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BOARD # 206: Exploring the Development of Systems Thinking in Engineering Education in Homeschooling Settings (WIP)

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Exploring the Development of Systems Thinking in Engineering Education in Homeschooling Settings (WIP)

Abstract

Systems thinking is fundamental to the engineering design process; however, an understanding of its development remains limited within homeschooling settings. This study, grounded in a conceptual framework that combines Integrated STEM Education and Systems Thinking, explores how homeschoolers develop systems thinking through participation in an integrated STEM learning experience. We report a qualitative case study design involving a team of three homeschoolers. An a priori coding was developed based on four cognitive learning objectives for systems thinking. Preliminary findings indicate that homeschoolers made progress in all learning objectives: apply terminology and concepts, defining the system, identify interactions, and create models of the system. The collaborative participation of parents and researchers in implementing the STEM experience fostered a learning environment that enabled homeschoolers of different ages to collaboratively develop their systems thinking. This study contributes to engineering education research by providing insights into the development of systems thinking among pre-college students within the homeschooling system.

Introduction

Systems thinking is a fundamental aspect of engineering education [1]. The challenges engineers face are not isolated entities but are part of complex systems encompassing technical and contextual dimensions. Systems thinking is essential for addressing these problems by recognizing relationships within and between systems [2]. Therefore, engineers frequently rely on systems thinking because it "involves understanding part–whole relationships, and how choices for parts of a system have consequences for the overall functioning of the whole system" [3, p. 496]. Systems thinking contributes to the engineering design process by ensuring that solutions address identified problems while considering the interconnections within the system and its links to other systems. Therefore, systems thinking is crucial for the development, sharing, testing, and refinement of engineering design ideas [4].

Systems thinking has been integrated into K–12 education through the Next Generation Science Standards (NGSS) cross-cutting concepts [5]. The National Academies of Sciences, Engineering, and Medicine (NASEM) propose transforming how science and engineering are taught in K–12, highlighting a shift from teaching that leads to ideas that are disconnected from phenomena to those that "involve more systems thinking and modeling to explain phenomena and to give a context for the ideas to be learned" [6, p. 85]. Therefore, it is essential to identify effective methods for teaching systems thinking [7]. However, Levy and Moore [5] highlight that this knowledge, particularly with elementary students, remains limited.

Additionally, there is a notable lack of research in the field of engineering education and systems thinking with homeschooling settings. Homeschooling is an educational system in which parents educate their children at home, rather than in formal school settings [8]. These children are known as *homeschoolers*. Homeschooling families often form homeschooling communities, where they work together to engage in learning activities [9]. In many of these communities, parents organize themselves to take on roles as instructors, while other parents assist with the development of activities [10]. This study addresses the need to expand our understanding of pre-college engineering students' development of systems thinking in homeschooling settings. The research question guiding this study is: How is systems thinking developed in pre-college homeschoolers when they participate in an integrated STEM learning experience?

Conceptual Framework

Integrated STEM Education

The NASEM emphasizes that "a single discipline will not best prepare graduates for the challenges and opportunities presented by work, life, and citizenship" [11, p. viii]. Therefore, an integrated STEM education approach has facilitated a shift toward a more interdisciplinary teaching perspective [12]. Integrated STEM encompasses more than the separate instruction of the disciplines of Science, Technology, Engineering, and Mathematics; its purpose is to enable all students to "learn to apply basic content and practices of the STEM disciplines to situations they encounter in life" [13, p. 5]. This approach advocates for *integrated STEM learning experiences* that allow students to connect ideas across disciplines [11]. These learning experiences are "practices of disciplinary knowledge, including science and/or mathematics, through the integration of the practices of engineering and engineering design of relevant technologies" [14, p. 955]. The design of integrated learning experiences requires the inclusion of complex, authentic, and real-world problems to provide students with meaningful learning experiences [1]. Participation in these integrated learning experiences not only enhances disciplinary knowledge but also creates opportunities for students to develop skills such as problem-solving, collaboration, and systems thinking [12, 15].

Systems Thinking

Systems thinking "represents a worldview, a way of thinking about the world that emerges as an individual develops the ability and willingness to see it holistically" [16, p. 950]. Two modes in the teaching of systems thinking can be identified: *abstracting mode* and *engaging mode* [17]. Abstracting mode helps students learn the concepts of systems thinking and its basic tools. However, this mode does not necessarily lead to students being able to effectively use systems thinking [18]. On the other hand, the engaging mode focuses on teaching systems thinking by encouraging students to apply this thinking to issues of their interest, such as sustainability and social responsibility [17, 18]. More specifically, while the abstracting mode "emphasizes abstracting of concepts, ideas of, and methodologies for systems thinking", the engaging mode "emphasizes engaging with specific situations" [17, p. 43]. Figure 1 displays a table based on Litzinger's [18] proposal, outlining cognitive learning objectives for systems thinking in engineering education, developed and mapped within the Framework for Science Education [4].

Cognitive Level	From crosscutting themes found in the Framework	Possible Learning Objectives
1. Apply basic terminology and concepts	Define relevant terms/concepts including system	Define and apply key terms/concepts. Apply key terms/concepts appropriately in describing a system
2. Define the system	Specify the boundary of the system being modeled	Define system boundary verbally and in graphical representations
3. Identify and characterize interactions	Identify interactions	Identify interactions within the system and between the system and its surroundings
4. Create models of the system	Create models of systems at different levels from lists and simple sketches	Create a verbal description of a system Create graphical representations of a system

Fig. 1. Learning objectives related to systems thinking, based on Litzinger [18].

Methods

This study adopts an exploratory qualitative case study design [19] aimed at describing the processes involved in the development of systems thinking among homeschoolers. A homeschooling community was selected to conduct the case study. To elicit systems thinking, an *integrated STEM learning experience* was designed for this study.

Participants

The homeschooling community selected for this study comprises 9 families with homeschoolers aged 4 to 11 years, totaling 22 children. In this community, the families meet twice a month to conduct collaborative educational activities and arrange events such as museum visits and company tours. Parents take on various roles to organize and facilitate teaching activities for their homeschoolers. When asked, the parents expressed that prior to the implementation of this study, they had not explicitly used activities aimed at promoting systems thinking. For this pilot implementation, nine participants were randomly selected. In forming the teams, we followed the parents' suggestions, as they highlighted that homeschoolers often have the freedom to create their own teams. This led to the formation of three teams: Homeschooler 1, an 11-year-old girl; Homeschooler 2, an 11-year-old boy; and Homeschooler 3, a 7-year-old boy. This WIP paper presents preliminary results from the analysis of one of the three teams.

Integrated STEM Learning Experience

The design of the integrated STEM learning experience for this study aligns with the engaging mode of teaching systems thinking [17, 18] by encouraging homeschoolers to apply their knowledge to issues related to social responsibility. Specifically, we selected the context of ocean acidification. This design also aligns with the recommendations of Moore et al. [1], who suggest that the design of STEM learning experiences should address problems that are parallel to those faced by engineers and scientists in the real world. Furthermore, NASEM [6] emphasizes that providing students in grades 6–12 with access to real-world data, such as ocean acidification and pH levels, fosters the generation of meaningful questions and facilitates the development of knowledge aligned with the Standards. Consequently, we designed the learning experience *"Ocean warriors: Homeschoolers tackling ocean acidification", which* includes three main activities:

1. Activity 1: The Acid Test – Uncovering the Secrets of pH and Ocean Acidification
   - Task 1: Investigating the Effects of Submerging Shells in Water and Vinegar
   - Task 2: Exploring and Measuring pH – Comparing Water and Vinegar
   - Task 3: Breathing into Water and Observing Changes in pH
2. Activity 2: Become a Storyteller
3. Activity 3: Designing Change – Reducing Ocean Acidification

Activities 1 and 2 were implemented in a single session (80 minutes), while Activity 3 was implemented a week later (45 minutes). To facilitate the experience an *instructor team* was formed, comprised of community homeschooling parents and the lead researcher of this study.

Data Collection and Data Analysis

Data collection involved audio recordings of students' discussions, presentations, and written work during the experience. All audio recordings were transcribed, and data were organized according to the respective teams. For this conference paper, the data was translated from Spanish to English by the authors. To address the research question, we employed an *a priori* *coding* [20], based on the cognitive learning objectives for systems thinking in engineering education from Litzinger [18]. For this WIP conference paper, we focused on analyzing the developmental processes of one team.

Preliminary Results

Activity 1: The Acid Test – Uncovering the Secrets of pH and Ocean Acidification

The homeschoolers engaged in formulating hypotheses, conducting experiments, making observations, and developing arguments. In Task 1, the homeschoolers were asked to predict what would happen to an eggshell submerged in water and another submerged in vinegar. The homeschoolers hypothesized that the vinegar would cause the eggshell to crumble, break, and sink, while they predicted that water would not affect the eggshell, allowing it to float. The 11-year-old students contributed more to the initial hypotheses. When the mother leading the activity asked the 7-year-old participant (Homeschooler 3) for her thoughts, she responded that she preferred to observe what would happen. After submerging the eggshells, observing the results for approximately 15 minutes, and recording their notes, the homeschoolers concluded that the vinegar caused visible damage to the eggshell, while the water did not. For this activity, eggshells were used instead of seashells due to the similar characteristics of both, and to reduce reaction times in water and vinegar. This similarity was explained to the homeschoolers. Upon completion of this task, both older and younger homeschoolers participated actively. The mother explained that the key difference between water and vinegar lies in their acidity, which can be measured using pH. In Task 2, the students measured and compared the acidity of water and vinegar. For measuring the pH, the homeschoolers used a pH test liquid, which works by adding a few drops of the liquid to the water or vinegar. The pH test liquid causes the water to change color, and the pH is determined by comparing the resulting color to a reference scale. From their observations, they concluded that the acidity of the vinegar was responsible for damaging the eggshells. In Task 3, the mother guided the children to measure the pH of water before and after blowing air into it through a straw. The homeschoolers observed a change in pH and remarked: **“***When we blow into the water, we increase the pH.”* A mother told the homeschoolers that when we blow, we release carbon dioxide. Building on this explanation, the homeschoolers stated *“When we blow into H_2O, we add carbon dioxide, which changes the water.”* Figure 2 shows that the homeschoolers included technical terms such as H_2O and carbon dioxide.

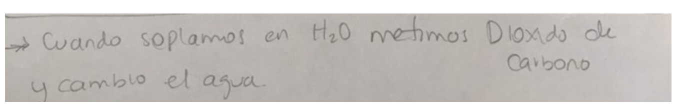

Fig. 2. Excerpt from the homeschoolers’ team working notes.

Activity 2: Become a Storyteller

Homeschoolers recorded their voices over a silent video depicting the process of ocean acidification. They created and recorded their own audio narratives to interpret the visual content. The transcription preserves the students’ technical expressions; for example, they used *H_2O* to refer to water and *CO_2* to refer to carbon dioxide. The team narrated:

> Team: Hello, I am the Earth. You, my human friends, and your activities have caused significant harm to my air and seas (Homeschooler 1). You release carbon dioxide, which acidifies my water, with H_2O and CO_2 turning it into carbonic acid which is deadly to me

(Homeschooler 3). Destroying my animals' food and with it my entire food chain (Homeschooler 2). In conclusion, you're not just harming me, you are harming yourselves. Help me! (Homeschooler 1).

Activity 3: Designing Change – Reducing Ocean Acidification

The students were asked whether changes could be made to reduce ocean acidification. Their responses included*: Factories could produce less smoke. Instead of driving to the store, we could walk. I thought maybe we could breathe less —I am just kidding! But if we coordinated errands to use the car only once instead of multiple times, that would help.*

The homeschoolers were then tasked with creating diagrams to explain their proposed solutions to reduce ocean acidification. Although the discussion was conducted in groups and teams, each homeschooler chose to independently create and present their own diagrams. They presented their ideas both graphically and verbally. Figure 3 shows the diagram created by Homeschooler 3, who explained:

> Homeschooler 3: If we reduce the use of smog, we pollute the air less which pollutes the water less which pollutes fewer shells, it can help the food chain, but much more, mmm, which helps the planet which helps ourselves.

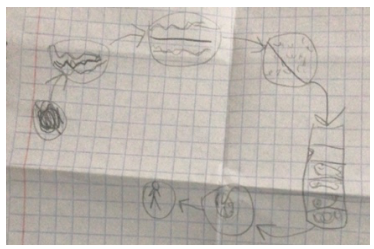

Fig. 3. Diagram built by homeschooler 3

At the end of all the homeschoolers' presentations, the instructors' team facilitated a conversation with the homeschoolers to explain that the design they created represents a system and that we are surrounded by many systems in the world. An excerpt from this conversation is:

> Instructors' Team: A system is composed of multiple elements, and if one element is altered, the others are affected as well. Is that correct?
> Homeschoolers: Yes!

Discussion and Preliminary Conclusions

The analysis highlights that the learning experience of this study has the potential to elicit the four learning objectives associated with system thinking [18]. Activity 1 was fundamental in introducing the homeschoolers to the concepts and terminology related to the ocean acidification. They articulated statements such as, *"when we blow into H_2O, we add carbon dioxide, which changes the water."* Therefore, the homeschoolers *apply basic terminology and concepts* (Cognitive Level 1, [18]) associated with the ocean acidification. Although the homeschoolers did not explicitly distinguish the boundaries of this system from other systems, they successfully *defined the system* (Cognitive Level 2, [18]) through both verbal and graphical representations. Moreover, they expressed their ideas by using indistinctly and fluently different terms to describe the phenomenon; sometimes in colloquial ways, such as "water" or "carbon dioxide", and others using more technical or scientific terms, such as "H_2O" and "CO_2". Activities 2 and 3 provided the homeschoolers with the opportunity *to identify and characterize interactions* (Cognitive

Level 3, [18]) and to *create models of the ocean acidification system* (Cognitive Level 4, [18]). Their storytelling and the diagrams indicate their ability to develop verbal and graphical descriptions of interactions “within a system and between a system and its surroundings” [18, p. 45]. The homeschoolers’ development of systems thinking led them to identify the elements of ocean acidification mirror to the description of Cunningham and Kelly [3], where modifications within the system have consequences for its overall functioning. Additionally, the homeschoolers’ suggestions for changes through their own actions align with Senge’s [21] emphasis on the sense of responsibility and community engagement in systems thinking. Distinct from traditional schooling, where children are grouped by age, homeschoolers typically learn alongside siblings and peer-homeschoolers of varying ages. Therefore, the instructors’ team, with active parental participation, was crucial for facilitating a meaningful learning experience. This experience fostered an inclusive learning environment in which homeschoolers of different ages navigated various cognitive levels of systems thinking. This study will contribute to engineering education research, as systems thinking is crucial for the development and refinement of engineering design ideas [4]. Additionally, it addresses the need to expand knowledge of systems thinking for pre-college students [7], with a particular focus on homeschooling settings. The next steps for this study will involve analyzing other teams of homeschoolers that will allow us to deepen the understanding of the development of system thinking.

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