental processes, design contexts, and constraints (Bucciarelli, 2003; Pleasant & Olson, 2019). One implication that can be drawn from this study is that students' EDP patterns are not haphazard nor linear but form several clustered sets of design iterations. Sequential analysis showed the specific patterns of the EDP, and we found repetitive cyclic loops in the problem and the solution phases.

This study found that engineering inquiry plays a significant role in driving the solution phase (Cross, 2021). Numerous studies have shown the same result that questioning plays a vital role in solving engineering problems (Mentzer, Becker, & Sutton, 2015; Shroyer et al., 2018). Our finding is closely aligned with the recent emphasis on engineering inquiry in teaching engineering (Dym et al., 2005; Fan, Yu, & Lin, 2020). Junginger (2007) noted, "to arrive at *good design* today, designers have to get involved in a systematic inquiry beyond aesthetics and functions" (p. 59). We found that inquiry as *Questioning* bridges problem and solution domains and plays an entry point for solution strategies such as *Designing*, *Modeling*, and *Predicting*. Considering the growing emphasis on scientific inquiry in recent STEM education, this implies that engineering design is a powerful learning tool to facilitate inquiry-based science and engineering practices with student-generated questions and supports the notion of shared practices in NGSS.

Bucciarelli (2003) commented that “designing is a social process” (p. 20). Pleasant and Olson (2019) also presented a nature of engineering (NOE) framework where they argued that contemporary engineering design requires teamwork, negotiations, and compromise with social skills. We found that *managing* was significant in planning, directing, and coordinating between the problem and solution phases. Students used *Managing* when they wanted to 1) shift the topic to another, 2) change a design step, 3) prompt related topics, or 4) control the design session. In this study, the sequence analysis showed *Managing* was bi-directionally associated with *Defining Problems* and *Analyzing*. Accordingly, *Modeling* and *Predicting* in the solution space had significant connections with the problem space via *Managing*. This result implies that STEM educators need to highlight effective managing and communication skills to promote diverse design iterations.

We assigned relatively straightforward design assignments to the lower grades, and it was confirmed that they tend to show less formalized thinking patterns than the upper graders. On the other hand, higher graders were given more complex design tasks, resulting in more consolidated patterns. There is little evidence to determine whether the sophistication of these patterns was due to a given problem or the students’ cognitive development. However, this result may corroborate previous studies that have found that more inexperienced designers tend to use limited design strategies (Atman et al., 2007; Mentzer, Becker, & Sutton, 2015). On the other hand, remarkably, we found that Door Alarm, which was given to fourth graders, had complex and diverse patterns that were similar to those used by six graders. This result may show that the level of sophistication in design thinking could vary depending on other factors, such as the problem structure, teaching style, and the content of the design task.

Many people have the misconception that engineering problems have a best solution (Crismond & Adams, 2012; Dym et al., 2005). The notion of a best approach is often mistakenly understood as *optimization*, which has led to this unproved belief (Bucciarelli, 2003). However, our study shows that students naturally take multiple pathways and iterations to arrive at a solution. This study shows that the EDP model is not simply sequential and that different cognitive patterns can emerge depending on various factors, such as grade level, types of design task, and complexity. Therefore, when introducing the EDP model to the classroom, teachers need to understand the nature of descriptive models and not just present the sequence of design steps. Also, teachers need to encourage students to explore divergent thinking for creative and innovative problem solving.

Abbreviations: CCSSM: Common Core State Standards for Mathematics; CTA: Concurrent Think-Aloud; GSEQ: Generalized Sequential Querier; NGSS: Next Generation Science Standards; STEM:

Science, Technology, Engineering, and Mathematics; SLED : Science Learning through Engineering Design.

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Author Contribution Euisuk Sung contributed to the design and implementation of the study; led data collection, analysis, and interpretation; and writing and revising the manuscript. Todd Kelley contributed to the design of the study and revising the manuscript. All authors read and approved the final manuscript.

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Data Availability The datasets analyzed during the current study are not publicly available due to the request made in the consent forms issued to participants.

Ethical Approval and Consent to Participant The study presented in this paper had the Purdue University - Institutional Review Board's approval. Therefore, all procedures performed in this study were under the ethical standards of the institutional and national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all students and parents included in the study.

References

Arık, M., & Topçu, M. S. (2020). Implementation of engineering design process in the K-12 science classrooms: Trends and issues. *Research in Science Education, 16*(1), 1-23. https://doi.org/10.1007/s11165-019-09912-x

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In K. W. Spence & J. T. Spence (Eds.), *The psychology of learning and motivation* (Vol. 2, pp. 89–195). https://doi:10.1016/S0079-7421(08)60422-3

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*. Available from http://www2.gsu.edu/~psyrab/gseq/

Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher, 18*(1), 32-42. https://doi.org/10.2307/1176008

Bucciarelli, L. L. (2003). *Engineering philosophy*. Dup Satellite.

Buchanan, R. (1992). Wicked problems in design thinking. *Design Issues, 8*(2), 5-21. https://doi.org/10.2307/1511637

Clarkson, J., & Eckert, C. (2004). *Design process improvement: a review of current practice*. UK: Springer.

Common Core State Standards Initiative. (2010). *Common core state standards for mathematics.* Washington, DC: 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

Cross, N. (2021). *Engineering design methods: Strategies for product design*. John Wiley & Sons, Inc.

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

Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. *Journal of Engineering Education, 94*(1), 103-120. https://doi.org/10.1002/j.2168-9830.2005.tb00832.x

Elio, R., & Scharf, P. B. (1990). Modeling novice to expert shifts in problem-solving strategy and knowledge organization. *Cognitive Science*, *14*(4), 579-639. https://doi.org/10.1207/s15516709cog1404_4

Ericsson, K. A., & Simon, H. A. (1993). *Protocol analysis: Verbal reports as data.* MIT Press.

Estapa, A. T., & Tank, K. M. (2017). Supporting integrated STEM in the elementary classroom: A professional development approach centered on an engineering design challenge. *International Journal of STEM education, 4*(1), 1-16. https://doi.org/10.1186/s40594-017-0058-3

Flavell, J. H., Miller, P. H., & Miller, S. A. (1993). *Cognitive development*. Prentice-Hall, Inc.

Fan, S. C., Yu, K. C., & Lin, K. Y. (2020). A framework for implementing an engineering-focused STEM curriculum. *International Journal of Science and Mathematics Education*, 1-19. https://doi.org/10.1007/s10763-020-10129-y

French, M. J. (1999). *Conceptual design for engineers* (3rd ed.). Springer-Verlag London

Gall, M. D., Gall, J. P., & Borg, W. R. (2007). *Educational research: An introduction*. New York, NY: Person Education.

Garry, F., Hatzigianni, M., Bower, M., Forbes, A., & Stevenson, M. (2020). Understanding K-12 STEM education: A framework for developing STEM literacy. *Journal of Science Education and Technology, 29*(3), 369-385. https://DOI:10.1007/s10956-020-09823-x

Haberman, S. J. (1978). *Analysis of qualitative data: Vol.: 1- Introductory topics*. Academic Press.

Halfin, H. H. (1973). Technology: A process approach. *Dissertation Abstracts International, 11*(1), 1111A.

Hay, L., Duffy, A. H., McTeague, C., Pidgeon, L. M., Vuletic, T., & Grealy, M. (2017). A systematic review of protocol studies on conceptual design cognition: Design as search and exploration. *Design Science,* 3, 1-36. https://doi.org/10.1017/dsj.2017.11

Hruschka, D., Schwartz, D., St. John, D., Picone-Decaro, E., Jenkins, R., & Carey, J. (2004). Reliability in coding open-ended data: Lessons learned from HIV behavioral research. *Field Methods, 16*(3), 307–331. https://doi:10.1177/1525822X04266540.

Hubka, V. (1980). *Principles of engineering design*. Butterworth Scientific.

Indiana Academic Standards. (2010). *Indiana academic standards for science*. Retrieved from https://www.in.gov/doe/students/indiana-academic-standards/

Jackson, A., Godwin, A., Bartholomew, S., & Mentzer, N. (2021). Learning from failure: A systematized review. *International Journal of Technology and Design Education, 32,* 1853–1873. https://doi.org/10.1007/s10798-021-09661-x

Jin, Y., & Benami, O. (2010). Creative patterns and stimulation in conceptual design. *Ai Edam, 24*(2), 191-209. DOI: https://doi.org/10.1017/S0890060410000053

Jin, Y., & Chusilp, P. (2006). Study of mental iteration in different design situations. *Design Studies, 27*(1), 25-55. https://doi/10.1016/j.destud.2005.06.003

Johnsey, R. (1995). The design process—Does it exist?. *International Journal of Technology and Design Education, 5*(3), 199-217. https://doi.org/10.1007/BF00769904

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/10.1108/02756660710760953

Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. International Journal of STEM education, 3(1), 1-11. https://doi.org/10.1186/s40594-016-0046-z

Landis, J. R., & Koch, G. G. (1977). An application of hierarchical kappa-type statistics in the assessment of majority agreement among multiple observers. *Biometrics, 33*(2), 363-374. https://doi/10.2307/2529786

Lawson, B. (1979). Cognitive strategies in architectural design. *Ergonomics, 22*(1), 59-68. https://doi/10.1080/00140137908924589

Lu, C. C. (2015). The relationship between student design cognition types and creative design outcomes. *Design Studies, 36*, 59-76. https://doi/10.1016/j.destud.2014.08.002

Maltese, A. V., Simpson, A., & Anderson, A. (2018). Failing to learn: The impact of failures during making activities. *Thinking Skills and Creativity, 30*, 116-124. https://doi/10.1016/j.tsc.2018.01.003

March, L. J. (1984). The logic of design. In N. Cross (Ed.), *Developments in design methodology* (pp. 265-276). John Wiley & Sons, Ltd.

Meadows, S. (2006). *The child as thinker: The development and acquisition of cognition in childhood* (2nd ed.). Routledge.

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/10.1002/jee.20105

Moodley, K., Gaigher, E. (2019). Teaching electric circuits: teachers' perceptions and learners' misconceptions. *Research in Science Education. 49*(1), 73–89. https://doi.org/10.1007/s11165-017-9615-5

Pleasants, J., & Olson, J. K. (2019). What is engineering? Elaborating the nature of engineering for K-12 education. *Science Education, 103*(1), 145-166. https://doi.org/10.1002/sce.21483

The NGSS Lead States. (2013). *Next Generation Science Standards: For states, by states.* National Academies Press.

Robson, S. (2006). *Developing thinking and understanding in young children: An introduction for students*. Routledge.

Schnittka, J., & Schnittka, C. (2016). ''Can I drop it this time?'' Gender and collaborative group dynamics in an engineering design-based afterschool program. *Journal of Pre-College Engineering Education Research (J-PEER), 6*(2), 1-24.

Shroyer, K., Lovins, T., Turns, J., Cardella, M. E., & Atman, C. J. (2018). Timescales and ideaspace: An examination of idea generation in design practice. *Design Studies, 57*, 9-36. https://doi.org/10.1016/j.destud.2018.03.004

Sung, E., & Kelley, T. R. (2019). Identifying design process patterns: a sequential analysis study of design thinking. *International Journal of Technology and Design Education, 29*(2), 283-302. https://doi.org/10.1080/09544828.2022.2042498

Thornton, S. (2002). *Growing minds: An introduction to cognitive development*. Palgrave Macmillan.

Wendell, K. B., Wright, C. G., & Paugh, P. (2017). Reflective decision-making in elementary students' engineering design. *Journal of Engineering Education, 106*(3), 356-397. https://doi.org/10.1002/jee.20173

Wynn, D. C., & Eckert, C. M. (2017). Perspectives on iteration in design and development. *Research in Engineering Design, 28*(2), 153-184. https://doi.org/10.1007/s00163-016-0226-3

Yu, K. C., Wu, P. H., & Fan, S. C. (2020). Structural relationships among high school students' scientific knowledge, critical thinking, engineering design process, and design product. *International Journal of Science and Mathematics Education, 18*(6), 1001-1022. ehttps://doi.org/10.1007/s10763-019-10007-2