2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #51086

WIP: Developing Systems Thinking through Internet of Things (IoT) Project-Based Learning in Electronics Education

Dr. Aziz Shekh-Abed, Ruppin Academic Center

Aziz Shekh-Abed is a lecturer in the Department of Electrical and Computer Engineering at Ruppin Academic Center, Israel. He holds a PhD in engineering education from the Technion - Israel Institute of Technology. His research focuses on project-based learning, systems thinking, abstract thinking, soft skills, and metacognition. Dr Shekh-Abed holds an MA in science education and a BSc in technology education, both from Tel Aviv University, Tel Aviv, Israel. He is listed in the Israeli Engineers and Architects Register, under the section of electronic engineering.

Developing Systems Thinking through Integrated IoT Project-Based Learning in High School Electronics Education

Abstract

This study investigates the role of Internet of Things (IoT) project-based learning (PjBL) as a systems-oriented educational environment for fostering systems thinking among high school electronics students. Systems thinking, defined as the ability to recognize the system as a whole, understand interactions and feedback mechanisms, trace information flows, and reason about design trade-offs within interconnected systems, is widely acknowledged as a core competence in engineering design. Despite its importance, systems thinking remains insufficiently assessed in secondary-level engineering education, where instruction often emphasizes component-level knowledge and linear problem-solving approaches.

The study is situated in a one-year high school electronics track involving 38 twelfth-grade students. Over the course of the program, students engage in a sequence of scaffolded design activities intentionally structured to increase system complexity and promote system-level reasoning. These activities include a foundational ESP32 assignment integrating analog and digital inputs and outputs; a conceptual examination focusing on data flow and control logic independent of programming syntax; a team-based proposal addressing a real-world engineering challenge; the development of open-ended IoT prototypes connecting an ESP32 edge device to a Raspberry Pi gateway via MQTT communication, with system logic and visualization implemented using Node-RED and InfluxDB dashboards; and a final project examination accompanied by structured reflection.

The integrated IoT projects constitute multi-layered systems that require students to coordinate hardware components, embedded software, communication protocols, data management, and visualization tools. While such projects reflect authentic engineering practice, they also pose substantial cognitive and system-level challenges for high school learners. Students are required to reason across multiple abstraction levels, manage interdependencies among subsystems, and troubleshoot failures that often span more than one system layer.

A predominantly qualitative research approach, complemented by descriptive quantitative analysis, was employed. Students' project artifacts were evaluated using a systems thinking rubric designed to capture varying levels of system-level reasoning in open-ended IoT projects. Preliminary analysis revealed variation across the five dimensions, with approximately 75% of students achieving moderate-to-high performance in component identification, compared to only about 20–22% demonstrating high-level performance in integration and trade-off reasoning. In parallel, students' reports, reflections, and instructor observations were analyzed to identify recurring design challenges, including hardware–software integration difficulties, coordination across

system layers, and time-management constraints. The study aims to inform the design of instructional scaffolds and assessment tools that better support systems thinking development in secondary-level engineering education.

1. Introduction

Contemporary engineering practice increasingly involves the design and operation of complex systems that integrate hardware, software, communication infrastructures, and data-driven processes. Engineers are therefore required not only to master individual components but also to reason about system architectures, interactions among subsystems, feedback mechanisms, and trade-offs that emerge from integration. Accordingly, systems thinking is widely recognized as a core competence in both engineering education and professional practice [1],[2].

Systems thinking is commonly described as the ability to understand a system as a whole, identify relationships among its components, trace flows of information or control, and anticipate the consequences of design decisions across multiple levels of abstraction [3],[4]. Research in engineering education has shown that students often struggle to move beyond local, component-focused reasoning toward holistic system-level understanding, particularly when dealing with complex, open-ended design tasks [5],[6]. These challenges are especially pronounced among novice learners, who may lack strategies for coordinating multiple representations and managing cognitive load.

Despite the growing emphasis on systems thinking in higher education, its development and assessment in secondary-level engineering and electronics education remain underexplored. High school electronics courses frequently emphasize procedural skills, such as circuit assembly or microcontroller programming, while providing limited opportunities for students to explicitly reason about system interactions and emergent behavior [7],[8]. Moreover, assessment practices at this level tend to focus on functional correctness rather than on students' system-level reasoning processes.

Project-based learning (PjBL) has been proposed as an effective pedagogical approach for promoting higher-order thinking and authentic engineering practices ([9],[10]. In particular, Internet of Things (IoT)–based projects offer a rich context for systems thinking, as they inherently involve multiple interacting layers, including sensing, embedded computation, communication, data management, and visualization. Prior studies suggest that such environments can support students' understanding of complex systems, but also introduce significant cognitive and coordination challenges [11],[12].

Importantly, engaging students in complex projects does not guarantee the development of systems thinking. Without intentional instructional design and appropriate assessment tools, students may focus on isolated technical issues rather than developing an integrated understanding of the system as a whole [13]. This highlights the need to examine not only the potential of IoT-based PjBL to foster systems thinking, but also the difficulties students encounter when designing and integrating multi-layered electronic systems in a high school context.

Accordingly, this study investigates the role of IoT project-based learning as a systems-oriented educational environment for twelfth-grade electronics students. The study focuses on a scaffolded sequence of design activities culminating in open-ended IoT projects that integrate an ESP32 microcontroller, a Raspberry Pi gateway, MQTT communication, Node-RED logic, and database-driven visualization. By examining both students' emerging systems thinking and the challenges they face during system integration, this work aims to contribute empirical and methodological insights that can inform instructional scaffolding and assessment practices in secondary-level engineering education.

This study contributes (1) empirical evidence of systems thinking development in a secondary-level IoT context, (2) a rubric-based operationalization of systems thinking tailored to multi-layered IoT systems, and (3) preliminary performance distributions that reveal differential development across foundational and higher-order systems thinking dimensions.

2. Theoretical Background

2.1 Systems Thinking in Engineering Education

Systems thinking has been widely recognized as a foundational competence for engineers operating in complex and interconnected technological environments. From a systems engineering perspective, systems thinking involves the ability to conceptualize a system as a coherent whole, identify system boundaries, understand interactions among components, trace flows of information or control, and anticipate emergent behavior resulting from integration [1],[3]. Rather than focusing solely on individual elements, systems thinking emphasizes relationships, feedback mechanisms, and trade-offs across multiple levels of abstraction [2],[4].

Within engineering education research, systems thinking has been associated with improved problem formulation, design decision-making, and the ability to manage complexity in open-ended tasks [6],[7]. However, empirical studies consistently show that learners—particularly novices—tend to approach complex problems using localized, component-focused reasoning strategies, which can hinder the development of holistic system understanding [5]. This gap between expert-like system reasoning and novice approaches highlights the need for instructional contexts that explicitly support systems thinking development.

Although systems thinking has gained increasing attention in undergraduate engineering programs, its role in secondary-level engineering and electronics education remains insufficiently explored. High school students typically encounter electronics through narrowly scoped tasks, such as assembling circuits or writing isolated code segments, which may not require explicit consideration of system interactions or emergent behavior [8]. Consequently, systems thinking at this level is often implicit, unscaffolded, and rarely assessed.

2.2 Project-Based Learning as a Framework for Systems Thinking

Project-based learning (PjBL) is grounded in constructivist learning theory and emphasizes learning through engagement with authentic, complex problems over extended periods of time [9],[10]. PjBL environments typically require learners to define problems, generate and evaluate design alternatives, implement solutions, and reflect on outcomes—processes that align closely with systems engineering practices.

Research suggests that PjBL can promote higher-order cognitive skills, including integration of knowledge across domains, collaborative problem solving, and metacognitive awareness [13]. Importantly, PjBL provides opportunities for students to encounter system-level complexity, making it a promising pedagogical approach for fostering systems thinking [14]. However, the presence of a project alone does not guarantee systems-level learning. Without intentional scaffolding, students may focus on task completion or local optimization rather than developing coherent system models [7].

At the high school level, implementing PjBL presents additional challenges, including limited instructional time, heterogeneous prior knowledge, and difficulties in assessing complex learning outcomes. These constraints underscore the importance of carefully designed project sequences and assessment tools that make systems thinking explicit and observable.

2.3 Internet of Things (IoT) Projects as Cyber-Physical Systems

Internet of Things (IoT) systems represent a class of cyber-physical systems characterized by the integration of physical devices, embedded computation, communication networks, and data-driven services [15]. Educational IoT projects typically involve multiple interacting layers, including sensing and actuation, embedded software, networking protocols, data storage, and visualization. As such, IoT-based learning environments inherently embody the complexity and interdependence that define system-level thinking.

Prior studies indicate that IoT projects can enhance students' understanding of real-world engineering systems by exposing them to end-to-end system architectures and authentic design constraints [11]. At the same time, research highlights that IoT projects introduce significant cognitive demands, particularly related to system integration, debugging across layers, and managing asynchronous processes [12]. These challenges are especially salient for high school students, who may lack prior experience with large-scale system integration.

From a theoretical standpoint, IoT projects can be viewed as learning laboratories for systems thinking, provided that students are guided to reason about interactions, dependencies, and trade-offs rather than treating technologies as isolated components. This perspective aligns with calls in engineering education to move beyond tool-focused instruction toward system-oriented learning experiences [1],[4].

2.4 Assessment of Systems Thinking

Assessing systems thinking remains a persistent challenge in engineering education. Traditional assessments often prioritize correctness or functionality, offering limited insight into students' reasoning about system structure and behavior [6]. To address this limitation, researchers have advocated for analytic rubrics that capture multiple dimensions of systems thinking, such as component identification, interaction analysis, and trade-off reasoning [4],[14].

In secondary education contexts, the lack of validated assessment tools further complicates efforts to study systems thinking development. This study responds to this gap by proposing a systems thinking rubric tailored to open-ended IoT projects, enabling the examination of both emerging system-level reasoning and the difficulties students encounter during system integration.

The design of the systems thinking rubric in this study is informed by these theoretical perspectives, mapping key dimensions such as component identification, interaction analysis, system integration, troubleshooting, and trade-off reasoning to established constructs in systems thinking literature. This alignment ensures that the assessment captures both foundational and higher-order aspects of system-level reasoning.

3. Research Objectives and Research Questions

3.1 Research Objectives

The overarching objective of this study is to investigate how Internet of Things (IoT) project-based learning (PjBL) can support the development of systems thinking among high school electronics students, while simultaneously identifying the challenges students encounter when designing and integrating complex electronic systems. More specifically, the study aims to:

1. Examine the extent to which integrated IoT projects foster systems thinking among twelfth-grade electronics students, with particular attention to system-level reasoning, integration across subsystems, and understanding of information flow and interactions.

2. Identify recurring cognitive and technical challenges that students experience during the design and implementation of multi-layered IoT systems, including difficulties related to hardware–software integration, communication, data handling, and system coordination.

3. Explore how students' systems thinking manifests in project artifacts and reflective documentation, providing insight into how learners reason about system structure, functionality, and trade-offs.

4. Develop and apply a systems thinking assessment rubric tailored to open-ended IoT projects, with the goal of making systems thinking visible and assessable in a secondary-level engineering context.

5. Inform instructional design and pedagogical scaffolding by generating evidence-based insights that can guide educators in supporting systems thinking development in complex, project-based electronics learning environments.

3.2 Research Questions

Guided by the above objectives, the study addresses the following research questions:

1. How is systems thinking manifested in high school students' open-ended IoT project work, as evidenced by their project artifacts and system designs?

2. What system-level challenges do students encounter when designing and integrating IoT systems that combine hardware components, embedded software, communication protocols, and data management tools?

3. Which dimensions of systems thinking (e.g., identification of components, understanding of interactions, integration across layers, and reasoning about trade-offs) are most and least evident in students' IoT projects?

4. How do students describe and reflect on their system design processes, challenges, and learning experiences during the IoT project?

5. How can insights from students' project artifacts, reflections, and observed challenges inform the design of instructional scaffolds and assessment tools to better support systems thinking development in high school electronics education?

4. Methodology

4.1 Research Design

This study adopts a predominantly qualitative research design complemented by descriptive quantitative analysis to examine the development of systems thinking and the challenges encountered by high school students during integrated IoT project-based learning. The design combines quantitative analysis of project artifacts using a systems thinking rubric with qualitative analysis of students' reports, reflections, and instructor observations. This approach enables triangulation of evidence related to both students' system-level reasoning and the difficulties they experience during system design and integration.

The study is conducted as a design-based educational investigation embedded within an authentic instructional context. Rather than isolating variables under controlled conditions, the research examines learning processes as they unfold during a scaffolded sequence of classroom activities.

4.2 Participants and Educational Context

Participants are 38 twelfth-grade students enrolled in a one-year high school electronics track. Students have prior experience with basic electronics concepts and introductory microcontroller programming, but limited exposure to networked systems, data-driven applications, or multi-layered system integration.

Instruction takes place within regular classroom and laboratory sessions and culminates in team-based IoT projects. Students work in small teams to design, implement, and test their systems.

4.3 Instructional Sequence and Learning Activities

The instructional design follows a scaffolded sequence intended to gradually increase system complexity and promote system-level reasoning:

1. Foundational ESP32 assignment:
   Students implement analog and digital input/output functionality, focusing on local behavior and basic debugging.

2. Conceptual examination: A written assessment evaluates understanding of data flow, control logic, and signal pathways independent of programming syntax.

3. Team-based proposal: Student teams identify a real-world problem and propose an IoT-based solution, including preliminary system architecture.

4. Open-ended IoT project: Teams develop integrated IoT systems connecting an ESP32 edge device to a Raspberry Pi gateway via MQTT communication. System logic and visualization are implemented using Node-RED and InfluxDB dashboards.

5. Final project examination and reflection: Students present their systems and submit written reflections addressing design decisions, challenges, and learning outcomes.

4.4 Data Sources

Multiple data sources are collected to address the research questions:

- Project artifacts: system architectures, source code, Node-RED flows, dashboards, and final prototypes.

- Written reports and reflections: students' descriptions of system design processes, challenges, and learning experiences.

- Instructor observations: documented observations recorded throughout the project implementation.

- Assessment artifacts: scores from the conceptual examination and final project evaluation.

4.5 Assessment Instrument: Systems Thinking Rubric

A systems thinking rubric has been developed specifically for this study to assess students' system-level reasoning as manifested in open-ended IoT projects. The rubric includes five dimensions:

1. Identification of system components and boundaries
2. Understanding of interactions and information flow
3. Integration across hardware, software, and communication layers
4. System-level troubleshooting and causal reasoning
5. Design justification and trade-off analysis

Each dimension is evaluated across five performance levels, ranging from limited to advanced systems thinking. The rubric was applied to final project artifacts to generate the preliminary performance distributions reported in Table 1. The rubric was developed based on established systems thinking frameworks and iteratively refined through its application in the instructional context, providing initial evidence of its alignment with observed student reasoning.

4.6 Data Analysis

Quantitative analysis involved rubric-based scoring of final project artifacts across the five systems thinking dimensions. Scores were aggregated into three performance categories (Low: Levels 1–2; Moderate: Level 3; High: Levels 4–5) to generate cohort-level distributions. These distributions are presented in Table 1. Preliminary qualitative insights are reported based on students' reports, reflections, and instructor observations, while a full thematic analysis is ongoing. An iterative coding process is being employed to identify recurring themes related to system-level challenges, integration difficulties, and learning strategies. Codes will be refined through multiple cycles to enhance analytical rigor.

Triangulation across data sources will be used to strengthen the credibility of findings and to relate observed challenges to rubric-based indicators of systems thinking. At this stage, the quantitative analysis is descriptive and intended to provide an initial overview of performance distributions across systems thinking dimensions.

4.7 Ethical Considerations

Participation in the study is voluntary. Students and their guardians provide informed consent for the use of anonymized learning artifacts and reflections for research purposes.

All data are anonymized prior to analysis, and the study is conducted in accordance with institutional and educational ethical guidelines.

4.8 Methodological Limitations

As the study is conducted within a single educational context and cohort, findings may not be directly generalizable to other settings. In addition, the systems thinking rubric is under development and has not yet undergone formal validation. These limitations are addressed by framing the study as exploratory and by emphasizing transparency in methodological design. Additionally, the absence of inter-rater reliability analysis represents a limitation, and future work will aim to establish the reliability and validity of the rubric through multiple evaluators.

5. Findings

This section presents preliminary findings derived from formative observations, interim project artifacts, students' written reflections, and instructor documentation collected during the implementation of the IoT project-based learning sequence. As final project artifacts will be systematically evaluated at the end of the school year, the findings reported here should be interpreted as emerging patterns rather than conclusive results.

Table 1 indicates a clear variation in students' performance across the five systems thinking dimensions, revealing a distinction between foundational and higher-order competencies. Performance was strongest in the identification of system components and boundaries and in understanding interactions and information flow, where the majority of students achieved moderate to high levels. This indicates that most students were able to recognize key system elements and describe basic system relationships and data flows within their IoT systems. These findings directly address Research Question 3 by revealing uneven development across foundational and higher-order systems thinking dimensions.

In contrast, substantially weaker performance was observed in higher-order dimensions. Integration across hardware, software, and communication layers showed the greatest difficulty, with the highest proportion of students at the low level and only a limited number demonstrating advanced integration. A similarly low distribution of high-level performance was evident in design justification and trade-off analysis, indicating that students rarely engaged in explicit reasoning about alternative solutions or system-level design decisions.

System-level troubleshooting and causal reasoning demonstrated an intermediate pattern. While high-level performance was less common, a considerable proportion of students operated at a moderate level, particularly in contexts involving cross-layer debugging. This suggests that troubleshooting activities supported the development of partial system-level reasoning, even when full integration and design justification were not achieved. Taken together, these results indicate that students' systems thinking develops unevenly, progressing from component recognition and interaction-level reasoning toward, but not consistently reaching, full system integration and evaluative reasoning.

Table 1. Summary of Systems Thinking Outcomes in IoT Projects (Preliminary Results)

Systems Thinking Dimension	Low (Level 1–2)	Moderate (Level 3)	High (Level 4–5)	Emerging Pattern
Identification of components & boundaries	~25%	~45%	~30%	Most students could list components; fewer clearly defined system boundaries
Understanding of interactions & data flow	~35%	~40%	~25%	Data flow reasoning improved during debugging
Integration across hardware, software, and communication layers	~40%	~38%	~22%	Integration was the most challenging dimension
System-level troubleshooting	~30%	~42%	~28%	Cross-layer debugging triggered deeper reasoning
Design justification & trade-offs	~45%	~35%	~20%	Trade-off reasoning was least evident

Across the project sequence, students demonstrated increasing engagement with system-level considerations, particularly as tasks shifted from isolated component implementation to integrated IoT system design. Early activities, such as the foundational ESP32 assignment, primarily elicited component-focused reasoning, with students concentrating on sensor readings, pin configurations, and code correctness.

As students progressed to the open-ended IoT projects, interim artifacts and design discussions revealed a gradual shift toward system-oriented reasoning. Many teams began to explicitly reference relationships among system components, such as the interaction between ESP32 sensing behavior, MQTT message structure, and Node-RED control logic. In reflective writing, several students described their systems using terms related to data flow, control pathways, and subsystem dependencies, indicating emerging awareness of the system as an integrated whole.

However, the depth and consistency of systems thinking varied considerably among teams. While some students articulated coherent system architectures and end-to-end information flow, others continued to reason primarily at the level of individual components.

Analysis of interim artifacts and instructor observations revealed several recurring challenges that constrained students' ability to reason holistically about their systems:

- Hardware–software integration difficulties, particularly when sensor behavior did not align with expected software responses.
- Communication-related challenges, including misunderstandings of MQTT publish–subscribe mechanisms and topic hierarchy.
- Cross-layer debugging difficulties, where faults originated in one subsystem but manifested in another (e.g., network delays affecting control logic).
- Time-management constraints, which limited opportunities for iterative refinement and system-level reflection.

These challenges often led students to adopt trial-and-error strategies focused on local fixes, rather than systematic diagnosis based on a global system model.

Iterative design and troubleshooting emerged as critical mechanisms for promoting systems thinking. Students who engaged in repeated cycles of testing, failure analysis, and redesign showed greater awareness of system interdependencies. In particular, debugging activities that required tracing data from sensors through communication channels to dashboards prompted students to reconsider assumptions about system behavior.

Instructor observations suggest that moments of system failure—such as broken data streams or inconsistent actuator responses—served as productive triggers for system-level reasoning when accompanied by guided questioning and reflection.

Student reflections provided additional insight into how learners perceived their system design processes. Many students explicitly acknowledged the complexity of integrating multiple technologies and reported that understanding "how everything connects" was more challenging than learning individual tools.

Several reflections indicated a shift in students' self-perception, from viewing the task as a collection of technical steps to recognizing it as a system design problem. At the same time, other students expressed frustration and uncertainty, highlighting the need for structured scaffolds to support system-level thinking. The overall pattern suggests that foundational systems thinking skills (component identification and interaction tracing) were more readily developed than higher-order integrative and trade-off reasoning skills.

6. Discussion

The purpose of this study was to examine how integrated IoT project-based learning can function as a systems-oriented learning environment for high school electronics students, while also identifying the challenges that may hinder the development of systems thinking. The preliminary findings suggest that IoT-based PjBL provides meaningful opportunities for systems-level reasoning, but that such reasoning does not emerge uniformly or automatically across students and teams.

Consistent with prior research on systems thinking and project-based learning, the findings indicate that exposure to multi-layered IoT systems encouraged students to move beyond component-level reasoning toward more holistic perspectives. As students progressed from isolated ESP32 tasks to integrated IoT prototypes, many began to articulate relationships among sensing, communication, control logic, and data visualization. This shift aligns with theoretical accounts that emphasize the role of authentic, complex tasks in promoting systems-oriented thinking.

However, the uneven development of systems thinking across teams highlights an important insight: complexity alone is insufficient. While IoT projects inherently embody system-level structures, students require opportunities—and support—to explicitly reason about those structures. Without such support, learners may remain focused on local functionality rather than developing integrated mental models of the system.

The recurrent challenges identified in this study—particularly those related to hardware–software integration, communication protocols, and cross-layer debugging—mirror difficulties reported in both secondary and higher education contexts. These challenges served a dual role: acting both as barriers to progress and as catalysts for deeper system-level reasoning when appropriately scaffolded.

The findings suggest that moments of system failure were especially influential in triggering systems thinking, as students were forced to trace causes across subsystems rather than apply isolated fixes. This observation supports theoretical perspectives that frame breakdowns and anomalies as critical drivers of learning in complex systems environments.

A key contribution of this study is the identification of system breakdowns and cross-layer debugging as pedagogical mechanisms that can trigger systems thinking. These moments of failure appear to shift students from localized problem-solving toward broader system-level reasoning, highlighting the instructional value of guided troubleshooting in complex learning environments.

Iterative design and troubleshooting emerged as central mechanisms for supporting systems thinking development. Students who engaged more fully in cycles of testing, failure analysis, and redesign demonstrated greater awareness of interdependencies and system behavior. Importantly, reflective activities appeared to mediate this process by encouraging students to externalize their reasoning and reconsider assumptions about system operation.

These findings reinforce the importance of embedding structured reflection and guided questioning within project-based environments. Reflection helped transform technical activity into conceptual learning by shifting attention from “making it work” to understanding why the system behaved as it did.

From an instructional perspective, the findings suggest that IoT-based PjBL can serve as an effective context for systems thinking development when accompanied by intentional scaffolding. Educators should explicitly emphasize system architecture, information flow, and integration strategies, rather than assuming that students will infer these concepts implicitly.

From an assessment perspective, the observed variability in systems thinking underscores the value of analytic rubrics that capture multiple dimensions of system-level reasoning. The proposed systems thinking rubric offers a structured way to make such reasoning visible, particularly in open-ended projects where traditional assessments may fall short. The final application of the rubric will provide further insight into its usefulness and limitations.

The discussion of findings must be interpreted in light of several limitations. The study is situated within a single high school context and involves one cohort of students, which limits generalizability. In addition, the findings presented here are preliminary and based on formative data; systematic rubric-based evaluation of final project artifacts is still forthcoming.

Future research will focus on completing the rubric-based analysis, examining relationships between different dimensions of systems thinking and specific design challenges, and refining instructional scaffolds to better support system-level learning. Longitudinal studies could also explore how early exposure to integrated systems influences students' later engineering learning trajectories. This study contributes to the literature by providing empirical evidence from a secondary education context, where systems thinking development has been comparatively underexplored.

7. Conclusions

This study examined Internet of Things (IoT) project-based learning as a systems-oriented educational environment for fostering systems thinking among high school electronics students. Through a scaffolded sequence of design activities culminating in open-ended IoT projects, the study explored both the potential of such environments to support systems thinking and the challenges students face when integrating complex electronic systems.

The findings suggest that integrated IoT projects provide meaningful opportunities for engaging with system-level concepts, including component interactions, information flow, and subsystem interdependencies. As students progressed from isolated component tasks to multi-layered system integration, many demonstrated emerging systems thinking, particularly during troubleshooting activities that required reasoning across system layers. These results indicate that IoT-based projects can support a shift from component-focused reasoning toward more holistic system understanding.

At the same time, systems thinking did not develop uniformly. Students encountered substantial cognitive and technical challenges related to hardware–software integration, communication protocols, cross-layer debugging, and time management. Without explicit instructional scaffolding, these challenges often led to localized problem solving rather than coherent system-level reasoning. Iterative design, troubleshooting, and structured reflection were found to play a critical role in supporting students' system-level understanding.

From an educational perspective, the study highlights the need to intentionally design IoT-based projects as systems learning experiences, with explicit emphasis on system architecture, information flow, and integration strategies. From a research perspective, this work extends systems thinking research to the high school electronics context and introduces a rubric-based approach for assessing systems thinking in open-ended IoT projects.

These findings suggest that systems thinking should be explicitly scaffolded through tasks that require cross-layer reasoning and integration, rather than assumed to emerge naturally from exposure to complex project-based environments.

References

[1] INCOSE, *INCOSE Systems Engineering Handbook*, 5th ed. Hoboken, NJ, USA: John Wiley & Sons, 2023.

[2] P. M. Senge, *The Fifth Discipline: The Art and Practice of the Learning Organization*. New York, NY, USA: Broadway Business, 2006.

[3] J. Boardman and B. Sauser, *Systems Thinking: Coping with 21st Century Problems*. Boca Raton, FL, USA: CRC Press, 2008.

[4] M. Frank, "Engineering systems thinking and systems thinking," *Systems Engineering*, vol. 3, no. 3, pp. 163–168, 2000.

[5] C. E. Hmelo-Silver and M. G. Pfeffer, "Comparing expert and novice understanding of a complex system from the perspective of structures, behaviors, and functions," *Cognitive Science*, vol. 28, no. 1, pp. 127–138, 2004.

[6] J. Mendoza-Garcia, A. Goncher-Sevilla, and M. Li, "Assessing systems thinking skills in engineering education: Addressing implementation challenges and unintended consequences in ill-structured problems," in *Proc. 2025 ASEE Annual Conf. & Exposition*, June 2025.

[7] C. L. Dym, A. M. Agogino, O. Eris, D. D. Frey, and L. J. Leifer, "Engineering design thinking, teaching, and learning," *Journal of Engineering Education*, vol. 94, no. 1, pp. 103–120, 2005.

[8] A. Shekh-Abed, "Assessing students' soft skills development: A case study of an Arduino-based engineering course," in *Proc. Int. Conf. Interactive Collaborative Learning (ICL)*, Cham, Switzerland: Springer Nature Switzerland, Sep. 2024, pp. 285–292.

[9] M. J. Prince and R. M. Felder, "Inductive teaching and learning methods: Definitions, comparisons, and research bases," *Journal of Engineering Education*, vol. 95, no. 2, pp. 123–138, 2006.

[10] A. Kolmos, E. de Graaff, and X. Du, "Diversity of PBL—PBL learning principles and models," in *Research on PBL Practice in Engineering Education*, Rotterdam, The Netherlands: Brill, 2009, pp. 9–21.
[11] A. J. Magana and T. de Jong, "Modeling and simulation practices in engineering education," *Computer Applications in Engineering Education*, vol. 26, no. 4, pp. 731–738, 2018.
[12] S. J. Dickerson and R. M. Clark, "Use of SPICE circuit simulation to guide written reflections and metacognition," *IEEE Transactions on Education*, vol. 65, no. 3, pp. 471–480, 2021.
[13] C. E. Hmelo-Silver, R. G. Duncan, and C. A. Chinn, "Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark," *Educational Psychologist*, vol. 42, no. 2, pp. 99–107, 2007.
[14] J. Lee, B. Bagheri, and H.-A. Kao, "A cyber-physical systems architecture for Industry 4.0-based manufacturing systems," *Manufacturing Letters*, vol. 3, pp. 18–23, 2015.
[15] M. D. Lammi and K. Becker, "Engineering design thinking," *Journal of Technology Education*, vol. 24, no. 2, pp. 55–77, 2013.